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Highlights

Electrical Distribution Networks

Engineering Design Problems

Discovering Thoughts, Inventing Future

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Why Femtocell Networks?

By Padmapriya Sambanthan & Tamilarasi Muthu

Abstract- Cellular communication has witnessed tremendous growth during the past couple of decades. It plays an inevitable role in day-today life and in modernizing the human society. Throughout the evolution of cellular networks, many standards have come into existence, in order to meet the growing demand of ubiquitous, high quality voice, data and multimedia services. Besides, next generation cellular networks are in the necessity to offer seamless services even at the cell-edges and indoor provinces where the requirement for the cellular services is never the less. Though there is a growing demand for higher data rate services every day, the conventional macro cell (MC) is unable to provide better coverage extension to cell-edge users. To handle indoor and outdoor traffic growth, the recent heterogeneous network has emerged with an answer in the form of small cell technology. A study on fem to cell (FC) network along with its challenges is elaborated in this paper.

Keywords: *long term evolution, small cells, fem to cell networks.*

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Why Femtocell Networks?

Padmapriya Sambanthan [α] & Tamilarasi Muthu [σ]

Abstract- Cellular communication has witnessed tremendous growth during the past couple of decades. It plays an inevitable role in day-today life and in modernizing the human society. Throughout the evolution of cellular networks, many standards have come into existence, in order to meet the growing demand of ubiquitous, high quality voice, data and multimedia services. Besides, next generation cellular networks are in the necessity to offer seamless services even at the cell-edges and indoor provinces where the requirement for the cellular services is never the less. Though there is a growing demand for higher data rate services every day, the conventional macro cell (MC) is unable to provide better coverage extension to cell-edge users. To handle indoor and outdoor traffic growth, the recent heterogeneous network has emerged with an answer in the form of small cell technology. A study on fem to cell (FC) network along with its challenges is elaborated in this paper. We concentrate on revealing the importance of fem to cells and its evolution phases. As well, the technical challenges faced in fem to cell network are detailed to this end.

Keywords: long term evolution, small cells, fem to cell networks.

I. Introduction

Telecommunication has come a long way from Grahambell's wired telephone to the Long Term Evolution's (LTE) multimedia services. Conventional wired network has left the long-lasting footprints in terms of radiation-free communication, despite it cannot extend its limited service to longer distances. To span communication networks globally, wireless communication evolved in the year 1960. Compared with wired communication, wireless communication has led to lesser hardware and signal processing complexities.

The cellular network, an integral part of our society, has subjected the wireless communication to many generations, in order to guarantee ubiquitous voice, data and multimedia services to each and every network users. The First Generation (1G) cellular network has evolved during 1980's provided voice-only analog communication. In addition to voice, the Second Generation (2G) has offered data, fax and message services to the network users. The 2G's digital phone equipment has ushered in the cellular networks to multimedia computing and entertainment services through Third Generation (3G) technology. The high-capacity systems have turned the 3G network as an all-inclusive network.

The requirement for anytime, anywhere services has shifted the paradigm of 3G towards the Fourth Generation (4G). The goal of 4G is to increase the capacity and the speed of wireless data networks by using Digital Signal Processing (DSP) and Orthogonal Frequency Division Multiplexing (OFDM) techniques, which exist around the turn of the millennium. With the application of Internet Protocol (IP) based architecture, the 4G networks attain lesser data transfer latency compared with the 3G networks. The succeeding Fifth Generation (5G) networks are another high speed IP based networks, aiming to deliver multimedia services at the rates of Terabytes.

In the recent years, cellular network has witnessed a huge network user growth and hence, the network operator finds it harder to accommodate more number of users over the limited amount of spectrum. A recent study of Cisco has forecasted that the demand for wireless data traffic is drastically increasing and the monthly demand is expected to reach 6.3 Exabyte by 2016, that is, a 26-fold increase in data traffic demand when compared with the year 2010 [1]. In addition, specific studies show that more than 50% of voice traffic and 70% of mobile data traffic originate from indoor and enterprise environments [2]. On the other hand, poor indoor coverage is experienced by 30% of business and 45% of household network users [3]. Therefore, to increase the revenue of network operator and to satisfy all type of network users, a special emphasis must be given to handle astonishing network user growth, spectral demand and indoor coverage necessity. It is remarkable that all the wireless network generations (1G to 4G) are highly motivated to handle growing network traffics over the costly spectrum.

On the contrary, the Macro-base Station (MBS) provides limited coverage to indoor and cell-edge subscribers. As the MBS operates at high frequency, the ability of short-wave signal to penetrate walls gets reduced. Network operators would need 30,000 base-stations to offer good geographic coverage in a densely populated urban area and the power used by each MBS are set to achieve "marginal" indoor coverage at the cell-edges [4]. Some research has found that MBSs are responsible for 10% of global carbon-di-oxide emission and this percentage is expected to double over the next decade [5]. Moreover, jumbo MBSs consume 2.5kW to 4kW of power for connecting the mobile devices to the core network. Out of this huge power, only 5% to 10% of

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the energy would emerge out as a useful radiated signal and the remaining input power is dissipated as heat.

In addition, the simultaneous traffic originating from dense network users overload the MBS, which creates higher service blocking probability over busy hours. To handle this circumstance, the cellular network is reformulated into LTE based heterogeneous networks.

As the name implies, the co-existence of many small-radius cells in the same geographical area and over the same set of frequency has given rise to the heterogeneous networks. The idea of overlaying small cells on the existing macro cell network's frequency not only overcomes the spectral demand, but also provides enhanced indoor coverage to the network users.

II. Smallcell Technology

One MBS per Macro cell (MC) is not sufficient to satisfy the service requirements of widely distributed outdoor as well as indoor users. Hence, to serve all users efficiently, the large MC coverage is divided into many tiny cells, called small cells, which bring the base station closer to the users. Small cells not only lend excellent radio signal reception inside buildings, but also guarantee high quality multi-media services to the users in shadow, edge and coverage holes of a network [6]. Frequency reuse between MC and small cell enhances network capacity and revenue of the operator as well.

The overall spectral efficiency on overlaying small cells on the existing MC network is much greater than that is achievable by MC alone.

The small cell deployment process is customer-friendly as the small cell owners do not require on-site technical assistance. Small cell subscribers enjoy good signal quality from the closely located plug-and-play base stations and hence, the user equipments require minimal battery power. Thus, small cell technology is the solution to handle prevailing network challenges like network user density, spectral demand, poor indoor and cell-edge coverage, non-guaranteed service quality, huge power consumption and green-vegetation hazard.

In general, cells define the coverage boundary or footprint, till which they can provide service to the associated users. Based on the cell radii and transmit power, cells are classified into four major types. Table 1 lists the cell types with respect to the decreasing cell radii and decreasing transmit power level [7]. Among them, fem to cell, pico cell and microcell are called as small cells, which are overlaid on conventional MC network.

Table 1: Various cell types and their radius and transmission power

Cell types	Typical Cell Radius	Transmission power values
Macrocell	1Km-2Km	40W
Microcell	250m-1Km	5W
Picocell	100m-300m	2W
Femtocell	10m-50m	200mW

It can be observed from the Table 1 that the Fem to cell (FC) is the smallest cell and the pico cell is the second smallest cell. Macro cells and microcells cover wider geographical area and they bring-in the disadvantages like tall antennas, huge operating power, greater path loss and fading effects. On the other hand, pico- and fem to-base stations are closely associated with their registered users, where the chance of signal attenuation and other propagation loss are very less. Hence, the service quality of pico cell and fem to cell is comparatively higher than that of macro cell and microcell.

Fig. 1 indicates that FCs are preferred for residential based network users, pico cells are suggested for indoor enterprise users, whereas microcells and macro cell are preferred for large organizations and huge geographical areas respectively. All these cells are deployed over the same licensed band and controlled by a single network operator. Vodafone, a globally known service provider, launched small cells in the name of "Full Signal" in July 2010 [8] and it has deployed 25,000 pico cell units and 100,000 FC units, as on 2013 [9].

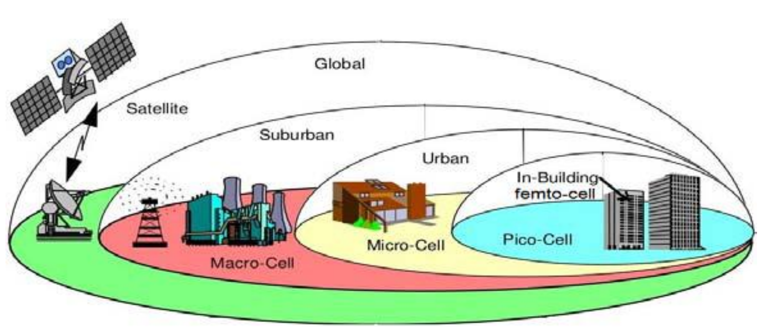
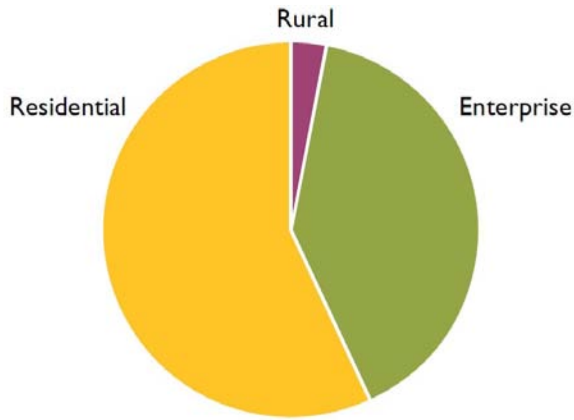


Fig. 1: Illustration of various types of cells

With the help of such small cells, the network operators are able to extend high quality coverage inside the subscriber house without the need for expensive high powered cellular towers. Small cells contribute in the growth of 4G standards and yield backward compatibility to 3G, 2G and 1G technologies as well. Hence, small cells are designed to offer superior indoor coverage at lower operating power with lesser path loss and fading effects.



Source: Informa Telecoms & Media

Fig. 2: Illustration of small cell deployment in the areas like residential, rural and enterprise environment

Major residential deployment, as shown in Fig. 2, highlights the takeover of FC technology (residential) compared with pico cell (enterprise) and microcell (rural) technologies. Thus, FCs are preferred by network users, who desire high quality indoor services.

III. The Best Candidate – Fem to cell

The theoretical concept of FC dates back to the year 1999, where Bell Research Labs first studied the small cell in the name of "home base station". The Alcatel brought a GSM-based home base station in the market in the year 2000. Later, in 2002, Motorola announced its 3G home base station, but the concept was yet found to be new. The FC concept became more famous in 2005 and the actual term FC was coined in 2006 [10]. Right then, a number of companies started trials and demonstrations on deploying FC technology.

A not-for-profit organization was formed by different vendors, operators and research organizations in July 2007 and was named as Fem to Forum [11].

FCs are subscriber deployed base stations, which provide guaranteed high quality voice, data and multimedia services to indoor communication devices, thereby offloading the MC traffic. FCs create small wireless coverage area and connect the registered network users to the cellular core network through subscriber's broadband Internet access. The low power Fem to-base Station (FBS) visually looks like an ordinary wireless router. FCs can concurrently serve 1 to 4 registered network users and can travel with the owners.

FCs operate at 20mW power with a coverage area of 10 to 15meters [12]. These low power nodes operate over licensed frequency band and hence provide backward compatibility to conventional cellular standards and forward compatibility to future cellular networks. They are cost effective solutions as they yield same performance as MBS, yet play a supplementary role to the power consuming MBS.

It is predicted that the future LTE-A networks would include FCs as one of the important member for the indoor cellular coverage. Deployment of FCs can enhance the total network capacity of more than three orders of magnitude [13]. The whole 4G FC market value is predicted to surpass $600 million in 2014. More than 5 million small cells have already been deployed and it is expected to reach 90 million units by 2016. ARC chart estimates that by 2017, a total of 5 million small cells would be deployed annually [14].

Worldwide, more than 47 leading operators have already deployed FCs in their existing network - encompassing public, enterprise and residential sectors [15]. In comparison with the existing MBS, the FBS consumes 40 times less power to deliver a signal to the indoor. This implies that FCs can increase the site density at the cell edges and at the indoor by 6.3 fold than that of an MC network [16].

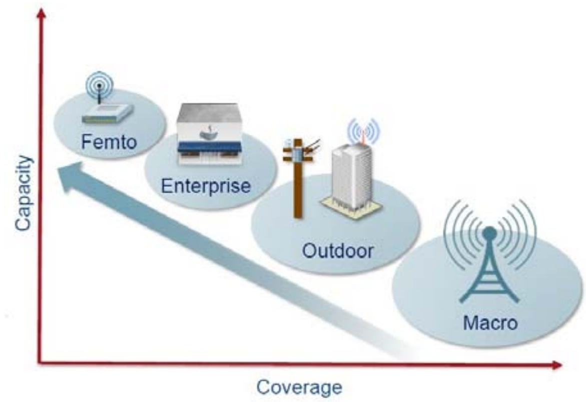
a) *Necessity of Fem to cell Networks*

The pursuit of FC network is due to the following fact: the capacity of a cell depends on the cell radius. From inverse square law, the total cell capacity is inversely proportional to the square of the cell radius.

$$\text{Capacity of a cell } \alpha \ \frac{1}{(\text{Cell radius})^2} \qquad (1)$$

If the cell radius is halved, the cell capacity is quadrupled. On correlating Table 1 and Equation (1), it is understood that the FC is the smallest cell among the prevailing cellular family and hence, FC is the best candidate to offer higher cell capacity.

Smaller the cell radius, closer the base station to its users. The signal degradation is negligible in such a scenario which improves received signal quality. Also, the registered users inside FC coverage may possess less mobility and the effect of fading is less and the aggregate throughput is more when compared to MC network. Hence, among various cell types, the short range FCs are preferred to as the best candidate for achieving higher cell capacity as shown in Fig. 3.



Source: Radisys Trillium

Fig. 3: Relation between coverage and cell capacity for various cell types

From the aspect of spectral efficiency, FCs play an important role in advancing the cellular networks. The conventional cellular network concept, called cell splitting [17] was invoked by LTE standard to enjoy the benefit of more users over limited spectrum. Donald postulates that the big MC coverage can be equally divided into multiple N subcells and each of them can have same set of frequency as of MC, with an extra care on efficient frequency planning. This concept enhances the cell capacity N times at the cost of careful network configuration and management procedures.

Out of contention, FCs offer numerous advantages like offloading MC traffic, guaranteed high quality indoor services, spectral efficiency, network capacity, multiuser diversity, non-emission of greenhouse gas and ubiquitous services to all users.

Due to its wide application, industry people call FCs as network in box, in-building coverage nodes, private network, plug-and-play base stations and low power access points. The FBSs are designed to support Global System for Mobile (GSM)/Code Division Multiple Access 2000 (CDMA2000) standards and are equipped with Global Positioning System (GPS) to sense the environment. Features such as frequency planning, sleep mode activation, synchronous operations with the under-laid MC network are attained through GPS enabled FBSs. In addition, self-configuring and self-organizing features in FC network greatly reduce the supervision task of the network operator. FC acts as a stand-alone, network integrating node that facilitates the co-existence of cross-tier users in FC proximity through proper access mode selection.

b) Fem to cell Network Model

The general FC network model is depicted in Fig. 4.The Fem to users (FUs) are connected to the operator core network through FBS and Fem to cell Management System (FMS). An FMS is a centralized FC coordinator, through which FC admission and management take place. It is an integral part of network operator cloud. Each FC or FBS can serve 3 to 4 FUs concurrently. The FBS aids the registered FUs in transmitting and receiving the intended signal to and from the operator core network. Cognitive enabled FBSs can sense and adapt to the environment.

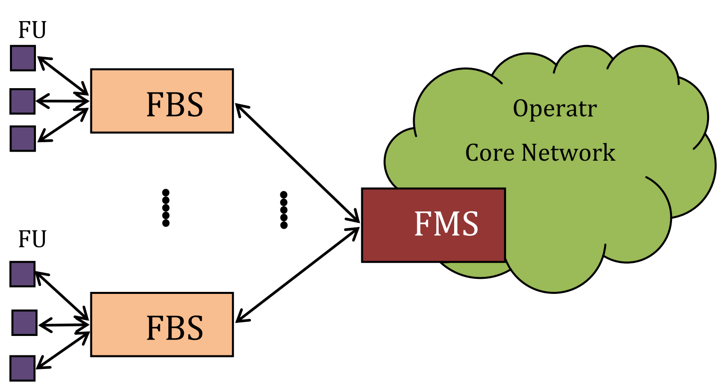


Fig.4: Fem to cell network model

The FCs are owned by FUs and hence, the FBSs posses plug-and-play nature on use's mobility. FMS organizes the FC clusters and provides service to the registered FUs in the cluster. Due to random FC deployment, the coverage area of neighboring FCs residing under an FMS may overlap. At any given point of time, each FMS is defined to take care of fixed number of FCs. With an increase in the number of FCs, new FMSs are deployed to handle the traffics originating from newly formed FCs.

It is noticeable from Fig. 5 that the spatially apart Macro users (MUs) and FUs are assigned with same set of frequency. Such type of frequency planning enhances the overall spectral efficiency and network capacity. The FC configuration procedure is as simple as configuring an IP modem. When FBS is powered on, it scans the network for a nearby-associated FMS. On tracking the existence of FMS's signal over the radio environment, FBS forwards its unique Fem to cell Identity (FC_ID) to FMS and gets registered to it. Upon FC_ID authentication, the FMS assigns the radio parameters to the FC.

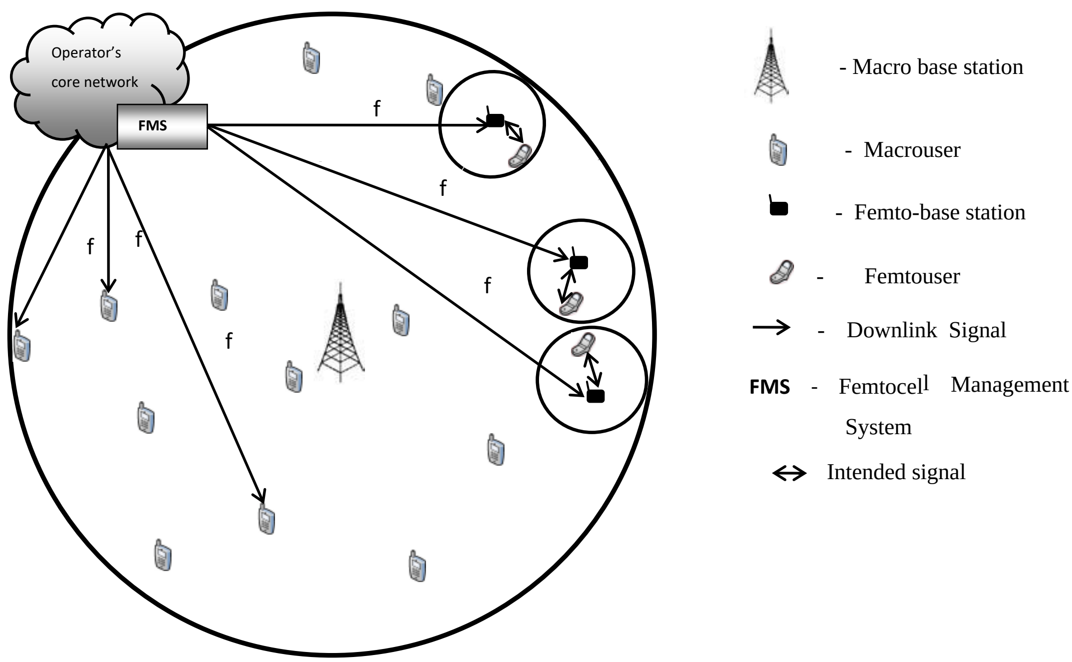


Fig. 5: Macro-fem to cell heterogeneous network model

Once configured, FCs periodically broadcast the FC_ID to intimate their presence to the FMS and neighboring FCs. Moreover, the self-configuring feature enables the FC to scan the environment and acquire knowledge about the neighbors on its own. The MC and FCs operate under the same network operator and therefore they can read and exchange common sets of information.

c) Comparison between FC and Wi-Fi Networks

Wireless Fidelity (Wi-Fi), the most popular wireless local area network, has evolved in the year 2005 [18], [19]. The standard of Wi-Fi is IEEE 802.11n and it is otherwise called as hotspot. Wi-Fi technology has brought the high speed data services closer to business organizations and enterprise environment. The growing pervasiveness of Wi-Fi has helped the 3G data network to extend beyond the personal computers. In comparison with Wi-Fi standard, the importance of FC technology is highlighted in Table 2.

Table 2: Comparisons between FC and Wi-Fi networks

Femtocell (FC)	Wireless Fidelity (Wi-Fi)
FC operates over a licensed frequency band (800MHz, 2.5GHz)	Wi-Fi operates over an unlicensed band(2.4GHz or 5GHz)
Coverage area spans 10 to 15meters and operating power is 20mW	Coverage area spans till 100meters and its operating power is 1W
Careful frequency planning is required as the FC utilizes the frequency bands of MC.	Wi-Fi does not require frequency planning as it is deployed over unlicensed band.
FC network provides superior quality *voice and data* services at the rate of 1Gbps	Wi-Fi offers *only data* service at the rate of 100Mbps.
Existing handsets can be utilized to access FC network	Wi-Fi technique demands Wi-Fi enabled device.
Same radio link is utilized by FU and MU. Hence, battery draining in FU handset is less.	Unlicensed radio is powered by the handset to activate the Wi-Fi service. It leads to faster battery draining.
No privacy or security issues	Has privacy and security issues due to unlicensed band operation
Supports power control through sleep Mode	There is no default sleep mode setting in Wi-Fi standard
Provides inter-tier and intra-tier Mobility	Provides mobility only within the legal Wi-Fi coverage area

IV. Conclusion

Fem to cell has carved a niche for itself among small cell family and most of the industry and research people view FC as the promising candidate in the next generation cellular networks. On recognizing the benefits of FC, most of the industry and business people celebrate FC as a prominent candidate in small cell family. However, a flip side investigation on FC technology reveals that the technology has also got some challenges to be addressed. In practice, improper access mode selection, dense FC deployment and seamless mobility of MU has lead to serious challenges like interference, backhaul bottleneck and handoff mechanisms respectively. Hence, to meet with the requirements of FC owners without affecting the network operator's revenue, more emphasis must be given in handling aforementioned challenges.

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Algorithm Development for Determination of Fault Location of Transmission Lines in a Branched Electrical Distribution Networks

By Elmir Khakimzyanov, Ramil Mustafin & Airat Tuityarov
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Abstract- The article proposes an algorithm for determining phase-to-phase fault of branched electrical networks power lines with 6-10 kV voltage. A feature of the algorithm is the application of the calculation theory of the emergency modes, taking into account the impact of network load and transient resistance in phase-to-phase faults.

Keywords: distribution network, phase-to-phase fault, the parameters of the emergency mode, the determination of fault location, transient resistance.

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Algorithm Development for Determination of Fault Location of Transmission Lines in a Branched Electrical Distribution Networks

Elmir Khakimzyanov [α], Ramil Mustafin [σ] & Airat Tuityarov [ρ]

Abstract- **The article proposes an algorithm for determining phase-to-phase fault of branched electrical networks power lines with 6-10 kV voltage. A feature of the algorithm is the application of the calculation theory of the emergency modes, taking into account the impact of network load and transient resistance in phase-to-phase faults.**

Keywords: distribution network, phase-to-phase fault, the parameters of the emergency mode, the determination of fault location, transient resistance.

I. Introduction

High rates of power grids development while reducing the specific numbers of operating personnel require the accelerated introduction of automation, including the fault location devices (FLD) on transmission lines (TL).

A variety of types and nature of faults and conditions of the power grid does not allow to obtain any universal algorithm for FLD.

According to this, a review of existing techniques for phase-to-phase faults and short circuits on the ground is reduced to the determination of section of the phase circuit by the use of sensors (indicators) of current, established, usually in areas of lines branching. The circuit rectification is conducted through the line bypassing by operation mobile team. Implementation of the methodology requires a serious financial investment (the cost of the project is proportional to the number of indicators of current), the organization of information transmission over a wireless communication channel [1-3]. Consequently, such indicators can be only "defining" points for the bypass route of the line.

Review of existing methods of FLD for more complex types of ground circuit (e.g. double ground circuit) does not give a clear idea of the accuracy of the distance calculations. As a rule, existing devices of the FLD determine only the fact of appearance of a double ground circuit, without specifying the characteristics of the fault (on the same or on different lines) and not indicating distances to points of damage. Thus, depending on the nature of a double ground circuit, the damage is defined as ground circuit determination or interphase short circuit [4-7]. There are FLD techniques and algorithms for a double ground circuit in electrical medium voltage networks with isolated neutral that are presented in works [8-12], novelty of these lies in the special scheme of resistance control devices connection at which the calculated emergency mode resistance is proportional to the distances to the locations of ground circuits.

FLD phase-to-phase faults are realized as one-way or two-way measurement fault quantities (FQ). Usually, by the calculation of short circuit loop resistance using symmetrical components of voltage and current of the line [2, 13-15]. This method is successfully applied in high voltage transmission lines that do not have branches. However, in the branched medium voltage networks accuracy of the method decreases due to the effect of load mode on branches of the network and the value of the transition resistance at the fault site.

The use of FLD devices based on the wave method requires special fault detection system configuration, and special high frequency joining devices line processing [16-18].

II. Algorithm Proposed For Solving The Problem

Modern methods of FLD on FQ imply assumptions that distort the results of calculation of the distance to the fault site. Such assumptions include the elimination of the influence of the load current or transition resistance in the place of short circuit [19]. Improving methods of FLD in FQ will reduce the error.

The algorithm is designed for determining distance to phase-to-phase short circuit (SC) of a complex configuration network with regard to the influence of the network load resistance and the transition resistance in the place of short circuit, indicating the damaged portion of the network.

To identify compensation algorithms, the network load and the resistance of the transition FQ has to be calculated on example of tri-end electric network with voltage of 10 kV (Fig. 1) and its equivalent circuit forward (reverse) sequence (Fig. 2) when two-phase short-circuit on the OL2 site (point K2).

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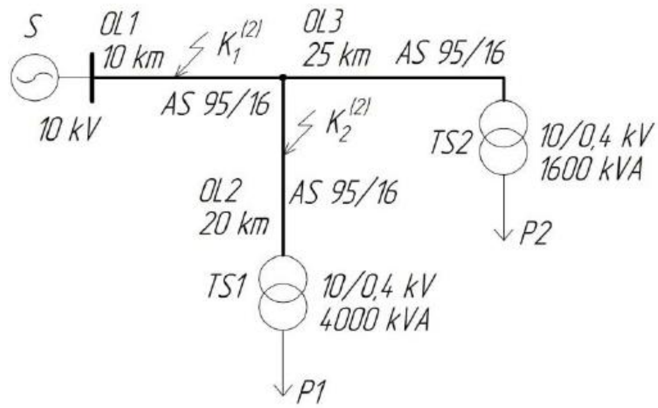

Fig. 1: Sample one-line electrical network with voltage of 10 kV: S– Feed the power grid with a voltage of 10 kV, TS1, TS2 of the transformer substation with the voltage of 0.4 kV LV, OL1–OL3 – sections of the considered line; P1, P2 – load consumers

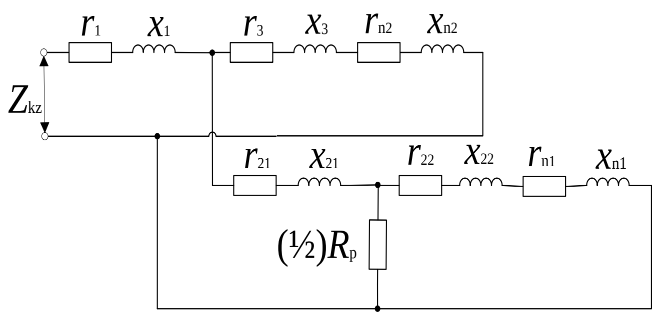

Fig. 2: An equivalent circuit of the direct (reverse) of the sequence design scheme of 10 kV network in emergency mode (smalllettering)

According to the equivalent circuit of the network in emergency mode (Fig. 2) full resistance Z_{kz} will be defined as:

$$Z_{kz} = Z_1 + \frac{(Z_3 + Z_{n2}) \cdot \left(Z_{21} + \dfrac{\dfrac{R_p}{2} \cdot (Z_2 - Z_{21} + Z_{n1})}{\dfrac{R_p}{2} + Z_2 - Z_{21} + Z_{n1}} \right)}{Z_3 + Z_{n2} + Z_{21} + \dfrac{\dfrac{R_p}{2} \cdot (Z_2 - Z_{21} + Z_{n1})}{\dfrac{R_p}{2} + Z_2 - Z_{21} + Z_{n1}}}, \quad (1)$$

where Zkz – impedance of the emergency mode defined by the phase-to-phase voltage with respect to the difference of currents of two phases (the classic circuit for measuring on resistance responsive to phase-to-phase damage [20-21]); Z_1, Z_2, Z_3 – impedance sections of transmission line; Z_{n1}, Z_{n2} – impedance of load of the consumers (including the resistance of the transformers TA); R_p is the contact resistance at the injury site.

In the expression (1) unknown quantity is the resistance Z_{21}, the inductive resistance of which is by way of transformation will be determined by a polynomial of 3rd degree:

$$C_0 + C_1 x_{21} + C_2 x_{21}^2 + C_3 x_{21}^3 = 0 . \quad (2)$$

Desired resistance x21 is obtained by discarding the imaginary roots of the equation, it will be proportional to the distance to fault on the section OL2:

$$L_к = x_{21} / x_{res} , \quad (3)$$

where Xres– resistivity direct sequence transmission lines.

Verification of the proposed FLD algorithm was conducted in the MatLab Simulink software package, in which the simulated circuit, shown in Fig. 1. has the parameters of the transmission line OL1-OL3: Gud = 0.33 Ω/km HUD = 0.37 Ohm/km; load: SP1 = 4000 kVA, SP2 = 1600 kVA, cosφ = 0,6. Point two-phase short-circuit (K2) on the line OL2 is set at a distance of 10 km from the start of the additional tap (20 km), the contact resistance Rp was equal to 20 Ohms.

Current and voltage oscillograms analysis in emergency mode showed the following results: the short-circuit current was 0.9 kA, the voltage across the tyre supply substation is 9.2 kV.

Distance to the fault by the formula (1-3) was identified as 10.8 km after the tap off, which is a 4% error of the FLD calculations.

Network damaged section identification is carried out by criterion of decrease in active power load as a result of changes in the parameters of network mode. So, in the event of short-circuit on the OL2 phase active power of the loads P1 into the joining was reduced to 1648 kW, and the load P2 to 1,077 kWh. Thus, the most profound reduction of active power on the load P1 indicates the damaged area OL2. Commited changes of output can be produced with the help of the analysis of electric energy digital meters indicators.

An additional criterion that allows to identify the damaged tap is the negative sequence voltage monitoring. The damaged consumer phase voltage negative sequence will be higher compared to consumers in the undamaged sections of the network [12].

Let's compare the results of FLD calculations with other techniques used in practice by the formula (1-3). So, the built-in function of the FLD waveform analysis in the Fast View program [22] indicates the 16.8 km (the error is 16%) distance to the fault site. In addition, this technique does not give information about the site location of the point KZ.

The closest solution to the designed algorithm is a patent solution [23]. The calculation using the presented technique indicated distance to a fault 13.9 km from the beginning of the tap off, the error is about 20%.

Thus, the distribution networks of medium voltage FLD algorithm was determined, based on the control FQ, which differs from other methods of FLD that perform calculating the distance to fault when considering a tree topology network, as well as the transient resistance of the fault.

A series of model studies show the magnitude effect of the load power and the values of the transition resistance at the fault site on the accuracy of the FLD process in the proposed method according to calculations by the formulas (1-3). Calculation error results are illustrated in figure (Fig. 3), which shows that at the maximum power load of the consumers is 8 MVA and the transition resistance of 25 Ω, the FLD error does not exceed 9%, which is lower compared to other techniques used in practice.

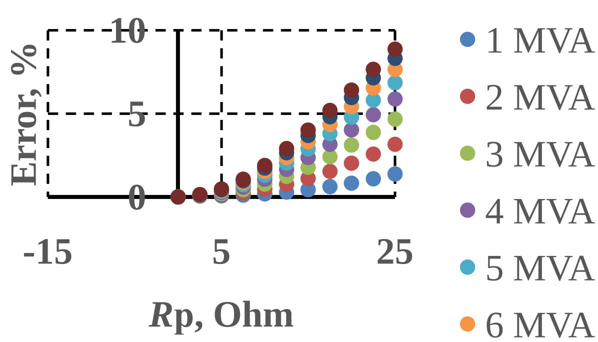

Fig. 3: Relative error depending on the transition resistance and load.

Calculation of the FQ on example of the same electric network with voltage of 10 kV (Fig. 1) in the two-phase short-circuit in the K1 at the site OL1 (distance to fault 5 km, the contact resistance is 20 Ohms). An equivalent circuit of the direct (reverse) sequence in emergency mode shown in Fig. 4.

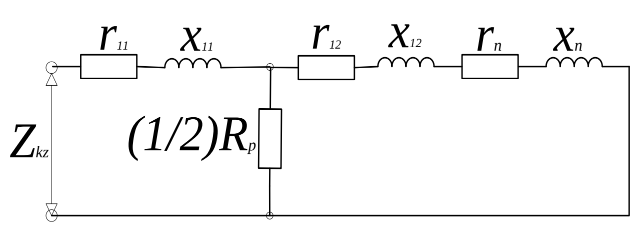

Fig. 4: An equivalent circuit of the direct (reverse) of the sequence design scheme of 10 kV network in emergency mode

In this case, the impedance Z_{kz} will be defined as:

$$Z_{kz} = Z_{11} + \frac{\frac{R_p}{2}\cdot(Z_1 - Z_{11} + Z_n)}{\frac{R_p}{2} + Z_1 - Z_{11} + Z_n}, \quad (4)$$

Where Z1=Z11+Z12 is the impedance of the main part of the transmission line, Zn is the impedance of consumers load (including the resistance of the transformers on TS) and lines defined by the formula:

$$Z_n = r_n + jx_n = \frac{(Z_2 + Z_{n1})\cdot(Z_3 + Z_{n2})}{Z_2 + Z_{n1} + Z_3 + Z_{n2}}. \quad (5)$$

Then, the solution of the FLD problem is similar to the first example.

FLD calculation according to the formulas (1-5) showed the following results: distance to fault was 5.1 km, the relative error is 1.6 %.

Built-in FLD waveform analysis function of Fast View program, and the method of [23] indicates 5.5 km distance to the fault site (the error is 10.7%).

However, the comparing analysis of changes in the active power of the loads P1 and P2 shows a slight divergence between them, which is the criterion of damage on the main section of the line. The active power of the loads P1 amounted to 1684 kW, and load N2 – 929 kW.

The fault distance calculation according to the presented method in networks with a large number of taps (of any configuration) will be similar to the two examples above.

The fault location algorithm can be realized on the existing microprocessor elements (the terminal), or on a separate computing device.

III. Conclusion

The algorithm of determining the distance to a two-phase fault is developed, considering the influence of load current and the transition resistance in the place of circuit, the error of which on average 10% lower compared to the existing and applied in practice the methods of the FLD.

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Non-Dominated Sorting Whale Optimization Algorithm (NSWOA): A Multi-Objective Optimization Algorithm for Solving Engineering Design Problems

By Pradeep Jangir & Narottam Jangir
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Abstract- This novel article presents the multi-objective version of the recently proposed the Whale Optimization Algorithm (WOA) known as Non-Dominated Sorting Whale Optimization Algorithm (NSWOA). This proposed NSWOA algorithm works in such a manner that it first collects all non-dominated Pareto optimal solutionsin achieve till the evolution of last iteration limit. The best solutions are then chosen from the collection of all Pareto optimal solutions using a crowding distance mechanism based on the coverage of solutions and bubble-net hunting strategy to guide humpback whales towards the dominated regions of multi-objective search spaces.For validate the efficiency and effectiveness of proposed NSWOA algorithm is applied to a set of standard unconstrained, constrained and engineering design problems.

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Strictly as per the compliance and regulations of:

Non-Dominated Sorting Whale Optimization Algorithm (NSWOA): A Multi-Objective Optimization Algorithm for Solving Engineering Design Problems

Pradeep Jangir α & Narottam Jangir σ

Abstract- This novel article presents the multi-objective version of the recently proposed the Whale Optimization Algorithm (WOA) known as Non-Dominated Sorting Whale Optimization Algorithm (NSWOA). This proposed NSWOA algorithm works in such a manner that it first collects all non-dominated Pareto optimal solutionsin achieve till the evolution of last iteration limit. The best solutions are then chosen from the collection of all Pareto optimal solutions using a crowding distance mechanism based on the coverage of solutions and bubble-net hunting strategy to guide humpback whales towards the dominated regions of multi-objective search spaces.For validate the efficiency and effectiveness of proposed NSWOA algorithm is applied to a set of standard unconstrained, constrained and engineering design problems. The results are verified by comparing NSWOA algorithm against Multi objective Colliding Bodies Optimizer (MOCBO), Multi objective Particle Swarm Optimizer (MOPSO), non-dominated sorting genetic algorithm II (NSGA-II) and Multi objective Symbiotic Organism Search (MOSOS).The results of proposed NSWOAalgorithm validates its efficiency in terms of Execution Time (ET) and effectiveness in terms of Generalized Distance (GD), Diversity Metric (DM) on standard unconstraint, constraint and engineering design problem in terms of high coverage andfaster convergence.

Keyword: non-dominated; crowing distance; nswoa algorithm; multi-objective algorithm;economic constrained emission dispatch.

I. Introduction

Optimization is a work of achieving the best result under given limitation or constraints. Now a day, optimization is used in all the fields like construction, manufacturing, controlling, decision making, prediction etc. The final target is always to get feasible solution with minimum use of resources. In this field computers make a revolutionary impact on every field as it provides the facility of virtual testing of all parameters that are involved in a particular design with less involvement of human efforts, benefits in less time consuming, human efforts and wealth as well.

Today we use computer-aided design where a designer designs a virtual system on computer and gives only command to test all parameters involved in that design without even the need for a single prototype.

A designer only to design and simulate a system and set all the parameter limitation for the computer.

Computer-aided design technique becomes more effective with the additional feature of auto-generation of solutions after it's mathematically formulation of any system or design problem. Auto generation of solution, this feature is come into nature with the development of algorithms. In past years, real world designing problems are solved by gradient descent optimization algorithms. In gradient descent optimization algorithm, the solution of mathematically formulated problem is achieved by obtaining its derivative. This technique is suffered from local minima stagnation[1, 2] more time consuming and their solution is highly dependent on their initial solution.

The next stage of development of optimization algorithms is population basedstochastic algorithms.These algorithms had number of solutions at a time so embedded with a unique feature of local minima avoidance. Later population based algorithms are developed to solve single objective at a time either it may be maximization or minimization on accordance the problems objective function. Some popular algorithms for single objective problems are Moth-Flame optimizer (MFO) [3], Bat algorithm (BA) [4], Particle swarm optimization (PSO) [5], Ant colony optimization (ACO) [6], Genetic algorithm (GA) [7], Cuckoo search (CS)[8], Mine blast algorithm (MBA) [9], Krill Herd (KH) [10], Interior search algorithm (ISA) [11] etc. These algorithms have capabilities to handle uncertainties [12], local minima [13], misleading global solutions [14], better constraints handling [15] etc. To overcome these difficulties different algorithms are enabled with different powerful operators. As mention above here is only objective then it is easy to measure the performance in

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terms of speed, accuracy, efficiency etc. with the simple operational operators.

In general, real world problems are nonlinear and multi-objective in nature.In multi-objective problem there may be some objectives are consisting of maximization function while some are minimization function. So now a day, multi-objective algorithms are in firm attention.

Let's take an example of buying a car, so we have many objectives in mind like speed, cost, comfort level, space for number of people riding, average fuel consumption, pick up time required to gain particular speed, type of fuel requirement either it is diesel driven, petrol driven or both etc. To simply understand multi-objective problem, from Fig. 1, we considertwo objectives, first cost and second comfort level. So we go for sole objective of minimum cost possible then we have to deny comfort level objective and vice-versa. It means real word problems are with conflicting objectives. So as, we are disabled to find an optimal solution like single objective problems. About multi-objective algorithm and its working is detailed described in next portion of the article.

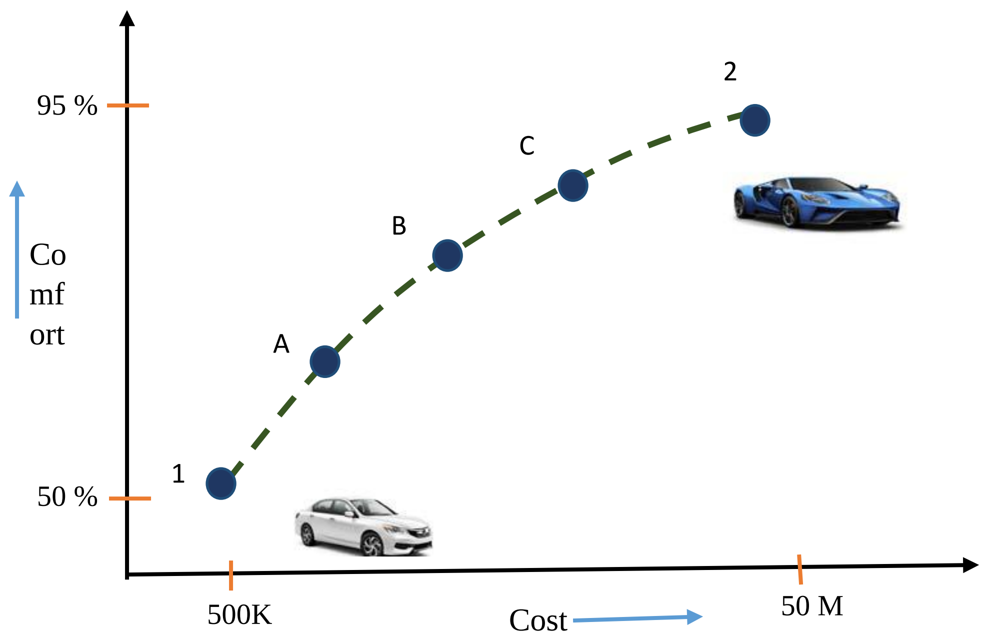

Fig. 1: Car-buying decision-making problem (Hypothetical multi-objective problem solutions)

The No free launch [16] theorem that logically proves that none of the only algorithm exists equally efficient for all engineering problem. This is the main reason that it allows all researcher either to propose new algorithm or improve the existing ones. This paper proposed the multi-objective version of the well-known whale optimization algorithm(WOA) [17]. In this paper non-sorted WOA (NSWOA) is tested on the standard un-constraint and constrainttest function along with some well-known engineering design problem, their results are also compared with contemporary multi-objective algorithms Multi objective Colliding Bodies Optimizer (MOCBO) [18], Multi objective Particle Swarm Optimizer (MOPSO)[19-20], Non-dominated Sorting Genetic Algorithm (NSGA) [21-23], non-dominated sorting genetic algorithm II (NSGA-II)[24] and Multi objective Symbiotic Organism Search (MOSOS)[25] that are widely accepted due to their ability to solve real world problem.

The structure of the paper can be given as follows: - Section 2 consists of literature; Section 3 includes the proposed novel NSWOAalgorithm; Section 4 consists of competitive results analysis of standard test functions as well as engineering design problem and section 5 includes real world application, finally conclusion based on results and future scope of work is drawn.

II. Literature Review

As the name describes, multi-objective optimization handlessimultaneously multiple objectives. Mathematically minimize/maximize optimization problem can be written as follows:

$$Minimize/maximize: \quad Fn \quad (\vec{x}) = \{fn_1(\vec{x}), fn_2(\vec{x}), \dots, f_{no}(\vec{x})\} \tag{2.1}$$

$$Subject\ to: \quad p_i(\vec{x}) \geq 0, \quad i = 1,2,\dots,q \tag{2.2}$$

$$t_i(\vec{x}) = 0, \quad i = 1,2,\dots,r \tag{2.3}$$

$$L_i^{lb} \leq x_i \leq U_i^{ub} \quad , \qquad i = 1,2,\ldots,k \tag{2.4}$$

Where q is the number of inequality constraints, *r* is the number of equality constraints,*k* is the number of variables, p_i is the i^{th} inequality constraints, *no* is the number of objective functions, t_i indicates the i^{th} equality constraints, and $[L_i^{lb},\ U_i^{ub}]$ are the boundaries of i^{th} variable.

Obviously, relational operators are ineffective in comparing solutions with respect to multiple objectives. The most common operator in the literate is Pareto optimal dominances, which is defined as follows for minimization problems:

$$\forall n \in \{1,2,\ldots,k\}: f_n(\vec{x}) \leq f_n(\vec{y}) \ \wedge \ \exists n \in \{1,2,\ldots,k\}: f_n(\vec{x}) < f_n(\vec{y}) \tag{2.5}$$

where $\vec{x} = (x_1, x_2, \ldots, x_k)$ and $\vec{y} = (y_1, y_2, \ldots, y_k)$.

For maximization problems, Pareto optimal dominance is defined as follows:

$$\forall n \in \{1,2,\ldots,k\}: f_n(\vec{x}) \geq f_n(\vec{y}) \ \wedge \ \exists n \in \{1,2,\ldots,k\}: f_n(\vec{x}) > f_n(\vec{y}) \tag{2.6}$$

where $\vec{x} = (x_1, x_2, \ldots, x_k)$ and $\vec{y} = (y_1, y_2, \ldots, y_k)$.

These equationsshow that a solution is better than another in a multi-objective search space if it is equal in all objective and better in at least one of the objectives. Pareto optimal dominance is denoted with $\prec$ and $\succ$. With these two operator's solutions can be easily compared and differentiated.

Population based multi-objective algorithm's solution consists of multiple solution. But with multi-objective algorithm we cannot exactly determine the optimal solution because each solution is bounded by other objectives or we can say there is always conflict between other objectives. So the main function of stochastic/population based multi-objective algorithm is to find out best trade-offs between the objectives, so called Pareto optimally set [26-28].

The principle of working for an ideal multi-objective optimization algorithm is as shown in Fig. 2.

Step No. -1 Find maximum number of non-dominated solution according to objective, it expresses the number of Pareto optimal set so as shows higher coverage

Step No. -2 Choose one of the Pareto optimal solution using crowding distance mechanism that fulfills the objectives.

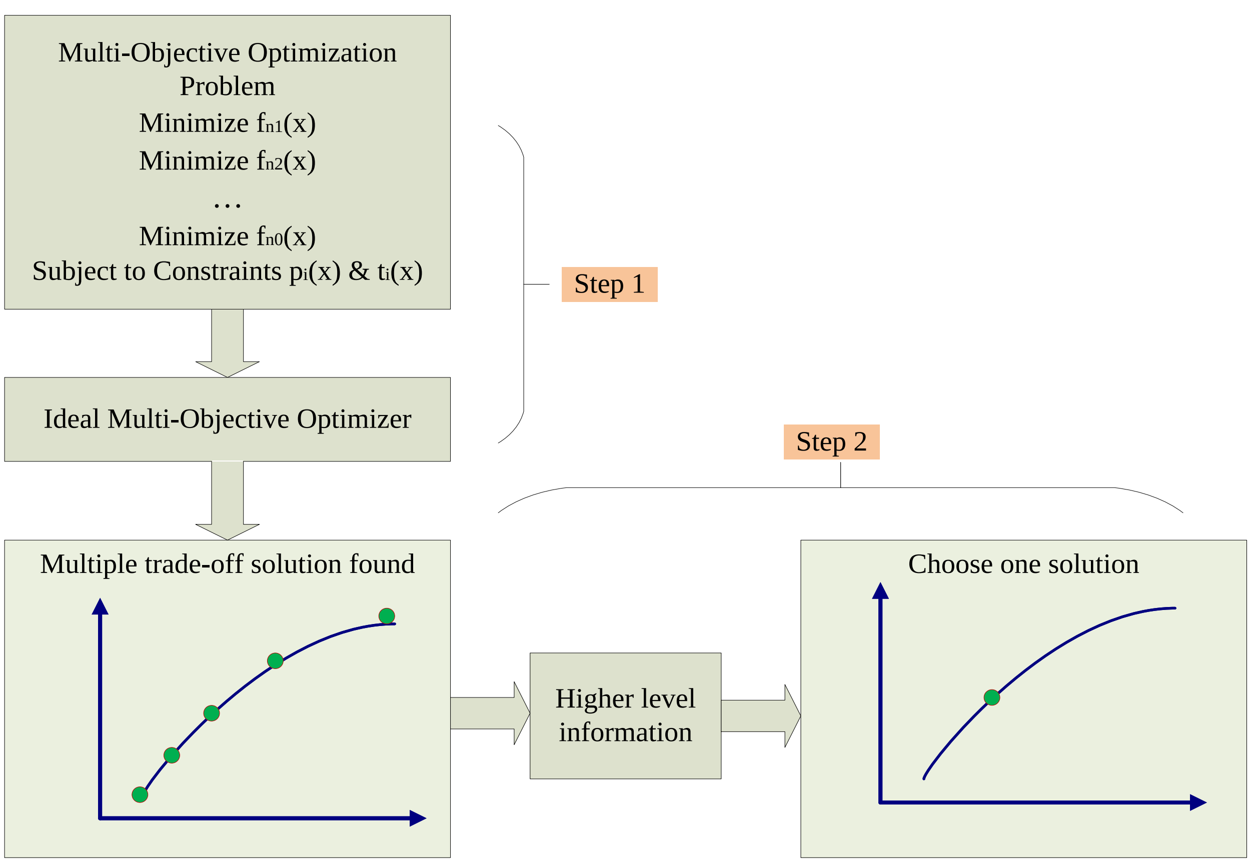

Fig. 2: Multi-objective optimization (Ideal) procedure

Now a day recently proposed sole objective algorithms are equipped with powerful operators to provide them a capability to solve multi-objective problems as well. In the same manner we proposed NSWOA algorithm in a hope that it will perform efficiently for multi-objective problems. These are: Multi-objective GWO [29], Multi-objective Bat Algorithm [30], Multi-objective Bee Algorithm [31],Pareto Archived Evolution Strategy (PAES) [32], Pareto-frontier Differential Evolution (PDE) [33], Multi-Objective Evolutionary Algorithm based on Decomposition (MOEA/D) [34], Strength-Pareto Evolutionary Algorithm (SPEA) [35, 36]andMulti-objective water cycle algorithm with unconstraint and constraint standard test functions [37][38].Performance measurement for approximate robustness to Pareto front of multi-objective optimization algorithms in terms of coverage, convergence and success metrics.

The computational complexity of NSWOA algorithm is order of $O\,(mn^2)$where N is the number of individuals in the population and M is the number of objectives. The complexity for other good algorithms in this field: NSGA-II, MOPSO, SPEA2 and PAES are $O\,(mn^2)$. However, the computational complexity is much better than some of the algorithms such as NSGA and SPEA which are of $O\,(mn^3)$.

III. Non-Dominated Sorting Whale Optimization Algorithm (NSWOA)

The Whale Optimization Algorithm (WOA) with sole objective was proposed by Mirjalili Seyedali and Andrew Lewis in 2016 [17]. It is basically a stochastic population based, nature inspired algorithm. In this algorithm the basic strategy based on special hunting nature of humpback whales.Some fact about humpback whales that they are: fancy creatures, biggest mammals in the world and have power of think, learn, judge, communicate, being emotional etc. They are also considered as predators as they never sleep, only half of the brain sleeps, as they have to breathe from surface of the ocean. One more interesting fact about whales is their hunting or foraging behavior to hunt small fishes. Such type of foraging behavior is known as bubble-net feeding strategy where whales went down in water approximate 10-15 meter and then after start to produce bubbles in a spiral shape encircles prey and then follows the bubbles and moves upward the surface. This foraging behavior is done by making distinct bubbles along with a circle or ‘9-shaped path’ represented in Fig. 3 and clearly explained in [54-56].

