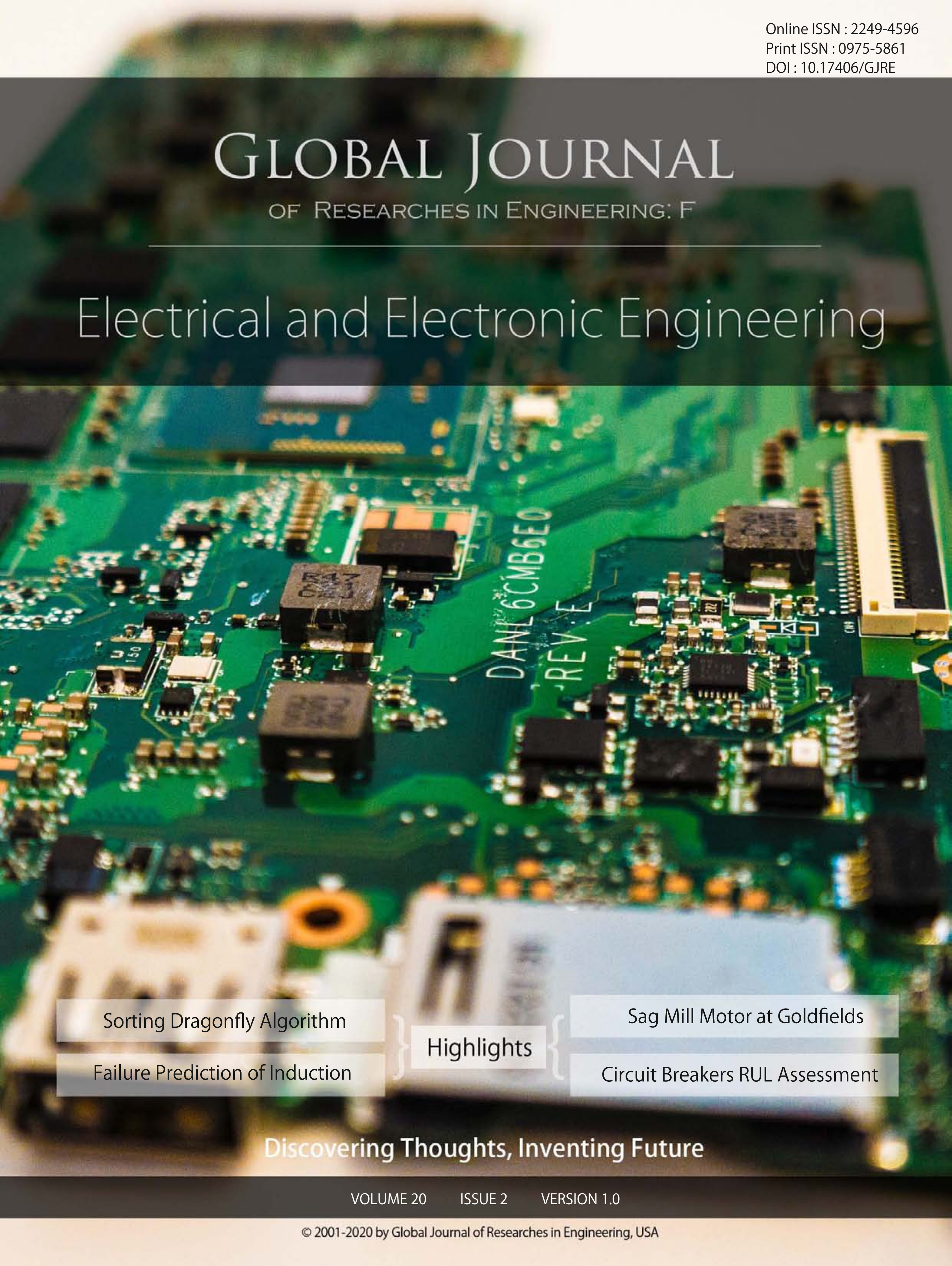
Online ISSN : 2249-4596
Print ISSN : 0975-5861
DOI : 10.17406/GJRE

Global Journal

of Researches in Engineering: F

Electrical and Electronic Engineering



Highlights

- Sorting Dragonfly Algorithm
- Failure Prediction of Induction
- Sag Mill Motor at Goldfields
- Circuit Breakers RUL Assessment

Discovering Thoughts, Inventing Future

VOLUME 20 ISSUE 2 VERSION 1.0

Global Journal of Researches in Engineering: F
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Volume 20 Issue 2 (Ver. 1.0)