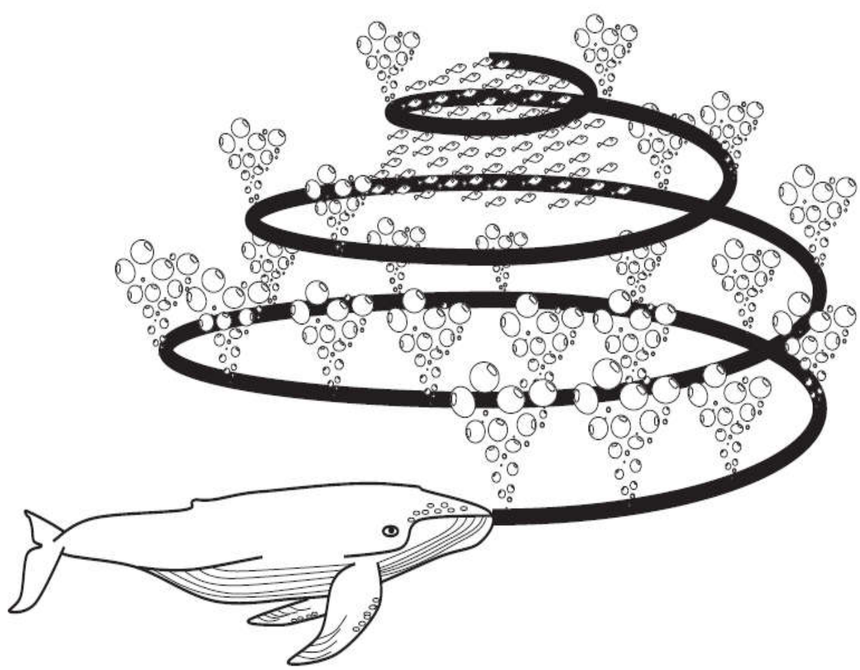

Fig. 3: Representation of foraging behavior or ‘9-shaped path’ of the humpback whales

Mathematical modelling of The Whale Optimization Algorithm:

a) Encircling Prey Equation

Humpback whale encircles the prey (small fishes) then updates its position towards the optimum solution over the course of increasing number of iteration from start to maximum number of iteration.

$$\vec{D} = \left| C.\vec{X}^*(t) - X(t) \right| \qquad (1)$$

$$\vec{X}(t+1) = \vec{X}^*(t) - \vec{A}.\vec{D} \qquad (2)$$

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Where: $\vec{A}, \vec{D}$ are coefficient vectors, t is current iteration, $\vec{X}*(t)$ is position vector of optimum solution so far and $X(t)$ is position vector.

Coefficient vectors $\vec{A}$, $\vec{D}$ are calculated as follows:

$$\vec{A} = 2\vec{a} * r - \vec{a} \tag{3}$$

$$\vec{C} = 2 * r \tag{4}$$

Where: $\vec{a}$ is a variable linearly decrease from 2 to 0 over the course of iteration and r is a random number [0, 1].

b) Bubble-net attacking method

In order to mathematical equation for bubble-net behaviour of humpback whales, two methods are modelled as:

i. *Shrinking Encircling Mechanism*

This technique is employed by decreasing linearly the value of $\vec{a}$ from 2 to 0. Random value for vector $\vec{A}$in rang between [-1, 1].

ii. *Spiral Updating Position*

Mathematical spiral equation for position update between humpback whale and prey that was helix-shaped movement given as follows:

$$\vec{X}(t+1) = \vec{D}'* e^{bt} * \cos(2\pi l) + \vec{X}*(t) \tag{5}$$

Where: l is a random number [-1, 1], b is constant defines logarithmic shape, $\vec{D}' = \left|\vec{X}*(t) - X(t)\right|$ expresses the distance between i-*th* whale to the prey mean best solution so far.

Note: We assume that there is 50-50% probability that whale either follow the shrinking encircling or logarithmic path during optimization. Mathematically we modelled as follows:

$$\vec{X}(t+1) = \begin{cases} \vec{X}*(t) - \vec{A}.\vec{D} & if \quad p < 0.5 \\ \vec{D}'.e^{bl}.\cos(2\pi l) + \vec{X}*(t) & if \quad p \geq 0.5 \end{cases} \tag{6}$$

Where: p expresses random number between [0, 1].

iii. *Search for prey*

$\vec{A}$ Vector can be used for exploration to search for prey; vector $\vec{A}$ also takes the values greater than one or less than -1. Exploration follows two conditions

$$\vec{D} = \left|\vec{C}.\overrightarrow{X_{rand}} - \vec{X}\right| \tag{7}$$

$$\vec{X}(t+1) = \overrightarrow{X_{rand}} - \vec{A}.\vec{D} \tag{8}$$

Finally follows these conditions:

- ➢ $\left|\vec{A}\right| > 1$ enforces exploration to WOA algorithm to find out global optimum avoid local optima
- ➢ $\left|\vec{A}\right| < 1$ for updating the position of current search agent/best solution is selected

Basic working of NSWOA algorithm is as follows:

➢ *Stage 1*

- First of all, initialize the population of the whales
- Randomly generated sets of whales and prey and their position vectorsare represented in matrix for convenience to understand
- Then fitness of each whale's positionis calculated on an according as objective function

➢ *Stage 2*

- Position of whales are updated as a spiral or helix shaped movement function and so as value of next position of whales is decided
- The value of absolute distance is achieved which is basically a distance between the current best solution (whales current position) to the final (prey position) optimal solution
- We assume that there is 50-50% probability that whale either follow the shrinking encircling or logarithmic path during optimizationmuch needed to update their position towards optimal one

➢ *Stage 3*

- Termination counter in integrated to limit/forcefully stop the search in uncertain search space (max. iteration counter to forcefully converge the search to optimal one)
- Size of the position vector matrix is continuously reduced over the course of iteration due to directed search to find global best solution
- Continuously position of the whalesis updated towards the optimal one viaeither follow the shrinking encircling or logarithmic path during optimizationequation for each iteration

➢ *Stage4*

- Likewise, multi-objective optimization the NSWOA algorithm is made to capable to store the pareto

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optimal solutions in a collectionset and make it as flexible to change solution over the course of iteration

- Solution is assigned a rank according to their ability as if a solution is not dominated by other solution is assigned rank1, dominated by only solution assigned rank 2 and so on & if collection set is full (archive size) over predefined size then some solutions that are less non-dominated (according to fitness value) in natureare directed to be out from the collection set according to the crowding distance mechanism.

This collection set is similar to the term achieve used in MOSOS and NSGA-II. It is a repository to store the best non-dominated solutions obtained so far. The search mechanism in NSWOA is very similar to that of WOA algorithm, in which solutions are improved using position vectors. Due to the existence of multiple best solutions, however, the best whales position should be chosen from the collection set.

In order to select solutions from the archive to establish tunnels between solutions, we employ a leader selection mechanism. In this approach, the crowding distance between each solution in the archive is first selection and the number of solutions in the neighbourhood is counted as the measure of coverage or diversity. We require the NSWOAalgorithm to select solutions from the less populated regions of the archive using the following equation to improve the distribution of solutions in the archive across all objectives.

This section proposes multi-objective version of the WOA algorithm called NSWOA algorithm. The non-dominated sorting has been of the most popular and efficient techniques in the literature of multi-objective optimization. As its name implies, non-dominated sorting sort Pareto optimal solutions based on the domination level and give them a rank. This means that the solutions that are not dominated by any solutions is assigned with rank 1, the solutions that are dominated by only one solution are assigned rank 2, the solutions that are dominated by only two solutions are assigned rank 3, and so on. Afterwards, solutions are chosen to improve the quality of the population base on their rank. The better rank, the higher probability to be chosen. The main drawback of non-dominated sorting is its computational cost, which has been resolved in NSGA-II.

The success of the NSGA-II algorithm is an evidence of the merits of non-dominated sorting in the field of multi-objective optimization. This motivated our attempts to employ this outstanding operator to design another multi-objective version of the WOA algorithm. In the NSWOA algorithm, solutions are updated with the same equations presented in equation 3.9. In every iteration, however, the solutions to have optimal position of whalesare chosen using the following equation:

$$P_i = c / Rank_i \qquad (3.9)$$

where *c* is a constant and should be greater than 1 and $Rank_i$ is the rank number of solutions after doing the non-dominated sorting.

This mechanism allows better solutions to contribute in improving the solutions in the population. It should be noted that non-dominated sorting gives a probability to dominated solutions to be selected as well, which improves the exploration of the NSWOA algorithm. Flow chart of NSWOA algorithm is represented as Fig. 4.

Constraint Handling Approach

With the extended literature survey we find that the population based algorithms are the common way to solve the multi-objective problems as they are more commonly provides the global solution and capable of handling both continuous and combinational optimization problem with a very high coverage and convergence. Multi-objective problems are subjected to various type of constraints like linear, non-linear, equality, inequality etc. So with these problems embedded it is very difficult to find simple and good strategy to achieve considerable solutions in the acceptable criterion. So in this paper NSWOA algorithm uses a very simple approach to get feasible solutions. In this mechanism, after generating number of solutions at each generation, all the desirable constraint checked and then some solution that fulfills the criterion of acceptable solution are selected and collected them in achieve. Afterward non dominated solutions added in archive as we find more suitable solution to get acceptable solution. So as if achieve is full then less dominated solutions are removed. Finally, according to crowing distance mechanism all these solutions (more suitable position of the whales) from archive is selected to get desired solution.

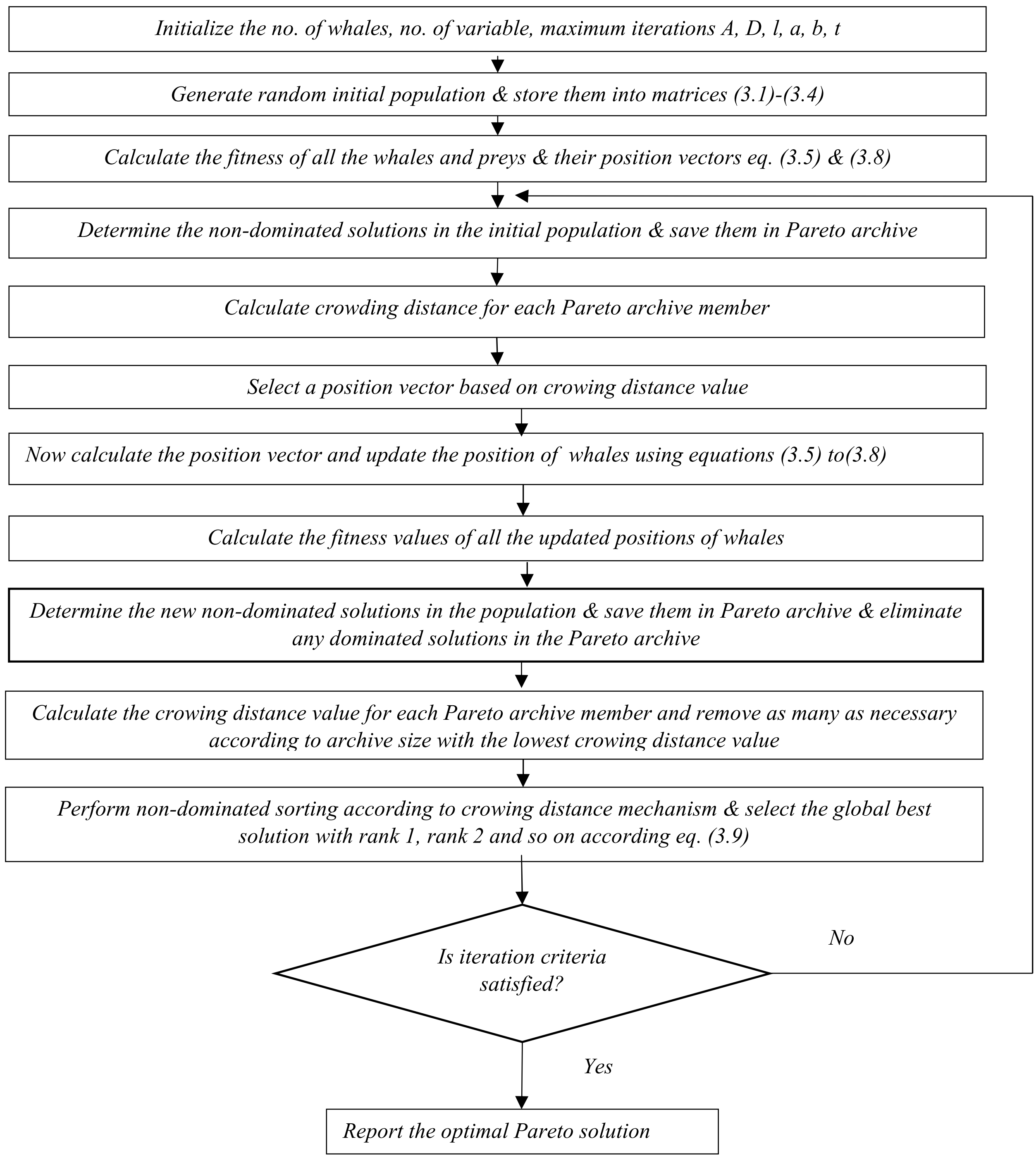

Fig. 4: Flow chart of NSWOA algorithm

IV. Results Analysis On Test Functions

For determine the performance of proposed NSWOA algorithm is applied to:

- A set of unconstraint and constraint standard multi-objective test functions
- Tested on well-known engineering design problems
- Non-linear, highly complex practical application known as economic constrained emission dispatch (ECED)
- With and Without stochastic integration of wind power (WP) in the next section
- A simple six-operating generational unit with power demand 1200 MW.

NSWOA algorithm is tested on seventeen different multi-objective case studies, including eight unconstrained test functions, five constrained test functions, and four real world engineering design problem, later algorithm is applied to the main application economic constrained emission dispatch with wind power (ECEDWP). These can be classified into four groups given below:

- Standard multi-objective unconstrained test functions (KUR, FON, ZDT1, ZDT2, ZDT3, ZDT4, SCHN1, and SCHN2)
- Standard multi-objective constrained test functions (TNK, OSY, BNH, SRN, and CONST)
- Real world engineering multi-objective design problem (Four bar truss design, welded beam design, speed reducer and disk brake design problem)
- Modeling of ECEDWP problem

Mathematical representation of these standard test functions is given in Appendix 1. (Multi-objective unconstrained test functions), 2. (Multi-objective constrained test functions), 3. (Engineering multi-objective design problem) with distinct characteristics like non-linear, non-convex, discrete pareto fronts and convex etc. are selected to measure the performance of proposed NSWOA algorithm. To deal with real world engineering design problem is really a typical task with unknown search space, in this article we include four different engineering problems are considered and performance is compared with various well known algorithms like MOWCA, NSGA-II, MOPSO, PAES and µ-GA multi-objective algorithms. Each algorithm is separately runs fifteen times and numeric results are listed in tables below. To measure the quality of obtained results we match their coverage of obtained true pare to front with respect to their original or true pare to fronts.

For numeric as well as qualitative performance of purposed NSWOA algorithm on various case studies we consider Generational Distance (GD) given by Veldhuizen in 1998 [39]for measuring the deviation of the distance between true pare to front and obtained pare to front, Diversity matric (Δ) also known as matrix of spread to measure the uniformly distribution of non-dominated solution given by Deb [24]and Metric of spacing (S) to represent the distribution of non-dominated distribution of obtained solutions by purposed algorithm given by Schott [40].

The mathematical representation of these performance indicating metric are as follows:

$$GD=\sqrt{\int_{i=1}^{n_{PFs}} d_i^2}\,/n \qquad (4.1)$$

where d_i shows the Euclidean distance (calculated in the objective space) between the i^{th} Pareto optimal solution achieved and the nearest true Pareto optimal solution in the reference set, n_{PFs} is the total number of achieved Pareto optimal solutions.

$$\Delta = \frac{\left|d_l+d_m+\int_{i=1}^{n_{PFs}}|d_i-d|\right|}{d_l+d_m+(n-1)d} \qquad (4.2)$$

where, d_l , d_m are Euclidean distances between extreme solutions in true pareto front and obtained pareto front. d_i shows the Euclidean distance between each point in true pare to front and obtained pare to front. n_{PFs} and 'd' are the total number of achieved Pareto optimal solutions and averaged distance of all solutions.

$$S = \sqrt{\frac{1}{n_{PFs}-1}\int_{i=1}^{n_{PFs}}(d_i-d)^2} \qquad (4.3)$$

where "d" is the average of all d_i, n_{PFs} is the total number of achieved Pareto optimal solutions, and $d_i = \min_j\left(|f_1^i(\vec{x}) - f_1^j(\vec{x})| + |f_2^i(\vec{x}) - f_2^j(\vec{x})\right)$ for all *i,j=1,2,…,n*. Smallest value of *"S"* metric gives the global best non-dominated solutions are uniformly distributed, thus if numeric value of d_i and d are same then value of *"S"* metric is equal to zero.

a) Results on unconstrained test problems

Like as above mentioned, the first set of test problems consist of unconstrained standard test functions. All the standard unconstrained test functions mathematical formulation is shown in Appendix A. Later, the numeric results are represented in Table 1 and best optimal pare to front is shown in Fig. 5.

All the statistical results are shown Table 1 suggests that the NSWOA algorithm effectively outperforms with most of the unconstraint test functions compare to the MOSOS, MOCBO, MOPSO and NSGA-II algorithm. The effectiveness of proposed non-dominated version of WOA (NSWOA algorithm) can be seen in the Table 1, represents a greater robustness and accuracy of NSWOA algorithm in terms of mean and standard deviation with the help of GD, diversity matrix along with computational time. However, proposed NSWOA algorithm shows very competitive results in comparison with the MOPSO, MOCBO and MOSOS algorithms and in some cases these algorithms perform better than proposed one. Pare to front obtained by proposed NSWOA algorithm shows almost complete coverage with respect to true pare to front.

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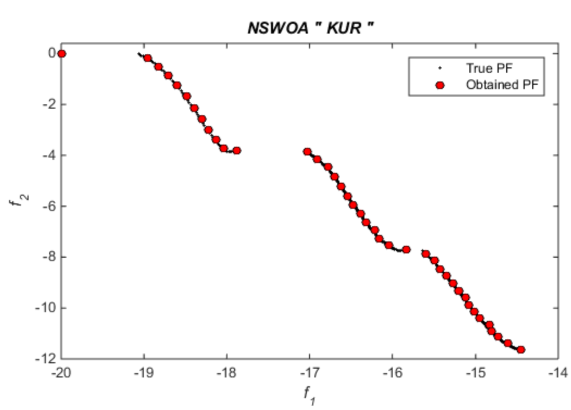
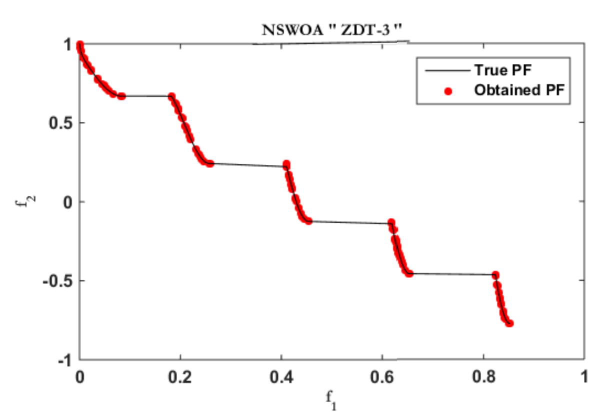
Table 1: Results of the multi-objective NSWOA algorithms (using GD, Δ, CT) on the unconstrained test functions employed

Algorithm→ Function↓	PFs	NSWOA MEAN±SD	MOSOS MEAN±SD	MOCBO MEAN±SD	MOPSO MEAN±SD	NSGA II MEAN±SD
KUR	GD	**0.00722±0.00211**	0.0075±0.0042	0.0083±0.0062	0.015±0.0075	0.0301±0.0043
	Δ	**0.02699±0.00025**	0.0295±0.0122	0.0357±0.0236	0.0991±0.031	0.0362±0.0240
	CT	**7.55752±0.43359**	10.7413±0.822	7.9531±0.5823	8.0532±0.621	20.4368±3.102
FON	GD	**0.00163±0.00022**	0.0019±0.0002	0.0022±0.0003	0.0042±0.000	0.0026±0.0003
	Δ	**0.28815±0.03648**	0.3875±0.0062	0.3955±0.0068	0.4158±0.008	0.3987±0.0082
	CT	09.6571±0.54537	11.4013±1.140	**8.6606±0.8862**	8.732±0.9134	22.0323±4.522
ZDT-1	GD	0.36659±0.06618	**0.3325±0.0256**	0.3337±0.0319	0.3348±0.035	0.3352±0.038
	Δ	**0.34579±0.00775**	0.3803±0.0122	0.3825±0.0125	0.3876±0.024	0.3905±0.0220
	CT	6.59899±0.00371	8.2351±0.0204	**3.1435±0.0193**	3.7533±0.006	11.2681±0.364
ZDT-2	GD	**0˙07001±0.00066**	0.0731±0.0010	0.0729±0.0005	0.0733±0.001	0.0725±0.0004
	Δ	**0.04133±0.06577**	0.4307±0.0007	0.4316±0.0007	0.4321±0.001	0.431±0.00075
	CT	4.65825±0.02000	8.2345±0.0457	**3.1502±0.0130**	3.6113±0.014	11.2811±0.024
ZDT-3	GD	**0.07132±0.03917**	0.1022±0.5187	0.0982±0.5007	0.1235±0.009	0.1147±0.0039
	Δ	0.69774±0.23268	0.6537±0.0052	**0.65325±0.002**	0.8234±0.108	0.7386±0.0474
	CT	8.77756±0.34789	13.4567±0.129	6.2846±0.1059	**8.3764±0.231**	14.3406±0.144
ZDT-4	GD	**0.49888±0.00022**	0.5015±0.0006	0.5078±0.0013	0.5146±0.001	0.5204±0.0019
	Δ	**0.35779±0.01477**	0.4585±0.0073	0.4795±0.0079	0.6543±0.024	0.7003±0.0089
	CT	7.87855±0.12275	13.9022±0.121	**6.6922±0.1440**	8.8203±0.218	14.8102±0.170
SCHN-1	GD	0.00999±0.00075	**0.0028±0.0024**	0.0031±0.0032	0.0032±0.003	0.0034±0.0042
	Δ	**0.50066±0.01477**	0.5295±0.1312	0.5302±0.1356	0.8582±0.164	0.5502±0.1360
	CT	11.7600±1.23165	8.2135±1.121	**5.4845±1.1320**	5.5721±1.133	17.9121±2.162
SCHN-2	GD	**0.04977±0.00188**	0.0705±0.0215	0.0932±0.0228	0.1497±0.022	0.3096±0.0217
	Δ	**0.65698±0.02888**	0.7821±0.0512	0.801±0.08326	0.8652±0.060	0.9562±0.0921
	CT	**5.79912±0.14008**	8.7015±0.4532	5.9751±0.2821	6.0272±0.582	18.421±2.1802





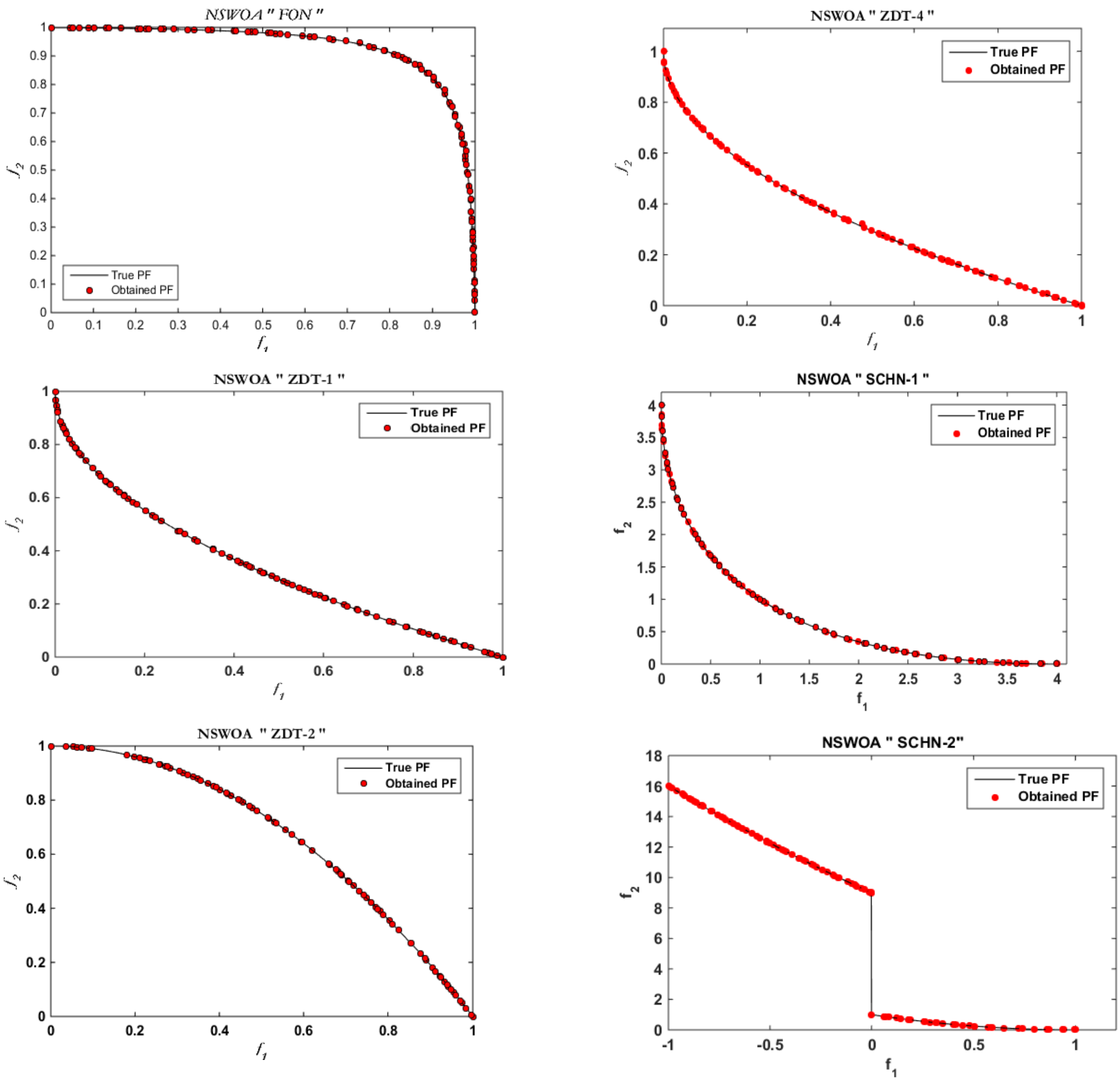


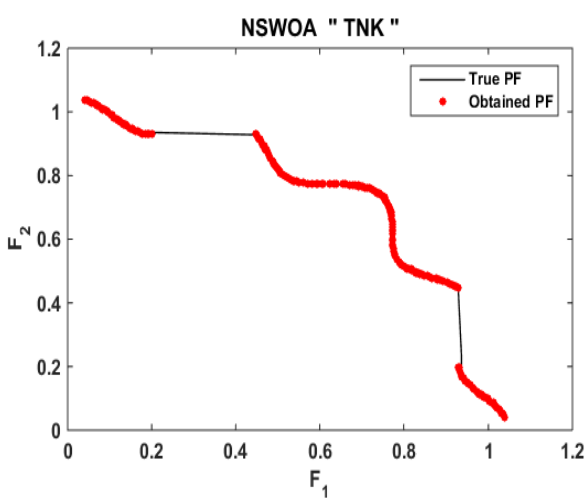
Fig. 5: Best Pareto optimal front of KUR, FON, ZDT1, ZDT2, ZDT3, ZDT4, SCHN1 and SCHN2 obtained by the NSWOA algorithm

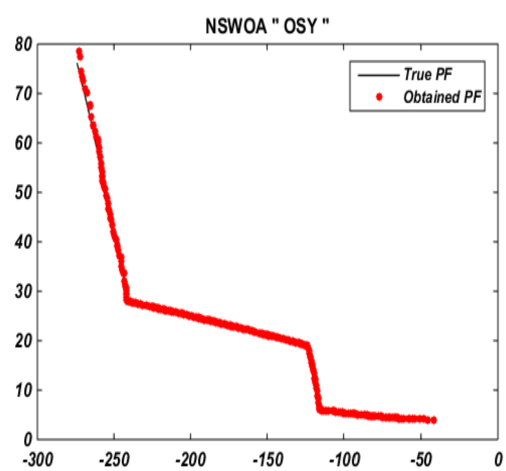
b) Results on constrained test problems

The next set of standard test functions consisting of constrained functions. For constrained test function it should be necessary that NSWOA algorithm has a capability of handling constraints so algorithm is equipped with a death penalty function to search agents that violate any of the constraints at any level [41]. For comparing the results of different algorithms, we have utilized GD and Δ metrics.

Table 2: Results of the multi-objective NSWOA algorithms on constrained test problems

Algorithm→ Function ↓	PFs	NSWOA MEAN±SD	MOSOS MEAN±SD	MOCBO MEAN±SD	MOPSO MEAN±SD	NSGA-II MEAN±SD
	GD	0.14566±0.00216	0.1508±0.0040	0.1528±0.0051	0.1576±0.0062	0.1542±0.0072
TNK	Δ	0.09996±0.05027	0.1206±0.0423	0.1242±0.0512	0.1286±0.0522	0.126±0.06242
	CT	10.7775±0.04668	15.1286±0.063	11.0104±0.052	12.0212±0.054	17.4204±0.055
	GD	0.10004±0.00029	0.1196±0.0031	0.1210±0.0041	0.1282±0.0042	0.1242±0.0043
OSY	Δ	0.54798±0.06679	0.5354±0.0616	0.5422±0.0712	0.5931±0.0721	0.5682±0.0751
	CT	15.4470±0.02008	20.2124±0.032	12.2104±0.030	14.6420±0.042	24.2204±0.039
	GD	0.14447±0.00488	0.1436±0.0062	0.1498±0.0076	0.1644±0.0078	0.1566±0.0042
BNH	Δ	0.44477±0.03786	0.4288±0.0625	0.4798±0.0721	0.4975±0.0632	0.4892±0.0832
	CT	07.5524±0.04587	16.2664±0.054	9.1544±0.0420	9.7452±0.0464	19.652±0.0511
	GD	0.05881±0.01499	0.0988±0.0014	0.1018±0.0015	0.1125±0.0026	0.1024±0.0032
SRN	Δ	0.20444±0.00098	0.2295±0.0017	0.2352±0.0019	0.2730±0.0023	0.^{2}468±0.0018
	CT	7.24456±0.00122	12.3254±0.012	7.3251±0.0082	9.2134±0.0083	17.0231±0.023
	GD	0.42115±0.02998	0.5162±0.0021	0.5202±0.0034	0.5854±0.0036	0.5532±0.0041
CONST	Δ	0.7865±0.000666	0.7122±0.0072	0.7235±0.0083	0.7344±0.0084	0.8126±0.0087
	CT	16.7555±0.00050	10.0112±0.003	5.2252±0.0028	6.4766±0.0035	14.0892±0.003





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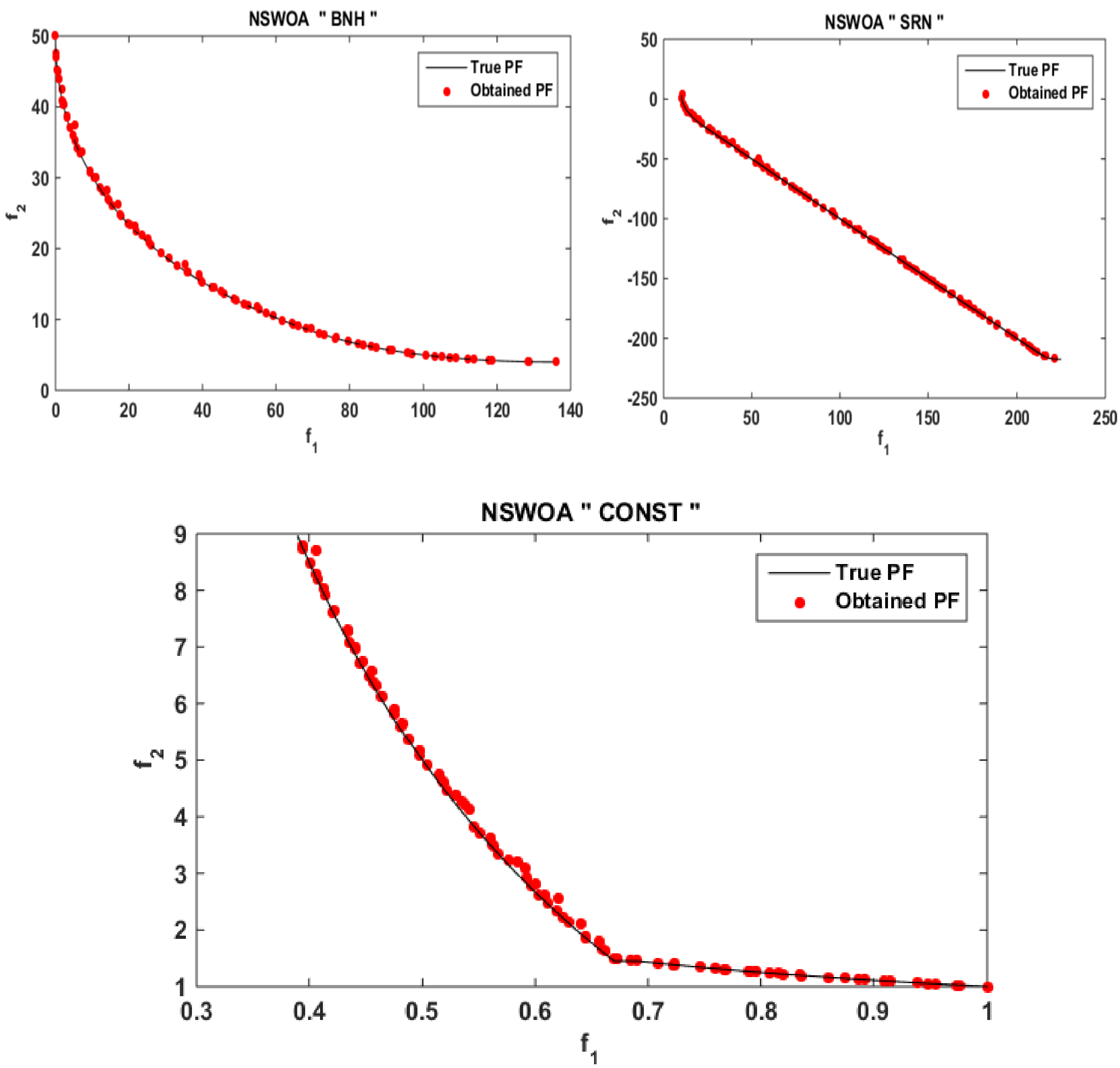

Fig. 6: Best Pareto optimal front TNK, OSY, BNH, SRN and CONST obtained by NSWOA algorithm

Table 2 suggests that the NSWOA algorithm comparatively performs better than other four algorithms for most of the standard constrained test functions employed. The best Pareto optimal fronts in Fig. 6 also helps in proving since all the Pareto optimal solutions exactly follow the true pare to fronts obtained from by NSWOA algorithm.

CONST function consists of concave front with linear front, OSY is similar to CONST but consists of many linear regions with different slops while TNK almost similar to wave shaped. These also suggests that NSWOA algorithm has a capability to solve various type of constraint problem. All the constraint test functions are mathematically given in Appendix B.

c) Results On Constrained Engineering Design Problems

The third set of test functions is the most complicated one and consists of four real engineering design problems. Mathematical model of all the four engineering design problem are given in Appendix C. Same as before both GD and diversity matrix is employed to measure the performance of NSWOA algorithm with respect to other algorithms to solve them, numeric results are given in Tables and Figure respectively shows the best optimal front obtained by NSWOA algorithm.

i. *Four-bar truss design problem*

The statistical results of four bar truss design problem [42] in given in Table 3 and best optimal front is given in Fig. 7. It consists of two minimization objectives displacement and volume with four design control variable mathematically given in Appendix C.

Table 3: Results of the multi-objective NSWO Aalgorithm on four-bar truss design problem in terms mean and standard deviation

PFs→ Methods ↓	GD	S
	MEAN±SD	MEAN±SD
NSWOA	0.1875±0.0414	1.9829±0.1102
MOWCA	0.2076±0.0055	2.5816±0.0298
NSGA-II	0.3601±0.0470	2.3635±0.2551
MOPSO	0.3741±0.0422	2.5303±0.2275
μ- GA	0.9102±1.7053	8.2742±16.831
PAES	0.9733±1.8211	3.2314±5.9555

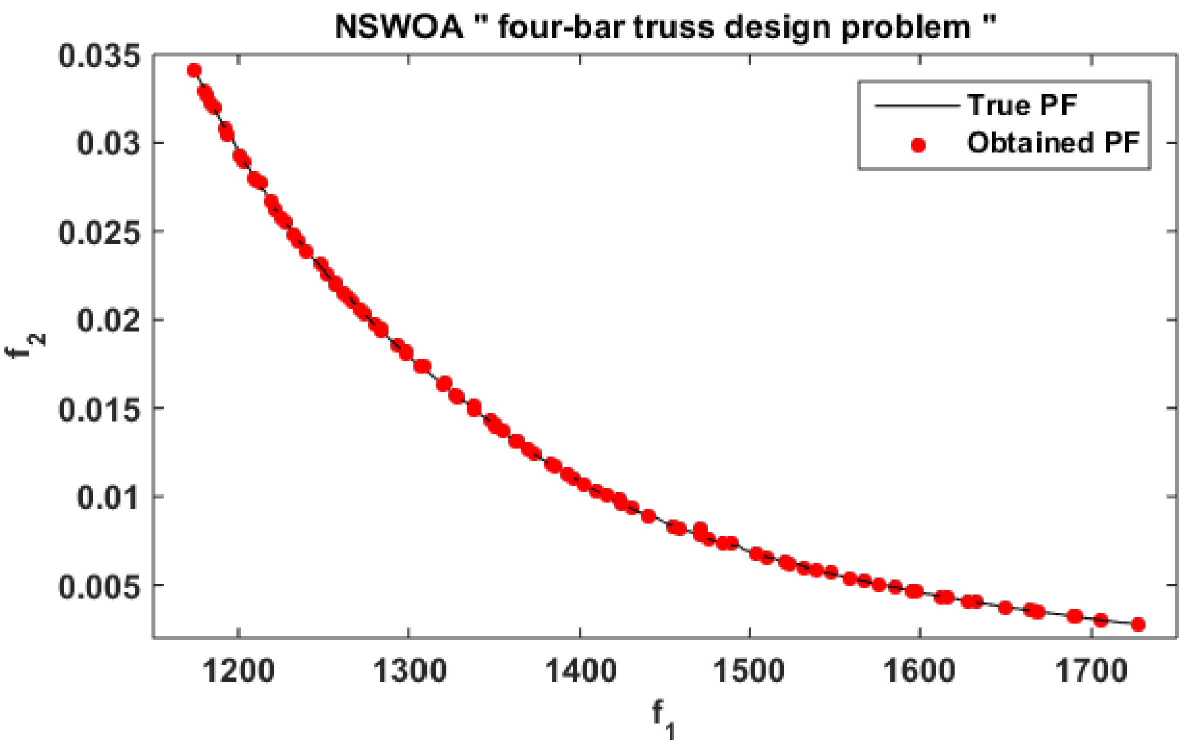

Fig.7: Pareto optimal front obtained by the NSWOA Algorithm for "Four –bus truss design problem"

ii *Speed-reducer design problem*

The statistical results of speed reducer design problem [43] is given in Table 4 and best optimal front is given in Fig. 8. It is a well-known mechanical design problem consists of two minimization objectives stress and weight with seven design control variable mathematically given in Appendix C.

Table 4: Results of the multi-objective NSWOA algorithm on speed-reducer design problem in terms mean and standard deviation

PFs→ Methods ↓	GD	S
	MEAN±SD	MEAN±SD
NSWOA	0.96469±0.41014800	1.778124±04.943415
MOWCA	0.98831±0.17894217	16. 68520±2.6969443
NSGA-II	9.843702±7.0810303	02.7654494±3.534978
μ- GA	3.117536±1.6781086	47.80098±32.8015157
PAES	77.99834±4.2102608	16.20129±4.26842769

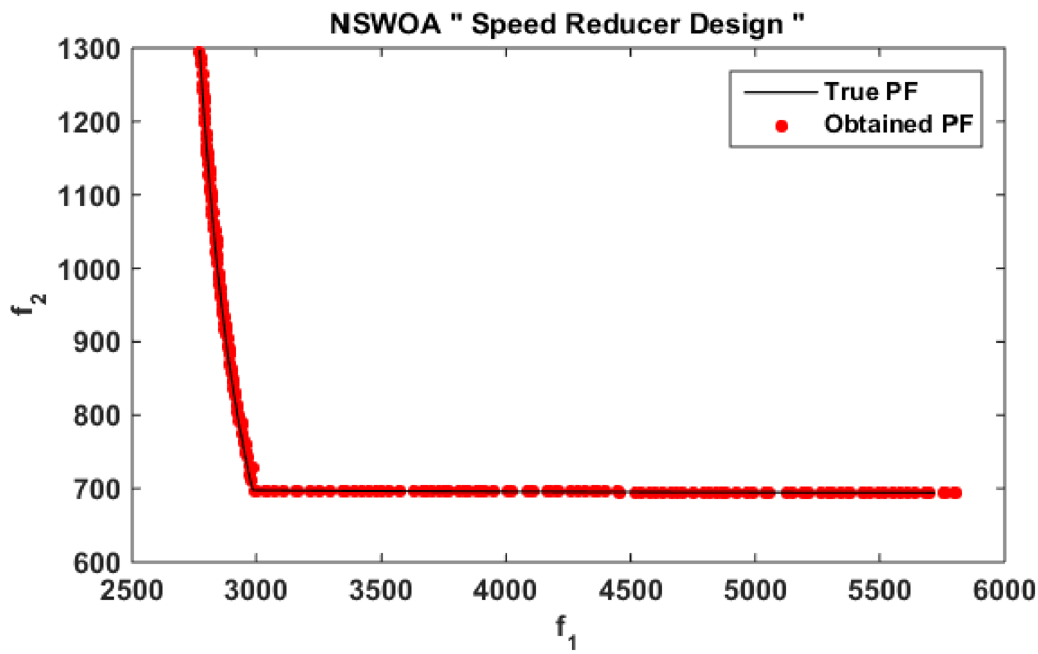

Fig.8: Pareto optimal front obtained by the NSWOA Algorithm for "Speed Reducer design problem"

iii. *Welded-beam design problem*

The statistical results of welded beam design problem [44] is given in Table 5 and best optimal front is given in Fig. 9. It is a well-known mechanical design problem consists of two minimization objectives fabrication cost and deflection of beam with four design control variable mathematically given in Appendix C.

Table 5: Results of the multi-objective NSWOA algorithms on welded-beam design problem in terms mean and standard deviation

PFs→ Methods ↓	GD	Δ
	MEAN±SD	MEAN±SD
NSWOA	0.03641±0.02588	0.75543±0.02777
MOWCA	0.04909±0.02821	0.22478±0.09280
NSGA-II	0.16875±0.08030	0.88987±0.11976
paε-ODEMO	0.09169±0.00733	0.58607±0.04366

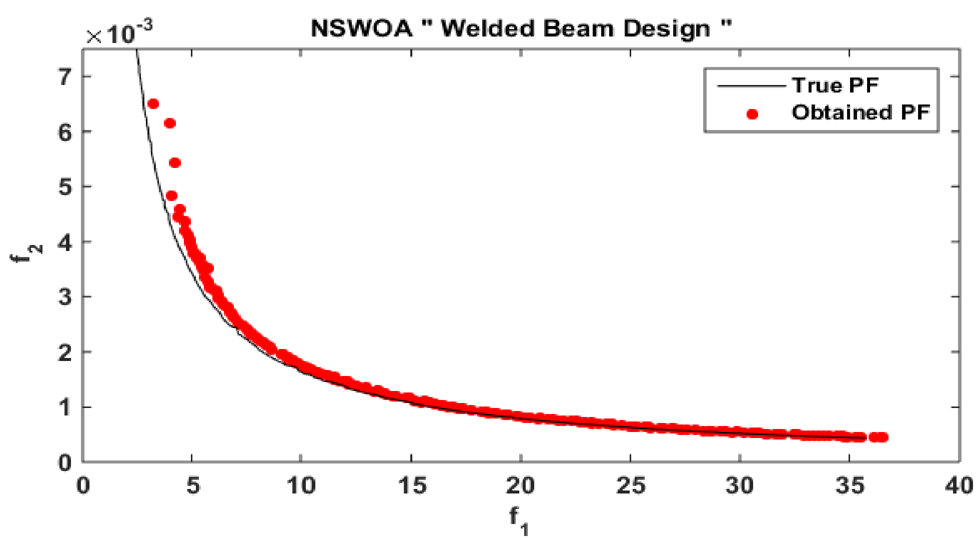

Fig.9: Paretooptimal front obtained by the NSWOA Algorithm for "Welded Beam Design problem"

iv. *Disk brake design problem*

The statistical results of welded beam design problem [44] is given in Table 6 and best optimal front is given in Fig. 10. It is a well-known mechanical design problem consists of two minimization objectives stopping time and mass of brake of a disk brake with four design control variable mathematically given in Appendix C.

Table 6: Results of the multi-objective NSWOA algorithms on the Disk brake design problem in terms mean and standard deviation

PFS→ Methods ↓	GD	Δ
	MEAN±SD	MEAN±SD
NSWOA	0.0577±0.27030	0.23341±0.05226
paε-ODEMO	2.6928±0.24051	0.84041±0.20085
NSGA-II	3.0771±0.10782	0.79717±0.06608
MOWCA	0.0244±0.12314	0.46041±0.10961

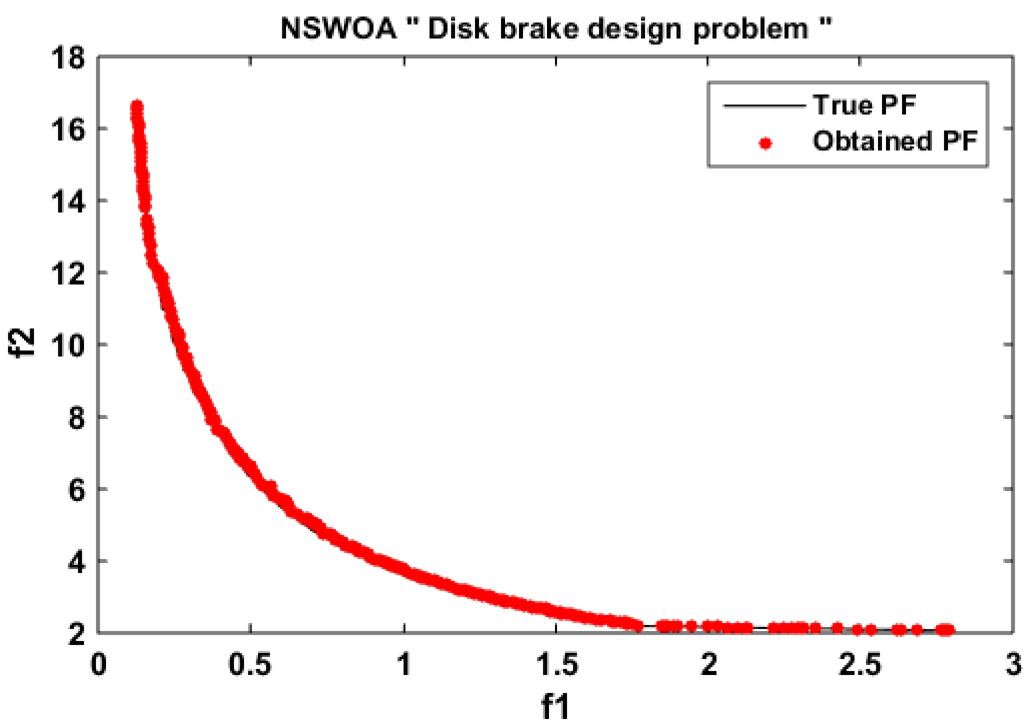

Fig.10: Paretooptimal front obtained by the NSWOA Algorithm for "Disk brake design problem"

Due to high complexity of engineering design problem it is really hard to gain results alike true pare to front but we can clearly see that optimal pare to obtained by NSWOA algorithm is covers almost whole solutions that are the actual/true solutions of an engineering design problem. From all above tested function we can conclude that problem either it consists of constraints or unconstraint problem NSWOA algorithm shows its capability to solve any kind of linear, non-linear and complex real world problem. So in the next section we attached a highly non-linear complex real problem to show its effectiveness regarding the real world complex application with many objectives.

d) *Formulation Of Economic Constrained Emission Dispatch (ECED) With Integration Of Wind Power (WP)*

i. *Mathematical Formulation Of Wind Power*

In case of wind power generation, the output power of wind generator is calculated with the help of a stochastic variable wind speed υ (meter/seconds). Wind speed is a variable function so their probability distribution plays a very important role. Wind speed mathematically formulated as two-parametric Weibull distribution function, probability density function (PDF) and cumulative distribution function (CDF) as follows:

$$s(v) = (k/c)\,(v/c)^{k-1} * \exp[-(v/c)^{k}],\ v \geq 0 \qquad (4.1)$$

$$S(v) = 1 - \exp[-(v/c)^{k}], v \geq 0 \qquad (4.2)$$

where, S(v) and s(v) are CDF and PDF respectively. Shape factor and scale factor are k and c respectively. The wind speed and output wind power are related as:

$$P_{wind} = \begin{cases} 0, & v < v_{in} \text{ or } v \geq v_{out} \\ P_{rated} \frac{v - v_{in}}{v_{rated} - v_{in}} & v_{in} \leq v < v_{rated} \\ P_{rated} v_{in} & \leq v < v_{out} \end{cases} \quad (4.3)$$

where, v_{rated} and P_{rated} are the rated speed of wind and rated power output. v_{out} and v_{in} are cut-out and cut-in speed of wind respectively. The CDF of P_{wind} in the boundary of [0, P_{rated}] on an accordance with the speed range of wind can be formulated as:

$$S(P_{wind}) = 1 - exp\left\{- \left[\left(1 + \frac{v_{rated} - v_{in}}{v_{in} * P_{rated}} P_{wind}\right) \frac{v_{in}}{c}\right]^k\right\} + \exp[-(v_{out}/c)^k] \quad 0 \leq P_{wind} < P_{rated} \quad (4.4)$$

Above equation is very meaningful to calculate the ECED problems with speculative wind power with variable speed.

ii. *Modeling of ECEDWP problem*

As wind power is formulated as system constraint, so the objective function of economic emission dispatch problem (EEDP) stays on unchanged as classical EEDP:

Fuel cost objective is given by:

$$Minimization \quad S(P_i) = \sum_i^N (a_i + b_i P_i + c_i P_i^2) \quad (4.5)$$

where, the thermal power generators cost coefficients are a_i, b_i, c_i for i-th generator, Sum of the total fuel cost of the system and N is the total number of generators. Total Emission is calculated by:

$$Minimization \; E(P_i) = \sum_i^N [\{(\alpha_i + \beta_i P_i + \gamma_i P_i^2) * 10^{-2}\} + \delta_i * \exp(\varphi_i * P_i)] \quad (4.6)$$

where, $\alpha_i, \beta_i, \gamma_i, \delta_i$ and φ_i are emission coefficients with valve point effect taking into consideration for i-th thermal generator.

iii. *System Constraints*

As wind power generation is considered as system constraint with the summation of stochastic variables the classical power balance constraint changes to fulfill the predefined confidence level.

$$P_r \sum_{i=1}^N (P_i + P_{Wind} \geq P_D + P_{Loss}) \geq \eta_{pbc} \quad (4.7)$$

where, η_{pbc} is confidence level that a power system must follow the load demand and so as it is selected nearer to unity as values lesser than unity represents high operational risk. P_{loss} represents system losses can be calculated by B-coefficient method given below:

$$P_{Loss} = \sum_{i=1}^N \sum_{j=1}^N P_i B_{ij} P_j + \sum_{i=1}^N P_i B_{i0} + B_{00} \quad (4.8)$$

So as to change above described power balance constrained equation into deterministic form can be solved as:

$$P_r\{P_{Wind} < P_D + P_{Loss} - \sum_{i=1}^N P_i\} = F(P_D + P_{Loss} - \sum_{i=1}^N P_i) \leq 1 - \eta_{pbc} \quad (4.9)$$

Assume that the wind turbine has same speed and same direction and combination of Eqs. (4) and (9), the power balance constraint is represented as:

$$P_D + P_{Loss} - \sum_{i=1}^N P_i \leq \frac{cP_{rated}}{v_{rated} - v_{in}} \left| \ln\left[\eta^{pbc} + exp * \left(\frac{v_{out}^k}{c^k}\right)\right]\right|^{\frac{1}{k}} - \frac{v_{in} * P_{rated}}{v_{rated} - v_{in}} \quad (4.10)$$

iv. *Reserve capacity system constraint*

So as to reduce the impact of stochastic wind power on system, up and down spinning reserve needs to be maintained [22]. Such reserve constraints formulated as [15] and [16] respectively:

$$P_r\{\sum_{i=1}^N (P_i^{max} - P_i) \geq P_{sr} + t_u * P_{Wind}\} \geq \eta_{urc} \quad (4.11)$$

$$P_r\{\sum_{i=1}^N (P_i - P_i^{min}) \geq t_d * (P_{rated} - P_{Wind})\} \geq \eta_{drc} \quad (4.12)$$

where, P_{sr} represents the reserve demand of conventional thermal power plant system and it generally keeps the maximum value of thermal unit, P_i^{max} and P_i^{min} are maximum and minimum output level of operational generators of i-th unit, η_{drc} and η_{urc} are predefined down and upper confidence level parameter respectively, t_u and t_d are the demand coefficients of up and down spinning reserves.

v. *Generational capacity constraint*

The real output power is bounded by each generators upper and lower bounds given as:

$$P_i^{Minimum} \leq P_i \leq P_i^{Maximum} \quad (4.13)$$

V. Test System For Economic Emission Dispatch Problem

a) 40-Operational Thermal Generating Unit

i. *Case Study I- 40 Thermal-Generator Lossless System Without Wind Power*

In this case forty operational generating unit is consider without integration of wind power means all the generating units are coal fired. Input parameters like generators operating limit, fuel cost coefficients and emission coefficients are given in Appendix D and in Table 11. extracted from [45]. System is considered lossless and its solution is compared with three well known multi-objective algorithms like SMODE [45], NSGA-II [45]and MBFA [46] in terms of various objectives such as best cost, best emission and best compromise between both objectives. Best compromise solution is then obtained by the fuzzy based method [47]. Total power demand for this system is 10500 MW. Results obtained by NSWOA algorithm is added to table 7 and best pare to front obtained by NSWOA algorithm is represented in Fig. 12.

Table 7 : Results of the multi-objective NSWOA algorithms for case study I- 40 thermal-generator lossless system without wind power

Case Study I	SMODE [45]			NSGAII [45]			MBFA [46]			NSWOA		
	Best emission	Best cost	Best compromise	Best emission	Best Cost	Best compromise	Best emission	Best cost	Best compromise	Best emission	Best cost	Best compromise
Cost ($/h)	156,700	119,650	124,230	128,490	124,380	126,180	129,995	121,415	123,638	127,555	**119,310**	**124,831**
Emission (tons/h)	**66,799**	377,560	96,578	93,002	153,560	99,671	176,682	356,424	188,963	87,123	408,020	**94,450**

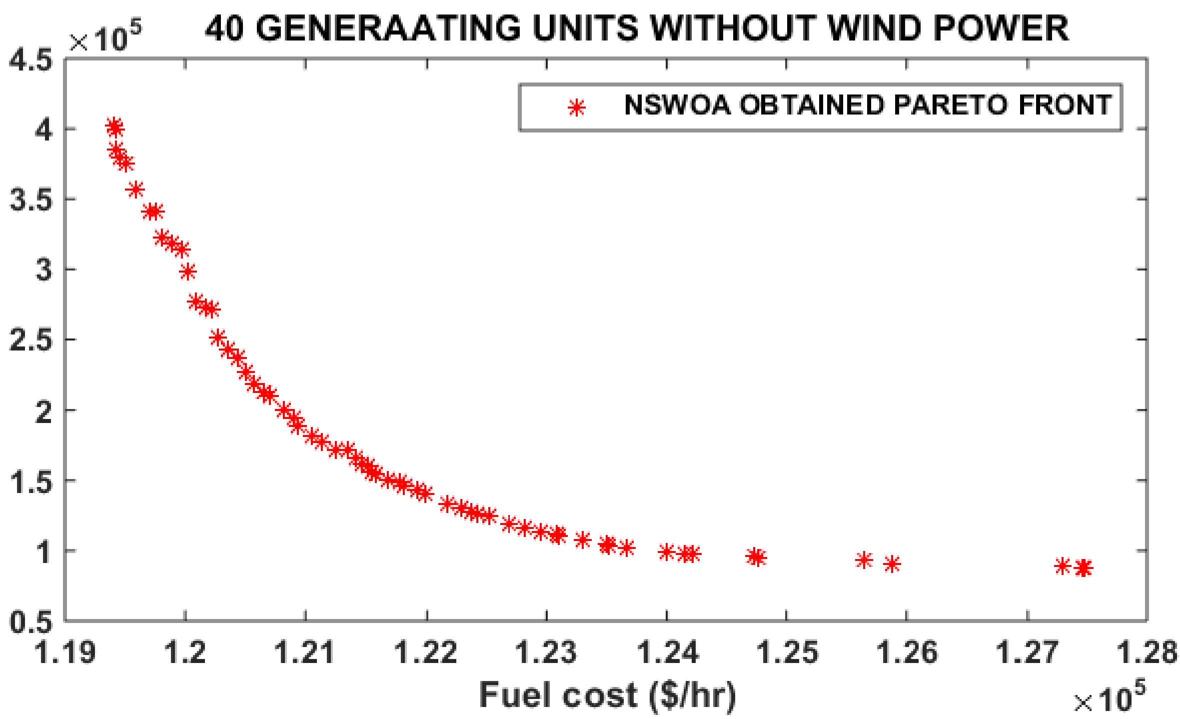

Fig. 12: Pareto optimal front obtained by the NSWOA Algorithm for "40 thermal-generator lossless system without wind power"

ii. *Case study II- 40 thermal-generator lossless system with wind power*

All the conditions are remaining same as case study I like input parameters and power demand. While integrating with wind power plant, the total rated output power of wind farm is set to 1000 MW [45, 47].Statistical results obtained by NSWOA algorithm is reported in Table 8 and best optimal front is represented in Fig. 13.

Table. 8: Results of Wilcox on test and simulation/computational time or speed

Case Study-II	SMODE[45]			NSGAII [45]			MOEA/D[51]			NSWOA		
	Best emission	Best cost	Best Compromise - Point	Best emission	Best cost	Best Compromise - Point	Best emission	Best cost	Best Compromise - Point	Best emission	Best cost	Best Compromise - Point
$\sum P_G$	10,245.76	10,177.55	10,225.71	10,241.72	10,242.09	10,241.63	10,244.43	10,242.71	10,242.8	10,241.6	10,224.18	10,236.58
P_W	254.24	322.45	274.29	258.28	257.91	258.37	255.568	257.294	257.156	255.321	276.81	263.75
Cost	153,830	116,430	123,590	132,410	122,610	126,240	154,0 0 0	115,770	120,950	145,636	118,789	123,449
Emission	54,055	385,770	68,855	73,894	121,850	78,860	55,754	440,240	79,485	56,508	179,098	68,804

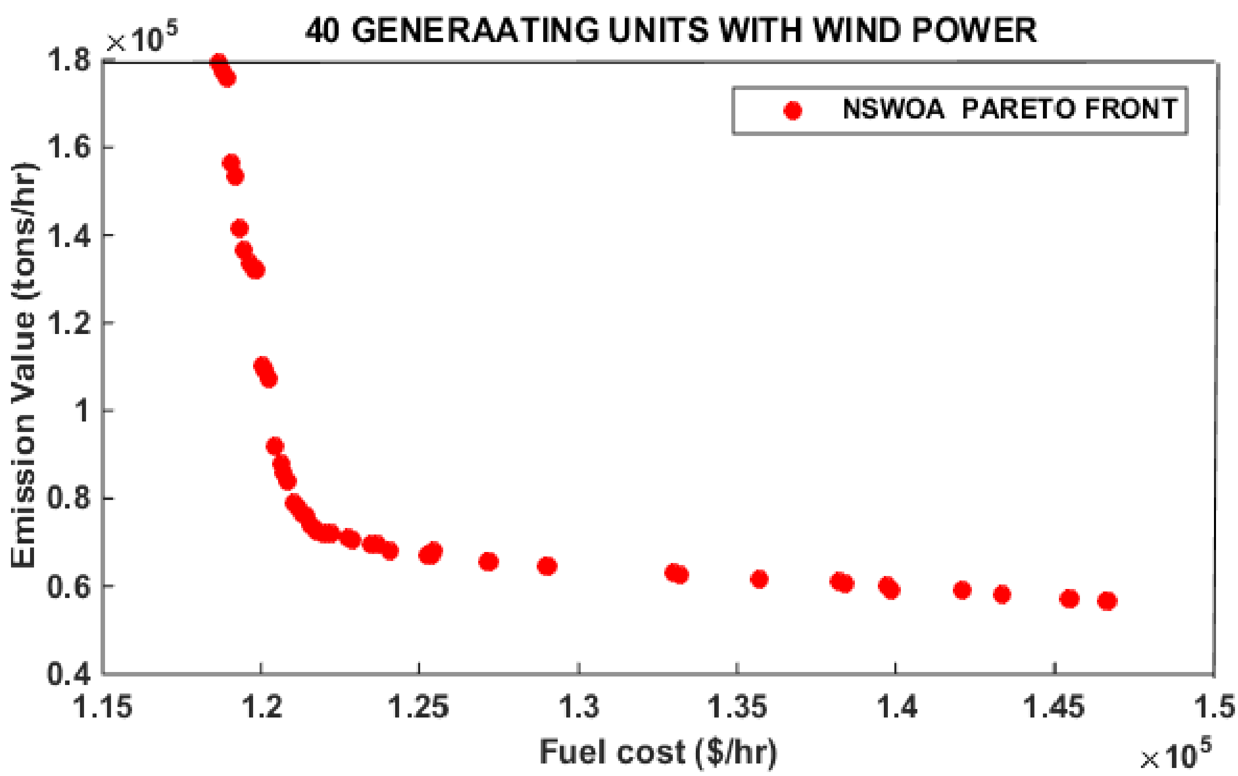

Fig. 13: Pareto optimal front obtained by the NSWOA Algorithm for "40 thermal-generator lossless system with wind power"

Table 9: Results of Wilcox on test and simulation/computational time or speed

		NSWOA	NSGAII[45]			NSWOA	NSGAII[45]
Case Study I Cost	Best Worst Mean Wilcox on test (H/P) Simulation speed (s)	119310 127555 124831 1/5.38e−10 14.98	124,380 147,760 131,710	Case Study II Cost	Best Worst Mean Wilcox on test (H/P) Simulation speed (s)	118,789 145,636 123,449–10 1/5.65e 19.876	122,610 173,060 134,880
Case Study I Emission	Best Worst Mean Wilcoxon test (H/P) Simulation speed (s)	87,123 408.020 189,284 1/5.54e−10 40.57	93,002 194,830 141,800 154.78	Case Study II Emission	Best Worst Mean Wilcox on test (H/P) Simulation speed (s)	56,508 179,098 104,185 1/5.65e−10 45.67	73,894 158,250 102,120 127.57

b) Test system with six operational generating unit

This test system consists of six operational generating unit with simply a quadratic fuel and emission objective function for a power demand of 1200 MW. Input data for operational generating unit loading limits and loss parameters are given in Table 12 of Appendix D extracted from [52, 53].

It is represented in Table 10 that with the objective of least cost objective minimum fuel cost is 6.4197e+04 $ and emission value is 1345.9 lb. But fuel cost increases to 6.992e+04 $ and emission value reduced to a numeric value 1242.7 lb with the objective of emission minimization. Compromise point or true operating point obtained by NSWOA algorithm for multi-objective combined economic emission dispatch (MOCEED) problem is as fuel cost is 6.4830e+04 $ that is higher than minimum fuel cost 6.4197e+04$ and lower than 6.992e+04 $ obtained during least cost and emission value objectives respectively. So as with emission value for true operating point is 1285 lb that is lower than 1345.9 lb and higher than 1242.7 lb obtained during least cost and emission value objectives respectively. Statistical value obtained for compromise point is compared with other techniques solves same MOCEED problem like SPEA2, NSGA-II and PDE in Table 10. Fig. 14 shows 100 non-dominated solutions as true pare to front for 6-opertaional generating for PD=1200 MW.

Table 10: Statistical performance comparison of NSWOA Algorithm for 6-operational generating unit system.

Parameters	**NSWOA**			**MODE[53]**	**PDE [53]**	**NSGAII[53]**	**SPEA2[53]**
	Economic dispatch	Emission dispatch	EED	EED	EED	EED	EED
P_1 (MW)	84.7275	125	107.9932	108.6284	107.3965	113.1259	104.1573
P_2 (MW)	93.4118	150	118.3631	115.9456	122.1418	116.4488	122.9807
P_3 (MW)	210	201.4824	210	206.7969	206.7536	217.4191	214.9553
P_4 (MW)	211.8607	198.8723	204.65	210.0000	203.7047	207.9492	203.1387
P_5 (MW)	315	288.5129	306.6592	301.8884	308.1045	304.6641	316.0302
P_6 (MW)	325	286.2913	303.8712	308.4127	303.3797	291.5969	289.9396
Cost ($)	64,197	65,992	64,830	64,843	64,920	64,962	64,884
Emission (lb)	1345.9	1242.7	1285	1286.0	1281.0	1281.0	1285

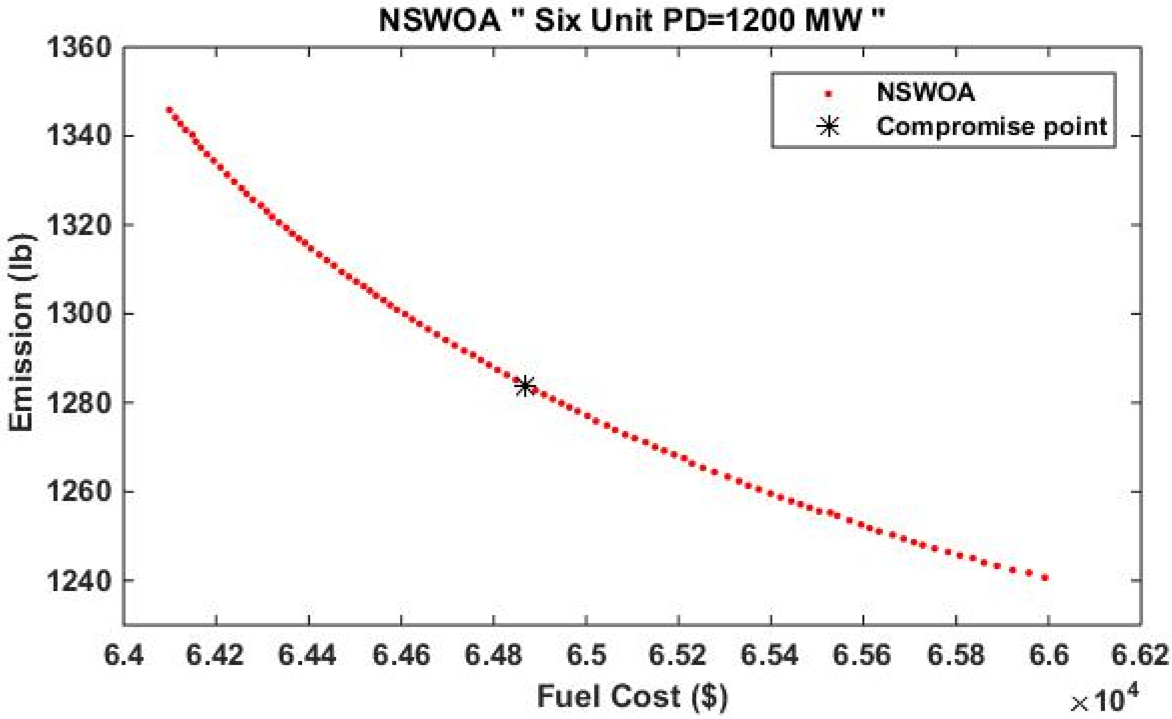

Fig. 14: Pare to optimal front obtained by the NSWOA Algorithm for "six operational generating unit system"

VI. Result Discussion

In almost all the cases that we consider in this article where NSWOA algorithm proves its effectiveness in both prospective quantitative and qualitative. From plots also evident that NSWOA algorithm follows the exact pare to front similar to the true pare to front for all constrained, unconstrained and complex engineering design problem. So as for real world application of economic emission dispatch problem and its integration with stochastic wind power generation. So for this application Wilcox on test (statistical test)is performed.

In Table 9 the signed rank test is presented in third row of each results whereas the calculation time is represented in forth row. For this test null hypothesis cannot be rejected at 5% level for numeric value '0' while null hypothesis is rejected at 5% level with the value of '1'. Where NSWOA algorithm performs superior to other algorithms that are considered for comparative purpose.

NSWOA algorithm shows good performance in both coverage and convergence as main mechanism that guarantee convergence in WOA and NSWO Aalgorithms are continuously shrink its virtual limitation using helix shaped or 9-shaped path strategy in the movement of whales for their random walk. Both mechanism emphasizes convergence and exploitation proportional to maximum number of generation (iteration). Since this complex task might degrade its performance compare to without limitation or free movement should be a concern. However, the numerical results expresses that NSWOA algorithm has a little effect of slow convergence at all.

NSWOA algorithm has an advantage of high coverage, which is the result of the selection of position of whales and archive selection procedure. All the position is updated according to their fitness value that enable the algorithm to direct the search space in right direction to find the best solution without trapped in local solution. Archive selection criteria follow all the rules of the entrance and exhaust of any value in it for each iteration and updated when its size full. Solutions of higher fitness in archive have higher probability to thrown away first to improve the coverage of the pare to optimal front obtained during the optimization process.

VII. Conclusion

In this paper the non-dominated sorting whale optimization algorithm-multi-objective version of recently proposed whale optimizationalgorithm (WOA) is proposed known as NSWOA algorithm. This paper also utilizes the bubble-net swarming strategy for exploration purpose used in its parent WOA version. The NSWOA algorithm is developed with equipping whale optimization algorithm with crowding distance criterion, an archive and whales position (accordance to ranking) selection method based on Pareto optimal dominance nature. The NSWOA algorithm is first applied on 17 standard test functions (including eight unconstraint, five constraint and four engineering design multi-objective problems) to prove its capability in terms of qualities and quantities showing numerical as well as convergence and coverage of pare to optimal front with respect to true pare to front. Then after NSWOA algorithm is applied to real world complex ECEDWP problem where algorithm proves its dominance over other well recognized contemporary algorithms. The numeric results are stored and represented in performance indices: GD, metric of diversity, metric of spacing and computational time. The qualitative results are reported as convergence and coverage in best pare to optimal front found in 15 independent runs. To check effectiveness of proposed version of algorithm the results are verified with SMODE, MOSOS, MOCBO, MOPSO, NSGA-II and other well recognize algorithms in the field of multi-objective algorithms. We can also conclude from the standard test functions results that NSWOA algorithm is able to find pare to optimal front of any kind of shape. Finally, the result of complex real world ECEDWP problem validates that NSWOA algorithm is capable of solving any kind of non-linear and complex problem with many constraint and unknown search space. Therefore, we conclude that proposed non-dominated version of WOA algorithm has various merits among the contemporary multi-objective algorithms as well as provides an alternative for solving multi or many objective problems.

For future works, it is suggested to test NSWOA algorithm on other real world complex problems. Also, it is worth to investigate and find the best constrained handling technique for this algorithm.

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Appendix A: Unconstrained multi-objective test problems utilized in this work.

KUR:

Minimize: $f_1(x) = \sum_{i=1}^{2}\left[-10\exp(-0.2\sqrt{x_i^2 + x_{i+1}^2})\right]$

$f_2(x) = \sum_{i=1}^{2}[|x_i|^{0.8} + 5sin(x_i^3)]$

$-5 \le x_i \le 5$

$1 \le i \le 3$

FON:

$$\min imize = \begin{cases} f_1(x) = 1 - \exp\left[-\sum_{i=1}^{n}(x_i - \frac{1}{\sqrt{n}})^2\right] & -4 \le x_i \le 4 \\ f_2(x) = 1 - \exp\left[-\sum_{i=1}^{n}(x_i + \frac{1}{\sqrt{n}})^2\right] & 1 \le i \le n \end{cases}$$

ZDT1:

Minimise: $\boldsymbol{f_1(x) = x_1}$

Minimise: $f_2(x) = g(x) \times h(f_1(x), g(x))$

Where:

$$G(x) = 1 + \frac{9}{N-1}\sum_{i=2}^{N} x_i\, h(f_1(x), g(x)) = 1 - \sqrt{\frac{f_1(x)}{g(x)}} \quad 0 \le x_i \le 1, 1 \le i \le 30$$

ZDT2:

Minimise: $f_1(x) = x_1$

Minimise: $f_2(x) = g(x) \times h(f_1(x), g(x))$

Where: $G(x) = 1 + \frac{9}{N-1}\sum_{i=2}^{N} x_i\, h(f_1(x), g(x)) = 1 - \left(\frac{f_1(x)}{g(x)}\right)^2 \quad 0 \le x_i \le 1, 1 \le i \le 30$

ZDT3:

Minimise: $f_1(x) = x_1$

Minimise: $f_2(x) = g(x) \times h(f_1(x), g(x))$

Where: $G(x) = 1 + \frac{9}{29}\sum_{i=2}^{N} x_i \; h(f_1(x), g(x)) = 1 - \sqrt{\frac{f_1(x)}{g(x)}} - \left(\frac{f_1(x)}{g(x)}\right)\sin(10\pi f_1(x)) \quad 0 \le x_i \le 1, 1 \le i \le 30$

ZDT4:

Minimise: $f_1(x) = x_1$

Minimise: $f_2(x) = g(x) \times h(f_1(x), g(x))$

$$h(f_1(x), g(x)) = 1 - \sqrt{\frac{f_1(x)}{g(x)}} \quad g(x) = 91 + \sum_{i=2}^{10}(x_i^2 - 10 * \cos(4\pi x_i))$$

SCHN-1 :

Minimize: $f_1(x) = x_i^2$

$f_2(x) = (x-2)^2 \; -A \le x \le A$

Where: value of can be from 10 to 10^5.

SCHN-2 :

Minimize: $$\begin{cases} f_1(x) = \begin{cases} -x, & if \quad x \le 1 \\ x-2, & if \quad 1 < x \le 3 \\ 4-x, & if \quad 3 < x \le 4 \\ x-4, & if \quad x > 4 \end{cases} \quad -5 \le x \le 10 \\ f_2(x) = (x-5)^2 \end{cases}$$

Appendix B: Constrained multi-objective test problems utilised in this work.

TNK:

Minimise: $f_1(x) = x_1$

Minimise: $f_2(x) = x_2$

Where: $g_1(x) = -{x_1}^2 - {x_2}^2 + 1 + 0.1Cos(16arctan\left(\frac{x_1}{x_2}\right))$

$$g_2(x) = 0.5 - (x_1 - 0.5)^2 - (x_2 - 0.5)^2 \; 0.1 \le x_1 \le \pi, 0 \le x_2 \le \pi$$

BNH:

This problem was first proposed by Binh and Korn [48]:

Minimise: $\boldsymbol{f_1(x) = 4{x_1}^2 + 4{x_2}^2}$

Minimise: $f_2(x) = (x_1 - 5)^2 + (x_2 - 5)^2$

Where: $g_1(x) = (x_1 - 5)^2 + {x_2}^2 - 25$

$g_2(x) = 7.7 - (x_1 - 8)^2 - (x_2 + 3)^2 \quad 0 \le x_1 \le 5, 0 \le x_2 \le 3$

OSY:

The OSY test problem has five separated regions proposed by Osyczka and Kundu [49]. Also, there are six constraints and six design variables.

Minimise: $f_1(x) = {x_1}^2 + {x_2}^2 + {x_3}^2 + {x_4}^2 + {x_5}^2 + {x_6}^2$

Minimise: $f_2(x) - [25(x_1-2)^2 + (x_2-1)^2 + (x_3-1)^2 + (x_4-4)^2 + (x_5-1)^2]$

Where: $g_1(x) = 2 - x_1 - x_2$
$g_2(x) = -6 + x_1 + x_2$
$g_3(x) = -2 - x_1 + x_2$
$g_4(x) = -2 + x_1 - 3x_2$
$g_5(x) = -4 + x_4 + (x_3-3)^2$
$g_6(x) = 4 - x_6 - (x_5-3)^2 0 \le x_1 \le 10, 0 \le x_2 \le 10, 1 \le x_3 \le 5, 0 \le x_4 \le 6, 1 \le x_5 \le 5, 0 \le x_6 \le 10$

SRN:

The third problem has a continuous Pareto optimal front proposed by Srinivas and Deb [50].

Minimise: $f_1(x) = 2 + (x_1-2)^2 + (x_2-1)^2$

Minimise: $f_2(x) = 9x_1 - (x_2-1)^2$

Where: $g_1(x) = {x_1}^2 + {x_2}^2 - 255$

$g_2(x) = x_1 - 3x_2 + 10 \; -20 \le x_1 \le 20, -20 \le x_2 \le 20$

CONSTR:

This problem has a convex Pareto front, and there are two constraints and two design variables.

Minimise: $f_1(x) = x_1$

Minimise: $f_2(x) = (1+x_2)/(x_1)$

Where: $g_1(x) = 6 - (x_2 + 9x_1)$, $g_2(x) = 1 + x_2 - 9x_1 \; 0.1 \le x_1 \le 1, 0 \le x_2 \le 5$

Appendix C: Constrained multi-objective engineering problems used in this work.

Four-bar truss design problem:

The 4-bar truss design problem is a well-known problem in the structural optimisation field [42], in which structural volume (*f1*) and displacement (*f2*) of a 4-bar truss should be minimized. As can be seen in the following equations, there are four design variables (*x1-x4*) related to cross sectional area of members 1, 2, 3, and 4.

Minimise: $\boldsymbol{f_1(x) = 200 * (2 * x(1) + sqrt(2 * x(2)) + sqrt(x(3)) + x(4))}$

Minimise: $f_2(x) = 0.01 * \left(\left(\frac{2}{x(1)}\right) + \left(\frac{2*sqrt(2)}{x(2)}\right) - ((2 * sqrt(2))/x(3)) + (2/x(1))\right)$
$1 \le x_1 \le 3, 1.4142 \le x_2 \le 3, 1.4142 \le x_3 \le 3, 1 \le x_4 \le 3$

Speed reducer design problem:

The speed reducer design problem is a well-known problem in the area of mechanical engineering [43], in which the weight (*f1*) and stress (*f2*) of a speed reducer should be minimized. There are seven design variables: gear face width (*x1*), teeth module (*x2*), number of teeth of pinion (*x3* integer variable), distance between bearings 1 (*x4*), distance between bearings 2 (*x5*), diameter of shaft 1 (*x6*), and diameter of shaft 2 (*x7*) as well as eleven constraints.

Minimise: $f_1(x) = 0.7854 * x(1) * x(2)^2 * (3.3333 * x(3)^2 + 14.9334 * x(3) - 43.0934) - 1.508 * x(1) * (x(6)\hat{}2 + x(7)\hat{}2) + 7.4777 * (x(6)\hat{}3 + x(7)\hat{}3) + 0.7854 * (x(4) * x(6)\hat{}2 + x(5) * x(7)\hat{}2)$

Minimise: $f_2(x) = ((sqrt(((745 * x(4))/(x(2) * x(3)))\hat{}2 + 16.9e6))/(0.1 * \ldots x(6)\hat{}3))$

Where: $g_1(x) = 27/(x(1) * x(2)\hat{}2 * x(3)) - 1$

$g_2(x) = 397.5/(x(1) * x(2)\hat{}2 * x(3)\hat{}2) - 1$

$g_3(x) = (1.93 * x(4)\hat{}3)/(x(2) * x(3) * x(6)\hat{}4) - 1$

$g_4(x) = (1.93 * x(5)\hat{}3)/(x(2) * x(3) * x(7)\hat{}4) - 1$

$g_5(x) = ((sqrt(((745 * x(4))/(x(2) * x(3)))\hat{}2 + 16.9e6))/(110 * x(6)\hat{}3)) - 1$

$g_6(x) = ((sqrt(((745 * x(5))/(x(2) * x(3)))^2 + 157.5e6))/(85 * x(7)^3)) - 1$

$g_7(x) = ((x(2) * x(3))/40) - 1$

$g_8(x) = (5 * x(2)/x(1)) - 1$

$g_9(x) = (x(1)/12 * x(2)) - 1$

$g_{10}(x) = ((1.5 * x(6) + 1.9)/x(4)) - 1$

$g_{11}(x) = ((1.1 * x(7) + 1.9)/x(5)) - 1$

$2.6 \le x_1 \le 3.6, 0.7 \le x_2 \le 0.8, 17 \le x_3 \le 28, 7.3 \le x_4 \le 8.3, 7.3 \le x_5 \le 8.3, 2.9 \le x_6 \le 3.95 \le x_7 \le 5.5$

Welded beam design problem:

The welded beam design problem has four constraints first proposed by Ray and Liew [44]. The fabrication cost (*f1*) and deflection of the beam (*f2*) of a welded beam should be minimized in this problem. There are four design variables: the thickness of the weld (*x1*), the length of the clamped bar (*x2*), the height of the bar (*x3*) and the thickness of the bar (*x4*).

Minimise: $f_1(x) = 1.10471 * x(1)^2 * x(2) + 0.04811 * x(3) * x(4) * (14.0 + x(2))$

Minimise: $f_2(x) = 65856000/(30 * 10^6 * x(4) * x(3)^3)$

Where: $g_1(x) = tau - 13600$

$g_2(x) = sigma - 30000$

$g_3(x) = x(1) - x(4)$

$g_4(x) = 6000 - P$

$0.125 \le x_1 \le 5, 0.1 \le x_2 \le 10, 0.1 \le x_3 \le 10, 0.125 \le x_4 \le 5$

Where

$$Q = 6000 * \left(14 + \frac{x(2)}{2}\right); D = sqrt\left(\frac{x(2)^2}{4} + \frac{(x(1) + x(3))^2}{4}\right)$$

$$J = 2 * \left(x(1) * x(2) * sqrt(2) * \left(\frac{x(2)^2}{12} + \frac{(x(1) + x(3))^2}{4}\right)\right)$$

$$alpha = \frac{6000}{sqrt(2) * x(1) * x(2)}$$

$$beta = Q * \frac{D}{J}$$

$$tau = sqrt\left(alpha^2 + 2 * alpha * beta * \frac{x(2)}{2 * D} + beta^2\right)$$

$$sigma = \frac{504000}{x(4) * x(3)^2}$$

$$tmpf = 4.013 * \frac{30 * 10^6}{196}$$

$$P = tmpf * sqrt\left(x(3)^2 * \frac{x(4)^6}{36}\right) * \left(1 - x(3) * \frac{sqrt\left(\frac{30}{48}\right)}{28}\right)$$

Disk Brake Design Problem:

The disk brake design problem has mixed constraints and was proposed by Ray and Liew [44]. The objectives to be minimized are: stopping time (*f1*) and mass of a brake (*f2*) of a disk brake. As can be seen in following equations, there are four design variables: the inner radius of the disk (*x1*), the outer radius of the disk (*x2*), the engaging force (*x3*), and the number of friction surfaces (x4) as well as five constraints.

Minimise: $f_1(x) = 4.9 * (10^{\wedge}(-5)) * (x(2)^{\wedge}2 - x(1)^{\wedge}2) * (x(4) - 1)$

Minimise: $f_2(x) = (9.82 * (10^{\wedge}(6)) * (x(2)^{\wedge}2 - x(1)^{\wedge}2))/((x(2)^3 - x(1)^{\wedge}3) * \ldots x(4) * x(3))$

Where: $g_1(x) = 20 + x(1) - x(2)$

$g_2(x) = 2.5 * (x(4) + 1) - 30$

$g_3(x) = (x(3))/(3.14 * (x(2)^{\wedge}2 - x(1)^{\wedge}2)^{\wedge}2) - 0.4$

$g_4(x) = (2.22 * 10^{\wedge}(-3) * x(3) * (x(2)^{\wedge}3 - x(1)^{\wedge}3))/((x(2)^{\wedge}2 - x(1)^{\wedge}2)^{\wedge}2) - 1$

$g_5(x) = 900 - (2.66 * 10^{\wedge}(-2) * x(3) * x(4) * (x(2)^{\wedge}3 - x(1)^{\wedge}3))/((x(2)^{\wedge}2 - x(1)^{\wedge}2))$

$55 \leq x_1 \leq 80{,}75 \leq x_2 \leq 110{,}1000 \leq x_3 \leq 3000{,}2 \leq x_4 \leq 20$

Appendix D:

Test system 1: 40-operational thermal generating unit

Unit	Pmin	Pmax	a_i	b_i	c_i	α_i	β_i	γ_i	ζ_i	λ_i
1	36	114	0.00690	6.73	94.705	0.048	-2.22	60	1.31	0.0569
2	36	114	0.00690	6.73	94.705	0.048	-2.22	60	1.31	0.0569
3	60	120	0.02028	7.07	309.54	0.0762	-2.36	100	1.31	0.0569
4	80	190	0.00942	8.18	369.03	0.054	-3.14	120	0.9142	0.0454
5	47	97	0.01140	5.35	148.89	0.085	-1.89	50	0.9936	0.0406
6	68	140	0.01142	8.05	222.33	0.0854	-3.08	80	1.31	0.0569
7	110	300	0.00357	8.03	287.71	0.0242	-3.06	100	0.655	0.02846
8	135	300	0.00492	6.99	391.98	0.0335	-2.32	130	0.655	0.02846
9	135	300	0.00573	6.6	455.76	0.425	-2.11	150	0.655	0.02846
10	130	300	0.00605	12.9	722.82	0.0322	-4.34	280	0.655	0.02846
11	94	375	0.00515	12.9	635.20	0.0338	-4.34	220	0.655	0.02846
12	94	375	0.00569	12.8	654.69	0.0296	-4.28	225	0.655	0.02846
13	125	500	0000421	12.5	913.40	0.0512	-4.18	300	0.5035	0.02075
14	125	500	0.00752	8.84	1760.4	0.0496	-3.34	520	0.5035	0.02075
15	125	500	0.00708	9.15	1728.3	0.0496	-3.55	510	0.5035	0.02075
16	125	500	0.00708	9.15	1728.3	0.0151	-3.55	510	0.5035	0.02075
17	220	500	0.00313	7.97	647.85	0.0151	-2.68	220	0.5035	0.02075
18	220	500	0.00313	7.95	649.69	0.0151	-2.66	222	0.5035	0.02075
19	242	550	0.00313	7.97	647.83	0.0151	-2.68	220	0.5035	0.02075
20	242	550	0.00313	7.97	647.81	0.0145	-2.68	220	0.5035	0.02075
21	254	550	0.00298	6.63	785.96	0.0145	-2.22	290	0.5035	0.02075
22	254	550	0.00298	6.63	785.96	0.0138	-2.22	285	0.5035	0.02075
23	254	550	0.00284	6.66	794.53	0.0138	-2.26	295	0.5035	0.02075
24	254	550	0.00284	6.66	794.53	0.0132	-2.26	295	0.5035	0.02075
25	254	550	0.00277	7.10	801.32	0.0132	-2.42	310	0.5035	0.02075
26	254	550	0.00277	7.10	801.32	1.842	-2.42	310	0.5035	0.02075
27	10	150	0.52124	3.33	1055.1	1.842	-1.11	360	0.9936	0.0406
28	10	150	0.52124	3.33	1055.1	1.842	-1.11	360	0.9936	0.0406
29	10	150	0.52124	3.33	1055.1	1.842	-1.11	360	0.9936	0.0406
30	47	97	0.01140	5.35	148.89	0.085	-1.89	50	0.9936	0.0406
31	60	190	0.00160	6.43	222.92	0.0121	-2.08	80	0.9142	0.0454
32	60	190	0.00160	6.43	222.92	0.0121	-2.08	80	0.9142	0.0454
33	60	190	0.00160	6.43	222.92	0.0121	-2.08	80	0.9142	0.0454
34	90	200	0.00010	8.95	107.87	0.0012	-3.48	65	0.655	0.02846
35	90	200	0.00010	8.62	116.58	0.0012	-3.24	70	0.655	0.02846
36	90	200	0.00010	8.62	116.58	0.0012	-3.24	70	0.655	0.02846
37	25	110	0.01610	5.88	307.45	0.095	-1.98	100	1.42	0.0677
38	25	110	0.01610	5.88	307.45	0.095	-1.98	100	1.42	0.0677

39	25	110	0.01610	5.88	307.45	0.095	-1.98	100	1.42	0.0677
40	242	550	0.00313	7.97	647.83	0.0151	-2.68	220	0.5035	0.02075

Test system 2: 6-operational thermal generating unit

Table 12: Input data for operational generating unit like loading limits and loss parameters of 6-unit system.

Unit	P_i^{min} (MW)	P_i^{max} (MW)	a_i ($/hr)	b_i ($/MWhr)	c_i ($/MW^2hr)	α_i (lb/hr)	β_i (lb/MWhr)	γ_i (lb/MW^2hr)
1	10	125	756.7988	38.539	0.15247	13.8593	0.32767	0.00419
2	10	150	451.3251	46.1591	0.10587	13.8593	0.32767	0.00419
3	35	210	1243.531	38.3055	0.03546	40.2669	−0.54551	0.00683
4	35	225	1049.998	40.3965	0.02803	40.2669	−0.54551	0.00683
5	125	315	1356.659	38.2704	0.01799	42.8955	−0.51116	0.00461
6	130	325	1658.57	36.3278	0.02111	42.8955	−0.51116	0.00461

Loss parameters:

$$A = \begin{bmatrix} 0.000140 & 0.000017 & 0.000015 & 0.000019 & 0.000026 & 0.000022 \\ 0.000017 & 0.000060 & 0.000013 & 0.000016 & 0.000015 & 0.000020 \\ 0.000015 & 0.000013 & 0.000065 & 0.000017 & 0.000024 & 0.000019 \\ 0.000019 & 0.000016 & 0.000017 & 0.000071 & 0.000030 & 0.000025 \\ 0.000026 & 0.000015 & 0.000024 & 0.000030 & 0.000069 & 0.000032 \\ 0.000022 & 0.000020 & 0.000019 & 0.000025 & 0.000032 & 0.000085 \end{bmatrix}$$

A1 = [0 0 0 0 0 0]

A3 = 0

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Equivalent Circuit-Level Characterization of 1.55 μm InGan Laser

By Md. Jahirul Islam & Md. Rafiqul Islam
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Abstract- In GaN is one of the most promising group III-V nitride materials recently focused for semiconductor based device fabrication. The advent of long haul optical communication system requires sophisticated and reliable lasing device. InGaN based lasers composited to have 0.8 eV bandgap energy produce coherent light of 1.55 μm. In this paper, the output characteristics of a heterostructured laser with InGaN as active layer is presented systematically. The circuit-level laser modeling is developed by solving the respective rate equations. This includes the conversion of the complete laser system into its equivalent electrical circuits. Thereafter, simulation was carried out using PSPICE to evaluate the electrical quantities e.g. output power, I-V characteristics, slope efficiency and transient response.

Keywords: equivalent circuit modeling, rate equations, hetero structure, quantum well laser (QWL), PSPICE.

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EQUIVALENTCIRCUITLEVELCHARACTERIZATIONOFINGANLASER

Strictly as per the compliance and regulations of:

Equivalent Circuit-Level Characterization of 1.55 μm InGaN Laser

Md. Jahirul Islam[α] & Md. Rafiqul Islam[σ]

Abstract- InGaN is one of the most promising group III-V nitride materials recently focused for semiconductor based device fabrication. The advent of long haul optical communication system requires sophisticated and reliable lasing device. InGaN based lasers composited to have 0.8 eV bandgap energy produce coherent light of 1.55 μm. In this paper, the output characteristics of a heterostructured laser with InGaN as active layer is presented systematically. The circuit-level laser modeling is developed by solving the respective rate equations. This includes the conversion of the complete laser system into its equivalent electrical circuits. Thereafter, simulation was carried out using PSPICE to evaluate the electrical quantities e.g. output power, I-V characteristics, slope efficiency and transient response. A bias voltage of 1.2 volts, threshold current of approximately 6 mA, turn on delay time of 3 ns and slope efficiency of 0.368 W/A are found. The findings are summarized in graphical representation and found to be consistent with numerical simulation of the system model.

Keywords: equivalent circuit modeling, rate equations, hetero structure, quantum well laser (QWL), PSPICE.

I. Introduction

Perhapse, the invention of lasers has been proven to be one of the most significant breakthroughs for technology in the last century [1]. Their applications extend to high speed communications, optical storage (e.g. CDs, DVDs, optical memories), barcode scanners in industrial machines, printers and even in medical science for spectroscopy and imaging, and also in destroying cancer tissues and unnecessary cells in human bodies [1-2]. In addition, modern technology facilitates with distance learning, online education and high speed online entertainment as well as instant communication from each corner of the world. This requires enormously data to be transported within a short period of time. Optical fiber communication system is one of the strongest candidates to overcome the associated problems. The issues with the constraints of noise, bulk volume of data, amount of signal power transmission, interference with other networks and nearby RF electromagnetic fields are greatly settle down with optical fiber system [3-4]. Ideally, 1.55 μm lasers are well suited for long haul communication at higher data rates due to minimal loss [5].

A number of semiconductor alloys such as ternary, quaternary and quintuplet elements are used to fabricate 1.55 μm laser diodes. For instance, materials including AlGaInAs, GaInNAsSb/GaAs, InGaAs/ InGaAs P, and GaInN AsSb/GaNAs [6-8] are the choices for the active layer of the lasers. However, often these ternary, quaternary and quintuplet materials are difficult to grow, and results in lasing problem.

A growing interest on the group III-IV nitride based semiconductor materials has recently been prompted towards light emitting diodes, lasers and solar cells [9-11]. The wider (0.7 – 6.2 eV) and direct bandgap, low electron effective mass, and high theoretical mobilities of these materials made them suitable for device applications [12]. A small amount of Ga in InN results in InGaN composite with 0.8 eV bandgap energy which is compatible with 1.55 μm wavelength.

The equivalent circuit modeling (ECM) is required to clearly understanding the lasers' working conditions and to verify compatibility with associated electrical driver circuits. The ECM using Shockley equation transfers the carrier and photonics numbers into current and voltage quantities, respectively. Numbers of studies investigated the ECM for quantum dot and quantum cascaded lasers [13-15]. However, to the best of authors' knowledge, the ECM of the proposed In GaN based laser is still unreported, and thus requires attention.

In this paper, we investigate the electrical equivalent circuit characteristics of a previously proposed [16] InGaN based heterostructure laser diode. The static current-voltage (I-V), output power-input current (L-I), output voltage, and transient conditions are discussed briefly. PSPICE circuit simulator has been used to demonstrate the lasers' electrical characteristics.

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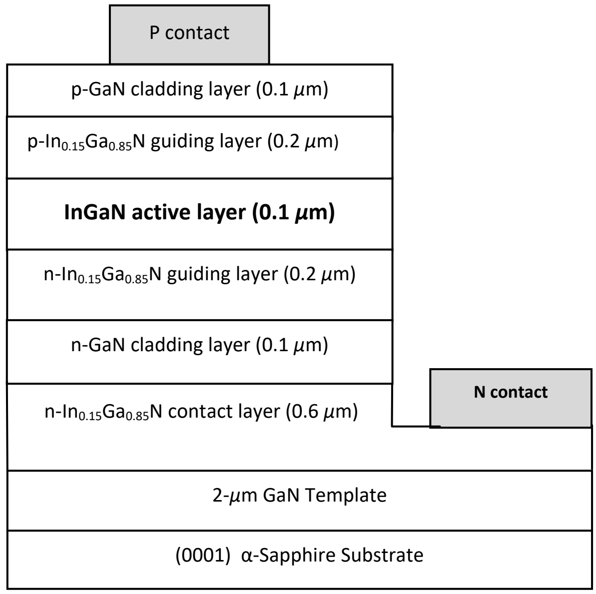

Fig.1: Schematic structure of the proposed InGaN based Quantum Well Laser (After Ref. [16]).

II. Proposed Laser Structure

The schematic structure of the proposed 1.55 μm quantum-well hetero structure lasers using InGaN is shown in Fig.1. A c-plane sapphire wafer is used as the substrate. The LD structure consists of 0.6 μm thick n-$In_{0.15}Ga_{0.85}N$ contact layer, 0.1 μm thick GaN cladding layer, 0.2 μm thick $In_{0.15}Ga_{0.85}N$ guiding layer, and a 0.1 μm thick InGaN active layer.

III. Mathematical Model

The rate equations for quantum well lasers are given by [17-18]

$$\frac{d\,N(t)}{dt} = \eta_i \frac{I(t)}{eV_a} - \frac{N(t)}{\tau_n} - g_0 \frac{N(t)S(t)}{1+\varepsilon S(t)} \qquad (1)$$

$$\frac{d\,S(t)}{dt} = -\frac{S(t)}{\tau_p} + \frac{\beta N(t)}{\tau_n}\Gamma_c + \frac{g_0 N(t)S(t)}{1+\varepsilon S(t)}\Gamma_c \qquad (2)$$

$$\frac{S}{P_f} = \frac{\lambda \tau_p}{\eta_c V_a hc} = \vartheta \qquad (3)$$

where N = equilibrium carrier concentration; I = injection current; $\frac{N(t)}{\tau_n}$ = the carrier recombination rate = $AN+BN^2+CN^3$, where A, B, and C are the unimolecular, radiative, and Auger recombination coefficients, respectively; S = photon density = S_{tot}/V_a, where, S_{tot} is again the total number of photons in the active volume; $\beta = \beta_A AN+\beta_B BN^2+\beta_C CN^3$, where β_A, β_B, and β_C are coupling coefficients; P_f = the output power, V_a = is the volume of a single QW; η_i = is the current-injection efficiency; Γ_c = is the optical confinement factor of one QW; g_0 = is the carrier dependent gain coefficient; τ_p = is the photon lifetime; λ= is the lasing wavelength; η_c = is the output-power coupling coefficient; and $\frac{1}{1+\varepsilon S(t)}$ = the gain saturation term.

IV. Model Implementation

To convert the rate equations into circuit model, multiplying Eqn. (1) by $\frac{eV_a}{\eta_i}$ and then simplifying we get

$$I = \frac{1}{\eta_i} I_n + \frac{\tau_n}{\eta_i}\frac{dI_n}{dt} + g_0 \frac{eV_a}{\eta_i}\frac{N_e \exp\left(\frac{eV}{nkT}\right) S(t)}{1+\varepsilon S(t)} \qquad (4)$$

where, $I_n = \frac{eV_a N(t)}{\tau_n}$ and $N = N_e \exp\left(\frac{eV}{nkT}\right)$.

Therefore, $$\frac{eV_a}{\eta_i}\frac{dN(t)}{dt} = \frac{\tau_n}{\eta_i}\frac{dI_n}{dt} \qquad (5)$$

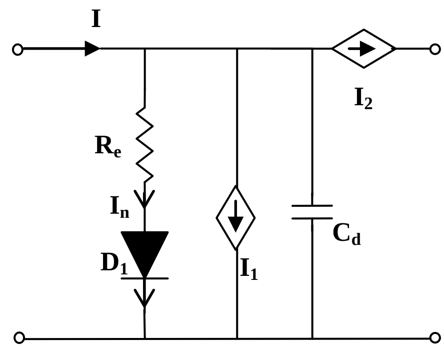

Fig. 2: PSP CE circuit model of Eqn. (4).

Current I of Eqn. (4) is equal to three related current components at quantum well regions i.e. I_n, $I_1 = \frac{\tau_n}{eV_a}\frac{dI_n}{dt}$ and the stimulated emission component I_2. The p-n heterojunction voltage V_j can be represented by one ohmic resistance R_e, series-connected with Shockley p-n junction diode (shown in Fig.2). $C_d = C_0\left(1-\frac{V_j}{V_d}\right)^{-\frac{1}{2}}$, a junction depletion capacitance is added to the circuit, where C_0 is the zero bias depletion capacitance, V_j is the junction voltage, V_d is the build-in potential.

Now, multiplying Eqn. (2) by eV_a we get,

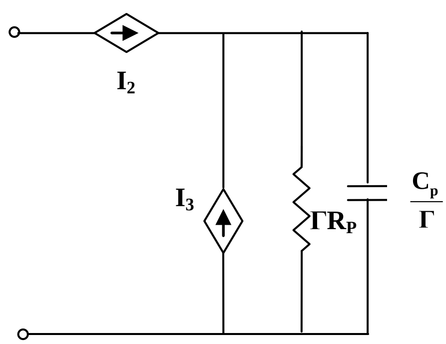

Fig. 3: PSPICE circuit model of Eqn. (8).

$$eV_a\frac{dS(t)}{dt} = -eV_a\frac{S(t)}{\tau_p} + eV_a\frac{\beta N(t)}{\tau_n}\Gamma_c + eV_a\frac{g_0 N(t)S(t)}{1+\varepsilon S(t)}\Gamma_c \quad (6)$$

which later reduces to

$$C_p\frac{dS(t)}{dt} + \frac{S(t)}{R_p} = G_0\frac{N(t)S(t)}{1+\varepsilon S(t)}\Gamma_c + \beta I_n\Gamma_c \quad (7)$$

Rearranging Eqn. (7), one can get

$$\frac{S(t)}{\Gamma_c R_p} + \frac{C_p}{\Gamma_c}\frac{dS(t)}{dt} = G_0\frac{N(t)S(t)}{1+\varepsilon S(t)} + \beta I_n \quad (8)$$

Where the parameters R_p and G_0 are defined by [19],

$$R_p = \frac{\tau_p}{C_p},\ G_0 = D\left(J_{nom} - 2\times10^{13}\right)^2.$$

Also, D= a constant and $J_{nom} = \frac{I_n}{V_a}$.

In Eqn. (8), the first two terms represent a resistance (in parallel) and a capacitance. Again, the optical emission consists of a spontaneous component stimulated component $G_0\frac{N(t)S(t)}{1+\varepsilon S(t)}$. These two components are modeled by two (I_3 and I_2) current sources as shown in Fig.3. Thus, the light output is proportional to the output node in voltage representation. The voltage representation is applicable if transmission channel and receiver circuit are included in the simulation.

Now from Eqns. (4) and (8), the total equivalent circuit for a single QW laser has been illustrated in Fig.4.

V. PSPICE CIRCUIT SIMULATION RESULTS

Unlike electronic devices that are usually characterized by current and voltage, optoelectronic devices are normally characterized by light intensity and current. Since light intensity cannot be represented by any physical circuit quantities, modeling optoelectronic devices by PSPICE circuit model is certainly not physically transparent.

The results of PSPICE circuit model for InGaN based laser developed according to the electrical equivalent circuit discussed in section IV, is presented in this section. The parameters used for the PSPICE simulation are listed in Table 1.

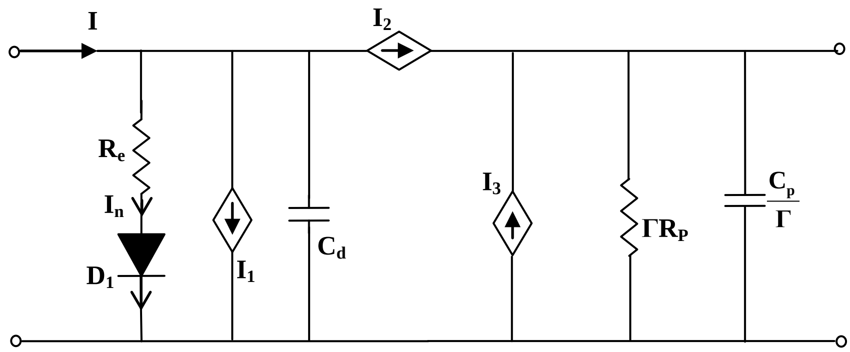

Fig. 4: Equivalent circuit model of a single quantum well laser.

Table 1: Parameters used in PSPICE circuit simulations [20].

Parameter	Unit	Value
R_e	Ω	0.468
R_p	Ω	29.4
R_s	Ω	2.0
τ_{ns}	ns	2.25
τ_{np}	ns	3
C_p	pF	0.102
C_d	pF	10
S_c	m^{-3}	10^{18}
D	$V^{-1}A^{-1}m^6$	$1.79 x 10^{-29}$
β_s	-	10^{-5}

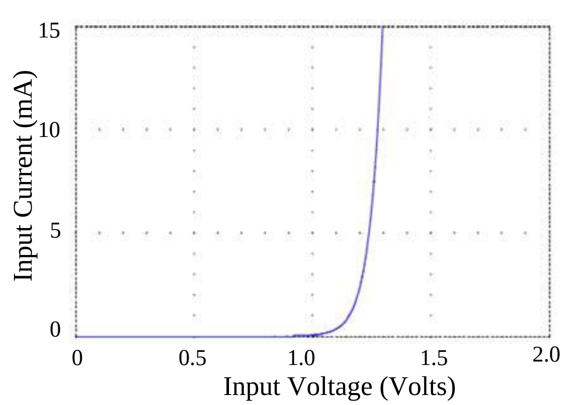

Fig.5: Current vs. voltage relationship for InGaN laser.