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Global Journal of Research in Engineering

Contents of the Issue

Global Journal of Researches in Engineering: F
Electrical and Electronics Engineering
Volume 20 Issue 2 Version 1.0 Year 2020
Type: Double Blind Peer Reviewed International Research Journal
Publisher: Global Journals
Online ISSN: 2249-4596 & Print ISSN: 0975-5861

Analysis of Weibull and Poisson Distribution use in Medium Voltage Circuit Breakers RUL Assessment

By Dragan Stevanovic

Abstract- In this paper, Weibull and Poisson distribution calculation are carried out with new data to conclude a conclusion are they suitable for circuit breakers remaining useful life assessment (RUL). Old data are covering a 10 years period consisting of measured voltage drop on CB contacts and number of tripped short circuit faults. In this paper, new data, from the last 3 years, would be used to make a comparison with old data and make conclusions have been probability distributions correctly chosen.

Keywords: circuit breaker, weibull, poisson, remaining useful life, risk.

GJRE-F Classification: FOR Code: 290903p

ANALYSISOFWEIBULLANDPOISSONDISTRIBUTIONUSEINMEDIUMVOLTAGECIRCUITBREAKERSRULASSESSMENT

Strictly as per the compliance and regulations of:

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I. Introduction

Electrical companies nowadays are facing a lot of pressure considering equipment maintenance or replacement on the one hand and reducing operating expenses on another hand. Maintaining old equipment can be an expensive task, and that's why power network operators should create a strategy of a most cost-effective method of equipment maintenance or replacement.

The same situation about equipment maintenance is happening at the Power Industry of Serbia. Among other equipment circuit breakers (CB) are a matter of concern, because most of CB's that are currently in operation are installed during 70es and 80es (minimum oil CB's), which means that they are at the end of their life, which is period characterized by increased number of faults and consequently increased maintenance.

Findings in this paper represent continuing of CB's RUL assessment [1]. After gathering recent data, it is useful to investigate results from previous research and try to make new conclusions.

In previous research [1], using Weibull distribution we determine CB's probability of failure by analyzing voltage drop values on its contacts, and using Poisson distribution the probability of failure if the number of short circuit trips exceeds limit value.

Both distributions were already used in literature and research for similar problems.

In [2], Weibull distribution was used for statistical analysis of age or wear out related CB faults.

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In[3],Poisson distribution was used for modeling component faults in the power system with statistical data from maintenance and repairs.

In [4] presents analysis of fault types and their consequences, with cost structure and maintenance strategies. During wear out period fault intensity of high voltage (HV) CB's follows Weibull distribution.

In [5], analysis of SF6 and minimum oil, CB's faults were performed. Research includes totally 1546 CB's from the Swedish and Finland power systems. Weibull distribution is assessing the RUL of CB's components, which were the source of the fault.

In [6] they use the same distribution for reliability, RUL, and fault intensity assessment of HV SF6 CB's.

In [7], few modified models of Weibull distribution were purposed for equipment reliability assessment in the power system. Least Squares method estimates parameters of Weibull distribution.

In [8] they use the same method for parameter estimation, where researchers are creating transformer lifetime model with Weibull distribution based on condition monitoring data.

II. Weibull Distribution Assessment

Basic recommendations when choosing distribution are following [9]:

- Choose distribution, which researchers most frequently use in the same field of work.
- Choose distribution, which gives the most conservative results.
- Choose a simpler type of distribution. For example, if two-parameter distribution gives similar results like three-parameter distribution, then two-parameter distribution should be used.

Researchers deploy Weibull distribution very often when equipment aging and reliability has to be analyzed [10]. Weibull distribution can describe three types of equipment states (infant mortality, a period of normal work, wear out state) through the bathtub curve [11].

Weibull cumulative distribution function represents the probability of failure in a given period(1). In this case, two-parameter distribution was used, which consists of slop parameter (η) and shape parameter (β).

Global Journal of Researches in Engineering (F) Volume XX Issue II Version I Year 2020

$$F(t) = 1 - e^{-\left(\frac{t}{\eta}\right)^{\beta}} \quad (1)$$

Slop parameter shows the time at which 63.2% of analyzed units fails. The shape parameter represents failure rate behavior and tells whether failures are decreasing or increasing. Shape parameter value has the following meaning:

- $\beta<1$ indicates infant mortality,
- $\beta=1$ period of normal work
- $\beta>1$ wear-out failures. The higher value of beta indicates a greater rate of failure.

a) Data analysis with Weibull distribution

One power company (which is part of the Electrical Industry of Serbia) owns all CB's which are part of analysis, and the same specialized work force is maintaining and monitoring their work years back. Totally 427 CB's were part of the analysis, and their monitoring process started in 2007.