The PSPICE circuit simulation evaluates the electrical characteristics such as current-voltage, transient response of the laser equivalent circuit. Figure 5 depicts the I-V response of the laser. As it is shown in the figure, the current initiates to flow at an applied voltage of approximately 1.20 volts and then increases abruptly. The threshold value of the voltage is approximately 1.20 volts.

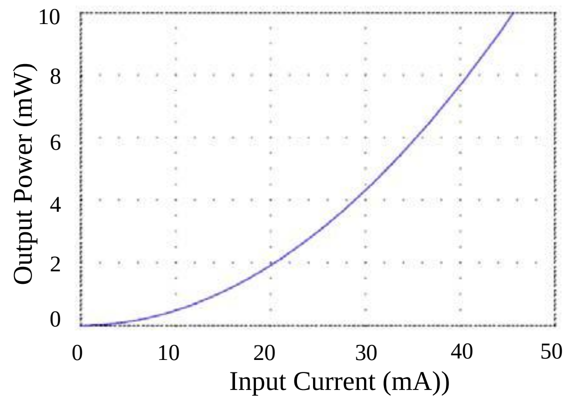

Fig.6: Output power-input current (L-I) characteristic of the proposed laser.

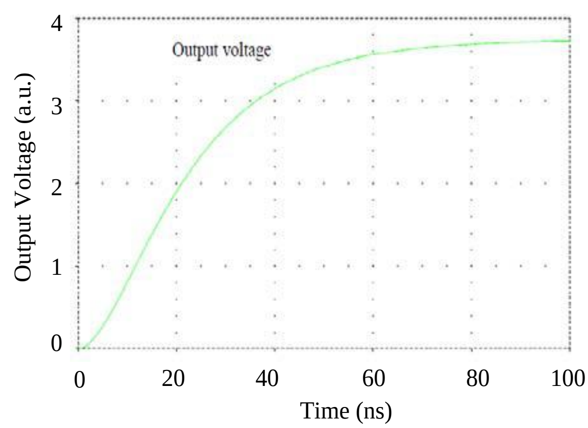

Fig.7: Output transient voltage of the laser.

Moreover, Fig.6 represents the output power with the variation of input current (L-I characteristics).The power output increases with the increase of input current. Threshold current of 6 mA and the slope efficiency of approximately 0.368 W/A are found from Fig.6.

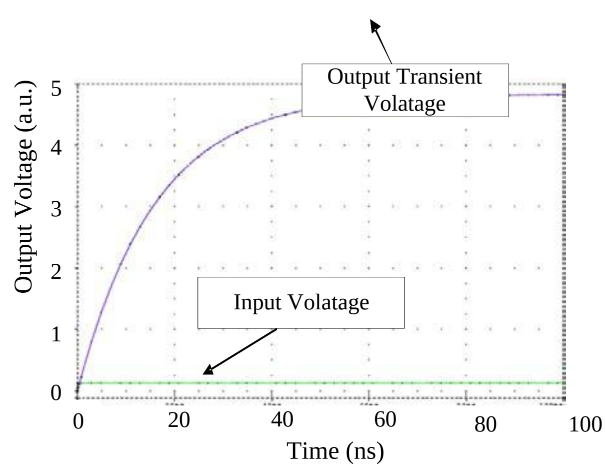

Fig.8: Turn on delay time of the quantum well laser.

The transient response of the laser is shown in Fig.7. The steady state values of output voltage are found after 60 ns. Turn on delay of 3 ns is calculated from Fig.8 for InGaN based laser. These results are in well consistent with the results obtained from the previous [16] discussions.

VI. Conclusion

A detailed electrical equivalent circuit model of 1.55 μm InGaN based laser has been studied numerically. The characteristics are realized through the development of the equivalent circuit modeling of the quantum well laser. The electrical circuit modeling of the laser is important to find out the electrical parameters. The PSPICE circuit simulation resulted in an increase in output power with the increase of input current. Threshold current of approximately 6 mA, bias voltage of 1.20 volts, slope efficiency of 0.368 W/A and turn on delay of 3 ns have been found from this circuit analysis. These electrical properties present the richness of InGaN based lasers, and are in agreement with the results of numerical simulations of the same model. Attention on ECM for the laser is important to understanding the electrical mechanism, and requires exhaustive investigation to be matched with electrical automatic power control, modulation scheme, level shifter and slow start circuits.

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A Novel Quasi Opposition Based Passing Vehicle Search Algorithm Approach for Largescale Unit Commitment Problem

By Pradeep Jangir & Arvind Kumar
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Keywords: unit commitment; quasi oppositional passing vehicle search algorithm; opposite based learning techniques; load scheduling; thermal unit scheduling; economic load dispatch.

GJRE-F Classification: FOR Code: 290903

ANOVELQUASIOPPOSITIONBASEDPASSINGVEHICLESEARCHALGORITHMAPPROACHFORLARGESCALEUNITCOMMITMENTPROBLEM

Strictly as per the compliance and regulations of:

A Novel Quasi Opposition Based Passing Vehicle Search Algorithm Approach for Largescale Unit Commitment Problem

Pradeep Jangir [α] & Arvind Kumar [σ]

Abstract- This paper presents a novel approach population based metaheuristics algorithm known as Quasi Oppositional Passing Vehicle Search (QOPVS) algorithm for solve the Unit commitment problem (UCP) of thermal units in an electrical power system. Passing vehicle search (PVS) algorithm is a population based algorithm which mechanism is inspired by passing vehicles on two-lane rural highways. As algorithms are population based so enables to provide improved solution with integration of powerful techniques. In this article, such a powerful technique named Opposite based learning techniques (OBLT) is integrated with proposed PVS algorithm. OBLT provides enough strength to proposed PVS algorithm to gain a better approximation for both current and opposite population at the same time, as it provide a solution which is more nearer solution from optimal based from starting by checking both solutions. Thermal unit scheduling problem is a nonlinear, non convex, discrete, complex and constrained optimisation problem. To verify the effectiveness of the proposed QOPVS algorithm is applied to some standard benchmark test function and various IEEE test systems with the number of thermal units 5-, 6-, 10-, 20-, and 40-unit in a 24-hour load scheduling horizon. The results show an improvement in the quality of solutions obtained compared with other methods results in the literature. The proposed algorithm is considerably fast and provides feasible near-optimal solutions. Simulations results have proved the performance of the proposed QOPVS algorithm to solving large UC problems within a faster convergence and reasonable execution time.

Keywords: *unit commitment; quasi oppositional passing vehicle search algorithm; opposite based learning techniques; load scheduling; thermal unit scheduling; economic load dispatch.*

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Nomenclature

UCP	*Unit Commitment Problem*	*h*	*Hour*
$F(P_i^h)$	*Fuel Cost of Unit i*	P_i^{max}	*Generator Maximum Limit*
TFC	*Total Fuel Cost*	U_i^h	*Status/Position of Unit i at Hour t (on = 1, off = 0)*
P_i^h	*Total Power Generation at Hour h*	P_i^{min}	*Generator Minimum Limit*
a_i, b_i, c_i	*Fuel Cost Coefficients*	CSH_i	*Cold Start Hour of Unit i*
SUC_i^h	*Start-up Cost at Hour h*	H_i^{UP}	*Minimum Up Time*
HSC_i	*Hot Start-Up Cost*	CSC_i	*Cold Start-Up Cost*
NG	*No. of Generator*	H_i^{Down}	*Minimum Down Time*
H	*Scheduled Time Horizon*	$H_{i,ON}^{h-1}$	*Continue ON Time at Hour (h-1)*
MDT_i	*Minimum Down Time of i-th Unit*	MDT_i^{ON}	*Number of Hours When i-th Unit online*
P_{load}^h	*Total Load Demand at Hour h*	$H_{i,Off}^{h-1}$	*Continue Off Time at Hour (h-1)*

R^h	*Spinning Reserve of System at Hour h*	$\gamma_i, \theta_i, \tau_i$	*Startup Cost Coefficient for Thermal-Unit*
α_l	*Power-flow on Transmission Line l*	$NBus$	*No. of Total Bus*
$S_{l,k}$	*Sensitivity Factor at Bus k*	$NLine$	*No. of Total Transmission Lines*
$P^h_{k,Bus}$	*Power Generation at Hour h*	$P^h_{k,load}$	*Load Demand at Hour h*
$P^h_{i,Upper}$	*The Highest Possible Power Generation at Hour h*	$P^h_{i,Down}$	*The Lowest Possible Power Generation at Hour h*
$(UPRamp)_i$	*Ramp-Up Rate of Unit i*	$(DownRamp)$	*Ramp-Down Rate of Unit i*
$X_i^{on}(h)$	*Duration for which Unit i is Continuously ON at Hour h*	MUT_i	*Minimum UP Time of i-th Unit*
$X_i^{off}(h)$	*Duration for which Unit i is Continuously Off at Hour h*	*PVS*	*Passing Vehicle Search*
QOPVS	*Quasi Oppositional Passing Vehicle Search*	*LP*	*Linear Programming*
SOOT	*Sole Objective Optimization Technique*	*OBLT*	*Opposite Based Learning Techniques*

I. Introduction

In general, real world problems are complex and nonlinear so it is a very difficult task to find out its solution. Optimization stands with every person wants to maximize its outcomes with its least possible utilization of resources. World surround us is a lot of natural behaviors for performing various task. Although the target of all individuals is to be survive, helping each other and working in a group. Basic theme of every meta-heuristic algorithms is come from natural incidents happening around us.

Now a day, engineering optimization is in its third generation of algorithms/techniques. In the first generation in early 1960s some mathematical techniques or deterministic techniques [1]-[3] are proposed like Linear programming (LPs), gradient based algorithm etc. to solve various engineering design problems. Advantages associated with deterministic technique is that they are less time consuming to find a solution, but disadvantage [4] is that they will not guarantees that a solution achieved with them is an optimal one. With first generation algorithms, there is high possibility to trap in local minima/maxima rather finding global optimal solution. Second generation of algorithms are problem specific algorithms and also their functionality depends on the initial guess of the solution, so these algorithms (simulated annealing) also need problem specific man power. These algorithms are also known as heuristic techniques.

Third generation of algorithms are known as meta-heuristic, improved heuristic techniques or evolutionary algorithms. This type of stochastic algorithms are basically population based or fitness oriented. These algorithms are basically inspired from natural activities incidents around us. Some of the natural behaviors are herding, migration, hunting, defending, navigation etc. The strength of meta-heuristic algorithms is based strongly on randomly generated initial solutions. Meta-heuristics algorithm consists of many solutions at each stage according to their fitness. So, there is almost negligible probability of entrapping in the local solution and higher probability of getting global optimal solution. Meta-heuristic techniques are also called direction search towards global best solution. As after each iteration solution of all individual are processed through sorting from higher quality solution to lower quality solutions. So, this technique is more efficient than other techniques. Meta-heuristic techniques are also integrated with some 'intelligence' or adaptive capability to converge towards global best solution. Other advantage of these type of algorithms is that they are not problem specific algorithms, having capability of solving many problems with negligible change in their structural computational model also no need to be an expertise in problem specific domain, so provides researchers a greater flexibility to apply them to number of problems. Only disadvantage associated with them is that they cannot provide global best solution in single run so researchers need to test their robustness by considering multiple runs for single problem to determine their performance or effectiveness to solve it.

Sole objective optimization technique (SOOT) is to achieve "the best" solution, which either may be minimization or maximization value of a sole objective function with respective to all different objectives into one in the environment of various equality or inequality bound of decision variable parameters. So, SOOT increases the burden of decision making significantly on the shoulders of the researcher. Population-based metaheuristic techniques acquires a collection of solutions, called a population, to learn or optimize the problem in a parallel way. Population is a main principle of the metaheuristic techniques. Successful metaheuristic techniques have to be cautiously modelled without caring of the starting point, so there is negligible probability to visit each and every possible problem domain to get the feasible region.

The electric power demand is much higher during day time compare night time due to larger industrial loads, larger usage by residential-population during early-morning & evening. The unit commitment problem has been approached by many techniques but only acceptably solved by two techniques: dynamic programming and Lagrangian relaxation. The problem of thermal unit scheduling is due to the integer nature of the problem that a unit can either be off-line or on-line. The modeling of thermal power plants, for accurate scheduling, is complicated.

In the past, many optimization algorithms based on a gradient search for solving the linear and non-linear equation but in gradient search method value of objective function and constraint unstable and multiple peaks if problem having more than one local optimum. Population-based nature–inspiredis a meta-heuristic optimization algorithm have an ability to avoid local optima and get a globally optimal solution that makes it appropriate for practical applications without structural modifications in the algorithm for used in different constrained or unconstraint optimisation problems. In Fig. 1 over view of the proposed UC-ELD Problem is shown.

In their article, the total fuel cost obtained through the Quasi Oppositional Passing vehicle search (QOPVS) algorithm is similar to the cost obtained through Passing vehicle search (PVS) algorithm. In this work, the QOPVS algorithm is used to solve the UC with more focus towards the tuning of algorithmic control parameters, thus producing an optimal solution in terms of minimum generation cost and less execution time. In all the literatures reported, either the Unit Commitment or the Economic Load Dispatch problem is solved individually. In this work meta heuristics techniques is proposed to dispatch the committed units thus minimizing the fuel cost and making the application more suitable for practical generating systems. For experiment analysis, the outcome of the experimental results is compared in terms of optimal solution, robustness, computational efficiency and algorithmic efficiency.

In the following sections, we discuss the Unit Commitment problem, Problem formulation in single area Unit Commitment problem with different constraints, PVS algorithm, passing vehicles mechanism on two-lane rural highway, opposite based learning techniques (OBLT), quasi oppositional passing vehicle search (QOPVS) algorithm, numerical results of benchmark objective function and case study, and finally conclusion of our work.

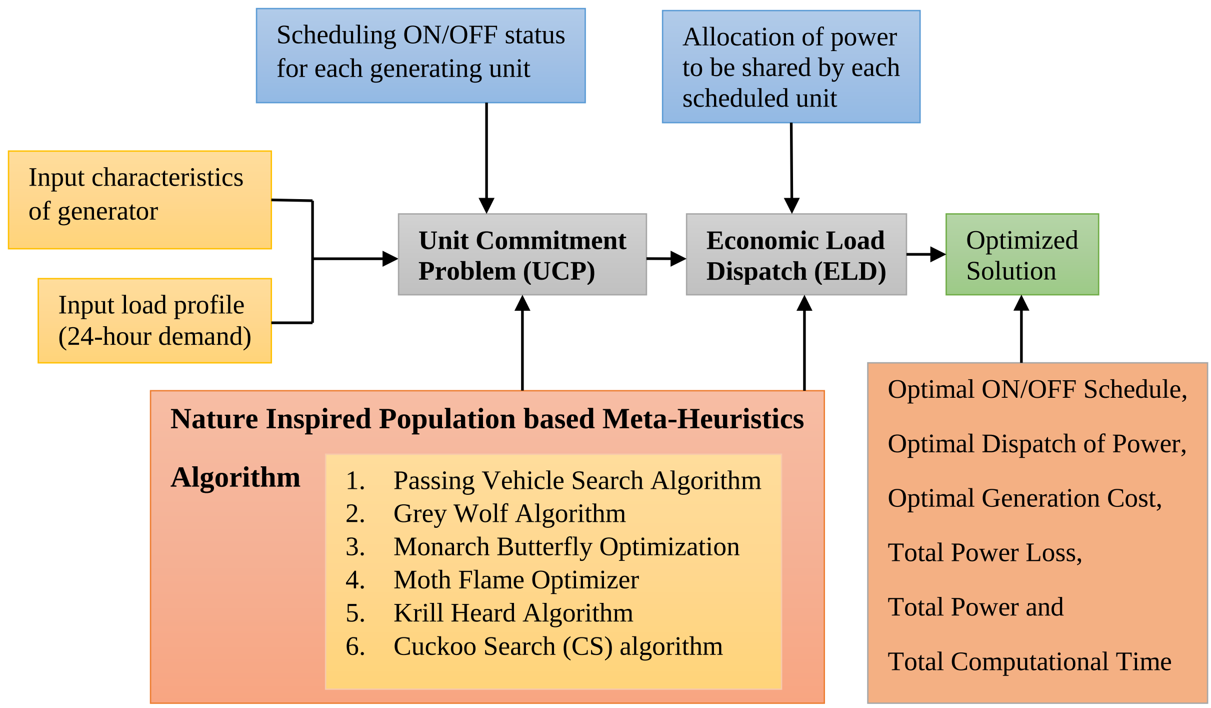

Fig. 1: Over view of the proposed UC-ELD Problem.

II. Literature Survey Of Unit Commitment Problem

The most talked-about optimization techniques for the solution of the unit commitment problem (UCP)are: (i) Priority-list schemes, (ii) Dynamic-programming (DP), & (iii) Lagrange algorithm (LA). Unit Commitment problem can be formulated as [5]-[25]: minimize generating cost and subject to many constrained such as (a) Minimum up and new down time constraints (b) Crew-constraints (c) Ramp-rate limits (d) Maximum and Minimum Power Limits (Generation limit constraints) (e) Generation ramp limit constraints (f) On/off line minimum level constraints (g) Transmission line constraints (g) Environmental constraints (h) Fuel limitation constraints (i) Unit hourly fuel mixing ratio constraints (j) Spinning reserve constraint (k) Power balance constraint (l) Deration of units (m) Unit status. Dynamic Programming Approach for Unit Commitment [5], A Unit Commitment Expert System [6], Fuzzy Dynamic Programming: An Application to Unit Commitment [7], Branch-and-Bound Scheduling for Thermal Generating Units [8], Unit Commitment Literature Synopsis [9] [10], A genetic algorithm based approach to thermal unit commitment of electric power systems describe in ref. [11]. A disadvantage of the GAs is that, since they are stochastic optimization algorithms, the optimality of the solution they provide cannot be guaranteed. Evolutionary Programming Based Economic Dispatch Units with Non-Smooth Fuel Cost Functions [12], Large scale unit commitment using a hybrid genetic algorithm [13], A Fuzzy Logic Approach to Unit Commitment [14], A Simulated Annealing Algorithm for Unit Commitment [15], A Genetic Algorithm for Solving the Unit Commitment Problem (UCP) of a Hydro-Thermal Power System [16], Unit Commitment with Transmission Security and Voltage Constraints [17], in ref., [18]-[29] UC and ELD problems with constraints are solved by different optimization techniques in power system.

During 2002, a fast solution technique for large scale Unit Commitment Problem using Genetic Algorithm is presented [30]. To reduce search space, unit integration technique is used and an intelligent mutation is performed using local hill-climbing optimization technique. A Genetic Algorithm Solution to the Unit Commitment Problem Based on Real-Coded Chromosomes and Fuzzy Optimization is implemented in [31]. They have reported that the fuzzy optimization had an impact on guiding the GA search and therefore assured finding a better fuel cost. A Particle Swarm Optimization approach to solve the economic dispatch considering the generator constraints is presented in [32]. Many nonlinear characteristics of the generator, such as ramp rate limits, prohibited operating zone, and non-smooth cost functions are considered in their method for practical generator operations. In ref. [33] attempted to explore the application of Economic Load Dispatch using Bacterial Foraging Technique with Particle Swarm Optimization based evolution. They showed that their technique had better information sharing and conveying mechanisms than other evolutionary methods including PSO, Bacterial Foraging (BF) and GA. In ref [34] developed the classical

Differential Evolution (DE) for solving ELD problems with specialized constraint handling mechanisms. A Comparative Study on Heuristic Optimization Techniques with an Improved Coordinated Aggregation-Based PSO [35] for ELD and UC problem by adding the regenerating population procedure in order to improve escaping from the local minimum. They employed a fuzzy decision theory to extract the best compromise solution.

Some of the most popular algorithms in this field are: Particle Swarm Optimization (PSO) [36], Differential Evolution (DE) [37], Evolutionary Programming (EP) [38] [39], Genetic Algorithms (GA) [40], [41], Ant Colony Optimization (ACO) [42]. Although these metaheuristic techniques are highly capable to provide promising solution for various challenging and real world design problems, But No Free Lunch theorem (NFLT) [43] permits researchers to propose new algorithms or to use an existing algorithm to improve the results of an existing problems. In Accordance to NFLT, all algorithms are effectively solving all optimization problems. So, one technique can be more efficient in solving a set of problems merely ineffective on another set of problems. This is the main reason for researchers to do more works in optimization area with a great zeal. Now some of the recently proposed algorithms in this field are: mimicking the social behavior based for different species like Monarch butterfly optimization (MBO) [44], Cuckoo Search (CS) algorithm [45], [46], Artificial Bee Colony (ABC) algorithm [47], Grey Wolf Optimizer (GWO) [48], Firefly Algorithm (FA) [49], [50], Cuckoo Optimization Algorithm (COA) [51]. Some physics based algorithms are like Ray Optimization algorithm (ROA) [52], [53], Colliding Bodies Optimization (CBO) [54], [55] algorithm with frequency constraint and discrete variable for truss bar design, Gravitational Search Algorithm (GSA) [56], Dolphin Echolocation (DE) [57], [58], Charged System Search (CSS) [59], [60] etc.

Further in the literature, we wish to add some recently proposed metaheuristic algorithms with different application in the well-recognized and reputed journals. Some of them are with various application like Trivedi, I. et al. with adaptive learning integrated with whale optimizer algorithm (AWOA) [61] in this article effectiveness of proposed work is tested on some standard test benchmark function. Well-recognized power system application that known as optimal power flow (OPF) problem is solved with different metaheuristic and hybrid metaheuristic technique [62], [63]. Another set of articles which consisting of popular power system application known as economic environment dispatch [64], [65], [66], and [67] considering problem such multi-objective as well as sole objective problem with and without renewable energy source involving various metaheuristic techniques comprising of different standard IEEE systems. This context also includes the improved version of popular krill herd technique like oppositional based krill herd [68], hybrid KH with quantum behaved PSO [69], improved KH [70] and stud krill herd algorithm [71].

III. Unit Commitment Problem

In the electrical power system, it is expected to have power instantaneously and continuously available etc. meet customers' demands. The economic operation depends upon following function such as a load forecasting, unit commitment, economic dispatch, security analysis etc. [72]. An overall solution of these problems is providing a continuous and reliable supply of electricity while maintaining the optimal cost of production and operation for the system. Unit Commitment is the most importance problems in operational scheduling of electrical power generation. in this start up and shut down (ON/OFF) operation are also involved to meet load demand for a short time. The objective is to minimize total production to meet system demand and reserve requirements. The main aim of this research paper is the solution of the Unit Commitment problems. The recent time installing of large thermal units, complexity of power network and other environmental pollution has again need to find better solution or approach for determination of economic-emission unit commitment schedule [73], [74]. In fig. 2(i) simple "peak-valley" load pattern is shown but fig. 2 (ii) Unit commitment schedule using shut-down rule is shown.

Based on the power requirements, the generating units are scheduled on an hourly basis for the next day's dispatch for the successive operating day. The system operators are able to schedule the On/Off status and the real power outputs of the thermal generating units to meet the total demand over a time horizon. There may exist large variations in the day to day load patterns, thus enough power has to be generated to meet the maximum load demand. In addition, it is not economical to run all the units every time. Hence it is necessary to determine the units of a particular system that are required to operate for given loads. The Economic Load Dispatch allocates power to the committed units thus minimizing the total generating/fuel cost. Constrained Economic Load Dispatch Problem is defined as the "The operation of generation facilities to produce energy at the lowest cost to reliably serve consumers, recognizing any operational limits of generation and transmission facilities". The two major factors to be considered while dispatching power to generating units are the cost of generation and the quantity of power supplied. The relation between the cost of generation and the power levels is approximated by a quadratic polynomial. To determine the economic distribution of load between the various generating units in a power plant, the quadratic polynomial in terms of the power output is treated as an optimization problem with total cost minimization as the objective function, considering various constraints.

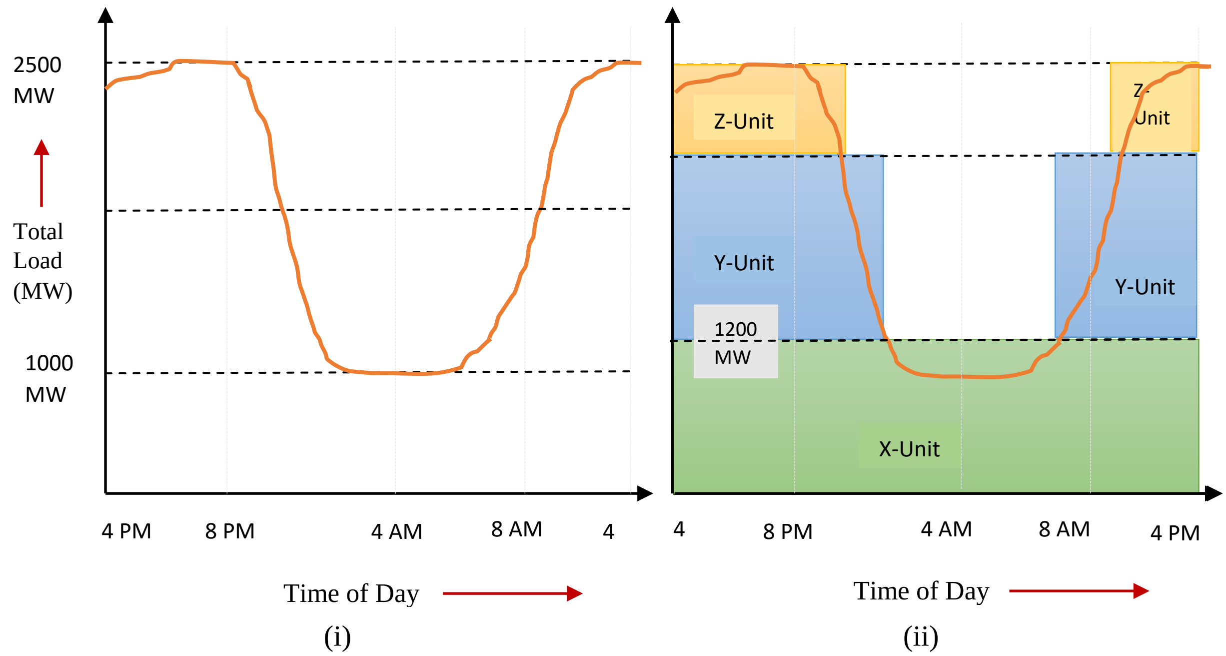

Fig. 2: (i) Simple "peak-valley" load pattern. (ii) Unit commitment schedule using shut-down rule.

The unit commitment problem can be solved by assigning priority for the generating units such that the most efficient unit is loaded first and then other units are loaded according to their efficiency. The security constraint unit commitment determines the generating unit schedules in a utility for minimizing the operating cost and satisfying the prevailing constraints such as a load balance, system spinning reserve, ramp rate limits, fuel cost constraints etc. The unit commitment problem is related to the class of complex combinational optimization problem. Unit Commitment can solve by finding the possible combination of the units and then select that combination which has the least operating cost between them but it required/consume a lot of time [75] [76]. Time-dependent start-up costs is shown in fig. 3.

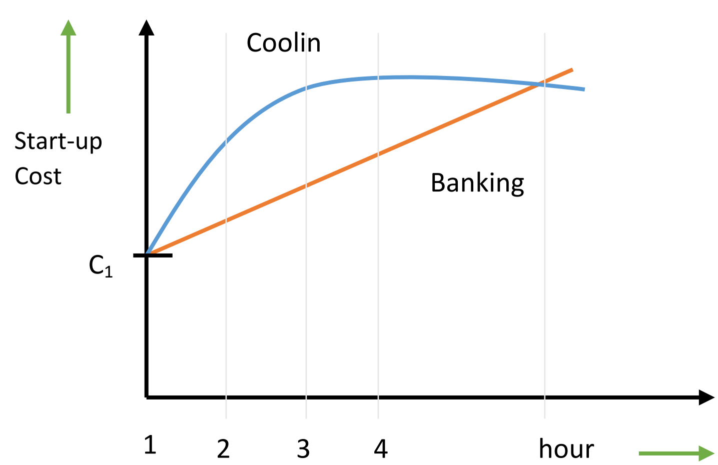

Fig. 3: Time-dependent start-up costs.

IV. Problem Formulation In Single Area UCP

The main aim of Unit Commitment is to schedule the generating units to minimize the operating and generating cost of power utilities. Fuel cost, start-up cost and shutdown cost including in operating cost. Fuel cost is determined by Economic Load Dispatch equation given as per follow.

$$\sum_{i=1}^{n} \quad F_i(Pg_i) = \sum_{i=1}^{n} \quad [a_i(Pg_i)^2 + b_i(Pg_i) + c_i], \quad i = 1,2, \dots, n \tag{1}$$

The total fuel cost over the given time horizon 'H' is

$$TFC = Min \sum_{i=1}^{NG} F\left(P_i^h, U_i^h\right) = \sum_{i=1}^{H} \sum_{i=1}^{NG} \left[a_i\left(P_i^h\right)^2 + b_i\left(P_i^h\right) + c_i + SUC_i^h * \left(1 - U_i^{h-1}\right)\right] * U_i^h, \quad i = 1,2, \dots, NG \tag{2}$$

Startup cost can be expressed as mathematically:

$$SUC_i^h = \begin{cases} HSC_i \,; for \; MDT_i \le MDT_i^{ON} \le (MDT_i + CSH_i) \\ CSC_i \,; \; for \qquad MDT_i^{ON} > (MDT_i + CSH_i) \end{cases}, \; i = 1,2, \dots, NG \; \& \; h = 1,2, \dots, H \tag{3}$$

$$SUC_i^h = \left[\gamma_i + \theta_i \left(1 - e^{-H_{i,ON}^{h-1}/\tau_i}\right)\right], i = 1,2, \dots NG \tag{4}$$

a) Equality and Inequality Constraint

a. *Equality Constraint (Power Balance Constraint)*

For the power balance sum of generation of unit in h^{th} hours is equal to total demand at h^{th} hours and it is given by following equation.

$$P_{load}^h + \sum_{i=1}^{NG} P_i^h * U_i^h = 0 \tag{5}$$

Where, NG is total number of generating units, P_i^h is the total power, U is the total units generated and P_{load}^h is the total demand.

b. *Spinning Reserve Constraint*

Due to the failure of the units or sudden change in load there is some reserve capacity of the plant or running plant run at the spinning capacity is known as spinning reserve capacity of the plant and it constraint is given by the following equation.

$$P_{load}^h + R^h - \sum_{i=1}^{NG} P_i^{max} * U_i^h \le 0 \tag{6}$$

c. *Thermal Constraint*

In the Thermal generation unit temperature is not constant, it is depending upon the load demand. So, it is take some time to return to online or in running condition. Maintenance of Thermal plant is manually controlled so maintenance needs at certain time limit. There are various thermal constraints as per follow.

d. *Minimum up and new down time constraints*

$$U_i^t = \begin{cases} 1\,; & if \; H_{i,ON}^{h-1} < H_i^{UP} \\ 0 \;\; ; & if \; H_{i,OFF}^{h-1} < H_i^{Down} \\ 0 \; or \; 1 \; ; & otherwise \end{cases} \tag{7}$$

❖ Minimum Up Time

If the units have been already shut down, then for restarting some time is required it is called Up Time and given by following equation.

$$X_i^{on}(h) \ge MUT_i \tag{8}$$

❖ Minimum Down Time

Times required for the shutdown of plant is called down time and it is given by following equation.

$$X_i^{off}(h) \ge MDT_i \tag{9}$$

e. *Crew Constraint*

If a plant consists more than two units, they cannot be turned on at the same time because there are not enough crew members to attend both unit at same time while starting up.

f. *Maximum and Minimum Power Limits (Generation limit constraints)*

Every plant consists their maximum and minimum power generation limits and it is given by following equation.

$$P_i^{min} * U_i^h \le P_i^h \le P_i^{max} * U_i^h, \; i = 1,2 \dots NG. \tag{10}$$

g. *On/off line minimum level constraints*

$$P_i^h = P_i^{min}, if \; U_i^{h-1} = 0 \; \& U_i^h = 1, \tag{11}$$

$$and \;\; U_i^h = 1 \; \& U_i^{h+1} = 0.$$

h. *Generation ramp limit constraints*

$$P_{i,Down}^h * U_i^h \le P_i^h \le P_{i,Upper}^h * U_i^h \tag{12}$$

Where,

$$P_{i,Upper}^h = minimum\left\{P_i^{max}, P_i^{h-1} + (UPRamp)_i * 60\right\}, if \; U_i^h = U_i^{h-1} = 1 \tag{13}$$

$$P_{i,Down}^h = minimum\left\{P_i^{min}, P_i^{h-1} - (DownRamp)_i * 60\right\}, if \; U_i^h = U_i^{h-1} = 1 \tag{14}$$

i. *Transmission line constraints*

$$-\alpha_l \leq \sum_{\substack{k=1 \\ k \neq Slack\ Bus}}^{NBus} \left[S_{l,k}\left(P_{k,Bus}^{h} - P_{k,load}^{h}\right) \leq (+\alpha_l)\right], l = 1,2, \ldots NLine. \quad (15)$$

V. PVS Algorithm

Passing vehicle search (PVS) algorithm [77] is a meta-heuristics population based algorithm which mechanism is inspired by passing vehicles on two-lane rural high ways that was first described by Poonam Savsani, & Vimal Savsani in 2016.The passing maneuver on two-lane rural highways is one of the most significant yet complex and important driving tasks. This process, though, is relatively difficult to quantify, primarily because of the many stages involved and the lengthy section of road that typically is needed to complete the maneuver. Road capacity, safety, and level of service are all affected by the passing ability of faster vehicles, particularly on two-lane highways. The ability to pass is influenced by a variety of parameters including the volumes of through and opposing traffic; the speed differential between the passing and passed vehicles; the highway geometry, particularly available sight distance; and human factors such as driver-reaction times and gap acceptance characteristics. The goal is to provide reliable input information for the design process of two lane highways, which involves the need for passing sight distances. The existing passing model, used by the AASHTO policy, was developed some four decades ago; it assumes a single passing vehicle and a single passed vehicle, both passenger cars. In reality, as many as 25 percent or more of the passing maneuvers may be classified as multiple passing, in which more than one vehicle is overtaken. In addition, because trucks generally have lower speeds than cars, a considerable number of passing maneuvers occur when passenger cars overtake trucks. In this study, single and multiple passing's are analyzed and the necessary sight distances for adequate design of two-lane rural highways are evaluated. The research is based on analysis of data collected by videotaping five tangent two-lane highway sections from high vantage points and one additional location where a helicopter hovered overhead. The components of the passing sight distance were evaluated on the basis of the measured distances that were necessary to complete the maneuvers safely [78].

The flow characteristics of a road cross-section are identified by time headway (TH) and vehicle speed (VS) distributions over time. Knowledge of both headway and speed distributions plays a significant role in several fields of traffic flow analysis and simulation [79]. In particular, we refer to operative analysis of road facilities in interrupted and uninterrupted flow conditions. Studies on VS modeling have been published for many years (Gerlough and Huber (1976) [80]; Luttinen (1996) [81]; Luttinen (2001) [82]; Dey et al. (2006) [83]; Zou and Zhang (2011) [84]; Zou et al. (2012) [85]).

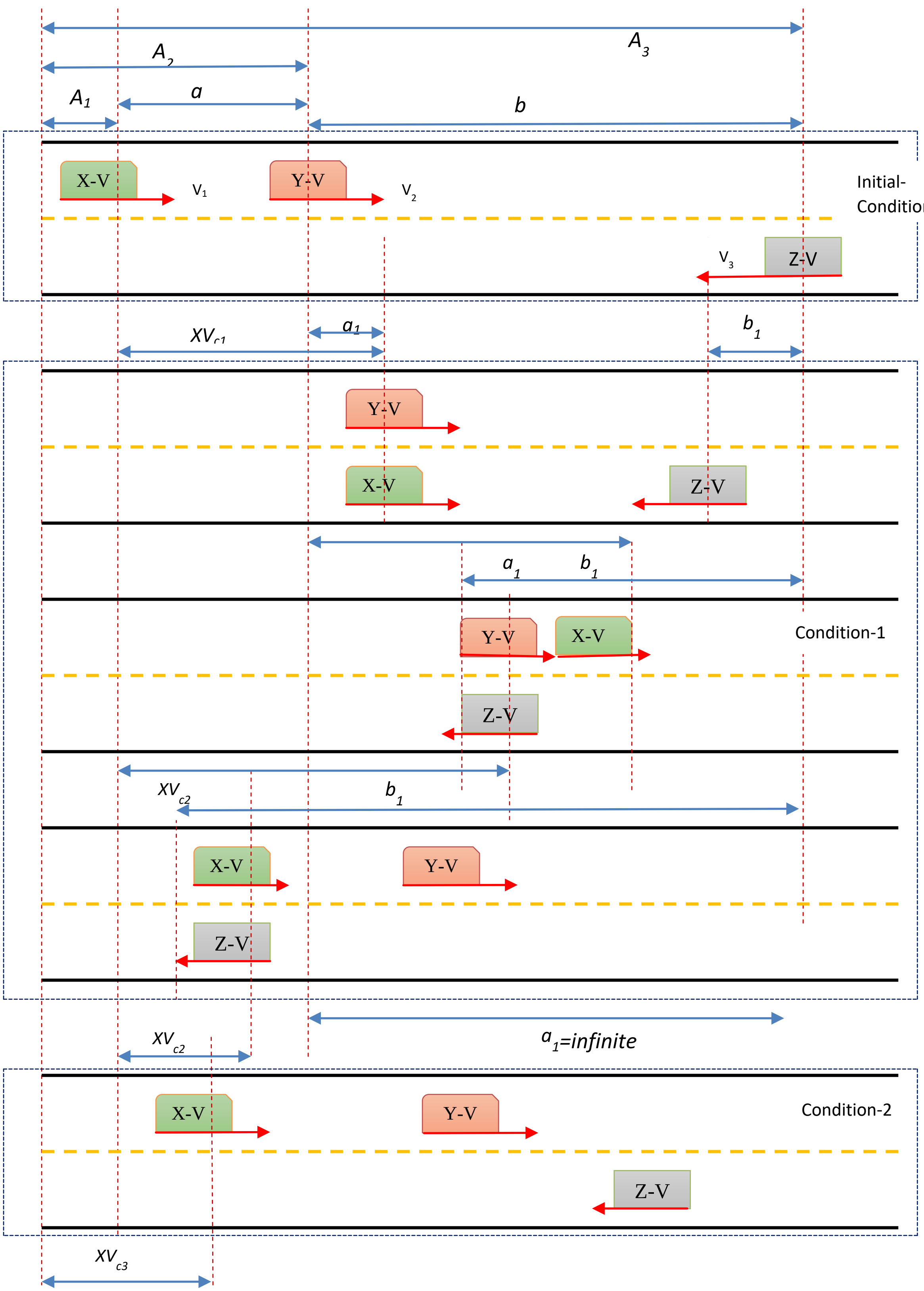

Fig. 4: Three vehicles passing mechanism on a two-lane-highways.

Algorithm: PVS Algorithm

Begin

Step 1: *Initialize and define parameters: Set population size (N), termination condition, FE_{max} (maximumfunction evaluations), g_{max} (number of generations), error, number of DV (design variables), bounds on design variables (lb & ub).*

Step 2:*Initialize the random generated populations and evaluate them for, i = 1, FE = 0, g = 1.*

Step 3: *Store the elite best solution and Select any two random populations k & l, k # l # i.*

Step 4: *Calculate distances (D10, D20, and D30) and velocities (V10, V20, and V30) of*

search agent X-V, Y-V, and Z-V respectively and Calculate velocity.

Step 5: Calculate distances *a, b, A_1, A_2, and A_3 using following equation:*

$A'_{io} = A_{io} + rand() * (A_{lo} - A_{io}),$

$A'_{io} = A_{io} + rand() * V_{coo} * (A_{io} - A_{lo})$ and

$$A'_{io} = A_{io} + rand() * (A_{io} - A_{ko})$$

Step 6: *Update the result if it is better than the previous result.*

Step 7: *Maintain diversity in the population by removing the duplicates as follows.*

for k= *1 : 2: N (Population size)*

if $A_k = A_{k+1}$

i = rand(design variables)*

$A_{k+1,I} = lb_i + rand*(ub_i - lb_i)$

end if

end for

Step 8: *Repeat the mechanism until the termination condition are satisfied.*

Stop.

Fig. 5: Pseudo code of PVS algorithm.

Paul Warnshu is (1967) constructed a computer simulation that modeled each individual vehicle's behavior directly. This simulation was intended to serve as a tool helping develop a theoretical description of the interaction between the two lanes and how that interaction influences the traffic flow in each lane. The simulation was coded in Fortran IV, and it assumed that the two-lane road extends infinitely in both directions by using a two-lane circular track and does not have any restrictions on speed and passing. The inputs, the flow rate in each lane, the distribution of the desired speed, the initial ordering of vehicles, and the initial spacing of vehicles could be specified by users. Each vehicle, based on other assumptions, travels at a fixed desired speed except for the following or passing condition. Passing maneuvers in the simulation were governed by the rules specified in the paper[86]. A car that intends to pass another car may do so only if its leader has a relatively lower desired speed, the oncoming vehicle is far enough for the vehicle to complete pass and the gap in front of the passed vehicle is sufficient for the vehicle to return to the normal lane after passing. Several other constraints were also made, such as the determination of the safe distance ahead of the passed vehicle and to the first oncoming vehicle when the passing is completed, that a vehicle may pass only one vehicle at a time, and that a vehicle may be passed by only one vehicle at a time.

The mathematical model for three vehicles passing mechanism on a two-lane-high ways is shown in Fig. 4. X-V (Back vehicle), Y-V (Front vehicle) and Z-V (Oncoming vehicle).

a – Distance between X-V and Y-V

b – Distance between Y-V and Z-V

A_1, A_2, A_3 – Distance from reference line
V_1, V_2, V_3– X-V, Y-V and Z-V vehicle velocities respectively.

A step wise procedure to implement PVS for the optimization of a given function is described in this section and PVS is explained with the aid of the Pseudo code in Fig.5.

VI. Opposite Based Learning Techniques (OBLT)

Now a day, meta-heuristic algorithms are much popular as they are able to provide optimal solution to all most all types (nonlinear, non convex, discrete etc.) of engineering problems. As algorithms are population based so enables to provide improved solution with integration of powerful techniques. In this article, such a powerful technique named OBLT (Opposite based learning techniques) is integrated with existing proposed PVS algorithm. As the effectiveness of the solution of optimization algorithm is basically depends on the population initialization, as it can affect the quality solution as well as the convergence speed. As most of the optimization algorithms uses random guess to produce an initial population in the absence of primary information about the global best solution. However, such type of purely random guess based solutions have higher probability to visiting or revising unproductive areas of unknown search space that adversely affects the quality solution and convergence speed. To overcome such a difficulty OBLT is proposed [87] to ameliorate individual solution by taking into account the current population as well as its opposite population simultaneously.

In most of the population based algorithms uses these initial population as current best and then directional search towards optimal one that's really a more time-consuming method, but OBLT provides enough strength to proposed PVS algorithm to gain a better approximation for both current and opposite population at the same time, as it provide a solution which is more nearer solution from optimal based from starting by checking both solutions. This approach is not only used only for initial solution but also used for each solution in current population.

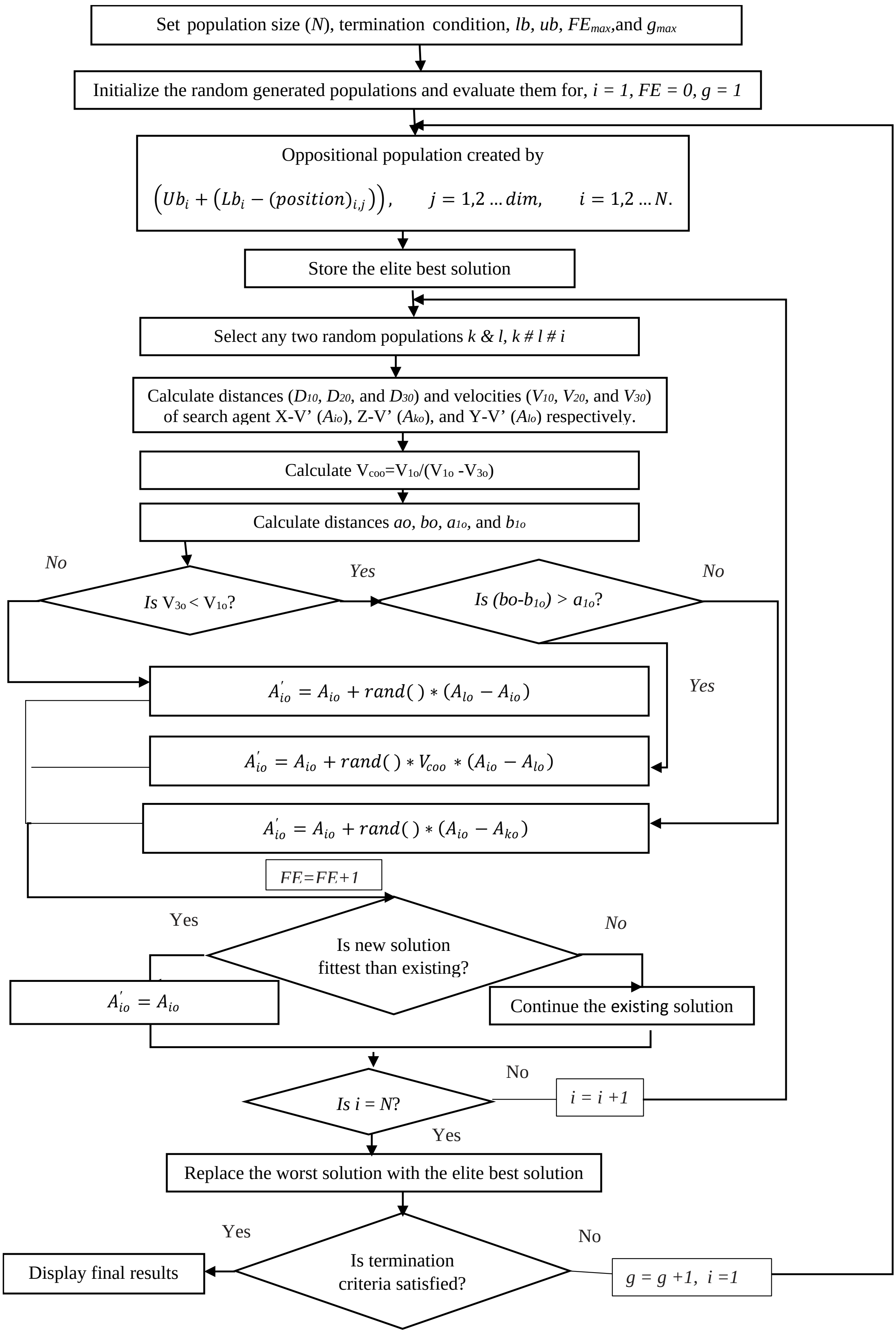

Fig. 6: Flowchart of Opposition based PVS algorithm. Mathematically OBLT can be modelled as

Opposite number: Assume Number (N) belong to a bounded set in the upper and lower range between *X and Y*. So, define as $N \in [X, Y]$. Then opposite number $(\dot{N})$ is expressed as:

$$\dot{N} = X + Y - N \quad (16)$$

Opposite point: Assume point $(P_i) = (N_1, N_2, N_3, \ldots N_t)$ be *t*-dimensional vector, where $N_i \in (X_i, Y_i)$ & $i = 1, 2, 3\ldots, t$. So, opposite point is: $\dot{P}_i = (\dot{N}_1, \dot{N}_2, \dot{N}_3\ldots\ldots\dot{N}_t)$ where $\dot{N}_i = X_i + Y_i - N_i$

After opposite point definition, oppositional based optimization is expressed as:

Assume $(P_i) = (N_1, N_2, N_3, \ldots N_t)$ be a point in *t*-dimensional space. Assume f (*) is fitness function used to measure candidate fitness. So as define in definition for opposition point $\dot{P}_i = (\dot{N}_1, \dot{N}_2, \dot{N}_3\ldots\ldots\dot{N}_t)$ is opposite of $P_i = (N_1, N_2, N_3, \ldots N_t)$. So now working of OBLT is changed as $f(P_i) \leq f(\dot{P}_i)$ then point P_i is replaced by $\dot{P}_i$. Similar approach is applied over each evaluated point simultaneously in order to move the search in a more closer to global best solution.

A step wise procedure to implement purposed Opposition based PVS algorithm is explained with the aid of the Flowchart inFig.6.

a) *Quasi-OBLT (Q-OBLT)*

Q-OBLT is primarily proposed by Rahnamayan et al. [88] to produce much better candidate solution by taking into account the current population as well as its quasi-opposite population simultaneously.

Assume $N \in [X, Y]$ *where* $N \in R$ *(Real number)* then its opposite number $(\dot{N})$ and its quassi-oppositional number (N_{qo}) are expressed as :

$$N_{qo} = rand*[(X+Y)/2, (X+Y-N)]$$

Assume point $(P) = (N_1, N_2, N_3, \ldots N_t)$ be *t*-dimensional vector, where $N_i \in (X_i, Y_i)$ & $i = 1, 2, 3\ldots, t$. So opposite point is: $\dot{P} = (\dot{N}_1, \dot{N}_2, \dot{N}_3\ldots\ldots\dot{N}_t)$ where $\dot{N}_1 = X_i + Y_i - N_i$ then quasi-opposite Solution is given by:

$$N_{qoi} = rand*[(X_i+Y_i)/2, (X_i+Y_i-N_i)] \text{ where } P_{qoi} = (N_{qo1}, N_{qo2}, N_{qo3}, \ldots N_{qot}) \quad (17)$$

b) *Quasi-opposite based optimization (Q-OBO)*

Assume $P_i = (N_1, N_2, N_3, \ldots N_t)$ be a point in *t*-dimensional space. Assume f (*) is fitness function used to measure candidate fitness. So as define in definition for quassi opposition point $P_{qoi} = (N_{qo1}, N_{qo2}, N_{qo3}, \ldots N_{qot})$ is quasi-opposite of $P_i = (N_1, N_2, N_3, \ldots N_t)$.

So now working of Q-OBO is changed as $f(P_i) \leq f(P_{qoi})$ then point P_i is replaced by P_{qoi}. Similar approach is applied over each evaluated point simultaneously in order to move the search in a more closer to global best solution.

VII. Numerical Results And Case Study

Firstly, The Proposed QOPVS optimization technique is applied on various standard un-constraints benchmark test functions such as Sphere, Schwefel 2.22, Schwefel 1.2, Schwefel 2.21, Quartic Function, Rastrigin Function, Ackley's Function, De Joung (Shekel's Foxholes), Kowalik's Function to verify the robustness and effectiveness. The objective function, dimension, range, and minimum value of objective function of all benchmark test functions are given in Table 2. The Proposed QOPVS method executed on PC with Intel Core i3 of 4 GB RAM. The initial control parameters of proposed QOPVS method such as population size, number of iterations, total trial runs etc. are given in Table 1. The numerical simulation result in terms of best, worst, average, median and statically results of PVS and Oppositional PVS algorithm is shown in Table 3. The fitness curve of best, worst, average, median and statically results of PVS and Quasi Oppositional PVS algorithm are shown in Fig 7 – Fig. 14. The optimized solutions are shown that QOPVS method is more effective compare to PVS method.

Table 1: The initial control parameters (population size, number of iterations, total trial runs) of proposed QOPVS and PVS algorithm.

Test System	Population Size (Search Agent No.)	Maximum No. of Iterations	Total Trial Runs
F1-F10	20	500	20
5-Unit System	30	50	10
6-Unit System	60	50	10
10-Unit System	30	50	10
20-Unit System	60	50	10
40-Unit System	60	50	10

Table 2: Description of benchmark test functions.