This research consists of two separate periods. Data for the first research are including period of 10 years (2007-2017), after that, next research includes new data from the last three years (2017-2020).

One of the main goals is to conclude whether new data follow Weibull distribution and is it justifiable to use it for this type of RUL assessment.

The calculation covers CB's in 5 different categories (considering feeder type and rated voltage) and with two subcategories (1. Normal voltage drop value, 2. Permissible voltage drop value is by 25% larger [12]), making that way ten different categories in total. By this categorization, we can observe RUL more clearly, and come to the conclusion what makes the greatest influence on CB's aging process.

Minitab 17 software and least square method [13] calculates Weibull distribution function with right-censored data (case when some devices didn't fail during the period of analysis) for all CB's categories.

For old and new data following values were calculated and compared: Weibull parameters and correlation coefficient. Table 1 shows all calculated values.

Table 1: Correlation coefficient values with old and new data

Feeder type	Correlation coefficient	
	until 2017 yr.	until 2020 yr.
Overhead +25%	0.985	0.986
Overhead	0.993	0.997
Underground +25%	0.976	0.984
Underground	0.965	0.977
10 kV feeders +25%	0.988	0.995
10 kV feeders	0.989	0.992
35 kV feeders +25%	0.972	0.971
35 kV feeders	0.984	0.989
All feeders +25%	0.989	0.988
All feeders	0.990	0.993

By observing the results of calculated correlation coefficient, it is obvious that with an increased number of the data correlation coefficient is becoming greater, which means that data are becoming closer to Weibull distribution.

Next, Weibull parameters (scale parameter and shape parameter) were calculated with new data and compared with old ones (Table 2). By observing Weibull parameters from table 2, two conclusions could be made (taking into account the results from a previous paper [1]); underground feeders (both criteria of voltage drop value limit) have the highest β while overhead feeder has the lowest value. Considering η parameter, 10 kV feeders (+25% limit voltage drop level) have a longer time to failure, while 35kV feeders have the lowest η value (they will fail sooner than 10kV CB's).

Table 2: Weibull parameters with old and new data

	Old data			New data		
Feeder type	η	β	Failed \ suspensions	η	β	Failed \ suspensions
Overhead +25%	39.09	5.147	100/87	39.42	5.069	111/78
Overhead	37.08	4.797	131/56	37.42	4.935	141/48
Underground +25%	41.54	6.055	63/169	44.52	5.268	66/167
Underground	38.09	6.070	97/135	40.23	5.490	101/134
10 kV feeders +25%	43.44	5.627	87/224	45.50	5.100	97/215
10 kV feeders	40.39	5.071	135/176	42.00	4.918	142/172
35 kV feeders +25%	35.24	5.593	79/31	35.78	5.419	80/30
35 kV feeders	33.83	5.615	96/14	34.14	5.662	99/11
All feeders +25%	40.37	5.582	166/255	41.77	5.206	177/245
All feeders	37.98	5.281	231/190	39.16	5.134	242/182

In Table 2, values are showing expected aging phenomena. The number of failed CB's is increasing, but on the other hand, with a greater number of data, a new insight could be perceived. Scale parameter (η) is, in most cases, slightly increased, which suggests that RUL is not as we were expecting with old data and that CB's survival time is slightly greater compared with previous research.