No.	Name	Function	Dim	Range	Fmin
F1	Sphere	$f(x)=\sum_{i=1}^{n} x_i^2 * R(x)$	10	[-100, 100]	0
F2	Schwefel 2.22	$f(x)=\sum_{i=1}^{n} \|x_i\| + \prod_{i=1}^{n} \|x_i\| * R(x)$	10	[-10, 10]	0
F3	Schwefel 1.2	$f(x)=\sum_{i=1}^{n}\left(\sum_{j-1}^{i} x_j\right)^2 * R(x)$	10	[-100, 100]	0
F4	Schwefel 2.21	$f(x)=\max_i \{\|x_i\|, 1 \le i \le n\}$	10	[-100, 100]	0
F5	Quartic Function	$f(x)=\sum_{i=1}^{n} i x_i^4 + random[0,1) * R(x)$	10	[-1.28, 1.28]	0
F6	Rastrigin Function	$f(x)=\sum_{i=1}^{n}\left[x_i^2 - 10cos(2\pi x_i) + 10\right] * R(x)$	10	[-5.12, 5.12]	0
F7	Ackley's Function	$f(x)=-20exp\left(-0.2\sqrt{\frac{1}{n}\sum_{i=1}^{n} x_i^2}\right) - exp\left(\frac{1}{n}\sum_{i=1}^{n} cos(2\pi x_i)\right) + 20 + e * R(x)$	10	[-32, 32]	0
F8	De Joung (Shekel's Foxholes)	$f(x)=\left(\frac{1}{500} + \sum_{j=1}^{25} \frac{1}{j + \sum_{i=1}^{2}(x_i - a_{ij})^6}\right)^{-1}$	2	[-65.536, 65.536]	1
F9	Kowalik's Function	$f(x)=\sum_{i=1}^{11} a_i - \left[\frac{x_i(b_i^2 + b_i x_2)}{b_i^2 + b_i x_3 + x_4}\right]^2$	4	[-5,5]	0.00030

Table 3: Comparison of PVS and QOPVS optimization results obtained for benchmark test functions.

Function	PVS Algorithm					QOPVS Algorithm				
	Results				Average Time	Results				Average Time
	Best	Average	Worst	Std. Dev		Best	Average	Worst	Std. Dev	
F-1	1.411e-14	5.3754e-14	2.2021e-13	4.3372e-14	0.74479	1.6431e-21	2.5963e-18	1.4521e-17	3.6831e-18	0.73802
F-2	1.697e-09	5.9822e-09	1.2286e-08	2.1853e-09	0.79375	6.1754e-13	1.2669e-11	3.3289e-11	7.6502e-12	0.78646
F-3	35.7346	665.6485	390.003	672.2774	4.001	0.80921	370.2777	3162.1078	622.4806	4.0854
F-4	0.014739	0.27627	1.0071	0.2707	0.88698	4.174e-05	0.15254	0.72393	0.15524	0.90208
F-5	0.0020987	0.0073105	0.013356	0.0028355	0.91146	0.0014466	0.0046641	0.008593	0.0018908	0.90469
F-6	3.5811e-11	9.4493	21.6723	6.6746	1.0026	0	0.12835	3.8506	0.6912	1.0094
F-7	1.0263e-08	2.1774e-08	3.3162e-08	6.5296e-09	1.0323	5.4294e-12	1.4009e-10	4.4921e-10	9.802e-11	1.0052
F-8	0.998	5.8583	13.7082	3.603	0.23594	0.998	4.575	12.6705	4.1729	0.22891
F-9	0.00057615	0.0057746	0.020364	0.0084414	0.035156	0.00041012	0.0026073	0.020381	0.0059235	0.033594

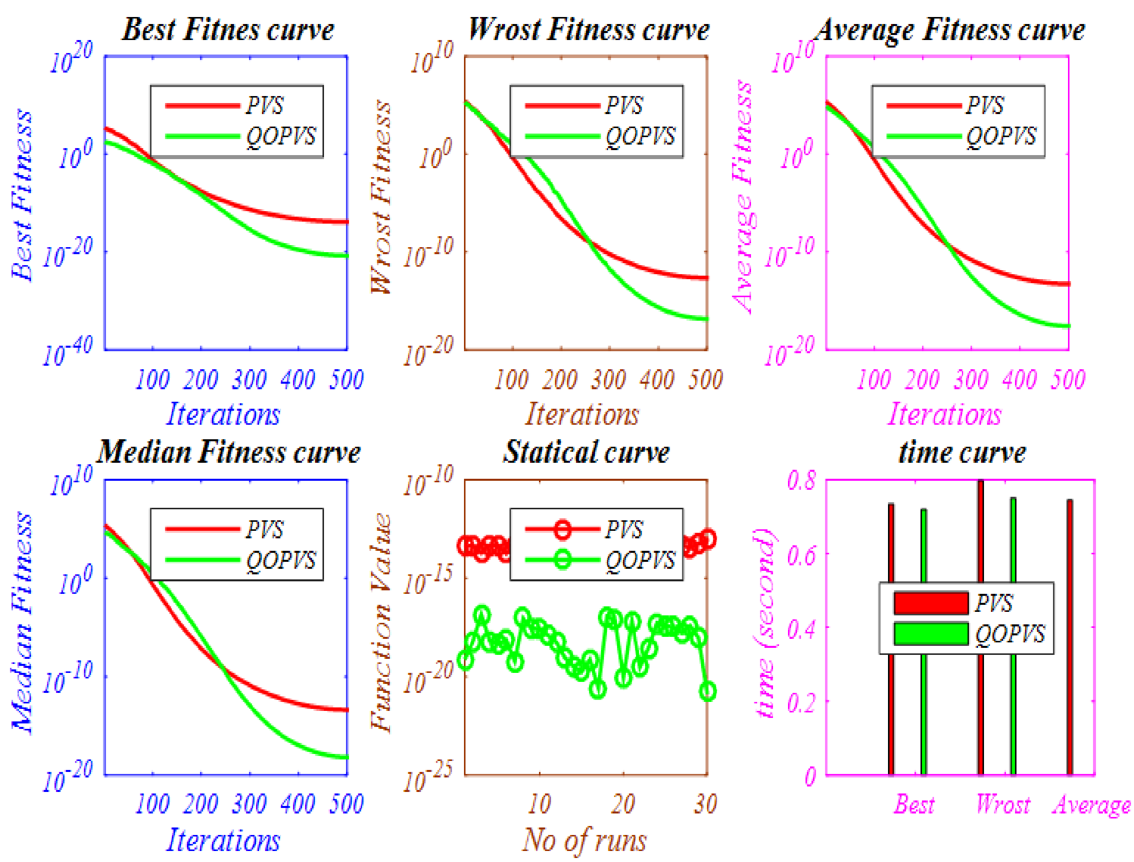

Fig. 7: Best fitness, worst fitness, average fitness of all vehicles, median fitness, statically and time curves for Function F1 (Sphere).

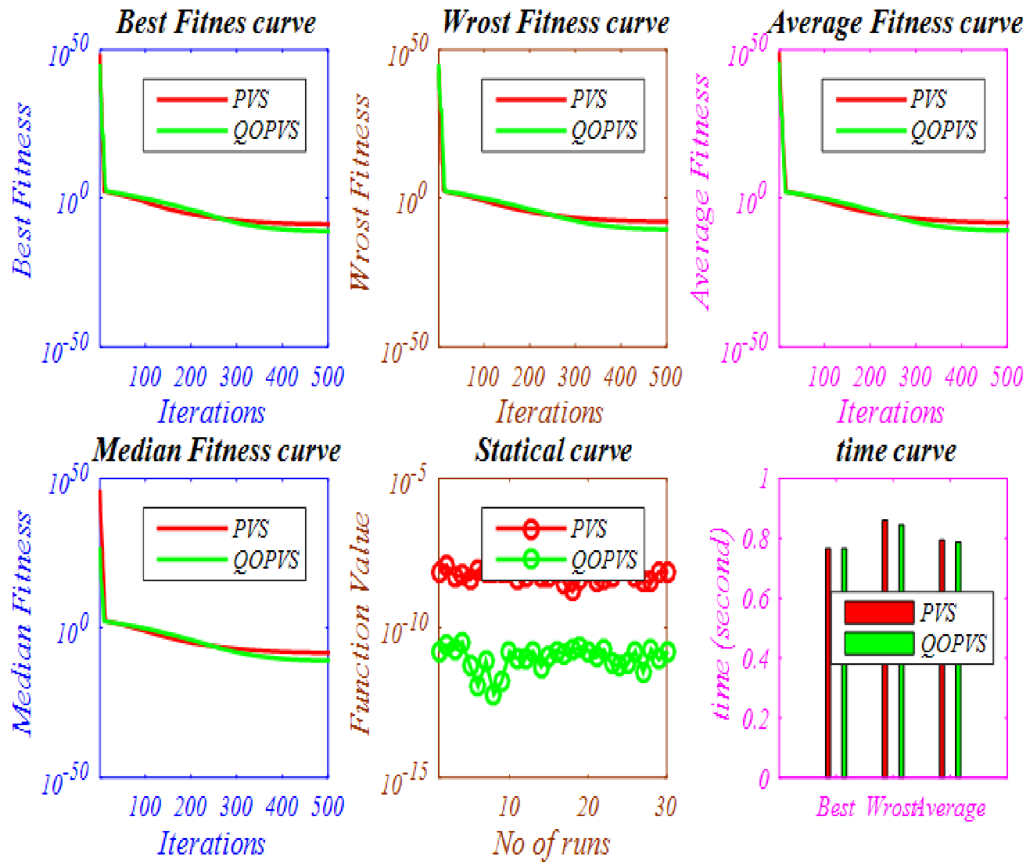

Fig. 8: Best fitness, worst fitness, average fitness of all vehicles, median fitness, statically and time curves for Function F2 (Schwefel 2.22).

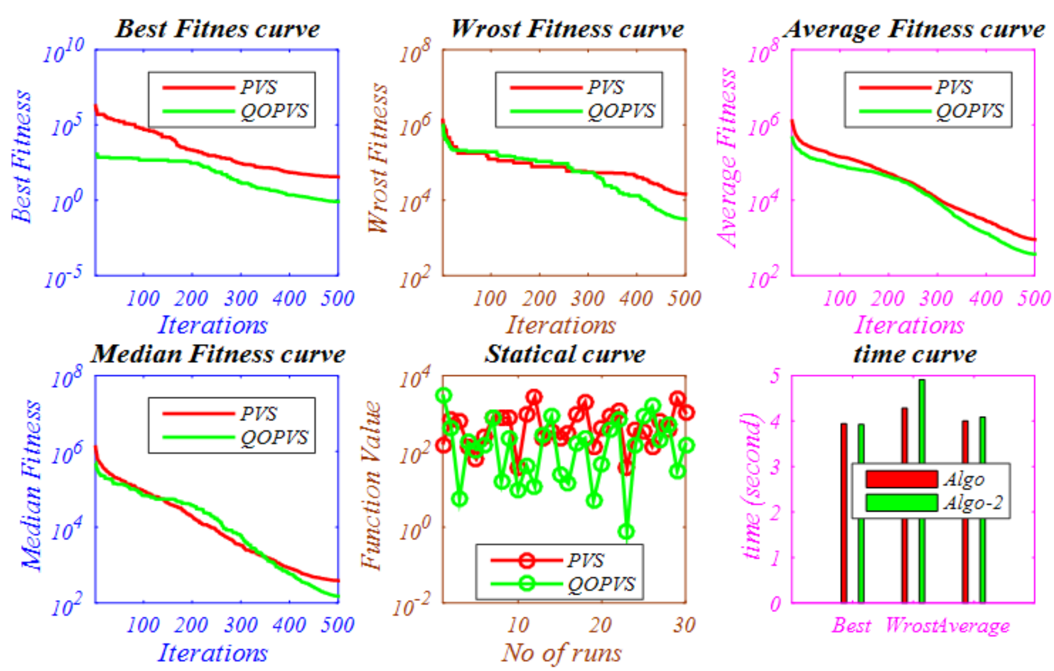

Fig. 9: Best fitness, worst fitness, average fitness of all vehicles, median fitness, statically and time curves for Function F3 (Schwefel 1.2).

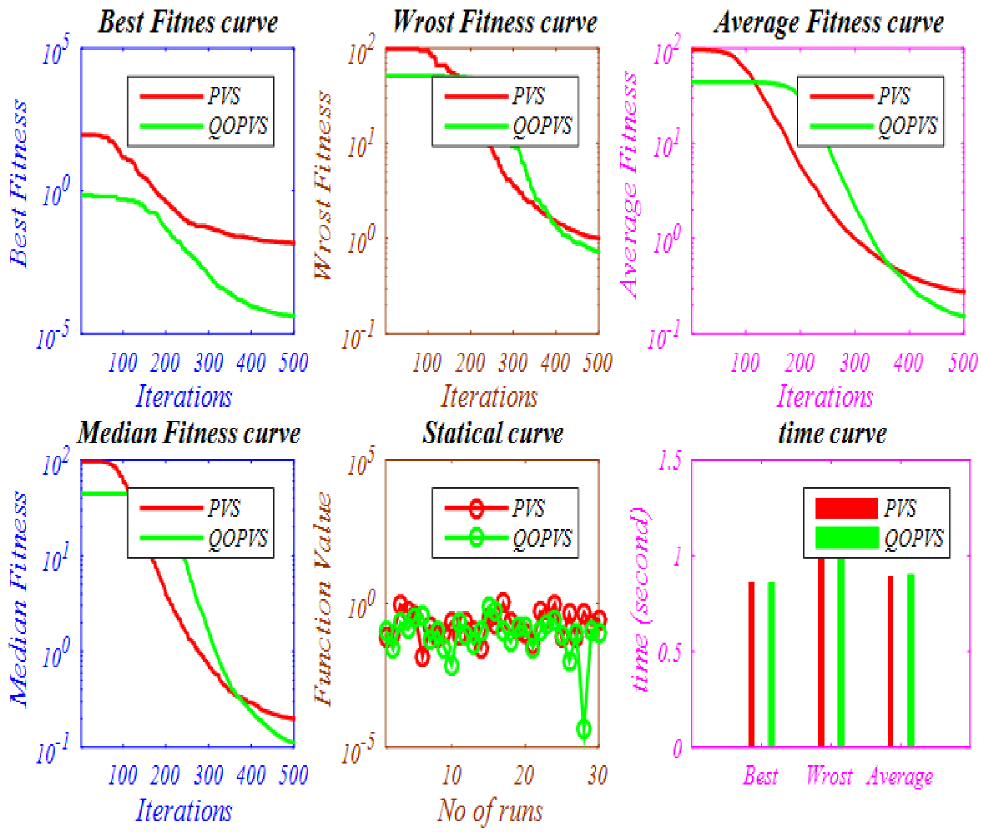

Fig. 10: Best fitness, worst fitness, average fitness of all vehicles, median fitness, statically and time curves for Function F4 (Schwefel 2.21).

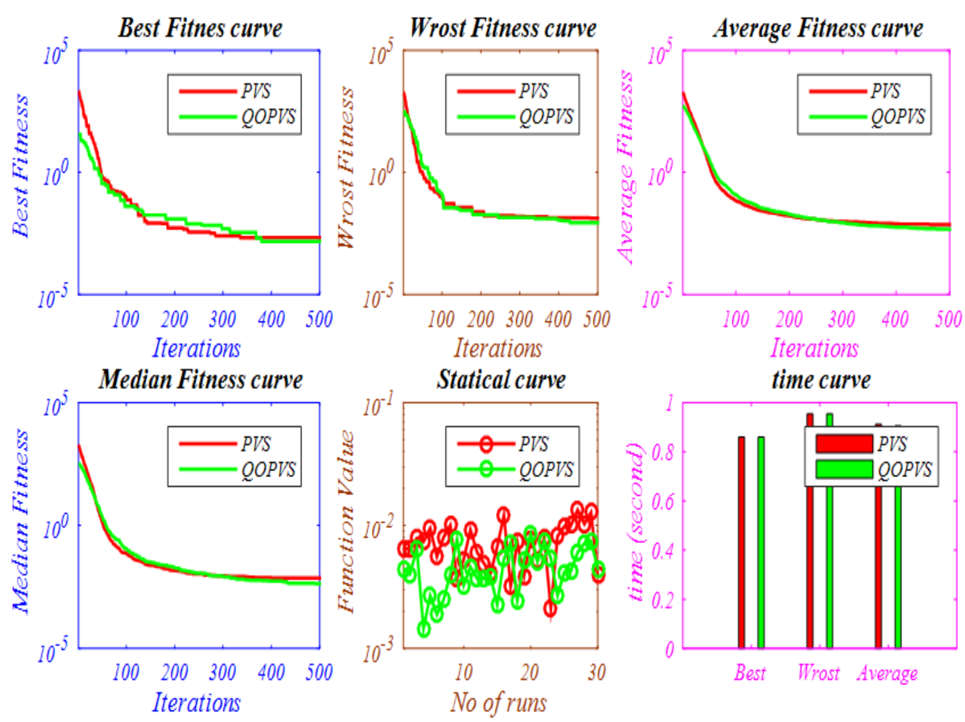

Fig. 11: Best fitness, worst fitness, average fitness of all vehicles, median fitness, statically and time curves for Function F5 (Quartic Function).

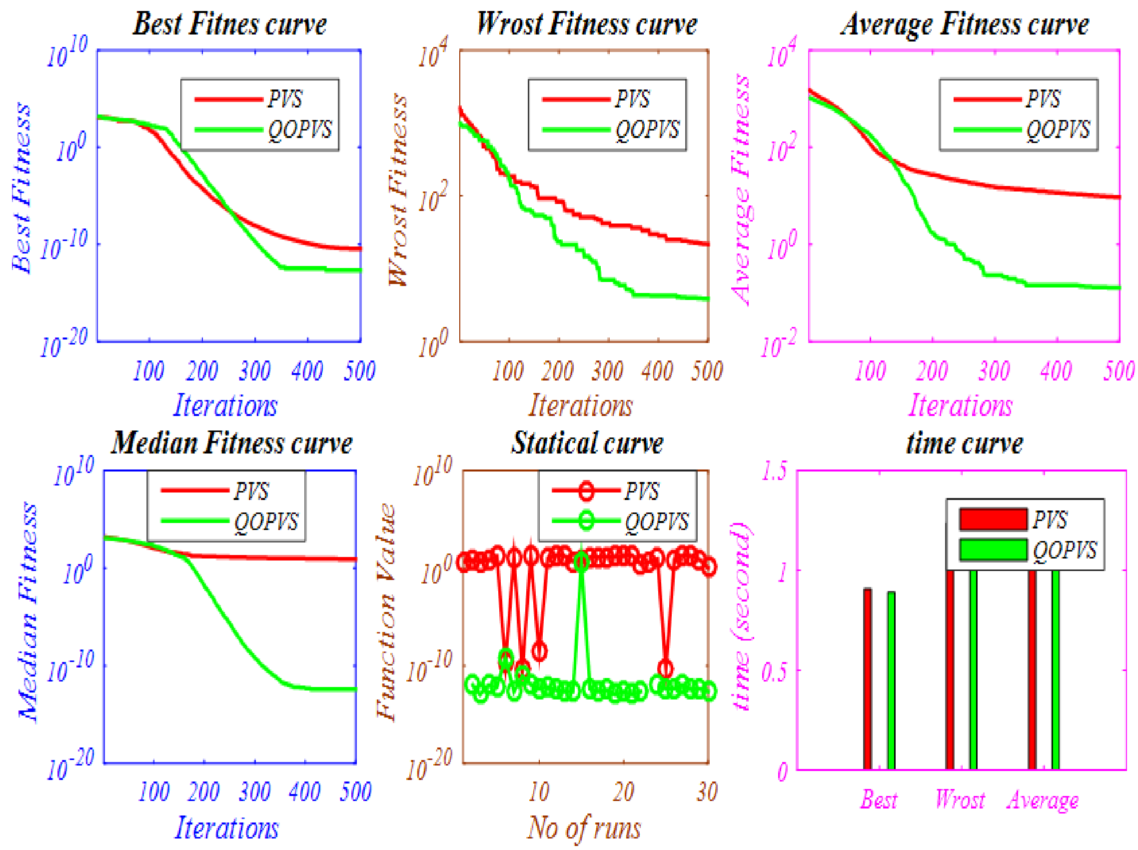

Fig. 12: Best fitness, worst fitness, average fitness of all vehicles, median fitness, statically and time curves for Function F6 (Rastrigin Function).

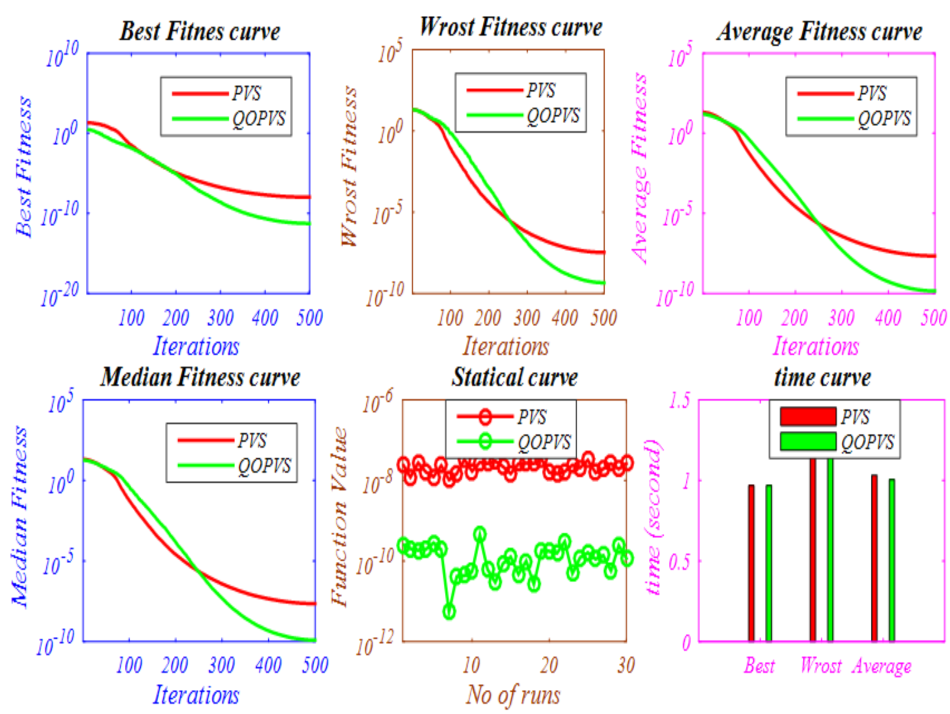

Fig. 13: Best fitness, worst fitness, average fitness of all vehicles, median fitness, statically and time curves for Function F7 (Ackley's Function).

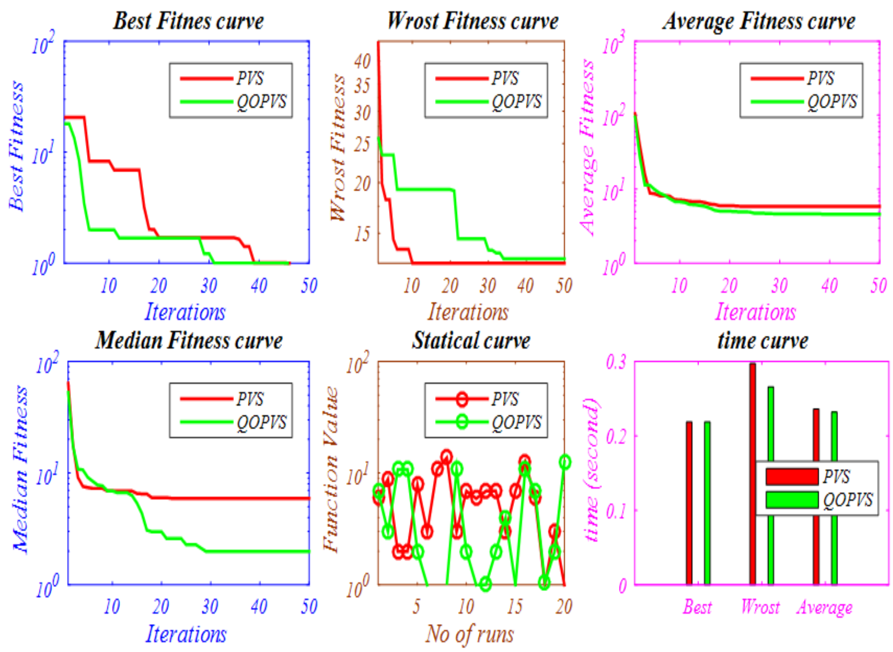

Fig. 14: Best fitness, worst fitness, average fitness of all vehicles, median fitness, statically and time curves for Function F8 (De Joung (Shekel's Foxholes)).

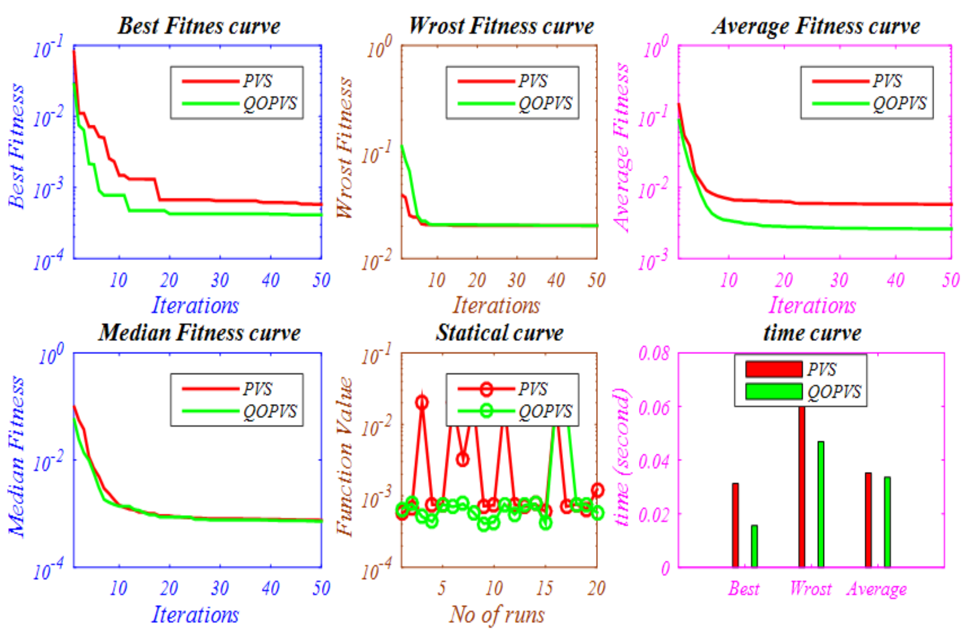

Fig. 14: Best fitness, worst fitness, average fitness of all vehicles, median fitness, staticallyand time curves for Function F9 (Kowalik's Function).

a) Case study

The proposed QOPVS optimization technique is applied for simulated on various test systems with the number of units 5-unit, 6-unit, 10-unit, 20-unit, and 40-unit are considered for 24-hour load scheduling horizon. For 10 generating unit system, 24-hour load demands are given in fig. 15 and for 5-unit, and 6-unit system 24-hour load demands are given in fig. 16. The 10 generating unit system data and load demands are taken from [89]. The spinning reserve (SR) for all test units is considered 10% of the hourly load demand but for 10-unit system also considered 5% of the hourly load demand. The initial control parameters of proposed QOPVS method such as population size (no. of search agent), number of iterations, total trial runs etc. are given in Table 1. For the 20-unit, and 40-unit test system the initial 10-units were duplicated and the demand was multiplied by 2 and 4 respectively. A PVS algorithm with complete state enumeration was also developed and used to solve the 10-unit problem. The solutions of the

PVS and the QOPVS, for the 10-unit problem, are identical. In other test runs not reported here, the QOPVS provided solutions even better than the PVS with complete state enumeration. For the larger problem sets the QOPVS solutions were compared with the solutions produced by the PVS algorithm, as the time and capacity requirements of the PVS algorithm with complete state enumeration are prohibitive for problems of this scale. In order to avoid misleading results due to the heuristic nature of the PVS, 10 runs were made for each problem set, with each run starting with different random populations. For a specific problem set, the generation limit increasing with the number of units. A run was considered successful if it converged on a solution equal to or better than that of the PVS algorithm.

The population size was 30 in all runs for 10-unit test system and 60 for 20-unit & 40-unit test system. In general, when the population size increases, the number of generations required by the PVS to converge to the optimum solution decreases. On the other. hand, the CPU time required for the evaluation of a generation increases almost proportional with the population size. The population of 30 search agents was chosen, after several tests runs concerning populations of 10-100 search agents, because it was slightly more efficient (i.e. it was faster in reaching the same solution with equal probability).

Optimal UC schedule of the 5-unit and 6-unit test system on 24-h scheduling horizon with one-hour interval considering 10% spinning reserve is shown in Table 4 and Table 6. The test results are shown in Table 5 and Table 7, for the QOPVS, all the Best, Average, Median, Worst and standard Deviation solutions produced are reported together with their difference as a percentage of the best solution. The optimized solution in terms of generation cost and time, the purposed QOPVS method give better result compare PVS method. Fig. 17and Fig. 18 shows the best fitness, worst fitness, average fitness of all vehicles, median fitness, statically and time curves of the proposed QOPVS method for 5-unit and 6-unit system UC problem respectively. Optimal UC schedule of the 10-unit test system on 24-h scheduling horizon with one-hour interval considering 5% spinning reserve is shown in Table 8. For the 10-unit test system, all the best, average, median, worst and standard deviation solutions produced are reported in Table 9. Fig. 19 shows the best fitness, worst fitness, average fitness of all vehicles, median fitness, statically and time curves of the proposed QOPVS method for 10-unit system UC problem.

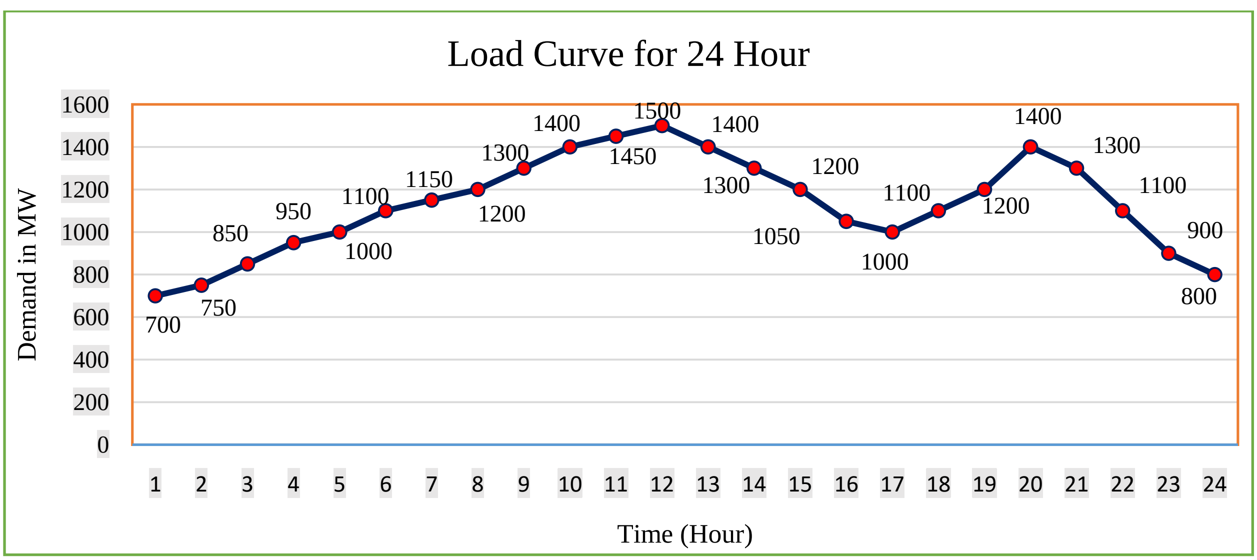

Fig. 15: 24-hour generation and load demand curve for 10-unit system.

Optimal UC schedule of the 10-, 20-, and 40-unit test system on 24-h scheduling horizon with one-hour interval considering 10% spinning reserve is shown in Table 10, Table 12 and Table 13 respectively. For the 10-, 20-, and 40-unit test system, all the best, average, median, worst and standard deviation solutions produced are reported together in Table 11 and Table 14 respectively. As shown in Table 14, for large systems (more than 10 units), the QOPVS constantly outperforms the PVS unit commitment. The QOPVS best, average and worst time reported concerns CPU time on PC with Intel Core i3 of 4 GB RAM. The scaling of the QOPVS execution time is less compare other methods [72], [74]. Analysis of the results presented in Table 14 shows that the QOPVS execution time and generation cost increases in a quadratic way with the number of units to be committed. Fig. 20 to Fig. 22 shows the best fitness, worst fitness, average fitness of all vehicles, median fitness, statically and time curves of the proposed QROPVS method for 10-unit, 20-unit, and 40-unit system UC problem respectively.

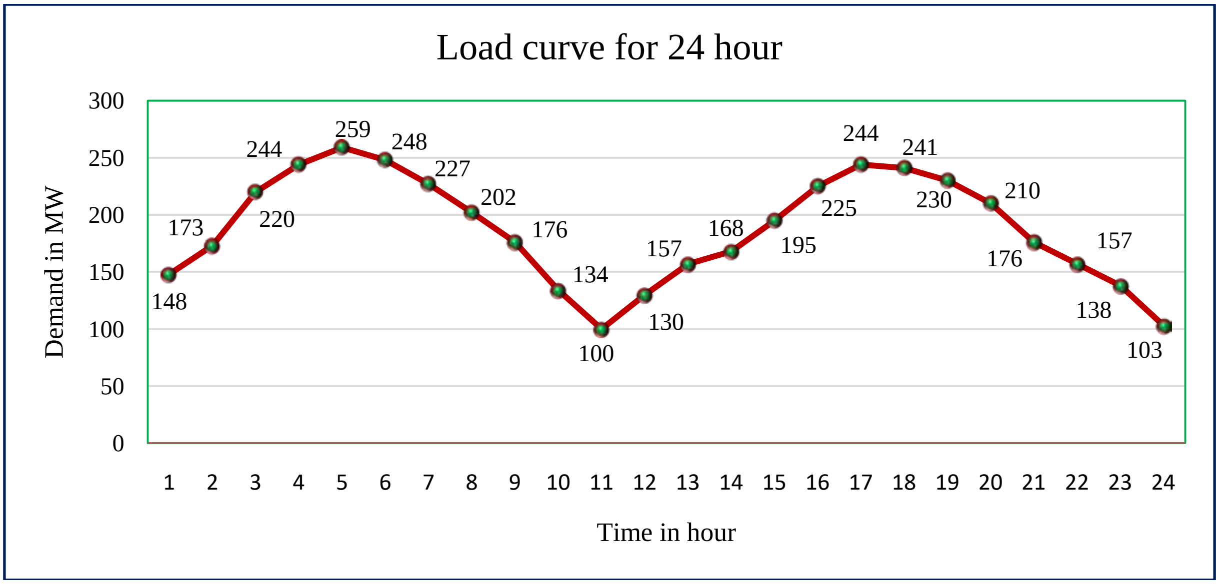

Fig. 16: 24-hour generation and load demand curves for 5-unit and 6-unit system.

Table 4: Optimal UC schedule of the 5-unit test system on 24-h scheduling horizon with 1-h interval considering 10% spinning reserve (QOPVS Results).

Hour	U-1	U-2	U-3	U-4	U-5	SR
1	148	0	0	0	0	148
2	173	0	0	0	0	173
3	220	0	0	0	0	220
4	244	0	0	0	0	244
5	238.9566	0	20.04341	0	0	259
6	248	0	0	0	0	248
7	227	0	0	0	0	227
8	202	0	0	0	0	202
9	176	0	0	0	0	176
10	134	0	0	0	0	134
11	100	0	0	0	0	100
12	130	0	0	0	0	130
13	157	0	0	0	0	157
14	168	0	0	0	0	168
15	195	0	0	0	0	195
16	225	0	0	0	0	225
17	244	0	0	0	0	244
18	241	0	0	0	0	241
19	230	0	0	0	0	230
20	210	0	0	0	0	210
21	176	0	0	0	0	176
22	157	0	0	0	0	157
23	138	0	0	0	0	138
24	103	0	0	0	0	103

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Table 5: Comparison of optimization results for 5-generating unit system.

Optimization Techniques	Generation Cost					Time		
	Best	Average	Median	Worst	SD	Best	Average	Worst
QOPVS [Proposed Technique]	11925.1274	11935.7714	11942.8673	11942.8673	8.6907	51.5	53.0266	54.25
PVS [Proposed Technique]	11928.1654	11939.7714	11940.8673	11948.6528	8.6907	50.8	52.8215	55.5

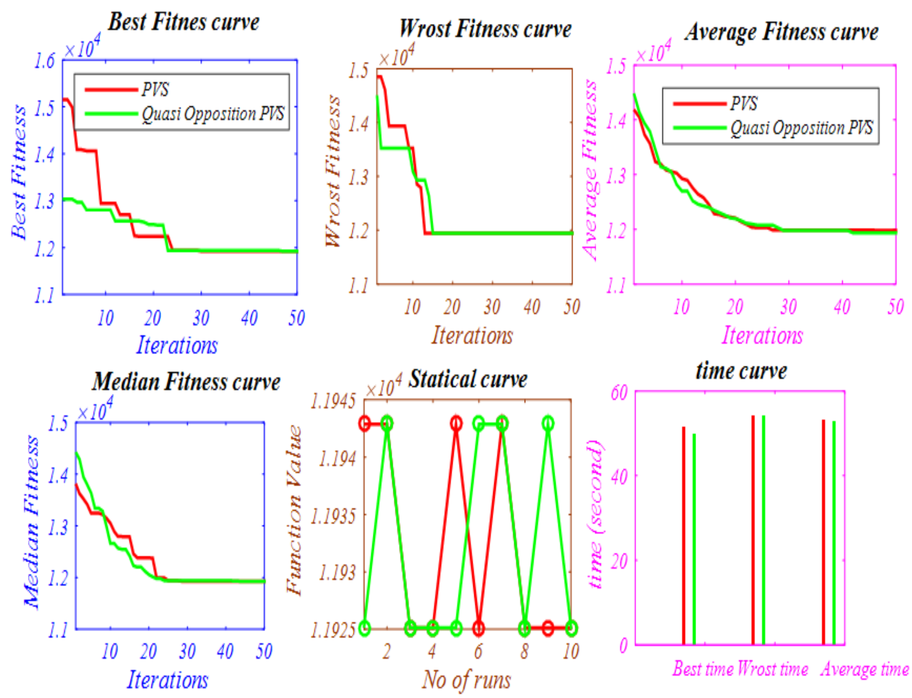

Fig. 17: Best fitness, worst fitness, average fitness of all vehicles, median fitness, statically and time curves of the proposed QOPVS method for 5-unit system considering 10% spinning reserve.

Table 6: Optimal UC schedule of the 6-unit test system on 24-h scheduling horizon with 1-h interval considering 10% spinning reserve (QOPVS Results).

Hour	U-1	U-2	U-3	U-4	U-5	U-6
1	148	0	0	0	0	0
2	173	0	0	0	0	0
3	174.1176	45.88235	0	0	0	0
4	193.8824	50.11765	0	0	0	0
5	200	59	0	0	0	0
6	197.1765	50.82353	0	0	0	0
7	179.8824	47.11765	0	0	0	0
8	159.2941	42.70588	0	0	0	0
9	176	0	0	0	0	0
10	134	0	0	0	0	0
11	100	0	0	0	0	0
12	130	0	0	0	0	0
13	157	0	0	0	0	0
14	168	0	0	0	0	0

15	195	0	0	0	0	0
16	178.2353	46.76471	0	0	0	0
17	193.8824	50.11765	0	0	0	0
18	191.4118	49.58824	0	0	0	0
19	182.3529	47.64706	0	0	0	0
20	165.8824	44.11765	0	0	0	0
21	176	0	0	0	0	0
22	157	0	0	0	0	0
23	138	0	0	0	0	0
24	103	0	0	0	0	0

Table 7: Comparison of optimization results for 6-generating unit system.

Optimization Techniques	Generation Cost					Time		
	Best	Average	Median	Worst	SD	Best	Average	Worst
QOPVS [Proposed Technique]	11925.1274	11935.7714	11942.8673	11942.8673	8.6907	51.5	53.0266	54.25
PVS [Proposed Technique]	11928.1654	11939.7714	11940.8673	11948.6528	8.6907	50.8	52.8215	55.5

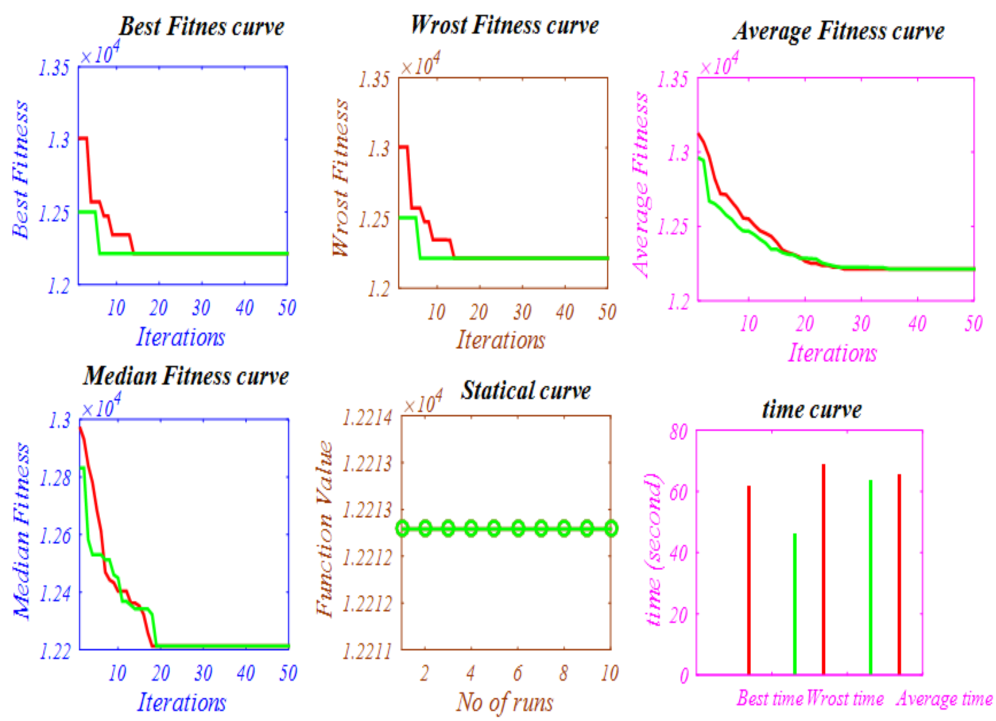

Fig. 18: Best fitness, worst fitness, average fitness of all vehicles, median fitness, statically and time curves of the proposed QOPVS method for 6-unit system considering 10% spinning reserve.

Table 8: Optimal UC schedule of the 10-unit test system on 24-h scheduling horizon with 1-h interval considering 5% spinning reserve (QOPVS Results).

Hour	U-1	U-2	U-3	U-4	U-5	U-6	U-7	U-8	U-9	U-10	SR
1	455	220	0	0	25	0	0	0	0	0	35
2	455	270	0	0	25	0	0	0	0	0	37.5
3	455	370	0	0	25	0	0	0	0	0	42.5
4	455	455	0	0	40	0	0	0	0	0	47.5
5	455	455	0	0	90	0	0	0	0	0	50
6	455	455	130	0	60	0	0	0	0	0	55

7	455	410	130	130	25	0	0	0	0	0	57.5
8	455	455	130	130	30	0	0	0	0	0	60
9	455	455	130	130	110	20	0	0	0	0	65
10	455	455	130	130	162	43	25	0	0	0	70
11	455	455	130	130	162	80	25	13	0	0	72.5
12	455	455	130	130	162	80	25	53	10	0	75
13	455	455	130	130	162	43	25	0	0	0	70
14	455	455	130	130	110	20	0	0	0	0	65
15	455	455	130	0	140	20	0	0	0	0	60
16	455	440	130	0	25	0	0	0	0	0	52.5
17	455	390	130	0	25	0	0	0	0	0	50
18	455	455	130	0	35	0	25	0	0	0	55
19	455	455	130	0	135	0	25	0	0	0	60
20	455	455	130	130	162	43	25	0	0	0	70
21	455	455	130	130	110	20	0	0	0	0	65
22	455	455	0	130	40	20	0	0	0	0	55
23	455	315	0	130	0	0	0	0	0	0	45
24	455	215	0	130	0	0	0	0	0	0	40
				U = Generating Unit							

Table 9: Comparison of optimization results for 10-generating unit system considering 5% spinning reserve.

Optimization Techniques	Generation Cost					Time		
	Best	Average	Median	Worst	SD	Best	Average	Worst
QOPVS [Proposed Technique]	557680 .714	558388 .3938	55838 7.4718	5590 08.914	368. 1285	66.84 38	76.0141	84.93 75
PVS [Proposed Technique]	557843 .339	558391 .0417	55845 7.4866	5588 11.059	262. 768	87. 875	94.5922	106.0 938

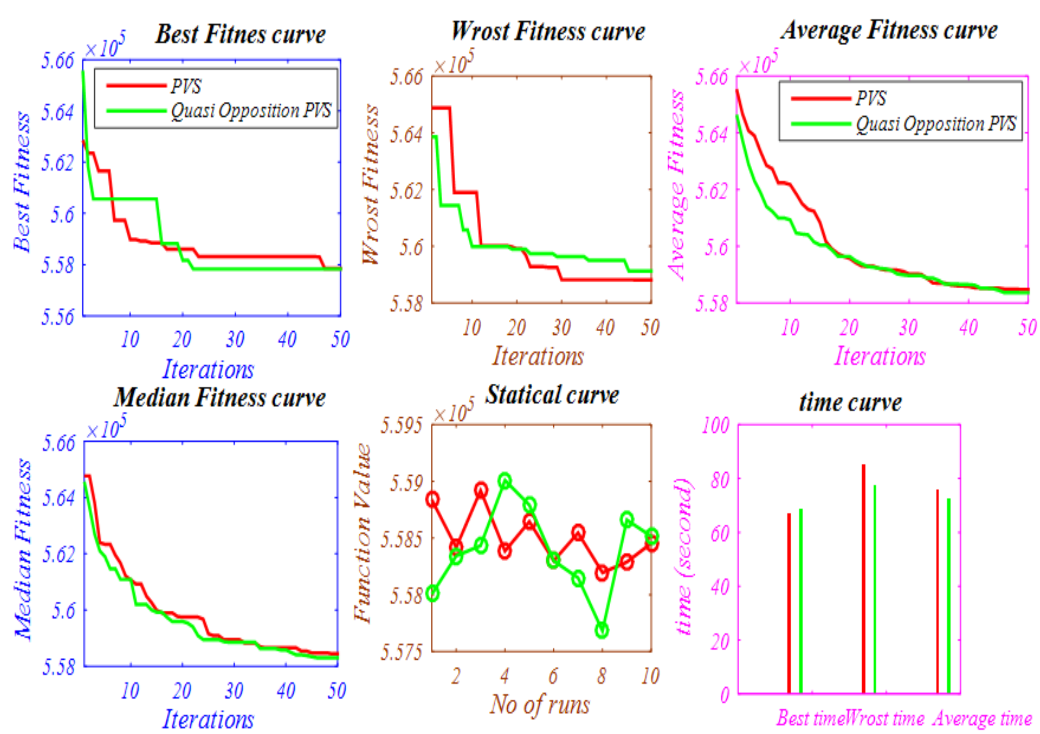

Fig. 19: Best fitness, worst fitness, average fitness of all vehicles, median fitness, statically and time curves of the proposed QOPVS method for 10-unit system considering 5% spinning reserve.

Table 10: Optimal UC schedule of the 10-unit test system on 24-h scheduling horizon with 1-h interval considering 10% spinning reserve (QOPVS Results).

Hour	U-1	U-2	U-3	U-4	U-5	U-6	U-7	U-8	U-9	U-10	SR
1	455	245	0	0	0	0	0	0	0	0	70
2	455	295	0	0	0	0	0	0	0	0	75
3	455	370	0	0	0	0	25	0	0	0	85
4	455	450	0	0	0	20	25	0	0	0	95
5	455	370	0	130	0	20	25	0	0	0	100
6	455	455	0	130	40	20	0	0	0	0	110
7	455	410	130	130	25	0	0	0	0	0	115
8	455	455	130	130	30	0	0	0	0	0	120
9	455	455	130	130	95	0	25	10	0	0	130
10	455	455	130	130	162	33	25	10	0	0	140
11	455	455	130	130	162	73	25	10	10	0	145
12	455	455	130	130	162	80	25	43	10	10	150
13	455	455	130	130	162	33	25	10	0	0	140
14	455	455	130	130	85	20	25	0	0	0	130
15	455	455	130	130	30	0	0	0	0	0	120
16	455	310	130	130	25	0	0	0	0	0	105
17	455	260	130	130	25	0	0	0	0	0	100
18	455	360	130	130	25	0	0	0	0	0	110
19	455	455	130	130	30	0	0	0	0	0	120
20	455	455	130	130	162	33	25	10	0	0	140
21	455	455	130	130	85	20	25	0	0	0	130
22	455	455	0	0	145	20	25	0	0	0	110
23	455	420	0	0	25	0	0	0	0	0	90
24	455	345	0	0	0	0	0	0	0	0	80

U = Generating Unit

Table 11: Comparison of optimization results for 10-generating unit system considering 10% spinning reserve.

S. No.	Optimization Techniques	Generation Cost					Time		
		Best	Average	Median	Worst	SD	Best	Average	Worst
1	QOPVS [Proposed Technique]	563712.108	564135.8193	563887.333	565066.888	466.4197	7.8969	8.8317	10.0094
2	PVS [Proposed Technique]	563730.418	564415.2063	564475.5893	565069.753	464.6139	9.0047	10.4658	11.0063

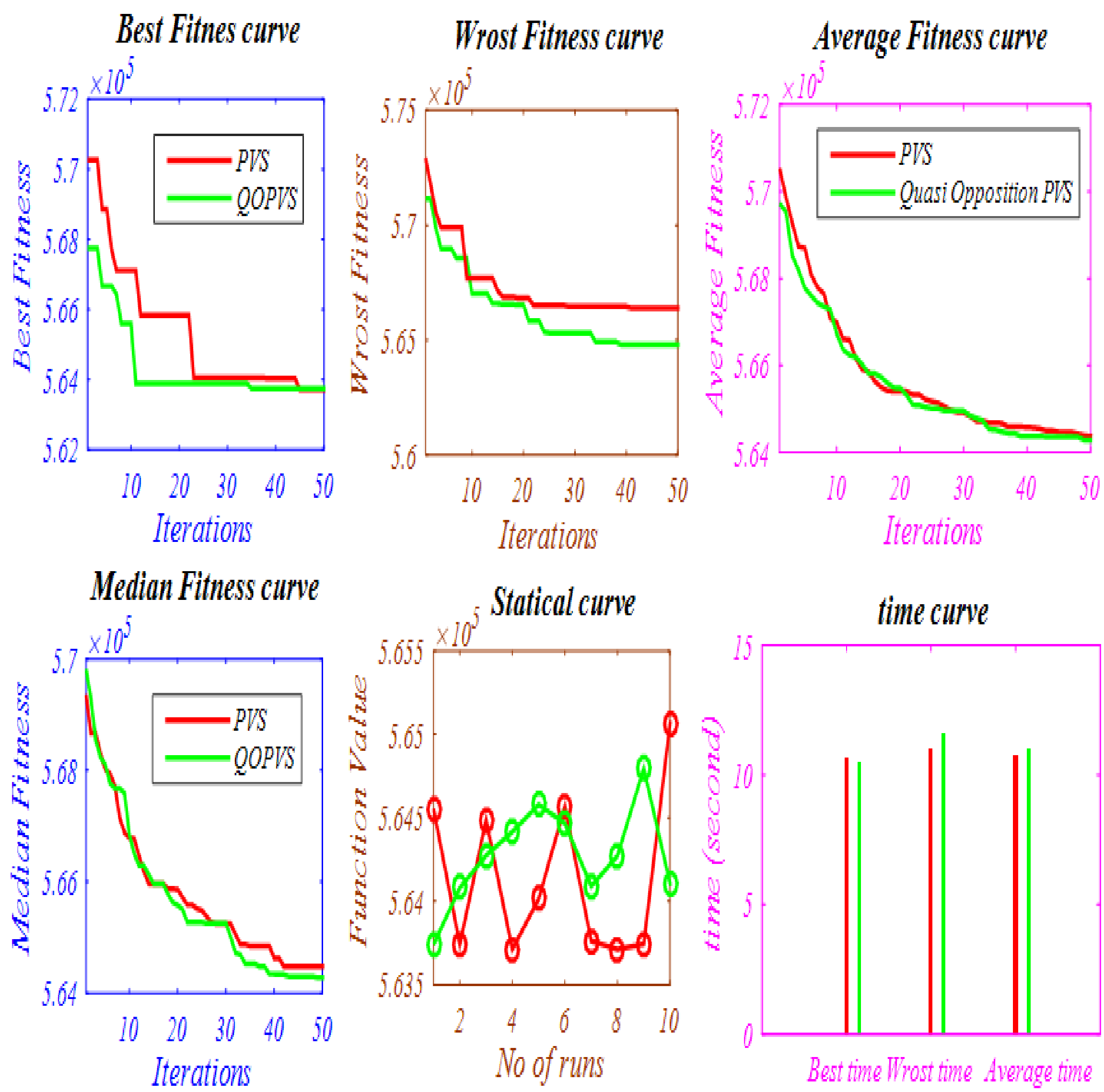

Fig. 20: Best fitness, worst fitness, average fitness of all vehicles, median fitness, statically and time curves of the proposed QOPVS method for 10-unit system considering 10% spinning reserve.

Table 12: Optimal UC schedule of the 20-unit test system on 24-h scheduling horizon with 1-h interval considering 10% spinning reserve (QOPVS Results).

Hour	U-1	U-2	U-3	U-4	U-5	U-6	U-7	U-8	U-9	U-10	U-11	U-12	U-13	U-14	U-15	U-16	U-17	U-18	U-19	U-20
1	455	232.5	0	0	25	0	0	0	0	0	455	232.5	0	0	0	0	0	0	0	0
2	455	282.5	0	0	25	0	0	0	0	0	455	282.5	0	0	0	0	0	0	0	0
3	455	382.5	0	0	25	0	0	0	0	0	455	382.5	0	0	0	0	0	0	0	0
4	455	455	0	0	80	0	0	0	0	0	455	455	0	0	0	0	0	0	0	0
5	455	455	0	0	162	0	0	0	0	18	455	455	0	0	0	0	0	0	0	0
6	455	455	0	0	125	0	0	0	0	0	455	455	130	0	125	0	0	0	0	0
7	455	455	130	0	110	0	0	0	0	0	455	455	130	0	110	0	0	0	0	0
8	455	455	130	0	160	0	0	0	0	0	455	455	130	0	160	0	0	0	0	0
9	455	455	130	130	130	0	0	0	0	0	455	455	130	130	130	0	0	0	0	0
10	455	455	130	130	162	0	68	0	0	0	455	455	130	130	162	0	68	0	0	0
11	455	455	130	130	162	80	78	0	0	0	455	455	130	130	162	0	78	0	0	0
12	455	455	130	130	162	80	60.5	55	0	0	455	455	130	130	162	80	60.5	0	0	0
13	455	455	130	130	162	68	0	0	0	0	455	455	130	130	162	68	0	0	0	0
14	455	455	130	130	162	0	0	0	0	0	455	455	130	0	162	66	0	0	0	0
15	455	455	0	130	160	0	0	0	0	0	455	455	130	0	160	0	0	0	0	0
16	455	440	0	130	25	0	0	0	0	0	455	440	130	0	25	0	0	0	0	0
17	455	390	0	130	25	0	0	0	0	0	455	390	130	0	25	0	0	0	0	0
18	455	455	0	130	47.5	0	25	0	0	0	455	455	130	0	47.5	0	0	0	0	0
19	455	455	0	130	120	20	25	0	0	10	455	455	130	0	120	0	25	0	0	0
20	455	455	130	130	162	80	53	0	0	0	455	455	130	0	162	80	53	0	0	0
21	455	455	130	130	162	80	0	0	0	0	455	455	0	0	162	80	36	0	0	0
22	455	440	130	130	0	0	0	0	0	0	455	440	0	130	0	20	0	0	0	0
23	455	315	130	0	0	0	0	0	0	0	455	315	0	130	0	0	0	0	0	0
24	455	0	130	0	0	0	0	0	0	0	455	430	0	130	0	0	0	0	0	0

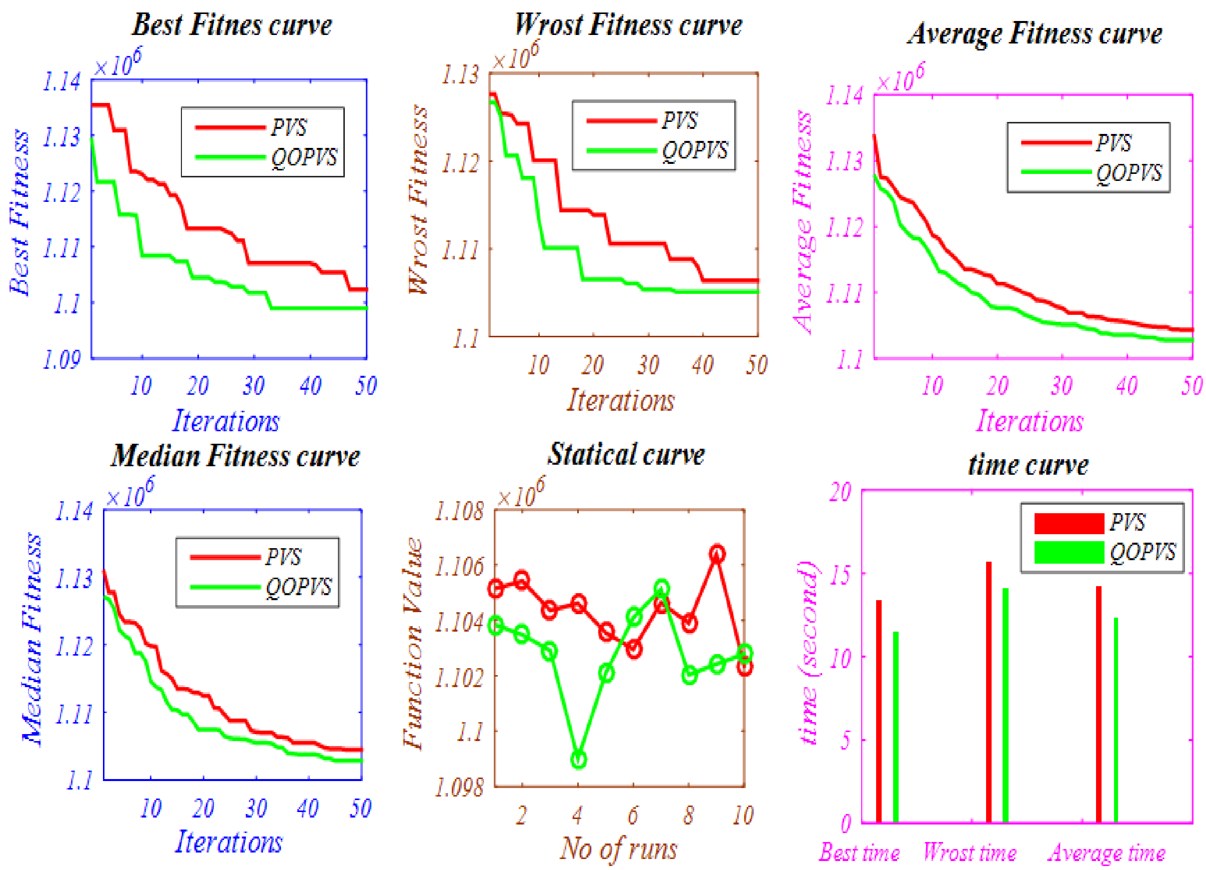

Fig. 21: Best fitness, worst fitness, average fitness of all vehicles, median fitness, statically and time curves of the proposed QOPVS method for 20-unit system considering 10% spinning reserve.

Table 13: Optimal UC schedule of the 40-unit test system on 24-h scheduling horizon with 1-h interval considering 10% spinning reserve (QOPVS Results) for first 20-units.

Hour	U-1	U-2	U-3	U-4	U-5	U-6	U-7	U-8	U-9	U-10	U-11	U-12	U-13	U-14	U-15	U-16	U-17	U-18	U-19	U-20
1	455	245	0	0	0	0	0	0	0	0	455	245	0	0	0	0	0	0	0	0
2	455	295	0	0	0	0	0	0	0	0	455	295	0	0	0	0	0	0	0	0
3	455	395	0	0	0	0	0	0	0	0	455	395	0	0	0	0	0	0	0	0
4	455	455	0	0	0	0	0	0	0	0	455	455	0	0	0	0	0	0	0	0
5	455	455	0	0	0	0	0	0	0	0	455	455	130	130	0	0	0	0	0	0
6	455	455	0	0	150	0	0	0	0	0	455	455	130	130	150	0	0	0	0	0
7	455	455	130	0	142.5	0	0	0	0	0	455	455	130	130	142.5	0	0	0	0	0
8	455	455	130	130	160	0	0	0	0	0	455	455	130	130	160	0	0	0	0	0
9	455	455	130	130	156.25	0	25	0	0	0	455	455	130	130	156.25	0	0	0	0	0
10	455	455	130	130	162	0	68	0	0	0	455	455	130	130	162	0	68	0	0	0
11	455	455	130	130	162	0	84.25	55	0	0	455	455	130	130	162	0	84.25	0	0	0
12	455	455	130	130	162	80	80.5	0	55	55	455	455	130	130	162	0	80.5	0	0	0
13	455	455	0	130	162	80	0	55	0	0	455	455	130	130	162	0	0	0	0	0
14	455	455	0	130	162	80	0	36	0	0	455	455	0	0	162	80	0	36	0	0
15	455	455	0	130	162	0	0	42	0	0	455	455	0	0	162	80	0	0	0	0
16	455	455	0	130	70	0	0	0	0	0	455	455	0	0	70	20	0	0	0	0
17	455	455	0	130	25	0	0	0	0	0	455	455	0	0	25	0	0	0	0	0
18	455	455	130	130	70	0	0	0	0	0	455	455	0	0	70	0	25	0	0	0
19	455	455	130	130	131.25	0	25	0	0	0	455	455	0	0	131.25	0	25	0	0	0
20	455	455	130	130	162	0	69	0	0	55	455	455	130	130	162	0	69	55	0	0
21	455	455	130	0	156.25	0	25	0	0	0	455	455	130	130	156.25	0	0	0	0	0
22	455	450	130	0	0	0	0	0	0	0	455	450	130	130	0	0	0	0	0	0
23	455	360	0	0	0	0	0	10	0	0	455	360	130	130	0	20	0	0	0	10
24	455	420	0	0	0	0	0	0	0	0	455	420	130	130	0	20	0	0	0	0

Hour	U-21	U-22	U-23	U-24	U-25	U-26	U-27	U-28	U-29	U-30	U-31	U-32	U-33	U-34	U-35	U-36	U-37	U-38	U-39	U-40
1	455	245	0	0	0	0	0	0	0	0	455	245	0	0	0	0	0	0	0	0
2	455	295	0	0	0	0	0	0	0	0	455	295	0	0	0	0	0	0	0	0
3	455	395	0	0	0	0	0	0	0	0	455	395	0	0	0	0	0	0	0	0
4	455	455	0	0	0	0	80	0	0	0	455	455	0	0	0	0	80	0	0	0
5	455	455	0	0	0	0	50	0	0	0	455	455	0	0	0	0	50	0	0	0
6	455	455	0	0	150	0	25	0	0	0	455	455	0	0	0	0	25	0	0	0
7	455	455	0	0	142.5	0	0	0	0	0	455	455	0	0	142.5	0	0	0	0	0
8	455	455	0	0	160	0	0	0	0	0	455	455	0	0	160	0	0	0	0	0
9	455	455	130	0	156.25	0	0	0	0	0	455	455	130	130	156.25	0	0	0	0	0
10	455	455	130	130	162	0	68	0	0	0	455	455	130	130	162	0	68	0	0	0
11	455	455	130	130	162	80	84.25	0	0	0	455	455	130	130	162	0	84.25	0	0	0
12	455	455	130	130	162	80	80.5	0	0	0	455	455	130	130	162	80	80.5	0	0	0
13	455	455	130	130	162	80	0	0	0	55	455	455	130	130	162	80	52	0	0	0
14	455	455	0	130	162	80	0	0	0	0	455	455	130	130	162	80	0	0	0	0
15	455	455	0	130	162	0	0	0	0	0	455	455	0	130	162	0	0	0	0	0
16	455	455	0	130	70	0	0	0	0	0	455	455	0	0	70	0	0	0	0	0
17	455	455	0	130	25	0	0	0	0	0	455	455	0	0	25	0	0	0	0	0
18	455	455	0	130	70	20	0	0	0	0	455	455	0	0	70	20	25	0	0	0
19	455	455	130	130	131.25	20	0	0	0	0	455	455	0	0	131.25	20	25	0	0	0
20	455	455	130	130	162	80	0	55	0	0	455	455	0	0	162	80	69	0	0	0
21	455	455	130	130	156.25	0	0	0	0	0	455	455	130	130	156.25	0	0	0	0	0
22	455	450	130	0	0	0	0	0	0	0	455	450	130	130	0	0	0	0	0	0
23	455	360	130	0	0	0	0	0	0	10	455	0	130	130	0	0	0	0	0	0
24	455	0	0	0	0	0	0	0	0	0	455	0	130	130	0	0	0	0	0	0

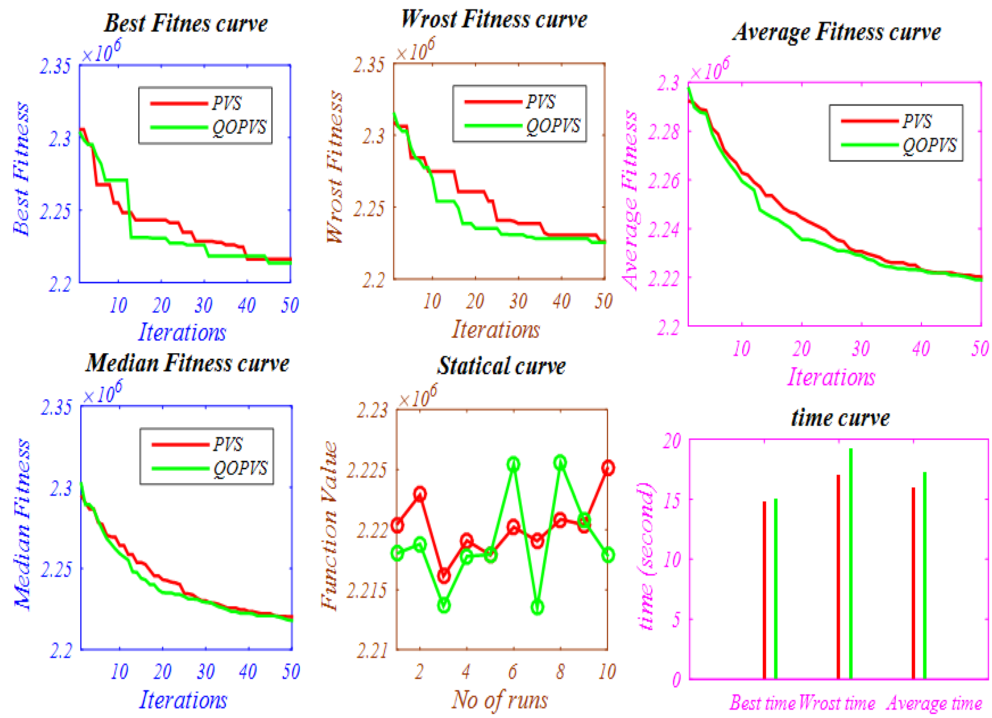

Fig.22: Best fitness, worst fitness, average fitness of all vehicles, median fitness, statically and time curves of the proposed QOPVS method for 40-unit system considering 10% spinning reserve.

Table 14: Analysis of optimization results for test generating units with 10 % spinning reserve.

No. of Units	Optimization Techniques	Generation Cost					Time		
		Best	Average	Median	Worst	SD	Best	Average	Worst
10-Unit System	QOPVS method	1099001.745	1102777.5224	1102842.70	1105124.19	1559.2	8.3281	9.8477	11.423
	PVS method	1101678.778	1103797.554	1104266.18	1105512.67	1220.5	13.432	14.2259	15.715
20-Unit System	QOPVS method	563712.108	564135.8193	563887.333	565066.888	466.41	7.8969	8.8317	10.009
	PVS method	563730.418	564415.2063	564475.5893	565069.753	464.61	9.0047	10.4658	11.006
40-Unit System	QOPVS method	2213498.258	2218934.799	2217969.86	2225611.72	3905.7	14.975	17.2084	19.234
	PVS method	2213785.464	2217343.558	2216791.30	2224758.98	2828.7	9.5609	11.5178	13.084

VIII. Conclusion

In this article, QOPVS Algorithm solution to the single area Unit Commitment problem has been presented. It was necessary to enhance a standard PVS implementation with the addition of problem specific operators and the varying quality function technique in order to obtain satisfactory unit commitment solutions. The results show an improvement in the quality of solutions obtained compared with other methods result.

A basic advantage of the QOPVS solution is the flexibility it provides in modelling both time-dependent and coupling constraints. Another advantage is that QOPVS can be very easily converted to work on parallel computers. However, our results indicate that the difference between the worst and the best QOPVS-provided solution is very small. Another advantage of QOPVS-UC algorithms is their less execution time. The proposed QOPVS optimization technique is applied for simulated on various test systems with the number of units 5-unit, 6-unit, 10-unit, 20-unit, and 40-unit are considered for 24-hour load scheduling horizon. It is observed that performance of proposed QOPVS algorithm is much better than compare to standard PVS and other conventional and heuristics algorithm. Convergence of proposed QOPVS is faster than standard PVS.

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Simulating Framework for Graphene Based Devices using Finite Difference Time Domain Method

By Abdullah Al Hadi & Syed Rafiee Abied
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Abstract- This paper focuses on studying a simulating framework for graphene based devices using finite-difference time-domain (FDTD) method. Conventional FDTD is modified for graphene material using Surface Boundary Condition (SBC) where grapheme considered as a two dimensional ultra-thin conductive sheet. Then a Perfectly Matched Layer (PML) technique is implemented to terminate the computational grids. Using the surface boundary condition technique to model the graphene thin layer significantly reduces the computational cost compared to using the conventional FDTD. The given formulation is accompanied by required validation.

Keywords: Graphene, FDTD, SBC, PML.

GJRE-F Classification: FOR Code: 090699

SIMULATINGFRAMEWORKFORGRAPHENEBASEDDEVICESUSINGFINITEDIFFERENCETIMEDOMAINMETHOD

Strictly as per the compliance and regulations of:

Simulating Framework for Graphene Based Devices using Finite Difference Time Domain Method

Abdullah Al Hadi [α] & Syed Rafiee Abied [σ]

Abstract- This paper focuses on studying a simulating framework for graphene based devices using finite-difference time-domain (FDTD) method. Conventional FDTD is modified for graphene material using Surface Boundary Condition (SBC) where grapheme considered as a two dimensional ultra-thin conductive sheet. Then a Perfectly Matched Layer (PML) technique is implemented to terminate the computational grids. Using the surface boundary condition technique to model the graphene thin layer significantly reduces the computational cost compared to using the conventional FDTD. The given formulation is accompanied by required validation.

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I. Introduction

Graphite materials come in a variety of forms. The 3-D graphite is the most commonly seen form, and the 1-D carbon nanotube (CNT) has been another recent research interest, especially in composite materials. The newly discovered graphene is the 2-D graphitic material, and is essentially the building block of the other forms. A 2-D crystal is in general hard to grow because as the lateral size of the crystal grows, the thermal vibration also rapidly grows and diverges on a macroscopic scale, which forces the 2-D crystallites to morph into a stable 3-D structure [1]. Graphene has many outstanding properties. Its electrical properties include its high carrier mobility, which is measured in various devices as 8000-10000 $cm^2V^{-1}s^{-1}$and could reach 200000 $cm^2V^{-1}s^{-1}$ in suspended grapheme [2]. Graphene's non-electronic properties bring a new dimension to graphene research. It was found to have a breaking strength of 40 N/m, reaching the theoretical limit, as well as a Young' smodulus of 1.0 TPa, which is a record value [3].Graphene field-effect transistors (FET) and graphene wafer scale integrated circuits have been fabricated and versatile graphene applications in EM and transformation optics has been developed in recent years.

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The nanopatch antenna simulation has done using FEKOand is discussed in [4]. The graphene transformation optics structures are discussed in [5] and simulation process has done using CST Microwave Studio. In both studies, the simulations are in the frequency domain, where the graphene conductivity is a complex number at a particular frequency. One can enter the conductivity value into the commercial software and run the simulation without making further modification to the software. Simulating graphene-based devices in time domain has several advantages. In this paper, the transient behavior of the device can be observed and studied and the result for a wide frequency band can be obtained from a single simulation in time domain.

The remainder of the paper is organized as follows: Section II introduces graphene transformation Optics. FDTD Modeling for graphene is discussed in section III. Implementation of SBC in 2-D FDTD for Graphene areprovided in section IV.PML loss parameters in discrete space are given in section V. Finally conclusion and future work is described in section VI.

II. Graphene Transformation Optics

Graphene has been investigated for its potential in material and transformation optics recently [5]. Graphene's conductivity is a function of the chemical potential, which depends on gate voltage, and/or chemical doping [6]. Its tunable conductivity allows it to shape electro-magnetic field into desired spatial patters which is a great advantage over the noble material.

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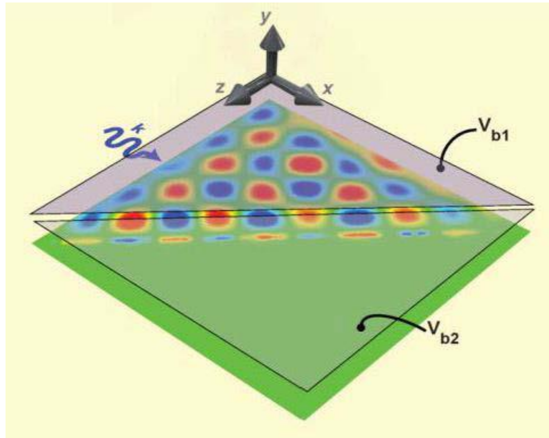

Figure 1: Graphene controlled by bias voltage

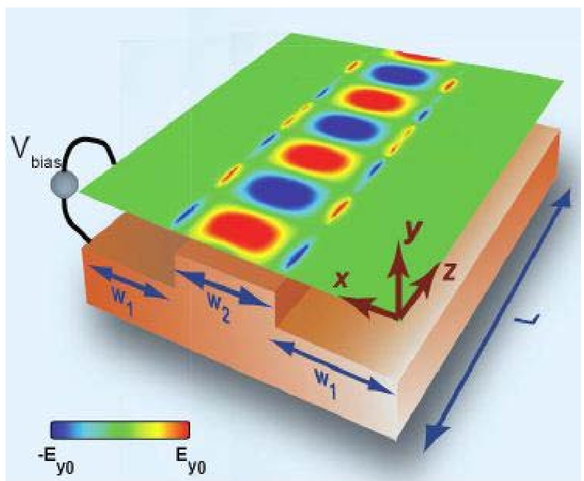

Figure 2: Graphene conductivity controlled by uneven ground plane

Figure 1 shows it is possible to have part of the graphene sheet supporting a surface Plasmon Polarition (SPP) wave while not on the other part, and this can be done by varying the sign of the imaginary part of the conductivity by varying the gate voltage [7] The tuning can be done in real time by varying the gate voltages. Figure 2 shows alternatively; an uneven ground plane underneath the graphene can be implemented to design the conductivity profile on the graphene.

III. Fdtd Modeling For Graphene

Finite-Difference Time-Domain (FDTD) is a popular electromagnetic modeling technique. It is easy to understand, easy to implement in software, and since it is a time-domain technique it can cover a wide frequency range with a single simulation run. The FDTD method belongs in the general class of differential time domain numerical modeling methods. Maxwell's (differential form) equations are simply modified to central-difference equations, discretized and implemented in software. The equations are solved in a leap-frog manner; that is, the electric field is solved at a given instant in time, then the magnetic field are solved at the next instant in time, and the process is repeated over and over again.

a) *Graphene Conductivity Model*

The graphene conductivity (in unit of [S]) is given by the Kubo formula,

$$\sigma(\omega,\mu_c,\gamma,T)=\frac{je^2(\omega-j2\gamma)}{\pi\hbar^2}\left[\frac{1}{(\omega-j2\gamma)^2}\int_0^\infty \epsilon\left(\frac{\partial f_d(\epsilon)}{\partial\epsilon}-\frac{\partial f_d(-\epsilon)}{\partial\epsilon}\right)d\epsilon-\int_0^\infty\frac{f_d(-\epsilon)-f_d(\epsilon)}{(\omega-j2\gamma)^2-4\left(\epsilon/\hbar\right)^2}d\epsilon\right] \quad (1)$$

In equation (1), $f_d(\epsilon)=(e^{(\epsilon-\mu_c)/k_BT}+1)^{-1}$ is the Fermi Dirac distribution, ω is the angular frequency in radians, γ is the scattering rate is per sec, T is the temperature in Kelvin, -e is the electron charge, $\hbar$ is the

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reduced Planck's constant, $k_B$is the Boltzmann constant, μ_c is the chemical potential in eV which can be controlled by chemical doping or by applying a bias voltage. The first term in equation is due to the intra-band contribution and the second term is from the inter-band contribution.

The Kubo formula can be simplified and the intra-band conductivity is,

$$\sigma_{intra}\,(\omega,\mu_c,\gamma,T) = \frac{je^2 k_B T}{\pi\hbar^2}\left(\frac{\mu_c}{k_B T} + 2\ln\left(e^{\left(-\mu_c/k_B T\right)} + 1\right)\right)\frac{1}{\omega - j2\gamma} \tag{2}$$

and the inter-band conductivity is as follows,

$$\sigma_{inter}\,(\omega,\mu_c,\gamma,0) = \frac{-je^2}{4\pi\hbar}\ln\left(\frac{2|\mu_c|-(\omega-j2\gamma)\hbar}{2|\mu_c|+(\omega-j2\gamma)\hbar}\right) \tag{3}$$

The intra-band conductivity is mainly account for the low frequency electrical transport and inter-band conductivity is for the optical excitations [8]. Taking the parameters used in graphene parallel plate waveguide, $\mu_c = 0.5\text{eV}$, $\gamma = 10^{12}$ and $T = 300\text{K}$, the corresponding conductivity values are plotted in the figure given below.

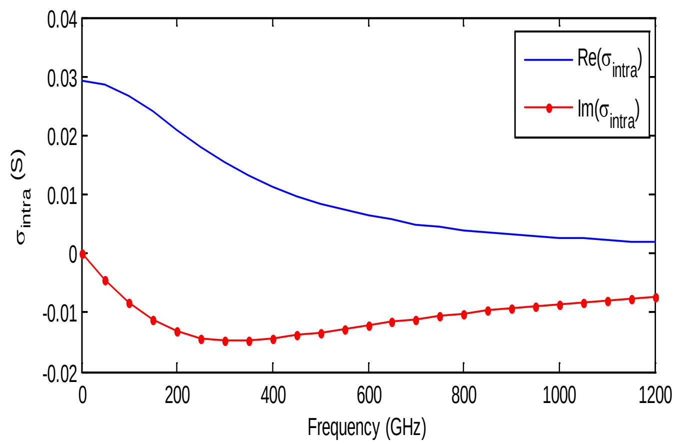

Figure 3: Graphene surface inter-band conductivity for$\mu_c = 0.5\text{eV}$, $\gamma = 10^{12}$ and $T = 300\text{K}$.

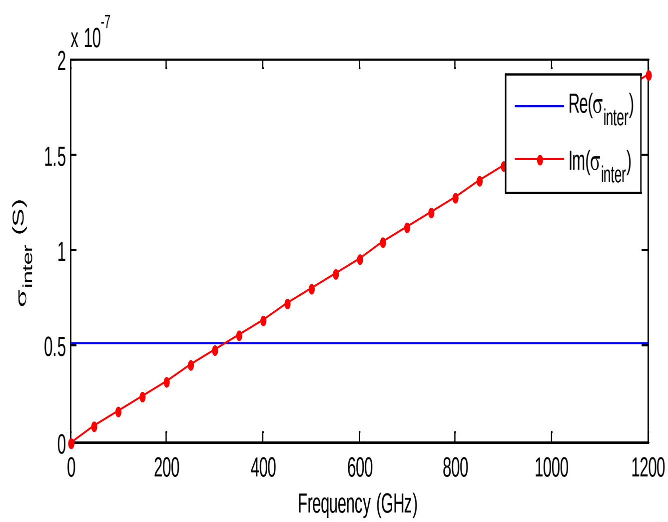

Figure 4: Graphene surface inter-band conductivity for$\mu_c = 0.5eV$, $\gamma = 10^{12}$and $T = 300K$.

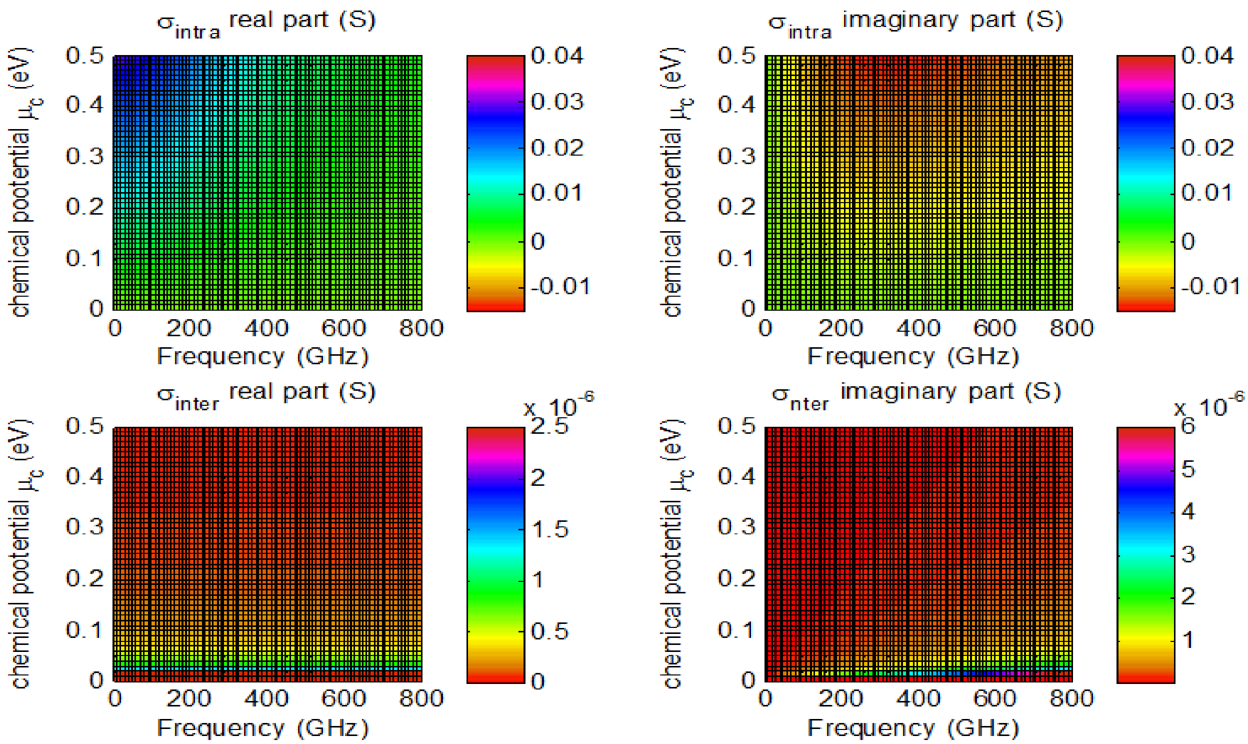

Figure 5: Graphene surface conductivity for $\mu_c = 0.5\text{eV}$, $\gamma = 10^{12}$ and $T = 300\text{K}$.

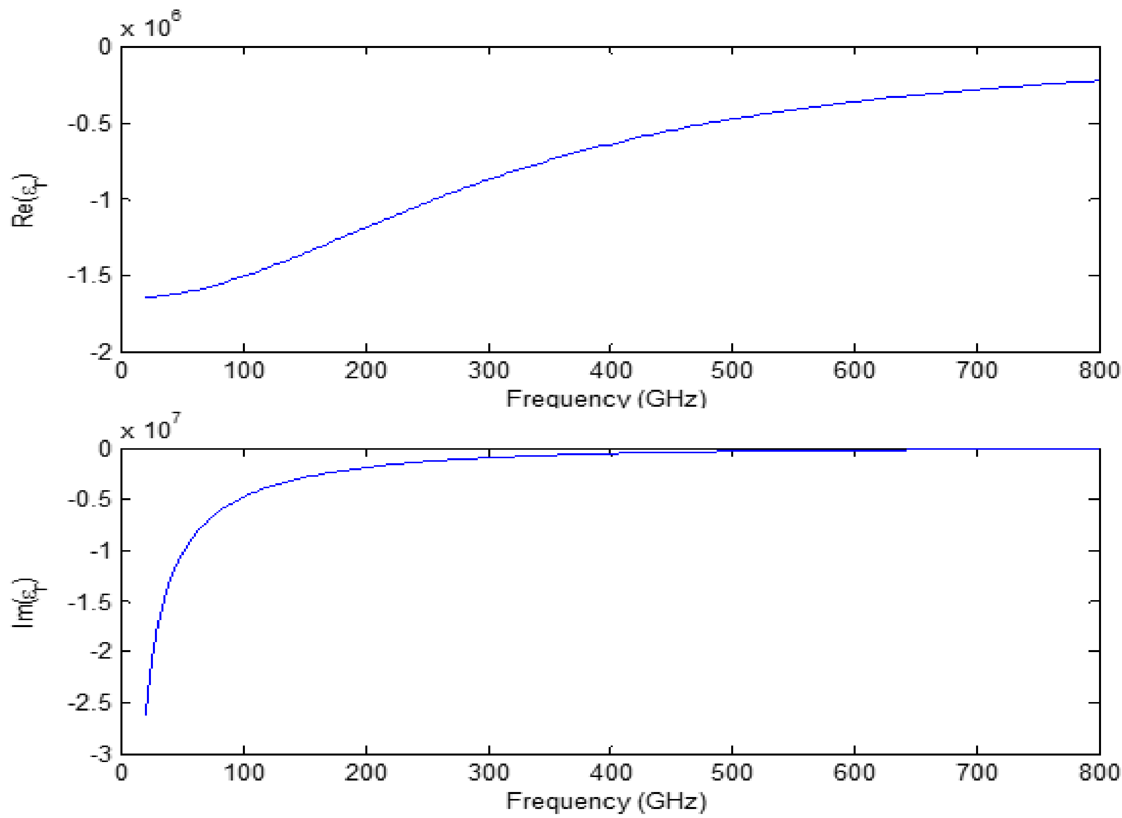

Figure 6: Graphene relative permittivity for $\mu_c = 0.5\text{eV}$, $\gamma = 10^{12}$ and $T = 300\text{K}$.

We can see from Figure 5 that in the frequency up to 800 GHz, the value of σ_{intra} dominates over that of σ_{inter} .Therefore σ_{inter} can be ignored for most simulations below optical range.

The expression of σ_{intra} is in fact a Drudge model and can be expressed as,

$$\sigma_{intra,s} = \frac{Q'}{j\omega + 2\gamma} \quad (4)$$

where,

$$Q' = \frac{e^2 k_B T}{\pi \hbar^2}\left(\frac{\mu_c}{k_B T} + 2\ln\left(e^{\left(-\mu_c/k_B T\right)} + 1\right)\right) \quad (5)$$

The surface conductivity can be converted as to the volumetric conductivity (in unit of [S/m]) by dividing $\sigma_{intra,s}$ by the thickness of graphene, which is assumed to be 1nm or 10e-9 m.

$$\sigma_{intra,v} = \frac{\sigma_{intra,s}}{10^{-9}} \quad (6)$$

$$\sigma_{intra,v} = \frac{Q}{j\omega + 2\gamma} \quad (7)$$

where,

$$Q(\mu_c, T) = \frac{Q'}{10^{-9}} = \frac{\left[\frac{e^2 k_B T}{\pi \hbar^2}\left(\frac{\mu_c}{k_B T} + 2\ln\left(e^{\left(-\mu_c/k_B T\right)} + 1\right)\right)\right]}{10^{-9}} \quad (8)$$

To find the relative permittivity (ϵ_r) from the conductivity, the following equations are used. The results of the simulation curve are shown in figure 6.

$$\epsilon_r = \epsilon' - j\epsilon'' \quad (9)$$

$$\epsilon'' = \frac{\sigma}{\omega\epsilon_0} \quad (10)$$

$$\epsilon_r = 1 - j\frac{\sigma}{\omega\epsilon_0} \quad (11)$$

$$\epsilon_r = 1 + \frac{Q}{j\omega\,\epsilon_0(j\omega + 2\gamma)} = 1 + \frac{Q/\epsilon_0}{-\omega^2 + 2\gamma j\omega} \quad (12)$$

IV. Implementation Of SBC In 2-D FDTD For Graphene

Let, the 2D computational domain is located in xy plane. So for TM mode, the fields components of electric and magnetic field are E_z , H_x and H_y .

The $\boldsymbol{H}_x$ field update equation for all other nodes is,

$$\boldsymbol{H}_x^{n+0.5}(i,j) = \boldsymbol{H}_x^{n-0.5}(i,j) - \frac{\Delta t}{\Delta y \mu_0}\{\boldsymbol{E}_z^n(i,j+1) - \boldsymbol{E}_z^n(i,j)\} \quad (13)$$

The $\boldsymbol{H}_y$ field update equation for all other nodes is,

$$\boldsymbol{H}_y^{n+0.5}(i,j) = \boldsymbol{H}_y^{n-0.5}(i,j) + \frac{\Delta t}{\Delta y \mu_0}\{\boldsymbol{E}_z^n(i+1,j) - \boldsymbol{E}_z^n(i,j)\} \quad (14)$$

And the $\boldsymbol{E}_z$ field update equation for all other nodes is,

$$\boldsymbol{E}_z^{n+1}(i,j) = \boldsymbol{E}_z^n(i,j) + \frac{\Delta t}{\varepsilon_0}\left\{\frac{\boldsymbol{H}_y^{n-0.5}(i,j) - \boldsymbol{H}_y^{n-0.5}(i-1,j)}{\Delta x} - \frac{\boldsymbol{H}_x^{n-0.5}(i,j) - \boldsymbol{H}_x^{n-0.5}(i,j-1)}{\Delta y}\right\} \quad (15)$$

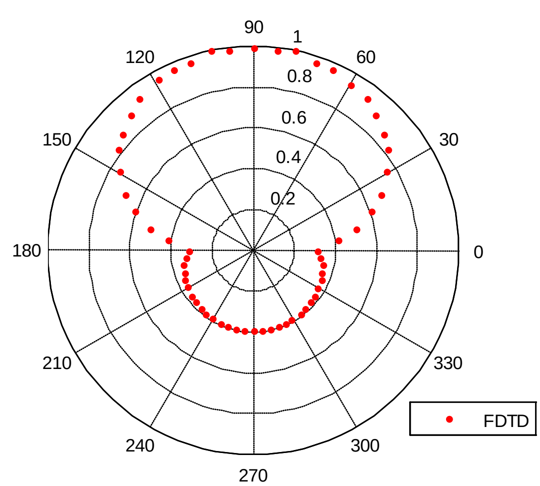

Figure 7: Normalized pattern of E_z at the wavelength of 100 um.

V. PML Loss Parameters In Discrete Space

The PML is usually backed by a PEC wall. The transmitted signal through the PML undergoes significant attenuation by the PML layer [9]. Again the reflected signal from the PEC wall also attenuated by the PML. In a PML, reflection coefficient $(R(\phi))$ is a function of the incident angle (ϕ) of the wave incidence on the PML. The reflection coefficient can be expressed as,

$$R(\phi) = \exp(-2\sigma_D \eta d cos\phi) \quad (16)$$

Here, η = wave impedance for free space
ϕ = wave incident angle
d = depth of PML layer
σ_D = conductivity of PML layer

$R(\phi)$is PML reflection error. It gives the relative magnitude of the spurious reflected wave, which enter back into the computational domain. The larger the$d$and σ_D, the lesser the reflection.

VI. Conclusion And Future Work

The simulated results matched with the analytical results. The given modified FDTD algorithm is able to simulate graphene based microwave problems where graphene is considered as very thin conductor .In order to extend the existing framework to model devices up to optical frequency, the inter band conductivity need to be taken into consideration. This can be done by applying the Pad´e approximation for graphene inter-band conductivity [10]. For devices operating at the high terahertz frequency range, where the intra-band conductivity and the inter-band conductivity have comparable magnitudes, both models are needed for accurate simulation results.

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Exergy and Thermoeconomic Analyses of Solar Aided Thermal Power Plants with Storage-A Review

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Abstract- Ever increasing energy demand, spiralling fuel prices dwindling resources and emissions foot print of fossil fuel based power generation has forced the world to increase the share of renewable energy based power generation. Out of all renewable energy sources (RES), solar has emerged as a viable option for addressing several challenges being faced by the power generation industry currently. Solar PV and solar thermal are the two options for solar based power generation.

Although Solar PV provides excellent energy solutions for small scale grid and off grid power generation, it is not suitable for large scale power generation.

Keywords: solar aided feed water heating, integrated solar combined cycle, exergy analysis, levelised cost of electricity generation, simple payback period.

GJRE-F Classification: *FOR Code: 850599*

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Strictly as per the compliance and regulations of:

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S. C. Kaushik [α] & Aadibhatla Sairam [σ]

Abstract- Ever increasing energy demand, spiralling fuel prices dwindling resources and emissions foot print of fossil fuel based power generation has forced the world to increase the share of renewable energy based power generation. Out of all renewable energy sources (RES), solar has emerged as a viable option for addressing several challenges being faced by the power generation industry currently. Solar PV and solar thermal are the two options for solar based power generation. Although Solar PV provides excellent energy solutions for small scale grid and off grid power generation, it is not suitable for large scale power generation. Now within solar thermal, solar alone power generation has not gained popularity due to high capital costs and poor thermal efficiency but solar integration with existing/new power plants (both coal fired thermal and gas fired combined cycle) popularly known as solar aided power generation has been widely accepted by several researchers. This technology has been widely in use in countries like U.S, Spain, Egypt, Morocco, Algeria, Iran and Mexico (NREL web site).Due to lower capital costs and better solar to electricity conversion efficiencies, solar aided thermal power plants have surpassed solar alone power plants. Solar energy can be integrated in a coal fired plant either for steam generation or for feed water heating. In a combined cycle plant, solar energy can be integrated either in the Brayton cycle or in the bottoming Rankine cycle. This chapter discusses in detail, various integration techniques, the application of exergy, economic and thermo economic principles in analysing these integrated cycles. Detailed economic analysis has been reviewed on the integrated cycles to ascertain their techno economic viability. The levelised cost of electricity generation (LCoE) and simple payback period have also been predicted for both the reference and integrated plants.

Keywords: solar aided feed water heating, integrated solar combined cycle, exergy analysis, levelised cost of electricity generation, simple payback period.

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I. Introduction

The usage of solar energy for power generation has been widely considered as a promising solution for reducing fossil fuel dependency, emissions footprint. For sustainable development and as a move towards greener power generation, the usage of solar energy has gained prominence across the countries having good solar potential. The solar energy can be converted in to electricity either through solar photovoltaic (PV) technology or through solar thermal power generation technology. However, solar PV is mostly suitable for distributed power generation due to its small scale generation capacities. For large scale power generation, solar thermal is better suitable than solar PV. Within the solar thermal power generation, one may go for either solar alone or solar aided power generation. In the solar alone thermal power generation, the concentrated solar energy is imparted either directly to working fluid or via a heat transfer fluid for steam generation. The generated steam can be used in the power block for power generation. However, the solar alone power generation suffers from higher capital costs, lower solar to electric conversion efficiencies and lower plant utilisation factors. The low solar to electric conversion efficiencies of solar alone systems can be attributed to low source temperature of cycle heat addition. The lower plant utilisation factors can be attributed to daily plant start-up and shut downs. Solar aided power generation in coal fired steam power plants involve adding the solar heat in an existing Rankine cycle either for additional steam generation or feed water preheating. The latter is popularly known as solar aided feed water heating (SAFWH). In a combined cycle power plant, solar energy can be added either in the topping Brayton cycle or bottoming Rankine (steam) cycle. These cycles are referred to as integrated solar combined cycle (ISCC) power plants. In the Brayton cycle, solar energy can be used to lower the gas turbine compressor inlet air temperature or it can be used for heating the compressor discharge air. In the bottoming cycle, the solar energy can be used for generating additional steam which increases the steam turbine power output. This chapter presents a bird's eye view of solar aided thermal power generation.

II. Review On Solar Collector And Storage Technologies

Concentrating solar power (CSP) technologies can be classified based on focus geometry as either line-focus concentrators (parabolic trough collectors and linear Fresnel collectors) or as point-focus concentrators (central receiver systems, parabolic dishes and Scheffler systems)[1].The line focus is less expensive and technically less difficult, but not as efficient as point focus. The other classification methodology on the basis of receiver type consists of fixed receivers which are stationary devices that remain independent of the plant's focusing device (linear Fresnel collectors and central receiver systems) and Mobile receivers move together with the focusing device thus collecting more energy (parabolic-troughs and parabolic dishes)[1].

The parabolic trough collector (PTC) system is one of the proven CSP technologies in the medium temperature range (100-400^{0}C) due to its good optical efficiency and low initial cost. Parabolic trough collector system consists of parallel rows of large reflective parabolic troughs which focus solar energy on to a central receiver pipe (also called absorber pipe or heat collector element) placed at the focal line of the parabolic surface. The receiver is designed to absorb the solar energy concentrated on it. The receiver is made up of high conductivity steel tubing with a black coating surrounded with a protective glass cover, the space in between the protective glass cover and the steel tube is evacuated to reduce convection and radiation losses. The solar energy concentrated at the receiver tube is absorbed by a circulating heat transfer fluid (HTF).The HTF exchanges this heat to feed water in a heat exchanger (HE). After exchanging heat with the feed water, the HTF returns back to the solar field for heat pick up. The parabolic trough collector is usually aligned to north-south axis and tracks the sun to focus the solar radiation on to the receiver tube placed at the focal point of the trough system. The parabolic trough collector system can focus the solar radiation at 30 to 100 times of its normal intensity on to the central receiver tube located at the focal plane[2].The parabolic trough collector system for commercial power generation has been used initially in the Solar Electric Generating System (SEGS) plants I to IX. These plants have been brought to commercial operation between 1985 and 1991 and are located in the Mojave Desert of California in US[3].The LS-3 solar collector assembly used at Kramer Junction in Mojave Desert of California (Source: Sandia National Laboratory, U.S) has been shown as Fig.1 In the year 2007, Nevada Solar One plant has deployed the parabolic trough collector system for its 64 MWe capacity plant[3].The first commercial parabolic trough power plant of Europe, And asol I has been generating electricity since December, 2008 followed by And asol II in the middle of 2009[3]. These plants are located in the southern part of the Spain. The US and Spain have most of these projects followed by several countries in the Sun Belt. Several projects are under planning/construction stage in countries like China, Egypt, Algeria, Morocco, Australia etc. As on 15/05/2016, a total of 5464.67 MW of net power has been under various stages of planning, development, construction and operation based on parabolic trough collector technology [3].

The Fresnel mirror type of CSP system is very much similar to parabolic trough systems but as a replacement of using trough shaped mirrors that track the sun, long flat mirrors at various angles are used that have the effect of focusing sunlight on one or more pipes containing HTF which are mounted above the mirrors. The comparative plainness of this type of system makes this relatively cheap to manufacture but suffers from lower energy conversion efficiency relative to high optical efficiency of dish and trough systems. In a Fresnel solar collector, a number of discreet mirrors approximate a large parabolic trough collector. These mirrors (reflectors) are capable of concentrating the solar radiation on the receiver approximately 30 to 60 times its normal intensity[2]. The receiver is placed at the focal line of the collector system to absorb maximum amount of solar radiation. The receiver is usually a bank of black coated parallel tubes placed inside an insulated inverted trapezoidal stainless steel cavity. These tubes are capable enough to withstand high pressures and kept close to each other to absorb maximum concentrated solar radiation. The cavity aperture is covered with glass shield to allow concentrated solar radiation. This also minimises the heat losses due to convection and radiation. The cavity is insulated with thermal insulation and is encased in a metallic envelope to minimise the heat losses. The concentrated solar energy is further transferred to the heat transfer fluid like thermic fluid or water. This solar energy can be used either for feed water heating or steam generation as per the need[2]. The first prototype of Fresnel collector was developed by Solarmun do from Belgium. In 2004, an Australian company named Ausra (the then solar heat and power) built Fresnel collector system for Liddell power plant in Australia. In 2008, Ausra built the first Fresnel solar only power plant in Bakersfield/California.

This has been shown as Fig.2.The first commercial Fresnel power plant in Europe, PE 1, was built by Novatech Solar AG (the then Novatech Biosol). This plant commissioned in 2009 is situated in Spain and has a capacity of 1.4 MWe [3].

A solar power tower system, also known as a central receiver system generates high temperature heat from incident solar radiation by focussing concentrated solar energy on to a central receiver. The system uses large number of flat, trackable mirrors called heliostats to concentrate the solar radiation on to a tall tower located in the middle of heliostat field. The energy can be concentrated up to 1500 times the incident solar radiation [2]. The concentrated heat energy absorbed by the receiver is transmitted to a circulating HTF. The HTF can be liquid sodium, molten salts, air or water. The HTF heated in the receiver is used to generate steam, which can be sent in to a steam turbine for power generation. Usually molten salt is used as working fluid in solar power tower. The liquid molten salt is circulated through the receiver from cold tank and gets heated up in the receiver then passed to the hot storage tank. The hot molten salt is circulated through a heat exchanger to generate steam [2].The Crescent Dunes solar power tower plant at Nevada in US is operating since 2015. This plant uses molten salt as heat transfer fluid and has 10 hours of thermal storage [3].

A parabolic dish collector uses an array of parabolic dish shaped mirrors to focus solar energy on to a receiver located at the focal point of the dish. The two axis tracking system of the concentrator tracks the sun. HTF is circulated in the receiver to absorb the heat from the receiver. The concentration ratio of the parabolic dish collector is varies between 300 and 3000 [4].

A thermal energy system (TES) basically stores the solar energy collected during peak sunny hours for later use during non-solar hours. TES decouples solar energy availability with electricity generation. There are numerous criteria to evaluate TES systems and applications such as technical, environmental, economic, energetic, sizing, feasibility, integration and storage duration. Each of these criteria should be considered carefully to ensure successful implementation [5]. A TES designer should possess or obtain technical information on TES such as types of storage appropriate for the application, the amount of storage required, the effect of storage on system performance, reliability and cost and the storage systems or designs available [5].The technical properties of the storage materials are a very important aspect of technical design of any TES system. The material used for storage should have an excellent thermal energy storage capacity. This greatly reduces the system volume and foot print and improves system efficiency. A good rate of heat transfer between the TES material and heat transfer fluid (HTF) is highly essential to achieve shorter charge and discharge cycles. The storage material should have excellent chemical and mechanical stability for a large number of charge and discharge cycles [6].The environmental criteria should ensure that the basic design and operational practices that are used for the TES should not impair the public health or natural ecology and environment. Materials used should not be toxic or dangerous if released, could adversely affect the environment during the manufacture, distribution, installation or operation of the storage system [5].The cost of TES mainly consists of the cost of storage material, heat exchanger and land cost [6]. The economic justification for storage system normally requires that the annualised capital and operating costs for TES be less than those required for primary generating equipment supplying the same service loads and periods [5]. The evaluation of cost effectiveness of TES include hourly thermal loads for the peak day, the electrical load profile of the base case system against which TES is being compared and the size of the storage system and the control methods used [5]. Economic information that is needed includes electricity demand charges and time of use costs, the costs of the storage and financial incentives available [5]. Economic evaluation and comparison parameters often determined include the simple payback period [5]. Other methods are also used to compare the annualised investment cost of a TES with annual electricity cost savings [5].

Based on the energy storage mechanism, Thermal energy storage systems can be classified as sensible heat, latent heat and chemical storage systems. The energy storage density (kWh/m^3) increases from sensible heat storage to chemical storage with latent heat storage in between these two. As far as the development is concerned, the sensible heat storage systems are highly developed followed by latent heat storage systems. The chemical storage systems are yet to be developed. The popularity of sensible heat storage systems can be attributed to their low cost of large number of available storage materials. However, they suffer from lower energy storage density and hence occupy large space. The latent heat storage systems have relatively larger storage densities than the sensible heat storage systems with charging and discharging taking place at nearly isothermal conditions.

However, latent heat storage systems have poor heat transfer thereby increasing the charge/discharge cycle time. To tackle this issue, heat transfer enhancement techniques have to be incorporated so that the rate of heat transfer between the heat transfer fluid and storage material is maximised. Chemical storage systems have the highest energy storage capacities among all. Their energy densities are of the order of GJ compared to latent heat storage systems which are of the order of MJ per m^3. But the chemical storage systems suffer from poor long term reversibility of chemical reactions, complicated reactor vessel design and poor chemical stability[6].The state of the art storage materials for sensible heat storage are molten salts particularly Hitec/Hitec XL and solar salt [6][7]. These molten salts are widely used in several parabolic trough systems [6] [7]. Before the use of molten salts, Therminol VP-1,which is syntheticoil, has been used in several parabolic trough power plants. The maximum operating temperature for use of Therminol VP-1 is limited to 400^0 C. The solar salt is relatively cheaper and has a maximum operating temperature of 585^0 C but its high melting temperature of 220^0 C necessitates the use of costly anti freezing agents **[6] [7]**.For latent heat storage, inorganic salts/salt eutectics and metals/metal alloys are the potential materials in view of higher operating temperatures required for CSP plants. The main disadvantage with most of the phase change materials (PCM) is their low thermal conductivity, which makes it necessary to adopt heat transfer enhancement techniques **[6] [7]**.The insertion of high conductivity materials like carbon cloth, brush etc. into the PCM, improves the heat transfer rate of composite material significantly **[6]**.

III. Solar Aided Coal Fired Power Plants

The solar energy can be successfully used in an existing/new coal fired thermal power plants for generation of steam or for preheating the feed water. This helps in increasing the cycle efficiency as this will either increase the steam turbine output (power boosting) for same fuel consumption or reduce the coal consumption (fuel saving) for the same turbine output depending on the plant operating mode. Either way, this is environment friendly as this will reduce the emission foot print. Coal fired power plants utilising solar energy in this way either for additional steam generation or feed water preheating are popularly known as solar aided coal fired power plants. Both cases will be discussed in detail in subsequent sections.

a) *Additional Steam Generation*

Using solar energy, steam can be generated in a solar boiler by either direct steam generation (DSG) or through a heat transfer fluid. The generated steam is used in an existing coal fired power plant for either additional power generation or for reducing fuel consumption. Usually, when solar energy is integrated with an existing coal fired power plant, the fuel saving mode of operation is preferred as it does not need resizing of turbo generator.

The Liddell power station at New South Wales, Australia uses a 9 MW_{th} solar boiler which feeds steaminto an existing 2000 MW coal fired power station. The solar field uses linear Fresnel reflector technology for solar energy capture. NREL has reported that the replacement of coal by the solar boiler will cut greenhouse gas emissions by approximately 5,000 tonnes per annum**[3]**.Kogan Creek Solar Boost project at Queensland region of Australia is set to become the largest solar integration with a coal-fired power station in the world. The project consists of a compact linear Fresnel reflector solar thermal augmentation of the existing Kogan Creek Power Station, increasing the power station's electrical output and fuel efficiency. The solar addition of 44 MW will enable the 750 MWcoal fired power station, already one of Australia's most efficient coal-fired power stations and Australia's largest single unit, to produce more electricity with the same amount of coal. The project will help avoid 35,600 tonnes of carbon dioxide per year annually**[3]**.The Colorado Integrated Solar Project (Cameo) was a hybrid CSP/coal plant approach using parabolic-trough solar technology.

A parabolic trough solar field provided thermal energy to produce supplemental steam for power generation at Xcel Energy's Cameo Station's Unit 2 (approximately 2 MWe equivalent) in order to decrease the overall consumption of coal, reduce emissions from the plant, improve plant efficiency, and test the commercial viability of concentrating solar integration. The plant was used for testing purposes until the coal plant was retired and the CSP plant was decommissioned**[3]**.

b) *Solar Aided Feed Water Heating (Safwh)*

Integration of solar energy with conventional power plants can be explored as a viable option for achieving cleaner and cheaper power generation. The steam generator (Boiler) of a conventional power plant generates steam at a high pressure and temperature. This high pressure steam is allowed to expand in high, intermediate and low pressure sections of a condensing steam turbine to generate power. The condensate collected in the hot well is pumped through various low and high pressure feed water heaters before it reaches the economiser. Bleed steam taken from various stages of different turbine sections are used for preheating of the feed water. The final feed water temperature is increased to match with boiler design steam parameters and economic cycle design considerations. This regenerative feed water heating is basically aimed at increasing the cycle efficiency. The number of feed water heaters and their steam extraction points depends upon the techno-economic considerations of cycle design optimisation.

The feed water cycle consists of two series of heaters. They are Low Pressure (LP) heaters and High Pressure (HP) heaters. The LP heater series consists of up to four low pressure heaters supplied with bled steam from low and intermediate pressure turbine sections. After passing through this heater group, condensate enters an open feed water heater known as deaerator where deaeration of feed water occurs. The deaerated feed water then enters the next series of HP heater group consisting of up to three feed water heaters taking bleed steam from high and intermediate pressure turbine sections.

In SAFWH, solar thermal energy at various temperature ranges is used to replace the bleed steam coming from various turbine extractions either partially or fully to preheat the condensate/feed water in the feed water heaters (FWH). This solar energy used for feed water preheating can be used either for saving the bled steam or for minimising the fuel consumption. When the saved bled steam is allowed to expand in the turbine, extra power can be generated, and is known as power boost mode. If the turbine power output is maintained constant, the fuel consumption reduces with solar aided feed water heating and this is known as fuel saving mode.

The thermodynamic advantages of using solar energy in the regenerative Rankine based power plant cycle have been found to be better than the solar stand-alone power generation **[8].**The Exergy Merit Index (EMI) (the ratio of the work generated by the saved steam to the exergy supplied by the solar heat) of solar aided systems can be greater than 100% while maximum efficiency of stand-alone solar thermal power plants never reach 100% **[8].**It has been observed that by the substitution of turbine bleed stream to high pressure feed water heaters alone with SAFWH results in about 5–6% instantaneous improvement in coal consumption and additional power generation for the fuel conservation and power boosting modes in comparison to reference power plants **[9].** Hu et al [2010] have demonstrated energy and exergy advantages of solar aided power generation by carrying a case study on a 500 MW power plant of Loy Yang power station located in Latrobe valley, Victoria, Australia using THERMOSOLV software. With 100% replacement of bleed steam for all closed feed water heaters, the power output was 572.5 MW in power boosting mode and with cycle efficiency increase by 6.65%**[10].** Yang et al. [2011] have demonstrated through a case study that solar aided power generation (SAPG) is an efficient way to utilise solar energy in the low and medium temperature range for power generation by replacing bleed steam with solar energy in feed water heaters. Four schemes were suggested to replace bleed steam of the feed water heaters. In the first scheme, bleed steam of first HP feed water heater was replaced with solar energy at 260^{0}C. In the second scheme, bleed steam of second HP feed water heater was replaced with solar energy at 200^{0}C. In the third scheme, bleed steam of all LP feed water heater was replaced with solar energy at 160^{0}C. In the fourth scheme, bleed steam of last LP heater with solar energy up to 100^{0}C**[11].** Dimityr Popov [2011] has modelled Rankine regenerative steam cycled power plant with Thermo flow software. The plant model incorporated a field with solar Fresnel collectors that directly heats boiler's feed water. The proposed plant modification was yielded substantial fossil fuel input reduction. The best results were obtained when the group of high pressure heaters is replaced and feed water temperature exceeds its original design case, having efficiency higher than 39%for the best solar hour of the year**[12].** Yan et al. [2011] analysed the performance of fossil fuel fired power plants with different MW outputs, subcritical, supercritical and ultra-supercritical plants with integration of solar energy at different temperature levels. They observed that at high temperature integration levels, better benefits could be obtained in terms of solar to power efficiency, fuel savings. They found that subcritical and supercritical plants are better options in comparison to ultra-supercritical plants with solar integration**[13].** Zekiyilmazoglu et al. [2012] carried out a case study on solar repowering of Soma thermal power plant of 22MWe located in Turkey**[14].** Bakos et al. [2013] have simulated the operation of the 300 MW lignite fired power plant of Ptolemaist integrated with a solar field of parabolic trough collectors using TRNSYS software in both power boosting and fuel saving modes. The power plant performance, power output variation, fuel consumption and CO_2 emissions were calculated. Furthermore, an economic analysis was carried out for both power boosting and fuel saving modes of operation and optimum solar contribution was estimated**[15].** Warrick et al. [2013] have compared solar aided power generation (SAPG) and stand-alone concentrating solar power (CSP) for a South African Plant. They found that the annual electricity generated from solar thermal at the SAPG plant is more than 25%greater than the stand-alone CSP plant. They have observed that if the cost of SAPG is taken as 72% of the cost of a stand-alone CSP, SAPG is 1.8 times more cost effective than the stand-alone CSP option**[16].** Jamel et al. [2013] have presented a review paper on advances in the integration of solar thermal energy with conventional and non-conventional power plants**[17].** Peng et al. [2014] have investigated solar aided feed water heating in a 330 MWe coal-fired power plant in Sinkiang Province of China. They have demonstrated the advantages of the solar aided coal-fired power plant under off-design conditions**[18].** Peng et al [2014] have also performed Exergy evaluation of a typical 330 MW solar-hybrid coal-fired power plant in China**[19].**

Boukelia et al. (2015) have performed 4E comparative study of 8 different configurations of parabolic trough solar thermal power plants with two different working fluids (Therminol VP-1 -oil and molten solar salt), with and without integrated thermal energy storage or/and backup fuel system. Their results have indicated that the configurations based on molten salt are better in terms of environmental and economic parameters**[20].** Hou et al. (2015) have done performance analysis of a solar aided plant in fuel saving mode**[21].**

c) Exergy Analysis Of Integrated Solar Aided Coal Fired Power Plant

The first step before performing an exergy analysis on an integrated solar aided coal fired plant is developing a conceptual integrated cycle. This involves

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collection of reference power plant heat and mass balance data, choice of feed water heater (s) for solar aided feed water heating, choice of direct/indirect heat transfer method for transferring the solar heat to feed water, arrangement of feed water heat exchanger and choice of heat transfer fluid (in case of indirect heat transfer), choice of solar collector system (depends on temperature of feed water entering and leaving the feed water heat exchanger) etc. among several others. Then site specific hourly average values of direct normal irradiance (DNI) have to be collected for simulation of solar field. Simulation of solar field yields the heat loss coefficient, receiver temperature and pressure loss in the HTF circuit etc. Then the thermodynamic properties of integrated cycle at salient points can be found by applying mass and energy balance to all cycle components.

The exergy rate balance for a steady flow process of an open system is given by

$$\sum_j \left(1-\frac{T_0}{T_j}\right)\dot{Q}_j+\sum_i\left(\dot{m}_i\psi_i\right)=\dot{W}_{CV}+\sum_e\left(\dot{m}_e\psi_e\right)+\dot{E}_D \tag{1}$$

In this equation, $\dot{E}_D$ is the rate of exergy destruction (Irreversibility) associated with the process. The irreversibility (Van Wylen et al, 1994) is also given by Gouy-Stodola theorem as

$$\dot{E}_D=T_0\dot{S}_{gen} \tag{2}$$

Here $\dot{S}_{gen}$ is the entropy generation associated with the process.

For a complex thermal system, the exergy analysis can be performed by analysing the components of the system individually.

The exergetic efficiency of a thermal system or system component is defined as the ratio of exergetic output to exergetic input.

$$\eta_{II}=\frac{\psi_O}{\psi_i} \tag{3}$$

Here the subscripts i and o refer to input and output respectively.

The exergy analysis of important components of the integrated solar aided coal fired power plant is given below:

Boiler

For the sake of exergy analysis, the boiler has been divided into combustion and heat transfer zones. The exergy balance for the combustion zone is given as:

$$\dot{m}_f\psi_f+\dot{m}_{air}\psi_b=\dot{m}_p\psi_p+\dot{E}_{D,C} \tag{4}$$

Where $\dot{m}_f$, $\dot{m}_{air}$ and $\dot{m}_p$ are the mass flow rates of fuel, air and the products of combustion respectively. $\dot{E}_{D,C}$, is the rate of exergy destruction in the combustion zone of the boiler.

Exergy of the coal and flue gasses have been calculated as explained in Kotas (1984) **[22].**

The Exergetic efficiency of combustion zone is defined as:

$$\eta_{II,C}=1-\frac{\dot{E}_{D,C}}{\dot{m}_f\psi_f+\dot{m}_{air}\psi_b}=1-\frac{T_0\dot{S}_{gen,C}}{\dot{m}_f\psi_f+\dot{m}_{air}\psi_b} \tag{5}$$

Where, $\dot{S}_{gen,C}$ is the associated entropy generation in the combustion zone of the boiler.

The exergy flow equation for the high temperature heat transfer zone becomes:

$$0=\dot{m}_p\left(\psi_p-\psi_0\right)-\dot{m}_{fwi}\left(\psi_1-\psi_{fwi}\right)-\dot{m}_{crh}\left(\psi_{hrh}-\psi_{crh}\right)-\dot{m}_{air}\left(\psi_b-\psi_0\right)-T_0\dot{S}_{gen,HT} \tag{6}$$

Where, the subscripts 1, fwi, crh and hrh refer to final super heater outlet, feed water inlet, cold reheat and hot reheat respectively.

The Exergetic efficiency of heat transfer zone is defined as:

$$\eta_{II,HT}=1-\frac{\dot{E}_{D,HT}}{\dot{m}_p(\psi_p-\psi_0)}=1-\frac{T_0\dot{S}_{gen,HT}}{\dot{m}_p(\psi_p-\psi_0)} \tag{7}$$

Where, $\dot{E}_{D,HT}$ and $\dot{S}_{gen,HT}$ are rate of exergy destruction and entropy generation in the heat transfer zone of the boiler respectively.

Steam Turbine

The exergy balance for a simple steam turbine section is given as

$$\dot{m}_1\psi_1 = \dot{m}_2\psi_2 + \dot{W}_T + \dot{E}_{D,T} \quad (8)$$

Where, the subscripts 1 and 2 refer to turbine inlet and exit conditions respectively. $\dot{W}_T$ and $\dot{E}_{D,T}$ are Turbine work output and rate of exergy destruction in the turbine section respectively.

The mass balance is given by

$$\dot{m}_1 = \dot{m}_2 \quad (9)$$

The exergetic (second law) efficiency of steam turbine is given by

$$\eta_{II,T} = \frac{\dot{W}_T}{\dot{m}_1(\psi_1 - \psi_2)} \quad (10)$$

Condenser

The exergy balance for condenser section is given as

$$\dot{m}_1\psi_1 = \dot{m}_2\psi_2 + \left(1 - \frac{T_0}{T_k}\right)\dot{Q}_{cond} + \dot{E}_{D,cond} \quad (11)$$

Where, subscripts 0,1, and 2 refer to ambient, condenser inlet and exit conditions respectively. T_k and $\dot{Q}_{cond}$ are temperature of heat rejection and rate of heat transfer from condenser respectively.

The mass balance is given by

$$\dot{m}_1 = \dot{m}_2 \quad (12)$$

The exergetic (second law) efficiency of the condenser is given by

$$\eta_{II,cond} = 1 - \frac{\dot{E}_{D,cond}}{\dot{m}_1(\psi_1 - \psi_2)} \quad (13)$$

Pump

The exergy balance for a pump can be expressed as

$$\dot{m}_1\psi_1 + \dot{W}_{pump} = \dot{m}_2\psi_2 + \dot{E}_{D,pump} \quad (14)$$

Where, the subscripts 1 and 2 refer to pump inlet and exit conditions respectively. $\dot{W}_{pump}$ and $\dot{E}_{D,pump}$ are pump work input and rate of exergy destruction in the pump respectively.

The mass balance is given by

$$\dot{m}_1 = \dot{m}_2 \quad (15)$$

The exergetic (second law) efficiency of the pump is given by

$$\eta_{II,pump} = \frac{\dot{m}_2(\psi_2 - \psi_1)}{\dot{W}_{pump}} \quad (16)$$

Feed Water Heater

The exergy balance for a feed water heater can be expressed as

$$\dot{m}_1\psi_1 + \dot{m}_s\psi_s = \dot{m}_2\psi_2 + \dot{m}_d\psi_d + \dot{E}_{D,fwh} \quad (17)$$

Where, the subscripts 1, 2, s and d refer to heater feed water inlet, exit, steam and drip respectively.

The mass balance is given by

$$\dot{m}_1 = \dot{m}_2 \quad (18)$$

$$\dot{m}_s = \dot{m}_d \quad (19)$$

The exergetic efficiency of feed water heater can be expressed as

$$\eta_{II,fwh} = 1 - \frac{\dot{E}_{D,fwh}}{\dot{m}_s(\psi_s - \psi_d)} \quad (20)$$

Solar Field

The exergetic solar power input to parabolic trough is given by

$$Ex_I = \dot{Q}_I * \left[1 - \frac{4}{3}\left(\frac{T_0}{T_s}\right) + \frac{1}{3}\left(\frac{T_0}{T_s}\right)^4\right] \quad (21)$$

Where T_s = 5600 K is apparent black body temperature of sun and T_0 is the ambient temperature and $\dot{Q}_I$ is the solar power incident on the mirror surface.

The exergetic solar power absorbed by the receiver is given as

$$Ex_a = \dot{Q}_a \left[1 - \frac{T_0}{T_r}\right] \quad (22)$$

Where T_r is the receiver temperature (K)

The useful exergetic gain by the heat transfer fluid for a segmental length is given as

$$Ex_u = \dot{m}_f(\psi_e - \psi_i) = \dot{m}_f[(h_e - h_i) - T_0(s_e - s_i)] \quad [23]$$

d) Economic Analysis Of Integrated Solar Aided Coal Fired Power Plant

Economic analysis is a very important step in the feasibility study of any power project. This involves finding the levelised cost of electricity (LCoE) for the life of the project, net present value and payback periods.

The economic analysis is very useful in managerial decision making and in the determination of worthiness of the chosen project.

The economic analysis involves estimation of capital costs, fuel costs, operation and maintenance (O&M) costs and other expenses. The first step in performing the economic analysis is estimation of capital costs of different plant equipment. The best way is to consider the actual cost data if it is available. In the absence of actual capital cost data, capital cost functions for different plant equipment may be considered for estimation of capital costs. The obtained costs have to be brought to the same reference year for which economic analysis has to be done by multiplying with cost index (CI). This capital cost for the reference year can be obtained by Cost for reference year = Purchase cost*CI for reference year/CI for year of purchase [24] Another method is to assume a certain percentage of escalation in costs every year from the year of purchase to reference year. The total capital costs are further classified as direct capital costs (DCC) and indirect capital costs (IDCC). Direct capital costs comprise the capital costs of power block, solar field including thermal storage system, land and site preparation. The cost of power block includes the costs of all equipments in the conventional plant, installation, piping, instrumentation and controls and electricals. The cost of solar field includes the cost of mirrors, support structure, foundation, absorber tubes, swivel joints, hydraulic and electrical drives, heat transfer fluid (HTF), HTF system, Electronic controls and electricals (ECE) and thermal storage system. The indirect capital costs comprise the Engineering, procurement and construction (EPC) costs, pre-operative expenses and interest during construction. Once total capital costs are known fixed capital costs per unit (USD/kWh) can be calculated by dividing the total capital costs (USD per kW) by net annual energy generated(kWh/kW). Fixed O&M cost per unit (USD/kWh) has been obtained by dividing the fixed O&M cost per kW by net annual energy generated. Total variable cost per unit (USD/kWh) can be obtained by adding variable O&M cost per unit and fuel cost per unit.

Three economic indicators are annualised cost of electricity generation (ACoE), Levelised cost of electricity generation (LCoE) and simple payback period. The ACoE can be obtained by adding fixed capital cost per unit; fixed O&M cost per unit and total variable cost per unit. To levelise the fuel, O&M-fixed and variable cost for the life of the plant, a levelizing factor has to be taken into account. LCoE can be obtained by adding fixed capital cost per unit and levelised fuel, fixed and variable O&M costs per unit. Simple payback period can be calculated by dividing total capital cost by net annual benefit. Sensitivity analysis can be performed to find out the variation of LCoE with discount rate, plant capacity factor and fuel cost.

e) Thermo economic Analysis Of Integrated Solar Aided Coal Fired Power Plant

Thermo economic analysis is a very useful technique, which is finding increasing application in the area of thermal systems design. This involves the integration of the exergy and economic principles in achieving the objective(s) of cost calculation of products generated by different devices in a large thermal system and/or optimising specific decision variables in minimising the cost [23].

Zhang et al. (2006) have done exergy cost analysis on a 300 MW pulverised coal fired power plant based on structural theory of thermo economics. Based on Fuel-Product concept, they have developed a productive structure of the reference power plant for carrying out thermo economic analysis[24]. M. Ameri et al. (2008) have carried out energy, exergy and exergo economic analysis on a 250 MW gas fired steam power plant in Iran. They have calculated the exergy destruction in all major components of the power plant and concluded that the rate of exergy destruction in the boiler is higher than the rate of exergy destruction of other components. They have carried out exergo economic analysis and found that the boiler has the highest cost of exergy destruction. They have developed a thermo economic optimisation model and found that the cost of exergy destruction and purchase cost can be considerably reduced by adjusting the extraction steam mass flow rate of and pressure of feed water heaters **[25].** L. Wang et al. (2012) have performed an exergoeconomic analysis on a coal fired ultra-super critical thermal power plant existing in China with an objective to understand the cost formation process and to evaluate economic performance of all components of the plant using SPECO (specific exergy costing) method **[26].** J.Uche et al. (2000) have carried out thermo economic optimisation of a steam power plant coupled with a multi stage flash desalination unit. They have developed a physical and a thermo economic model of the plant in carrying out the thermo economic optimisation **[27].** Amin M Elsafi (2015) has performed an exergy and exergoeconomic analysis on sustainable direct steam generation solar power plants. For each component of the plant, exergy and exergy-costing balance equations have been formulated based on fuel-product concept **[28].** Zhai et al. (2016) have analysed a solar-aided coal-fired power generation system based on thermo-economic structural theory.

They have applied thermo economic structural theory on a solar aided thermal power plant compared the performance in both fuel saving and power boosting mode. They have observed that the coal consumption rate has reduced by 15.04 g/kWh in fuel-saving mode.

The power output is 57.2 MW higher in power-boosting mode. They have found that thermo economic cost of electricity has been increased due to large investment in solar field**[29].**

For carrying out the thermo economic analysis on an integrated solar aided thermal power plant, a physical model has been developed by aggregating and disaggregating certain plant equipment. The turbine sections can be disaggregated into several units. The solar field and thermal energy storage system can be aggregated into one single unit.

Further, a productive structure has to be developed based on the fuel-product approach. In the fuel product approach, fuel to specific plant equipment means the different resources consumed by that plant equipment in delivering a product. The resources (fuel) for different plant equipment are exergetic flow (FB), Negentropic flow (FN)/electricity (FW) and capital cost of the component (FZ). In a productive structure diagram, plant equipment is represented by a rectangle. Incoming arrows to particular equipment represent the resources consumed and outgoing arrows from that equipment represent the product generated by it. Bifurcations are represented by circles and junctions are represented by rhombuses. Junctions are basically distributing resources among different plant equipment.

The capital cost of k^{th} plant component per unit time can be obtained from the equation

$$F\dot{Z}_k = FZ_k * CRF * \varphi / N \qquad [25]$$

Where, FZ_k is the capital cost of the plant equipment, CRF is the capital recovery factor, φ is the maintenance factor (≈ 1.06) and N is the plant annual operating hours respectively.

Capital recovery factor (CRF) can be calculated from the equation

$$CRF = \frac{i*(1+i)^n}{((1+i)^n - 1)} \qquad [26]$$

Where, "I" is the interest rate (taken as 10%) and "n" is the plant life in years (≈25) respectively. A set of linear equations can be formulated based on the productive structure for each plant equipment, junctions and bifurcations. These linear equations can be solved to find out the costs of all major flow streams in the reference plant.

IV. Solar Aided Combined Cycle Power Plants

The integration of solar thermal energy with conventional gas fired combined cycle power plants (CCPP) has gained wide acceptance among the countries with high solar potential like U.S, Spain, Egypt, Morocco, Algeria, Iran and Mexico**[3].** These plants are popularly known as integrated solar combined cycle (ISCC) power plants. The Kuraymat ISCC plant, 100 kM south of Cairo in Egypt comprises two gas turbines of 40 MWe each and one steam turbine of 70 MWe with a parabolic trough solar field capable to generate 200 GWh per annum**[30].**The plant generates 20 MWe of solar based electrical power**[3] [30].** The plant integrates solar energy in the bottoming (steam) cycle by heating the feed water leaving the preheater and sending it to super heater located in the heat recovery steam generator. The plant uses Therminol VP-1 as the heat transfer fluid. The solar field was provided by Flag sol GmbH. The Archimede concentrating solar power project operating in Sicily, Italy is a parabolic trough plant which produces steam (4.72 MWe equivalent) sent to a combined-cycle steam turbine rated at 130 MW. The parabolic trough system of this plant is the first one to use the molten salt as heat transfer fluid. This plant has 08 hours of thermal storage **[3].** The Agua Prieta II ISCC in Mexico is an under construction (Status date: 30 October, 2013) ISCC plant where, the fossil fuel is partially replaced with solar energy [3]. This plant has an overall capacity of 478 MW comprising of 464 MW with combined cycle and 14 MW with solar. Duct burners are provided to produce 14 MWe output when solar is not in operation. ISCC Ain Beni Mathar is an ISCC plant operating in Morocco which has a combined plant output of 470 MWe which includes a solar based power output of 20 MWe **[3].**This plant like Agua Prieta II

ISCC, partially replaces fossil fuel with solar energy. However, this plant has no thermal storage system unlike Agua Prieta II ISCC [3].ISCC Duba I is an under construction project having a capacity of 43 MWe expected to start production in year 2017 [3].

a) Solar Integration In The Brayton Cycle

The solar thermal energy can be integrated with a conventional CCPP either in topping cycle or bottoming cycle or both. The topping cycle solar integration can be gas turbine (GT) inlet air cooling using solar operated vapor absorption chiller [31] or heating the gas turbine compressor discharge air [32].

i. Solar Operated Vapour Absorption Chiller For Gas Turbine (Gt) Inlet Air Cooling

Dimityr Popov, 2014[31] has proved that inlet air cooling of gas turbines in a combined cycle configuration using solar assisted vapour absorption chiller has lower specific incremental capital costs and requires smaller land area than other options. The options considered in his study are an integrated solar combined cycle with medium temperature integration, inlet air cooling using a mechanical chiller and a vapour absorption chiller. He has clearly indicated that ISCCPP's suffer from following drawbacks:

- Low power output during cloud cover and night time. This causes part load operation of steam turbine and hence higher heat rate and higher cost of electricity generation. This needs thermal energy storage.
- Cycle efficiency suffers as the solar heat is added at low temperatures. Hence the solar contribution of ISCCPP's even at best locations where solar conditions are excellent is between 2 to 6%.
- Not possible for existing combined cycle plants as the steam turbine size needs to be increased.

On contrary to the ISCCPP's, the solar operated vapour absorption chiller offers several advantages. The power output of a gas turbine reduces drastically with increase in ambient temperature. Usually hot summer season is the peak demand season so power output reduction from gas turbines is definitely a cause of concern for power generators. So in general, most of the gas turbine plants resort to various methods of inlet air cooling. Inlet air cooling can be achieved by either evaporative cooling techniques or by using chillers. The evaporative cooling methods involve using wetted media, Inlet fogging etc. [31].The temperature of cooled air in evaporative cooling is always higher than the ambient wet bulb temperature. However, with chilling techniques, temperatures well below the wet bulb temperatures can be achieved. These chillers can be mechanical chillers or vapour absorption chillers (VAC). Mechanical chillers consume electrical energy for running of refrigerant compressor. However vapour absorption chiller systems do not use significant electrical energy as they need a low temperature heat source (hot water or steam) for their operation [31]. As mentioned by Dimityr Popov, (2014)[31], there is an excellent match between gas turbine power output reduction during hot weather conditions and abundance of solar energy for steam generation during the same period for gas turbine inlet air cooling. Said et al. (2015) [33] have performed design and analysis of a solar powered absorption refrigeration system modified to increase its COP using refrigerant storage. They have observed an increase of 8% in COP over the conventional design by using the refrigerant storage. Kaynakli et al. (2015)[34] have performed energy and exergy analysis of a double effect absorption refrigeration system based on different heat sources. Bakos et al, (2013) [35]have carried out techno economic assessment of an integrated solar combined cycle power plant in Greece using line-focus parabolic trough collectors using Transys software. Baghernejad et al. (2010) have carried an exergy analysis of an integrated solar combined cycle system and found that maximum exergy destruction (29.62%) occurs in the combustor of gas turbine [36].

ii. Solar Heating Of Gt Compressor Discharge Air

Another application of solar energy in Brayton cycle is heating the compressor discharge air. The compressed air from the gas turbine compressor is allowed in to a pressurised receiver placed on a central tower. Heliostat field is made to focus on to the pressurised receiver for heating the air. This will increase the temperature of air entering the gas turbine combustor [32]. This kind of solar integration in the topping (Brayton) cycle of a combined cycle power plant greatly reduces the fuel consumption without affecting the gas turbine output.

b) Solar Integration In The Bottoming Cycle

In the bottoming cycle solar integration, there are three integration levels based on the fluid temperature capability [37]. They are referred to as high/medium and low temperature integration technologies. In high temperature integration, solar tower systems can be used to generate super-heated steam at temperatures up to 545^0 C [37]. This steam is allowed to mix with the superheated steam generated in heat recovery steam generator (HRSG) before admitting to high pressure turbine. Reheating is also possible in the solar [37]. Ugolini et al, (2009) have mentioned that for the medium temperature solar integration technologies generating steam up to around 395^0 C, it is best to generate dry saturated steam at high pressure and mix with the steam coming from HRSG HP drum. In the low temperature integration, low pressure steam is generated using linear Fresnel collectors which can be sent to cold reheat line or in to the LP admission line [37].

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i. *Low Temperature Solar Integration*

Low temperature solar integration technologies involve fluid temperatures between 250^0 C and 300^0 C. However, the actual temperature of integration depends on the type of gas turbine plant with which integration has to be done. Linear Fresnel reflectors are most widely used for low temperature solar integration with combined cycle power plants. As described by Ugolini et al. (2009) **[37],** it is possible to generate steam at two different pressure levels for integration with steam cycle.

The first one is to generate dry saturated steam at 30 bar pressure and admit it to cold reheat line. The second one is to generate dry saturated steam at 5 bar pressure and admit it to low pressure (LP) steam admission line **[37].**The feed water take off temperature must be below the saturation temperature corresponding to the pressure of the steam generated **[37].**

ii. *Medium Temperature Solar Integration*

Medium temperature solar integration with combined cycle power plants has been considered as a proven technology. The best practice for medium temperature solar integration is to maximise feed water heating (sensible heat addition) in the heat recovery steam generator (HRSG) so that only latent heat is added in the solar field **[37].**This will not only reduces the solar field size but also maximises the heat recovery from exhaust gasses in the HRSG. In view of this, it is always better to take the feed water for solar heating from the last high pressure economiser exit. This maximises the solar conversion efficiency **[37].**Once sensible heat addition to HP feed water is finished in the HRSG, latent heat addition should be accomplished in the solar field. A separator vessel is usually provided at the outlet of solar field, so that any moisture can be removed before it is mixed with the steam leaving the HP drum. Alternatively, the wet steam leaving the solar field may be sent to HP drum for water separation from steam. The parabolic trough collectors are widely used for medium temperature solar integration. The trough collectors have the advantage of maturity in technological development and higher optical efficiencies in comparison to linear Fresnel collectors.

iii. *High Temperature Solar Integration*

The high temperature solar integration involves generating superheated steam at temperatures up to 545^0 C and allowing this steam to mix with the superheated steam leaving the HP super heater before it is allowed to expand in the high pressure turbine **[37].**A heliostat field focuses the collected solar radiation on to a receiver placed on top of a tower. A heat transfer fluid collects the solar energy from the receiver and exchanges in turn with the feed water in a solar boiler.

The cold reheat steam leaving the high pressure turbine can be sent back to solar boiler for reheating **[37].**The high temperature solar technology has got minimum integration issues as this has minimum impact on the HRSG **[37].**

c) *Exergy Analysis Of Direct Steam Generation Solar Aided Cc Plant*

The exergy analysis of direct steam generation solar aided CC plant involves the exergy analysis of individual plant equipment of the integrated plant.

Compressor (C)

The mass and energy balance for air compressor is

$$\dot{m}_1 = \dot{m}_2 \quad [27]$$

The exergy balance for the compressor is

$$\dot{m}_1\psi_1 + \dot{m}_1\psi_{1v} + \dot{W}_c = \dot{m}_2\psi_2 + \dot{m}_2\psi_{2v} + T_0\dot{s}_{gen,C} \quad [28]$$

Here, $\dot{m}$, h, w and $\dot{W}_c$ are mass flow rate of air, enthalpy of the air, the specific humidity of air and rate of compressor respectively. The subscripts 1, 2 and v refer to compressor inlet, discharge and water vapour respectively. $\dot{S}_{gen,C}$, is the rate of entropy generation in the compressor.

Exergy destruction (irreversibility) in the compressor is

$$\dot{E}_{D,C} = T_0\dot{s}_{gen,C} = \dot{m}_1 T_0(s_2 - s_1) \quad [29]$$

The exergy efficiency of the compressor is

$$\eta_{II,c} = \frac{\dot{m}_1(\psi_2 - \psi_1)}{\dot{W}_c} \quad [30]$$

Combustion Chamber (CC)

The mass and energy balance for the combustion chamber is

$$\dot{m}_2(1+w) + \dot{m}_f = \dot{m}_3 \quad [31]$$

Where $\dot{m}_2$, $\dot{m}_f$ and $\dot{m}_3$ are the mass flow rates of air, fuel and combustion products and h_2, h_{2v} and h_3 are the enthalpy of air entering the combustion chamber, enthalpy of water vapour entering the combustion chamber and enthalpy of combustion products leaving the combustion chamber respectively.

The subscripts 2 and 3 refer to the inlet and exit of the combustion chamber.

The energy efficiency of the combustion chamber is The exergy balance for the combustion chamber is

$$\dot{m}_2\psi_2 + w^* \dot{m}_2\psi_{2v} + \dot{m}_f\psi_f = \dot{m}_3\psi_3 + \dot{E}_{D,CC} \quad [32]$$

Where, ψ_f and $\dot{E}_{D,CC}$ are standard chemical exergy of the fuel and rate of exergy destruction in the combustion chamber respectively.

The exergy efficiency of the combustion chamber is

$$\eta_{II,cc} = \frac{(\dot{m}\psi)_g}{(\dot{m}\psi)_{a+f}} = \frac{\dot{m}_3\psi_3}{\dot{m}_2\psi_2 + w^* \dot{m}_2\psi_{2v} + \dot{m}_f\psi_f} \quad [33]$$

GAS Turbin (GT)

The mass and energy balance for gas turbine is

$$\dot{m}_3 = \dot{m}_4 \quad [34]$$

Here, $\dot{m}$, h and $\dot{W}_{gt}$ are mass flow rate of combustion gasses, enthalpy of the combustion gasses, rate of gas turbine work and energy loss in the gas turbine respectively. The subscripts 3 and 4 refer to the gas turbine inlet and outlet.

The exergy balance for the gas turbine is

$$\dot{m}_3\psi_3 = \dot{m}_4\psi_4 + \dot{W}_{gt} + T_0\dot{s}_{gen,GT} \quad [35]$$

Exergy destruction (irreversibility) in the gas turbine is

$$\dot{E}_{D,GT} = T_0\dot{s}_{gen,GT} = \dot{m}_3T_0(s_4 - s_3) \quad [36]$$

The exergy efficiency of the gas turbine is

$$\eta_{II,gt} = \frac{\dot{W}_{gt}}{\dot{m}_3(\psi_3 - \psi_4)} \quad [37]$$

Heat ReCovery Steam Generator (HRSG)

The mass balance for the heat recovery steam generator (HRSG) is

$$\dot{m}_{fgi} = \dot{m}_{fgo} \quad [38]$$

$$0 = \dot{m}_{fgi}(\psi_{fgi} - \psi_{fgo}) - 2^* \dot{m}_{hpei}(\psi_{hpeo} - \psi_{hpei}) - 2^* \dot{m}_{hpevo}(\psi_{hpsho} - \psi_{hpevo}) - 2^* \dot{m}_{lpei}(\psi_{lpeo} - \psi_{lpei}) - \dot{m}_{cphi}(\psi_{cpho} - \psi_{cphi}) - T_0 s_{gen}, hrsg \quad [39]$$

The exergy efficiency of HRSG is

$$\eta_{II,hrsg} = \frac{2^* \dot{m}_{hpei}(\psi_{hpeo} - \psi_{hpei}) + 2^* \dot{m}_{hpevo}(\psi_{hpsho} - \psi_{hpevo}) + 2^* \dot{m}_{lpei}(\psi_{lpeo} - \psi_{lpei}) + \dot{m}_{cphi}(\psi_{cpho} - \psi_{cphi})}{\dot{m}_{fgi}(\psi_{fgi} - \psi_{fgo})} \quad [40]$$

Where, the subscripts fg, hpe, hpev, lpe and cph refer to flue gas, high pressure evaporator, high pressure evaporator, low pressure economiser and condenser preheater respectively. I and o refer to inlet and outlet respectively.

The exergy analysis of Steam plant equipment has been already explained in section 3.3.

d) Economic Analysis Of Combined Cycle Power Plant

The base cost estimate fora conventional natural gas fired combined cycle facility can be obtained from either actual plant capital cost data or Updated Capital Cost Estimates for Utility Scale Electricity Generating Plants obtained from Independent Statistics & Analysis, U. S. Energy Administration & Information**[38].**This includes the cost of civil structural material and installation, mechanical equipment supply and installation, electrical/instrumentation & control, project indirects which include engineering, distributable costs, scaffolding, construction management & start up, EPC cost, fee & contingency and owner costs. Land cost can be obtained by multiplying the cost of land per acre with the land area of CCPP. The fixed operation and maintenance (O&M) cost (FOM), Plant capacity factor and auxiliary power consumption can be obtained from tariff norms of local electricity tariff regulator. A suitable escalation rate in fuel/O&M-fixed & variable cost and prevailing fuel cost in USDollar per million BTUneeds to be considered in the economic analysis. The detailed procedure as explained in section 3.4 has to be followed for carrying the economic analysis.

e) *Economic Analysis Of Direct Steam Generation Solar Aided Cc Plant*

The additional capital cost of the integrated plant (due to increased size of turbo generator) can be calculated on pro rata basis from the Updated Capital Cost Estimates for Utility Scale Electricity Generating Plants obtained from Independent Statistics & Analysis, U. S. Energy Administration & Information. Additional land requirement for the installation of solar field (Parabolic trough collector system), site improvement costs and cost of the solar field including storage can be obtained from NREL's (SAM 2015.1.30)**[39]**.The detailed procedure as explained in section 3.4 has to be followed for carrying the economic analysis.

f) *Economic Analysis Of Integrated Solar Ccpp With Solar Operated Vapour Absorption Chiller For Gas Turbine (Gt) Inlet Air Cooling*

The incremental capital cost of the vapour absorption chiller system for power enhancement in gas turbines over and above the rated load can be obtained from literature available online. Punwani (2004)**[40]** has shown that the incremental capital cost of the vapour absorption chiller system for power enhancement in gas turbines over and above the rated load is 427.328 USD/KW. The detailed procedure as explained in section 3.4 has to be followed for carrying the economic analysis.

V. Conclusions

It has been realised world over that for sustainable development; the percentage share of power generation through renewable energy sources needs to be increased significantly. This assumes a greater importance in the wake of continuously dwindling fossil fuel resources, associated pollution and greenhouse gas emissions etc. The use of solar energy for power generation is gaining importance day by day due to these reasons. In countries like India and China, where major power generation is coal based, the concept of solar aided feed water heating (by either complete/partial substitution of turbine bleed steam) can be successfully employed by retrofitting the existing units under renovation & modernisation (R&M) programmes of power stations. The same is true with integrated solar combined cycle power plants. The payback periods are good and bound to reduce further due to continuous on going improvements in the design and manufacturing of solar collector and receiver systems. Moreover, integration of thermal energy storage (TES) with the solar field will further improve the system reliability.

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Source: Sandia National Laboratory, U.S

Fig.1: LS-3 Solar collector assembly at Kramer Junction (SEGS, Mojave Desert, California, U.S)

Source: NREL website

Fig.2: Kimberlina solar thermal power plant, (A linear Fresnel reflector based plant near Bakersfield, California.)

Source: http://www.solarreserve.com/en/global-projects/csp/crescent-dunes

Fig.3: Crescent Dunes solar power tower plant at Nevada, U.S

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Cost Optimization Depending on Load Compositions in Isolated Wind Diesel Based Multi Units System

By Nitin Kumar Saxena & Ashwani Kumar
Wolaita Sodo University,

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Keywords: ancillary services, reactive power compensation cost analysis, voltage control, wind diesel based multi units system.

GJRE-F Classification: FOR Code: 090699

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Strictly as per the compliance and regulations of :

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Nitin Kumar Saxena [α] & Ashwani Kumar [σ]

Abstract- Public Private Partners (PPPs) have to be competitive in electricity market by deciding economic tariffs not only for power consumption but for several ancillary services too. The procurement of reactive power, as an ancillary service for voltage control especially in isolated power systems, involves cost investment and thus needs to be remunerated. The reactive power demands for different load compositions are different so their remuneration rates must also be different. Role of static compensation along with dynamic compensation becomes important in reducing the overall compensation cost. Since the participation of static compensator degrades the voltage profile so its involvement with dynamic compensation must be optimized by keeping the system voltage response within its pre decided range of performance. The main contributions of this paper are; (i) Development of reactive power balancing model in isolated wind diesel based multi units system, (ii) Optimization for reactive power compensation participations keeping voltage response in its pre decided transient parameters, and (iii) Cost analysis for reactive power compensation in system for different load compositions.

Keywords: ancillary services, reactive power compensation cost analysis, voltage control, wind diesel based multi units system.

Nomenclature

ΔQ_{SG1} and ΔQ_{SG2}: Incremental change in reactive power generated by two Synchronous Generators

ΔQ_{IG1} and ΔQ_{IG2}: Incremental change in reactive power absorbed by two Induction Generators

ΔQ_{SLM} and ΔQ_{DLM}: Incremental change in reactive power absorbed by static and dynamic load

ΔQ_{ST}: Incremental change in reactive power generated by STATCOM

ΔQ_{FC}: Incremental change in reactive power generated by Fixed Capacitor V: Load terminal voltage

ΔV: Incremental change in load voltage due to load and/or input disturbances

$(D_v)_{SLM}$: Transfer function of reactive power change to voltage change for static load model

$(D_v)_{DLM}$: Transfer function of reactive power change to voltage change for dynamic load model

X_{m1} and X_{m2}: Magnetising reactance referred to stator side in two Induction generators

Q_{FC}^{ss}, Q_{ST}^{ss} and Q_{ST}^{ts}: Reactive power by fixed capacitor and STATCOM at steady state and dynamic conditions

$C1(x)$ and $C2(x)$: Cost function of FC and ST respectively

I. Introduction

In recent scenario, power utilities are facing many challenges in planning and commission of new transmission lines especially for remotely located consumers and therefore, they are promoting non grid connected generators for such less populated remote areas [1]. Depletion of conventional fuels in nature also motivates utilities to shift electricity production towards renewable energy sources. Renewable energy sources that are available in abundant, are being focussed for electrification of remote areas but their intermittent nature and seasonal availability reduces the system reliability for fulfilling the continuous power demand of end users. Hence, conventional fuel operated generators are coupled with renewable based generators to develop reliable power systems. Such systems are popularly called an Isolated Hybrid System (IHS). Sager Island Project in India, Dachen Island in China and Tin City in USA are the few examples of installed wind diesel based IHSs [2].

In such systems wind operated self excited induction generator is used for supplying base load demand and peak load demand is supplied by diesel operated synchronous generator. Since synchronous generator is used for peak load demand, it has to work for a wide range of system load demand during its operation. The power generation using diesel system must be reduced and even shut down during light-load periods or for good wind conditions. Synchronous generators are also suggested to run at their rated output for most efficient operations. This can be achieved by replacing a single unit power generation with multi units power generation [3]. It is also reported that multi diesel systems allow a variety of possible operation and control strategies. Therefore, multi diesel systems of small rating can give satisfactorily result compare with single large rating unit [4, 5]. It is also reported that multi wind systems can attenuate the

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effect of power fluctuations produced due to wind intermittent nature [6]. It must also be noticed that a need for short-term storage can also be eliminated in IHSs with power generation capacity made up with multi wind and multi diesel machines. Therefore, multiple generation units can be incorporated to improve operation performance and benefit from quantities of scale benefits. Multi units IHS have many technical, economical and operational issues due to grid isolation, hybrid configuration of generation units, random behaviour of consumers load.

The Indian power sector has garnered significant interest from private players. Public Private Participation (PPP) model explore the new era for economical studies in power system. In India, private sector share in power generating capacity has increased from 13 per cent in financial year 2006-07 to 33 per cent as on Jan 2015. India's total generating capacity is around 255 GW, of which, the private sector accounts for the almost 36 per cent. Going forward, the private sector is likely to account for a major share of the additional capacity and investments (almost 50 per cent); wherein, Public Private Participation (PPP) is likely to be the preferred route for such ventures. It has been reported that 88% renewable energy sources are installed by private sectors in India [1]. In modern era of distribution system, several distribution companies (DISCOs) can be worked together for supplying the power to end user. This concept proposes a healthy competition among the different discos for providing power at cheaper rate along with the power quality.

Therefore, PPPs have to be competitive in electricity market by deciding economic tariffs not only for power consumption but for several ancillary services too. The procurement of reactive power, as an ancillary service for voltage control especially in isolated power systems, involves cost investment and thus needs to be remunerated.

The selection of compensation techniques is also much influenced by load dynamics and its parameters [8-10]. Fast acting device (STATCOM) for reactive power compensation gives better results of voltage regulation in system but at the same time they increase system compensation cost much. On the other side, static compensator (Fixed Capacitors) has very low cost but alone cannot be suitable for reactive power compensation in the system. Therefore, a hybrid use of compensating devices; static as well as dynamic compensators can be used together for better solution of optimal reactive power compensation [11].

In this paper, effect of load composition has been focussed for deciding the participation among static and dynamic reactive power compensators, and therefore the cost of reactive power compensation for voltage control in multi units IHS. A MATLAB based procedure is developed to find optimum participation for system reactive power compensation for different load composition. System performances are compared for three different load compositions for 10% huge disturbances in load reactive power demand and wind input real power in system.

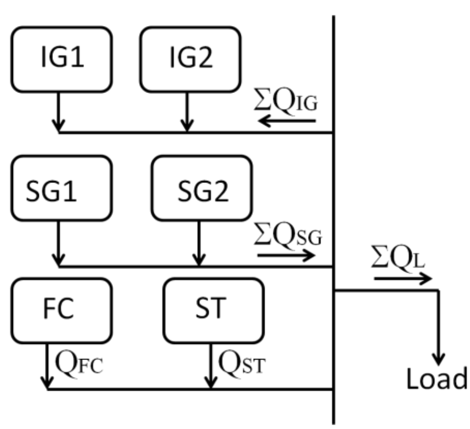

Fig. 1: Reactive power arrangements in multi units HIS

II. System Mathmatical Modelling

A 5.0 MW wind diesel based multi units system is simulated in this paper. Reactive power flow in multi units IHS is represented in Fig. 1 having two induction generators IG1 and IG2, two synchronous generators SG1 and SG2, fixed capacitor FC, STATCOM ST. Load model is developed by combining the static and dynamic load models together into different proportions. The ratings for all system components are given in Table 1. Under steady state reactive power balance equations can be elaborated as,

$$\Delta Q_{IG2} + \Delta Q_{IG1} + \Delta Q_{SLM} + \Delta Q_{DLM} = \Delta Q_{SG1} + \Delta Q_{SG2} + \Delta Q_{FC} + \Delta Q_{ST} \quad (1)$$

System is simulated for 10% sudden changes in system input wind power and load demand. Due to these disturbances, system net reactive power is;

$$\Delta Q = \Delta Q_{SG1} + \Delta Q_{SG2} + \Delta Q_{FC} + \Delta Q_{ST} - \Delta Q_{IG2} - \Delta Q_{IG1} - \Delta Q_{SLM} - \Delta Q_{DLM} \quad (2)$$

This surplus reactive power ΔQ will increase the system voltage by changing electromagnetic energy absorption in magnetizing reactance of both induction generators at the rate $\frac{dE_m}{dt}$ and consuming more reactive power in load [12]. Therefore, net surplus reactive power in s plane for multi units system;

$$\Delta Q(s) = \left\{ s\frac{V}{\omega}\left(\frac{1}{X_{m1}} + \frac{1}{X_{m2}}\right) + (D_v)_{SLM} + (D_v)_{DLM} \right\} \Delta V(s) \quad (3)$$

Comparing Eq. (2) and (3),

$$\Delta Q_{SG1} + \Delta Q_{SG2} + \Delta Q_{FC} + \Delta Q_{ST} - \Delta Q_{IG2} - \Delta Q_{IG1} - \Delta Q_{SLM} - \Delta Q_{DLM} = \left\{ s\frac{V}{\omega}\left(\frac{1}{X_{m1}} + \frac{1}{X_{m2}}\right) + (D_v)_{SLM} + (D_v)_{DLM} \right\} \Delta V(s) \quad (4)$$

Eq. (4) gives a reactive power balance expression for IHS. The each component in these IHS has a well established transfer function showing relation of its reactive power change with voltage change [13]. A MATLAB simulink model is developed with the help of these all components transfer functions and reactive power balance equation as presented in Eq. (4). A combined block diagram for multi units IHS is shown in Fig. 2

Synchronous generator SG1, SG2 and induction generator IG1, IG2 are used to release active power as demanded by the load. Induction generators and load demand reactive power form the system for its operation during steady state condition. This reactive power demand further increases for dynamic conditions. SGs alone are unable to provide adequate reactive power to the system and hence extra reactive power compensators ST and FC are used to provide fast and economic compensation for IHS [14]. FC cannot adjust its reactive power magnitude for system dynamic conditions therefore it is called static device. While ST can adjust its reactive power magnitude by changing its firing angle depending on the dynamic conditions and therefore it is called dynamic compensator. A PI controller is used for getting the control signal to adjust reactive power compensation by setting firing angle. Genetic algorithm (GA) based tuning method is proposed in this paper to get gain constants K_P and K_I as shown in Fig. 2. Genetic algorithm is a probabilistic algorithm that searches the space of compositions of the available functions and terminals under the guidance of a fitness measure for many generations and finally stops when reaching individuals that represent the optimum solution to the problem. Minimization of performance index using ISE (Integral of Square Error) criterion based conventional method is used for deciding reference values of gain constants K_P and K_I in GA [15-16].

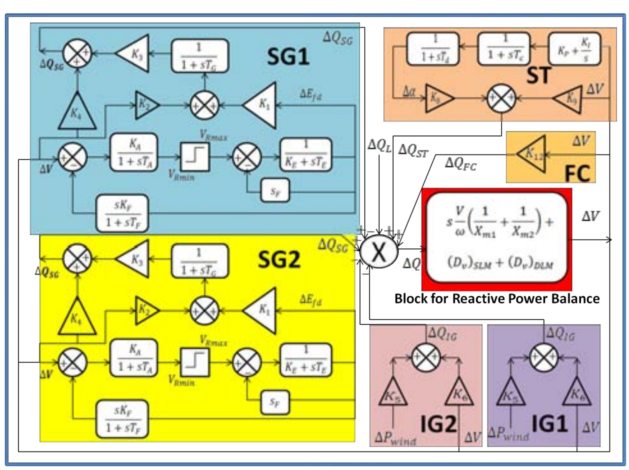

Fig. 2: Simulink block diagram for multi units IHS

In remote areas, most of the load is either commercial type or residential type. A realistic load model can be developed by clubbing the participation of static and dynamic load models. It has already been concluded that fraction of static load model is more in such areas compare to dynamic load model but still presence of dynamic load model cannot be ignored in these areas [17]. The load behaviours are much influenced by the presence of induction motors in these areas, so induction motor load is considered as dynamic load composition in this load model. An exponential load type is modelled as static load [18].

Table 1: Typical system and components rating used for simulation

System capacity	$5.0\ MW$
Load	$5.0\ MW$
Base power	$5.0\ MVA$
Base voltage	$400\ V$
Type of system	Multi Units
Induction generator	$1.5\ MW \times 2\ units$
Synchronous generator	$1.0\ MW \times 2\ units$

Table 2: Different load compositions used for response and cost based study of HIS

Load pattern	SLM	DLM	Total load
1	5 MW	0 MW	5 MW
2	4 MW	1 MW	5 MW
3	3 MW	2 MW	5 MW

Exponential type load model as SLM and fifth order induction motor load model as DLM is considered for this paper. Transfer functions for SLM and DLM have been developed and the complete procedure is explained by the author in ref. [19]. To study the influence of different load compositions in cost based study of reactive power compensation and voltage control of IHS; three different load compositions are being compared in this study. These three patterns are given in Table 2.

III. Selection Procedure For Participation Of Static And Dynamic Compensators

The selection procedure for participation among static and dynamic reactive power compensator depends on the choice of investors profit domain and the supply quality required by the end user. If end users are ready to compromise with the quality of power, investors can provide power at cheaper rates. It is being assumed that IHS is designed by an independent investor who used to decide participation of reactive power compensators. For cost analysis, compensation cost functions for reactive power compensators are defined in [11, 20, 21]. Cost of fixed capacitor is very low compare to STATCOM but fixed capacitors do not respond for system dynamics. STATCOM alone can provide an adequate solution of reactive power compensation for system voltage control but it makes system very costly. It is assumed that the cost of reactive power in system includes only the reactive power production cost of generators and capacitors [22]. For dynamic condition, reactive power can only be generated through fast acting dynamic compensating device but steady state reactive power requirement can be planned through participation of static as well as dynamic compensators so that overall compensation cost may be reduced. The role of static compensation deforms the voltage response in system and hence participation of fixed capacitor with STATCOM is optimized up to the extent of voltage variation within the permissible range. A procedure for selecting the static and dynamic reactive power compensators are discussed and developed by the author. A MATLAB program is developed with two important aspects; (i) Minimizing the cost of compensation under steady state through participation of fixed capacitor as static compensator along with STATCOM as dynamic compensator, and (ii) Participation of static compensator with dynamic compensation upto the extent where system voltage response remain in its pre defined acceptable range. Objective function J represents a cost function for reactive power compensators during steady state and dynamic state as in Eq. (5). This objective function J is solved for cost functions of ST and FC, equality and inequality constraints given in Eqs. (6) to (11).

$$J = \{C1(Q_{FC}^{ss}) + C2(Q_{ST}^{ss})\} + C2(Q_{ST}^{ts})\} \quad (5)$$

Equality constraints;

$$Q_{demand} = Q_{release} \quad (6)$$

$$Q_{demand} = Q_{IG1} + Q_{IG2} + Q_{SLM} + Q_{DLM} - Q_{SG1} - Q_{SG2} \quad (7)$$

$$Q_{release} = Q_{FC}^{ss} + Q_{ST}^{ss} \quad (8)$$

Inequality constraints;

$$0 \leq Q_{ST}^{ss} \leq Q_{demand} \quad (9)$$

$$0 \leq Q_{FC}^{ss} \leq Q_{demand} \quad (10)$$

$$V_{min} \leq \Delta V \leq V_{max} \quad (11)$$

$$settling\ time \leq settling\ time_{acceptable} \quad (12)$$

Acceptable range of voltage response should be decided first using reference case in which compensation is achieved with the help of STATCOM only. With the help of these parameters, acceptable range of parameters is decided. The decision is based on the overall mutual acceptance of power quality between end user and investor in terms of system voltage response.

IV. Resuts and Discussion

This paper is organized to understand the effect of load compositions on system voltage response and reactive power compensation cost during dynamic conditions in wind diesel based multi units IHS. Fig. 1 gives a single line diagram for this studied system with corresponding system ratings in Table 1. Transfer functions for all the system components are assembled for developing a simulink model as shown in Fig. 2. ST is used for providing fast acting dynamic compensation while FC is used for static compensation. Advance tuning methods are available in literature [23, 24]. In this paper, ST gain constants K_P and K_I are evaluated using GA based tuning methods with parameters as; double vector population type, tournament function selection with size 2, reproduction scattered crossover function of 0.8 and forward migration direction. To decide reactive power participation between ST and FC, a reference value is evaluated using only ST as a reactive power compensator first. With this reference response, acceptable range for voltage response is decided. Acceptable range that is decided for the selecting participation among static and dynamic reactive power compensators are;

- The voltage response should be stable.
- Voltage deviation should reach to zero in minimum time and absolute value of voltage rise and dip should not be exceeding more than 0.05 pu of reference case voltage rise and dip values.
- Settling time should not be beyond 0.01 sec of settling time of reference case voltage response.

Now the required reactive power is supplied by numbers of samples of ST and FC satisfying the Eq. (8). Compensation cost of each sample is also evaluated. Samples are sorted on the basis of predefined acceptable range and the sample of least compensation cost among is chosen as the best selection of participation among ST and FC.

For three load patterns shown in Table 2, a comparative study for reactive power compensation and cost is given in Table 3. A comparative study among voltage response, ST and FC reactive power deviations are presented in Fig. 3 to 5. It can be concluded that the system with static load has least settling time and requires least value of dynamic compensation. With increase in dynamic load participation, overall reactive power requirement in increasing therefore compensation cost increases with increase in dynamic load pattern. ST supplies reactive power for dynamic conditions and it takes longer time to be stabilized after disturbances. It can also be observed that optimum selection of reactive power compensation reduces the overall compensation cost of the system because of the introduction of static compensator with dynamic compensator. Especially, different load compositions allow the different participation of compensator and hence the cost of compensation depends on the load behavior.

Table 3: Study for reactive power compensation and cost among different load compositions

	Load pattern 1	Load pattern 2	Load pattern 3
Q_{ST}^{ss} in pu	0.1031	0.1063	0.1054
Q_{FC}^{ss} in pu	0.1475	0.1652	0.1870
$C(Q_{ST}^{ss})$ in $ per hour	0.5904	0.6086	0.6034
$C(Q_{FC}^{ss})$ in pu	0.0973	0.1091	0.1234
$oC\ \ st\ at\ ss$	0.6878	0.7177	0.7268
Q_{ST}^{ts} in pu	0.2036	0.2056	0.2083
$C(Q_{ST}^{ts})$ in $ per hour	1.1658	1.1773	1.1927
$Total\ cost$ in $ per hour	1.8536	1.8950	1.9195

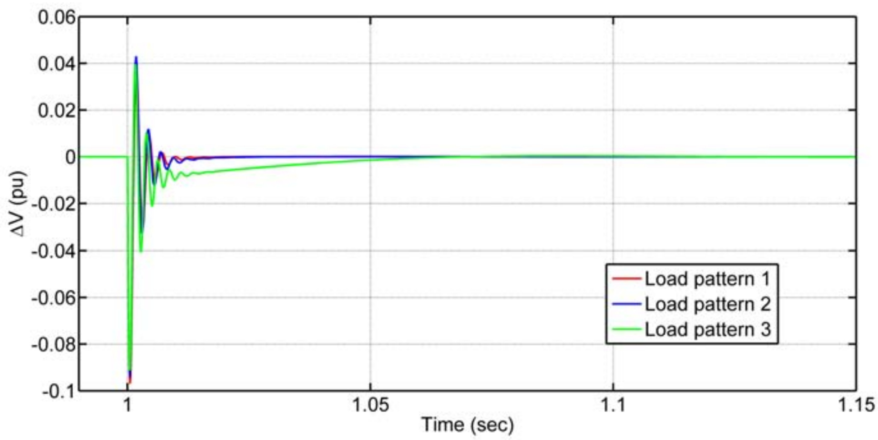

Fig. 3: Comparative study for ΔV for different load patterns

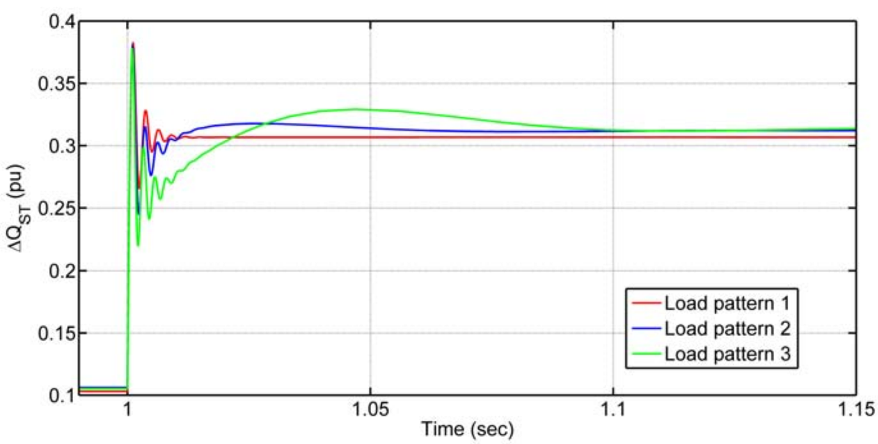

Fig. 4: Comparative study for ΔQ_{ST} for different load patterns

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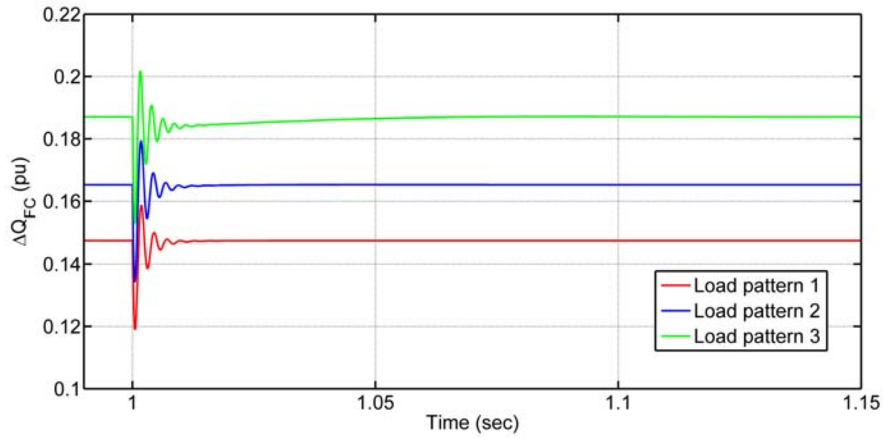

Fig. 5: Comparative study for ΔQ_{FC} for different load patterns

V. Conclusions

In this paper, a model is proposed to understand the different tariff structures based on reactive power compensation cost as ancillary service that may be provided by the discos depending on the load compositions. Reactive power compensation cost for three different load compositions is presented in this paper for multi units isolated wind diesel base system. Optimization technique is verified for multi units system and for all load compositions. It has been investigated that more compensation is required for the load having high composition of dynamic load. Hence, author tried to investigate the economical aspects for reactive power compensation in multi units based isolated hybrid power system especially with different participations of load compositions. Mathematical expressions are developed for multi units IHS and assembled to develop a MATLAB simulink model. This model is tested for 10% disturbances in input wind real power and load reactive power demand. Hence, this method helps to procure the reactive power compensation model in system depending on the desired voltage response and purchasing power of the customer.

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Appendix 1

Induction Generator

$IG\ power\ factor = 0.9\ lagging$, $slip = -4\%$, $efficiency = 90\%$, $voltage = 400\ V$, $frequency = 50\ Hz$

Synchronous Generator

$SG\ power\ factor = 0.9\ lagging$, $voltage = 400\ V$, $frequency = 50\ Hz$

Fixed capacitor

$voltage = 400\ V$, $frequency = 50\ Hz$

STATCOM

$voltage = 400\ V$, $frequency = 50\ Hz$, $Switching\ frequency = 10\ kHz$

Appendix 2

Constants used in simulink model

$$K_1 = \frac{X_d^{'}}{X_d},\quad K_2 = \left(X_d - X_d^{'}\right)\frac{Cos\delta}{X_d},\quad K_3 = \frac{V.Cos\delta}{X_d^{'}},\quad K_4 = \frac{E_q^{'}.Cos\delta - 2V}{X_d^{'}},\quad K_5 = \frac{X_{eq}}{R_P - \left\{\left(\left(R_P - R_{eq}\right)^2 + X_{eq}^2\right)/2\left(R_P - R_{eq}\right)\right\}}$$

$$K_6 = \frac{2V}{\left(R_P - R_{eq}\right)^2 + X_{eq}^2}\left[X_{eq} - \frac{R_P X_{eq}}{R_P - \left\{\left(\left(R_P - R_{eq}\right)^2 + X_{eq}^2\right)/2\left(R_P - R_{eq}\right)\right\}}\right],$$

$$K_7 = \frac{2V}{X_C},\ K_8 = kV_{dc}VBSin\alpha,\ K_9 = -kV_{dc}BCos\alpha$$

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Design and Analysis of Compact UWB BPF Using Parallel Coupled Microstrip Line With DGS

By Satish Chand Gupta, Mithlesh Kumar & Ramswaroop Meena

Rajasthan Technical University

Abstract- This paper presents design and analysis of a simple and compact ultra-wideband (UWB) band-pass-filter using parallel-coupled micro strip line with DGS.A two poles filter is designed by a parallel couple micro strip line. A rectangular defective ground plane is used to enhance coupling between lines i.e. better return loss in UWB range. Simulation of this proposed filter is carried out on CST MWS software, and fabricated using microwave laminate GML 1000 of dielectric constant 3.2 and height 0.762mm with loss tangent 0.001.Measured results are compared with simulation results with good agreement. The electrical equivalent model of this filter is also presented in this paper.

Keywords: multi-mode resonator (MMR), fractional bandwidth (FBW), ultra-wide band (UWB), band pass filter (BPF), parallel-coupled micro strip line(PCML),defective ground plane structure (dgs).

GJRE-F Classification: FOR Code: 090607

DESIGNANDANALYSISOFCOMPACTUWBBPFUSINGPARALLELCOUPLEDMICROSTRIPLINEWITHDGS

Strictly as per the compliance and regulations of:

Design and Analysis of Compact UWB BPF Using Parallel Coupled Microstrip Line With DGS

Satish Chand Gupta[α], Mithlesh Kumar[σ] & Ramswaroop Meena[ρ]

Abstract- This paper presents design and analysis of a simple and compact ultra-wideband (UWB) band-pass-filter using parallel-coupled micro strip line with DGS.A two poles filter is designed by a parallel couple micro strip line. A rectangular defective ground plane is used to enhance coupling between lines i.e. better return loss in UWB range. Simulation of this proposed filter is carried out on CST MWS software, and fabricated using microwave laminate GML 1000 of dielectric constant 3.2 and height 0.762mm with loss tangent 0.001.Measured results are compared with simulation results with good agreement. The electrical equivalent model of this filter is also presented in this paper. The equivalent model of this filter is verified by comparing the frequency response of equivalent circuit of the filter and simulated frequency response of this filter.

Keywords: multi-mode resonator (MMR), fractional bandwidth (FBW), ultra-wide band (UWB), band pass filter (BPF), parallel-coupled micro strip line(PCML),defective ground plane structure (dgs).

I. Introduction

In 2002, Federal Communication Commission (FCC) released Ultra wide band (UWB) system from 3.1 GHz to 10.6 GHz for the use of indoor and hand-held systems. Ultra-wideband (UWB) band pass filters play a key role in the development of UWB systems [1]. After the release of UWB, there were lot of challenges to design such a band pass filters with a pass band of the frequency range (3.1 GHz - 10.6 GHz), and a fractional bandwidth of 110% for conventional filter design. Initially broad band filters were designed, and covered only 30 to 40 % of UWB not the whole UWB [2].In [3-7] many researcher reported various techniques, like aperture compensation, micro strip-coplanar waveguide structure design, ground plane aperture technique and multiple-mode resonator were used to design UWB filters. Many new techniques [8-13], like U-shaped Slot Coupling [8],asymmetric parallel-coupled lines [9],right/left-handed transmission line [10],differential-mode wide band BPF using two stage branch-line structure with open circuited stubs [11],tunable harmonic stepped-impedance resonators [12] and parallel coupled line micro strip structure [13] were used to design the UWB filter.

The synthesis of UWB filter has been carried out by various approaches presented in [14-15].

The transfer function of the proposed UWB was synthesized having two short circuited stubs with two stages of stepped impedance resonators (SIRs)[14].In[15],series multi conductor transmission lines (MTLs) and ashunt MTL were used to design various UWB filters and a new approach was presented to synthesis the transfer function of UWB filter.

In this paper a design and analysis of a compact UWB filter is presented. In section 2, design and development of the UWB filter using single PCML and DGS is demonstrated. The electrical analysis of the filter is mentioned in section 3.Finally paper is concluded in section.4.

II. Design of UWB Filter

The layout of the proposed structure is shown in Fig.1 which consist a quarter wavelength parallel coupled micro strip line (PCML) with a rectangular shaped DGS. The designed structure of filter is optimized by using CST Microwave Studio software on the microwave laminate GML 1000 of dielectric constant 3.2,height h = 0.762 mm and loss tangent 0.001.The design parameters of the proposed filter are mentioned in TABLE 1.

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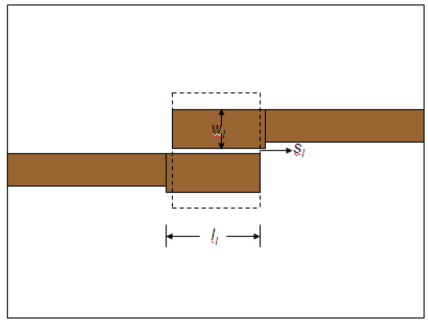
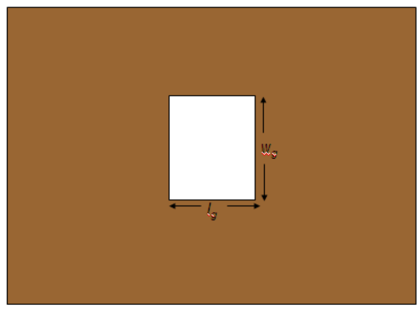


(a)



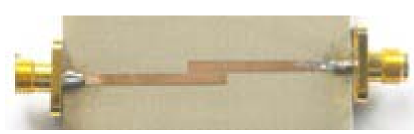
(b)

Fig.1: Schematic of UWB filter (a) Front view (b) Back view

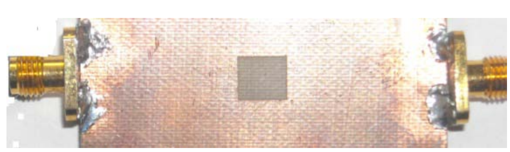
Table1: Design Parameters Of The UWB Filter

l_l (mm)	w_l (mm)	s_l (mm)	l_g(mm)	w_g(mm)
6.99	1.86	0.11	6.74	6.0

The optimized structure of this filter is fabricated using conventional microwave integrated circuits (MIC) technology, the photograph of the fabricated filter is shown in Fig.2.The frequency response (S_{11}&S_{21}) of this fabricated filter is measured on Agilent Tech. E5071C ENA Vector Network Analyzer. The measured frequency response is compared with simulated frequency response which is in close approximation, and it is shown in Fig.3 (a).It is observed from the frequency response of the fabricated filter, that the pass band of this filter exists from 3.1 GHz to 10.9 GHz, insertion loss (S_{21}) of -0.5 dB and return loss (S_{11}) better than 10 dB. The group delay is also measured and compared with simulation value, and it is observed that this filter having a flat group delay of value 0.35 ns approximately, which is shown in Fig.3 (b).A slight mismatch in the results is due to imperfection in fabrication process, quality of substrate and SMA connectors. The surface current distribution at center of the frequency 6.85 GHz is shown in Fig.3(c), which is uniform along the structure of the filter, from port 1 to port 2 indicates good pass band behavior of the filter.

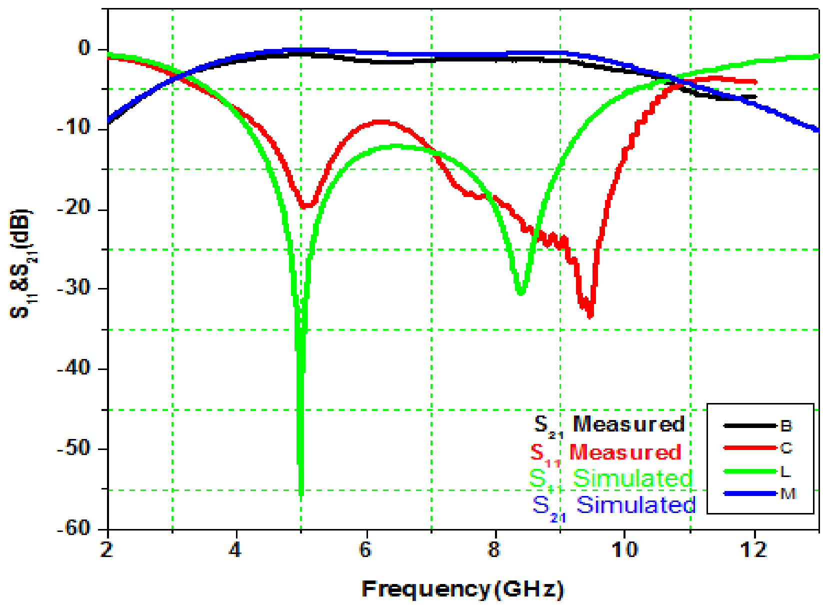


(a)

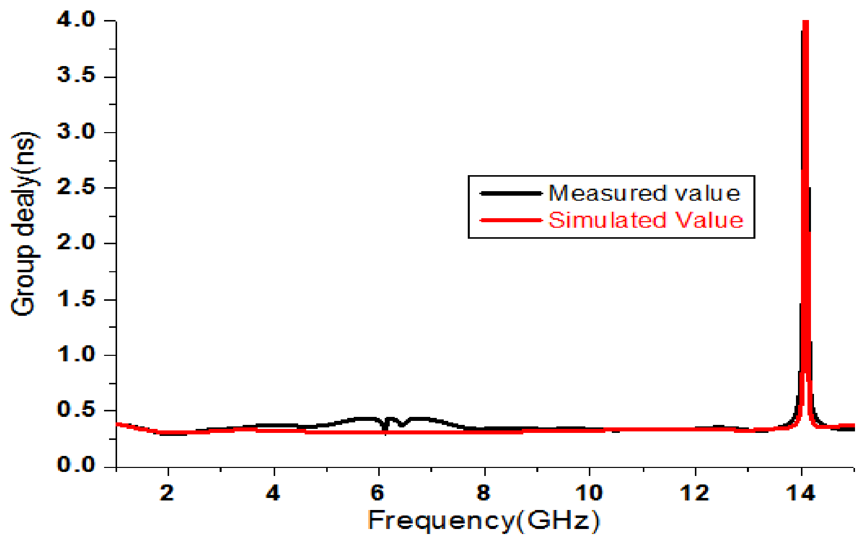


(b)

Fig.2: Photograph of fabricated filter (a) Front view (b) Back view

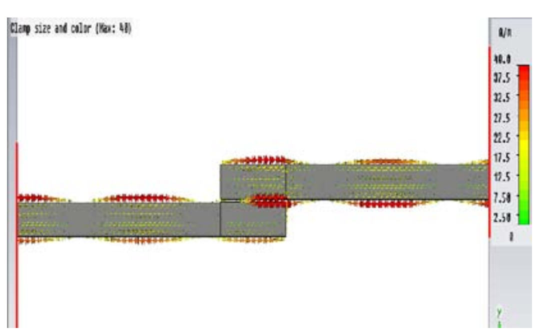


(a)

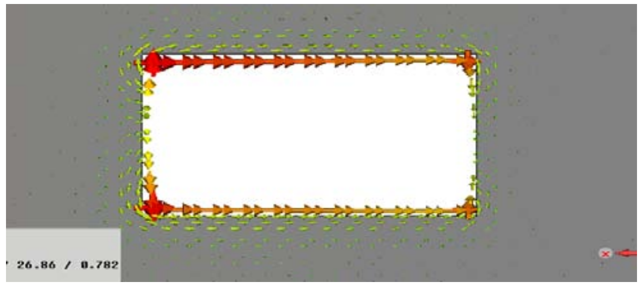


(b)

Fig.3: (a) Comparison of Frequency responses (b) Group delay



(c)

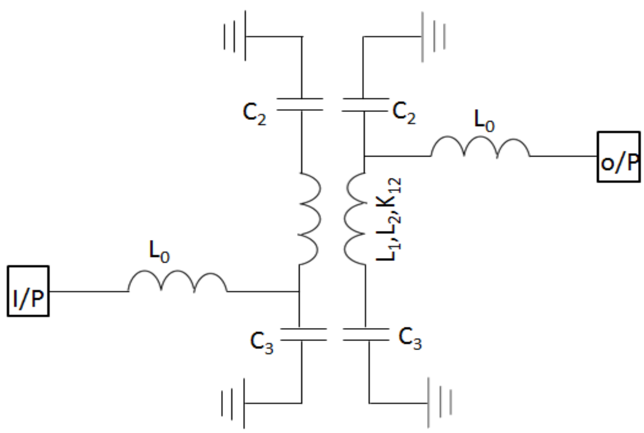


(d)

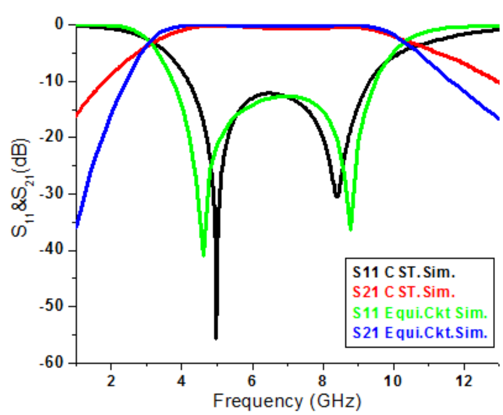
Fig.3: (c) Surface current density at center frequency 6.85 GHz (top View) (d) Bottom View

III. Electrical Analysis Of The Filter

The proposed filter consist one parallel coupled micro strip line with DGS and 50 ohm transmission line. The PCML can be represented by a two mutually coupled inductors (L_1, L2, K_{12}) and capacitance of the line Ci (between line and ground plane).The 50 ohms transmission feed line can be represented by a lumped value inductor L_0.The electrical equivalent circuit of the proposed UWB filter is shown in Fig.4(a).This circuit is optimized and simulated on circuit simulator SERENIDE SV8.5 for values L_0=0.8215 nH,K_{12}=0.6218 ,L_1=L_2=3.55 nH and C_2=C_3=0.456 pF. The comparison of frequency responses of this UWB filter is on CST MWS and equivalent circuit on SERENIDE SV 8.5 shown in Fig.4 (b).



(a)



(b)

Fig.4: (a) Electrical equivalent circuit of UWB filter (b) Comparison of frequency response

The circuit shown in Fig.4 (a) can be analyzed by network circuit theory, and it can be redraw in simplified form shown in Fig.5

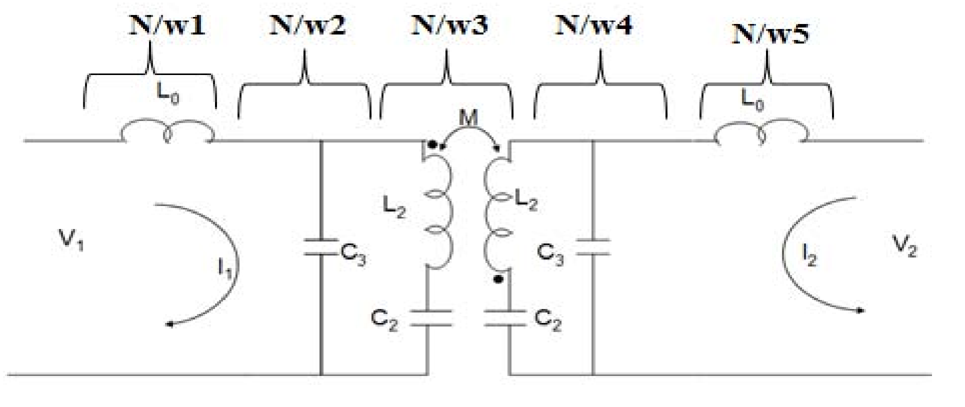


Fig.5: Simplified electrical equivalent of UWB filter.

ABCD-parameters of the circuit shown in Fig.5 can be determined by considering the cascade connection of the networks.

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & SL_0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ SC_3 & 1 \end{bmatrix} \begin{bmatrix} \dfrac{SL_2 + \dfrac{1}{SC_2}}{-SM} & \dfrac{\left(SL_2 + \dfrac{1}{SC_2}\right)^2 - (SM)^2}{-SM} \\ \dfrac{1}{-SM} & \dfrac{SL_2 + \dfrac{1}{SC_2}}{-SM} \end{bmatrix} \begin{bmatrix} 1 & 0 \\ SC_3 & 1 \end{bmatrix} \begin{bmatrix} 1 & SL_0 \\ 0 & 1 \end{bmatrix} \quad \text{-- (1)}$$

For the simplification of the matrix multiplication, we have assumed some constant parameters.

Where S= j =j2πf

$$P = \frac{SL_2 + \dfrac{1}{SC_2}}{-SM}$$

And

$$Q = \frac{\left(SL_2 + \dfrac{1}{SC_2}\right)^2 - (SM)^2}{-SM}$$

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & SL_0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ SC_3 & 1 \end{bmatrix} \begin{bmatrix} P & Q \\ \dfrac{1}{-SM} & P \end{bmatrix} \begin{bmatrix} 1 & 0 \\ SC_3 & 1 \end{bmatrix} \begin{bmatrix} 1 & SL_0 \\ 0 & 1 \end{bmatrix} \quad \text{......... (2)}$$

Let $R = 1 + S^2 L_0 C_3$

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$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} R & SL_0 \\ SC_3 & 1 \end{bmatrix} \begin{bmatrix} P & Q \\ \frac{1}{-SM} & P \end{bmatrix} \begin{bmatrix} 1 & SL_0 \\ SC_3 & R \end{bmatrix} \quad \ldots\ldots\ (3)$$

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} PR - \frac{L_0}{M} & QR + SPL_0 \\ SC_3P - \frac{1}{SM} & SC_3Q + P \end{bmatrix} \begin{bmatrix} 1 & SL_0 \\ SC_3 & R \end{bmatrix} \quad \ldots\ldots\ (4)$$

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} PR - \frac{L_0}{M} + SC_3QR + S^2PL_0C_3 & SL_0PR - \frac{SL_0^{\ 2}}{M} + QR^2 + SPRL_0 \\ 2SC_3P - \frac{1}{SM} + S^2C_3^{\ 2}Q & S^2L_0C_3P - \frac{L_0}{M} + SC_3RQ + PR \end{bmatrix} \quad \text{-----}\ (5)$$

The insertion and return loss of UWB filter can be calculated by converting the ABCD-parameters into S-parameters. To calculate these, we assume $\Delta = A + BY_o + CZ_0 + D$

$$\Delta = \frac{Z_0^{\ 2}\left\{2SC_3PR - \frac{1}{SM} + S^2C_3^{\ 2}Q\right\} + 2Z_0\left\{PR - \frac{L_0}{M} + SC_3\left(QR + PL_0^{\ 2}\right)\right\} + 2SPL_0R - \frac{SL_0^{\ 2}}{M} + QR^2}{Z_0} \quad \text{--}\ (6)$$

Similarly, we assume that $\Delta_1 = A + BY_0 - CZ_0 - D$

$$\Delta_1 = \frac{2SPL_0R - \frac{SL_0^{\ 2}}{M} + QR^2 - Z_0^{\ 2}\left(2SC_3P - \frac{1}{SM} + S^2C_3^{\ 2}Q\right)}{Z_0} \quad \text{--------}\ (7)$$

The S_{11} & S_{21} parameters to be calculated by using the final values of ABCD-parameters with help of following equations,

$$S_{11} = \frac{A + BY_0 - CZ_0 - D}{A + BY_0 + CZ_0 + D} = \frac{\Delta_1}{\Delta} \quad \text{-------------------}\ (8)$$

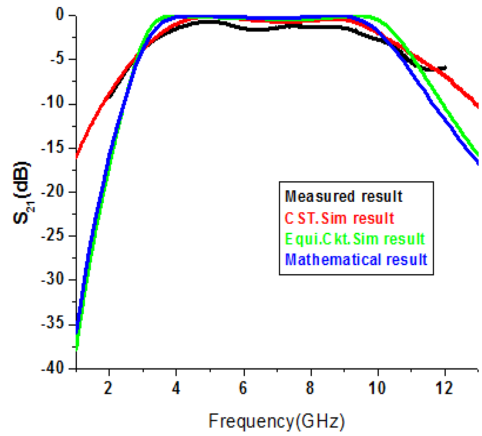
$$S_{21} = \frac{2}{A + BY_0 + CZ_0 + D} = \frac{2}{\Delta} \quad \text{-------------------}\ (9)$$

Where, $Y_0 = \frac{1}{Z_0}$ and $Z_0 = 50\Omega$

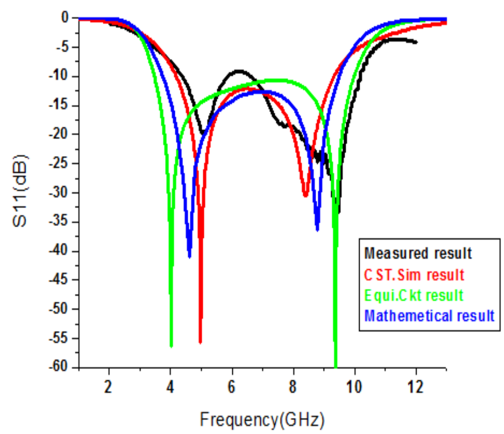
$$S_{11}\ (\text{dB}) = 20 \log_{10} |S_{11}| \quad \text{----------------}\ (10)$$

$$S_{21}\ (\text{dB}) = 20 \log_{10} |S_{21}|$$

The expression of S11 and S21 obtained from equation 8-9 in terms of frequency is solved by using MATLA Band comparison among the responses(S11&S21) are shown in Fig.6.The close approximation in the measured response, CST simulation response, equivalent circuit response and its mathematical model response verify the approach of equivalent circuit of the proposed filter.



(a)



(b)

Fig.6: Comparison of results (a) S_{21}(b) S_{11}

IV. Conclusions

A simple and compact two poles UWB band pass filter using PCML with DGS is implemented. It is observed that the introduction of DGS in micro strip line circuit enhance the bandwidth of the system. The electrical analysis of this proposed filter is carried out by conventional circuit theory. The size of filter is of size (7.0mm ×6.0mm) and such filter may be useful for the systems of UWB communication.

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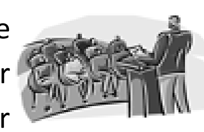

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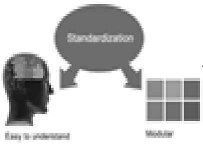

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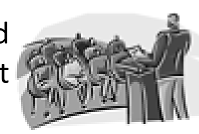

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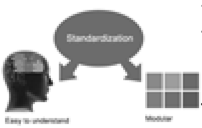

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Proofs must be returned to the dean at dean@globaljournals.org within three days of receipt.

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Before start writing a good quality Computer Science Research Paper, let us first understand what is Computer Science Research Paper? So, Computer Science Research Paper is the paper which is written by professionals or scientists who are associated to Computer Science and Information Technology, or doing research study in these areas. If you are novel to this field then you can consult about this field from your supervisor or guide.

TECHNIQUES FOR WRITING A GOOD QUALITY RESEARCH PAPER:

1. Choosing the topic: In most cases, the topic is searched by the interest of author but it can be also suggested by the guides. You can have several topics and then you can judge that in which topic or subject you are finding yourself most comfortable. This can be done by asking several questions to yourself, like Will I be able to carry our search in this area? Will I find all necessary recourses to accomplish the search? Will I be able to find all information in this field area? If the answer of these types of questions will be "Yes" then you can choose that topic. In most of the cases, you may have to conduct the surveys and have to visit several places because this field is related to Computer Science and Information Technology. Also, you may have to do a lot of work to find all rise and falls regarding the various data of that subject. Sometimes, detailed information plays a vital role, instead of short information.

2. Evaluators are human: First thing to remember that evaluators are also human being. They are not only meant for rejecting a paper. They are here to evaluate your paper. So, present your Best.

3. Think Like Evaluators: If you are in a confusion or getting demotivated that your paper will be accepted by evaluators or not, then think and try to evaluate your paper like an Evaluator. Try to understand that what an evaluator wants in your research paper and automatically you will have your answer.

4. Make blueprints of paper: The outline is the plan or framework that will help you to arrange your thoughts. It will make your paper logical. But remember that all points of your outline must be related to the topic you have chosen.

5. Ask your Guides: If you are having any difficulty in your research, then do not hesitate to share your difficulty to your guide (if you have any). They will surely help you out and resolve your doubts. If you can't clarify what exactly you require for your work then ask the supervisor to help you with the alternative. He might also provide you the list of essential readings.

6. Use of computer is recommended: As you are doing research in the field of Computer Science, then this point is quite obvious.

7. Use right software: Always use good quality software packages. If you are not capable to judge good software then you can lose quality of your paper unknowingly. There are various software programs available to help you, which you can get through Internet.

8. Use the Internet for help: An excellent start for your paper can be by using the Google. It is an excellent search engine, where you can have your doubts resolved. You may also read some answers for the frequent question how to write my research paper or find model research paper. From the internet library you can download books. If you have all required books make important reading selecting and analyzing the specified information. Then put together research paper sketch out.

9. Use and get big pictures: Always use encyclopedias, Wikipedia to get pictures so that you can go into the depth.

10. Bookmarks are useful: When you read any book or magazine, you generally use bookmarks, right! It is a good habit, which helps to not to lose your continuity. You should always use bookmarks while searching on Internet also, which will make your search easier.

11. Revise what you wrote: When you write anything, always read it, summarize it and then finalize it.

12. Make all efforts: Make all efforts to mention what you are going to write in your paper. That means always have a good start. Try to mention everything in introduction, that what is the need of a particular research paper. Polish your work by good skill of writing and always give an evaluator, what he wants.

13. Have backups: When you are going to do any important thing like making research paper, you should always have backup copies of it either in your computer or in paper. This will help you to not to lose any of your important.

14. Produce good diagrams of your own: Always try to include good charts or diagrams in your paper to improve quality. Using several and unnecessary diagrams will degrade the quality of your paper by creating "hotchpotch." So always, try to make and include those diagrams, which are made by your own to improve readability and understandability of your paper.

15. Use of direct quotes: When you do research relevant to literature, history or current affairs then use of quotes become essential but if study is relevant to science then use of quotes is not preferable.

16. Use proper verb tense: Use proper verb tenses in your paper. Use past tense, to present those events that happened. Use present tense to indicate events that are going on. Use future tense to indicate future happening events. Use of improper and wrong tenses will confuse the evaluator. Avoid the sentences that are incomplete.

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18. Pick a good study spot: To do your research studies always try to pick a spot, which is quiet. Every spot is not for studies. Spot that suits you choose it and proceed further.

19. Know what you know: Always try to know, what you know by making objectives. Else, you will be confused and cannot achieve your target.

20. Use good quality grammar: Always use a good quality grammar and use words that will throw positive impact on evaluator. Use of good quality grammar does not mean to use tough words, that for each word the evaluator has to go through dictionary. Do not start sentence with a conjunction. Do not fragment sentences. Eliminate one-word sentences. Ignore passive voice. Do not ever use a big word when a diminutive one would suffice. Verbs have to be in agreement with their subjects. Prepositions are not expressions to finish sentences with. It is incorrect to ever divide an infinitive. Avoid clichés like the disease. Also, always shun irritating alliteration. Use language that is simple and straight forward. put together a neat summary.

21. Arrangement of information: Each section of the main body should start with an opening sentence and there should be a changeover at the end of the section. Give only valid and powerful arguments to your topic. You may also maintain your arguments with records.

22. Never start in last minute: Always start at right time and give enough time to research work. Leaving everything to the last minute will degrade your paper and spoil your work.

23. Multitasking in research is not good: Doing several things at the same time proves bad habit in case of research activity. Research is an area, where everything has a particular time slot. Divide your research work in parts and do particular part in particular time slot.

24. Never copy others' work: Never copy others' work and give it your name because if evaluator has seen it anywhere you will be in trouble.

25. Take proper rest and food: No matter how many hours you spend for your research activity, if you are not taking care of your health then all your efforts will be in vain. For a quality research, study is must, and this can be done by taking proper rest and food.

26. Go for seminars: Attend seminars if the topic is relevant to your research area. Utilize all your resources.

27. Refresh your mind after intervals: Try to give rest to your mind by listening to soft music or by sleeping in intervals. This will also improve your memory.

28. Make colleagues: Always try to make colleagues. No matter how sharper or intelligent you are, if you make colleagues you can have several ideas, which will be helpful for your research.

29. Think technically: Always think technically. If anything happens, then search its reasons, its benefits, and demerits.

30. Think and then print: When you will go to print your paper, notice that tables are not be split, headings are not detached from their descriptions, and page sequence is maintained.

31. Adding unnecessary information: Do not add unnecessary information, like, I have used MS Excel to draw graph. Do not add irrelevant and inappropriate material. These all will create superfluous. Foreign terminology and phrases are not apropos. One should NEVER take a broad view. Analogy in script is like feathers on a snake. Not at all use a large word when a very small one would be sufficient. Use words properly, regardless of how others use them. Remove quotations. Puns are for kids, not grunt readers. Amplification is a billion times of inferior quality than sarcasm.

32. Never oversimplify everything: To add material in your research paper, never go for oversimplification. This will definitely irritate the evaluator. Be more or less specific. Also too, by no means, ever use rhythmic redundancies. Contractions aren't essential and shouldn't be there used. Comparisons are as terrible as clichés. Give up ampersands and abbreviations, and so on. Remove commas, that are, not necessary. Parenthetical words however should be together with this in commas. Understatement is all the time the complete best way to put onward earth-shaking thoughts. Give a detailed literary review.

33. Report concluded results: Use concluded results. From raw data, filter the results and then conclude your studies based on measurements and observations taken. Significant figures and appropriate number of decimal places should be used. Parenthetical remarks are prohibitive. Proofread carefully at final stage. In the end give outline to your arguments. Spot out perspectives of further study of this subject. Justify your conclusion by at the bottom of them with sufficient justifications and examples.

34. After conclusion: Once you have concluded your research, the next most important step is to present your findings. Presentation is extremely important as it is the definite medium though which your research is going to be in print to the rest of the crowd. Care should be taken to categorize your thoughts well and present them in a logical and neat manner. A good quality research paper format is essential because it serves to highlight your research paper and bring to light all necessary aspects in your research.

Informal Guidelines of Research Paper Writing

Key points to remember:

- Submit all work in its final form.
- Write your paper in the form, which is presented in the guidelines using the template.
- Please note the criterion for grading the final paper by peer-reviewers.

Final Points:

A purpose of organizing a research paper is to let people to interpret your effort selectively. The journal requires the following sections, submitted in the order listed, each section to start on a new page.

The introduction will be compiled from reference matter and will reflect the design processes or outline of basis that direct you to make study. As you will carry out the process of study, the method and process section will be constructed as like that. The result segment will show related statistics in nearly sequential order and will direct the reviewers next to the similar intellectual paths throughout the data that you took to carry out your study. The discussion section will provide understanding of the data and projections as to the implication of the results. The use of good quality references all through the paper will give the effort trustworthiness by representing an alertness of prior workings.

Writing a research paper is not an easy job no matter how trouble-free the actual research or concept. Practice, excellent preparation, and controlled record keeping are the only means to make straightforward the progression.

General style:

Specific editorial column necessities for compliance of a manuscript will always take over from directions in these general guidelines.

To make a paper clear

· Adhere to recommended page limits

Mistakes to evade

- Insertion a title at the foot of a page with the subsequent text on the next page
- Separating a table/chart or figure - impound each figure/table to a single page
- Submitting a manuscript with pages out of sequence

In every sections of your document

· Use standard writing style including articles ("a", "the," etc.)

· Keep on paying attention on the research topic of the paper

· Use paragraphs to split each significant point (excluding for the abstract)

· Align the primary line of each section

· Present your points in sound order

· Use present tense to report well accepted

· Use past tense to describe specific results

· Shun familiar wording, don't address the reviewer directly, and don't use slang, slang language, or superlatives

· Shun use of extra pictures - include only those figures essential to presenting results

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The summary should be two hundred words or less. It should briefly and clearly explain the key findings reported in the manuscript--must have precise statistics. It should not have abnormal acronyms or abbreviations. It should be logical in itself. Shun citing references at this point.

An abstract is a brief distinct paragraph summary of finished work or work in development. In a minute or less a reviewer can be taught the foundation behind the study, common approach to the problem, relevant results, and significant conclusions or new questions.

Write your summary when your paper is completed because how can you write the summary of anything which is not yet written? Wealth of terminology is very essential in abstract. Yet, use comprehensive sentences and do not let go readability for briefness. You can maintain it succinct by phrasing sentences so that they provide more than lone rationale. The author can at this moment go straight to shortening the outcome. Sum up the study, with the subsequent elements in any summary. Try to maintain the initial two items to no more than one ruling each.

- Reason of the study - theory, overall issue, purpose
- Fundamental goal
- To the point depiction of the research
- Consequences, including definite statistics - if the consequences are quantitative in nature, account quantitative data; results of any numerical analysis should be reported
- Significant conclusions or questions that track from the research(es)

Approach:

- Single section, and succinct
- As a outline of job done, it is always written in past tense
- A conceptual should situate on its own, and not submit to any other part of the paper such as a form or table
- Center on shortening results - bound background information to a verdict or two, if completely necessary
- What you account in an conceptual must be regular with what you reported in the manuscript
- Exact spelling, clearness of sentences and phrases, and appropriate reporting of quantities (proper units, important statistics) are just as significant in an abstract as they are anywhere else

Introduction:

The **Introduction** should "introduce" the manuscript. The reviewer should be presented with sufficient background information to be capable to comprehend and calculate the purpose of your study without having to submit to other works. The basis for the study should be offered. Give most important references but shun difficult to make a comprehensive appraisal of the topic. In the introduction, describe the problem visibly. If the problem is not acknowledged in a logical, reasonable way, the reviewer will have no attention in your result. Speak in common terms about techniques used to explain the problem, if needed, but do not present any particulars about the protocols here. Following approach can create a valuable beginning:

- Explain the value (significance) of the study
- Shield the model - why did you employ this particular system or method? What is its compensation? You strength remark on its appropriateness from a abstract point of vision as well as point out sensible reasons for using it.
- Present a justification. Status your particular theory (es) or aim(s), and describe the logic that led you to choose them.
- Very for a short time explain the tentative propose and how it skilled the declared objectives.

Approach:

- Use past tense except for when referring to recognized facts. After all, the manuscript will be submitted after the entire job is done.
- Sort out your thoughts; manufacture one key point with every section. If you make the four points listed above, you will need a least of four paragraphs.

- Present surroundings information only as desirable in order hold up a situation. The reviewer does not desire to read the whole thing you know about a topic.
- Shape the theory/purpose specifically - do not take a broad view.
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Procedures (Methods and Materials):

This part is supposed to be the easiest to carve if you have good skills. A sound written Procedures segment allows a capable scientist to replacement your results. Present precise information about your supplies. The suppliers and clarity of reagents can be helpful bits of information. Present methods in sequential order but linked methodologies can be grouped as a segment. Be concise when relating the protocols. Attempt for the least amount of information that would permit another capable scientist to spare your outcome but be cautious that vital information is integrated. The use of subheadings is suggested and ought to be synchronized with the results section. When a technique is used that has been well described in another object, mention the specific item describing a way but draw the basic principle while stating the situation. The purpose is to text all particular resources and broad procedures, so that another person may use some or all of the methods in one more study or referee the scientific value of your work. It is not to be a step by step report of the whole thing you did, nor is a methods section a set of orders.

Materials:

- Explain materials individually only if the study is so complex that it saves liberty this way.
- Embrace particular materials, and any tools or provisions that are not frequently found in laboratories.
- Do not take in frequently found.
- If use of a definite type of tools.
- Materials may be reported in a part section or else they may be recognized along with your measures.

Methods:

- Report the method (not particulars of each process that engaged the same methodology)
- Describe the method entirely
- To be succinct, present methods under headings dedicated to specific dealings or groups of measures
- Simplify - details how procedures were completed not how they were exclusively performed on a particular day.
- If well known procedures were used, account the procedure by name, possibly with reference, and that's all.

Approach:

- It is embarrassed or not possible to use vigorous voice when documenting methods with no using first person, which would focus the reviewer's interest on the researcher rather than the job. As a result when script up the methods most authors use third person passive voice.
- Use standard style in this and in every other part of the paper - avoid familiar lists, and use full sentences.

What to keep away from

- Resources and methods are not a set of information.
- Skip all descriptive information and surroundings - save it for the argument.
- Leave out information that is immaterial to a third party.

Results:

The principle of a results segment is to present and demonstrate your conclusion. Create this part a entirely objective details of the outcome, and save all understanding for the discussion.

The page length of this segment is set by the sum and types of data to be reported. Carry on to be to the point, by means of statistics and tables, if suitable, to present consequences most efficiently.You must obviously differentiate material that would usually be incorporated in a study editorial from any unprocessed data or additional appendix matter that would not be available. In fact, such matter should not be submitted at all except requested by the instructor.

Content

- Sum up your conclusion in text and demonstrate them, if suitable, with figures and tables.
- In manuscript, explain each of your consequences, point the reader to remarks that are most appropriate.
- Present a background, such as by describing the question that was addressed by creation an exacting study.
- Explain results of control experiments and comprise remarks that are not accessible in a prescribed figure or table, if appropriate.
- Examine your data, then prepare the analyzed (transformed) data in the form of a figure (graph), table, or in manuscript form.

What to stay away from

- Do not discuss or infer your outcome, report surroundings information, or try to explain anything.
- Not at all, take in raw data or intermediate calculations in a research manuscript.
- Do not present the similar data more than once.
- Manuscript should complement any figures or tables, not duplicate the identical information.
- Never confuse figures with tables - there is a difference.

Approach

- As forever, use past tense when you submit to your results, and put the whole thing in a reasonable order.
- Put figures and tables, appropriately numbered, in order at the end of the report
- If you desire, you may place your figures and tables properly within the text of your results part.

Figures and tables

- If you put figures and tables at the end of the details, make certain that they are visibly distinguished from any attach appendix materials, such as raw facts
- Despite of position, each figure must be numbered one after the other and complete with subtitle
- In spite of position, each table must be titled, numbered one after the other and complete with heading
- All figure and table must be adequately complete that it could situate on its own, divide from text

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The Discussion is expected the trickiest segment to write and describe. A lot of papers submitted for journal are discarded based on problems with the Discussion. There is no head of state for how long a argument should be. Position your understanding of the outcome visibly to lead the reviewer through your conclusions, and then finish the paper with a summing up of the implication of the study. The purpose here is to offer an understanding of your results and hold up for all of your conclusions, using facts from your research and generally accepted information, if suitable. The implication of result should be visibly described. Infer your data in the conversation in suitable depth. This means that when you clarify an observable fact you must explain mechanisms that may account for the observation. If your results vary from your prospect, make clear why that may have happened. If your results agree, then explain the theory that the proof supported. It is never suitable to just state that the data approved with prospect, and let it drop at that.

- Make a decision if each premise is supported, discarded, or if you cannot make a conclusion with assurance. Do not just dismiss a study or part of a study as "uncertain."
- Research papers are not acknowledged if the work is imperfect. Draw what conclusions you can based upon the results that you have, and take care of the study as a finished work
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- Give details all of your remarks as much as possible, focus on mechanisms.
- Make a decision if the tentative design sufficiently addressed the theory, and whether or not it was correctly restricted.
- Try to present substitute explanations if sensible alternatives be present.
- One research will not counter an overall question, so maintain the large picture in mind, where do you go next? The best studies unlock new avenues of study. What questions remain?
- Recommendations for detailed papers will offer supplementary suggestions.

Approach:

- When you refer to information, differentiate data generated by your own studies from available information
- Submit to work done by specific persons (including you) in past tense.
- Submit to generally acknowledged facts and main beliefs in present tense.

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- The **major constraint** is that you must independently make all content, tables, graphs, and facts that are offered in the paper. You must write each part of the paper wholly on your own. The Peer-reviewers need to identify your own perceptive of the concepts in your own terms. NEVER extract straight from any foundation, and never rephrase someone else's analysis.
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Topics	Grades		
	A-B	**C-D**	**E-F**
Abstract	Clear and concise with appropriate content, Correct format. 200 words or below	Unclear summary and no specific data, Incorrect form Above 200 words	No specific data with ambiguous information Above 250 words
Introduction	Containing all background details with clear goal and appropriate details, flow specification, no grammar and spelling mistake, well organized sentence and paragraph, reference cited	Unclear and confusing data, appropriate format, grammar and spelling errors with unorganized matter	Out of place depth and content, hazy format
Methods and Procedures	Clear and to the point with well arranged paragraph, precision and accuracy of facts and figures, well organized subheads	Difficult to comprehend with embarrassed text, too much explanation but completed	Incorrect and unorganized structure with hazy meaning
Result	Well organized, Clear and specific, Correct units with precision, correct data, well structuring of paragraph, no grammar and spelling mistake	Complete and embarrassed text, difficult to comprehend	Irregular format with wrong facts and figures
Discussion	Well organized, meaningful specification, sound conclusion, logical and concise explanation, highly structured paragraph reference cited	Wordy, unclear conclusion, spurious	Conclusion is not cited, unorganized, difficult to comprehend
References	Complete and correct format, well organized	Beside the point, Incomplete	Wrong format and structuring

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