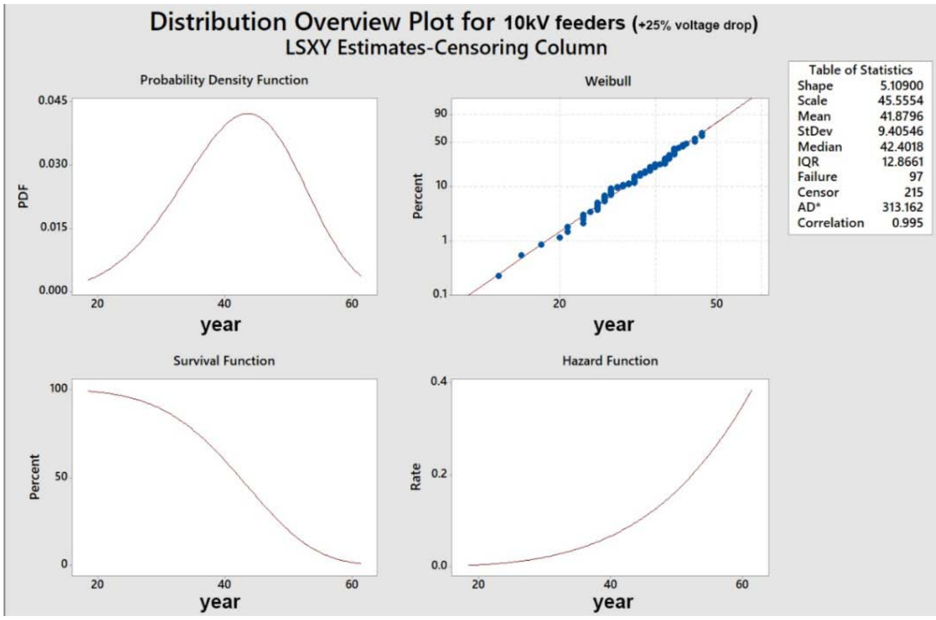

Figure 1: Example of Weibull distribution graphs and values for 10kV feeders +25%

III. Poisson Distribution Assessment

Poisson distribution [14, 15] is the discrete distribution used for modeling a number of events which are appearing in a specific period. Poisson distribution for calculation probability for a known number of past events (*k*) in the time interval (*t*) is [16]:

$$P(k) = \frac{(\lambda t)^k e^{-\lambda t}}{k!} \quad (2)$$

Where is:

k – the number of faults in period (*t*)
λ – fault intensity
t – a time interval
$P(r)$ – the probability of appearing *r* number of faults in period *t*

Cases of Poisson distribution use[17]:

1. Researcher can present an event with the whole number
2. The occurrence of an event doesn't depend on any other event
3. Mean value of event occurrence in a specific period is known
4. Number of events is countable

In the power system, Poisson distribution can predict faults such as short circuit faults. The number of those faults depends on feeder type (underground or overhead) and also by the area configuration where power network is situated (residential area, forest). Another influencing factor is weather condition and power network quality.

Procedure for Chi-Square Goodness of Fit Test

One of the methods for determining are date follow Poisson distribution is the Chi-squared test (χ^2 test). This method represents a test of statistical hypothesis and is used to determine a significant difference between expected and observed intensity [18].The Chi-squared test can test hypothesis do analyze data follow a certain distribution. It can also test Poisson distribution[19]. The calculation is carried out in the following way [20, 21]:

$$\chi^2 = \sum \frac{(O-E)^2}{E} \quad (3)$$

Where is:

χ^2–Chi-squared value
O – observed value
E – expected value

1. Hypothesis formulation:
   a. Null hypothesis: H_0: data *X*is following Poisson distribution- $X \sim Poisson$
   b. Alternative hypothesis: H_1: data *X* doesn't follow a Poisson distribution
2. Calculation of Chi-squared test:
   Table 3 presents a number of short circuit trips on one 10kV feeder.

Table 3: Number of observed short-circuit trips on 10kV feeder

Year	Number of trips
2013	0
2014	0
2015	0
2016	0
2017	0
2018	1
2019	1

Using values from table 3, we calculate each fault intensity (Table 4).

Table 4: Faults intensity in a period of 7 years

Number of faults (k)	Intensity (n)
0	5
1	2
2	0
3	0
4	0
5	0
6	0
7	0
8	0
9	0
>10	0

K represents a number of faults during *n*=*7* years.

The mean of the Poisson distribution is:

$$\lambda = \frac{(0\cdot5+1\cdot2+2\cdot0+3\cdot0+4\cdot0+5\cdot0+6\cdot0+7\cdot0+8\cdot0+9\cdot0+10\cdot0)}{7}$$

$$\lambda = 0.2857 \quad (4)$$

Example (5) and 6) are presenting expected fault intensity calculation, and the table 5 presents values of that calculation.

$$p_0 = P(K=0) = \frac{e^{-0.2857}(0.2857)^0}{0!} = 0.7515 \quad (5)$$

$$E_0 = 0.7515\cdot 7 = 5.26 \quad (6)$$

Table 5: Expected number of faults

Number of faults (k)	Poisson	Observed	Expected (E_0)
0	0.7515	5	5.2603
1	0.2147	2	1.5030
2	0.0307	0	0.2147
3	0.0029	0	0.0204
4	0.0002	0	0.0015
5	0.0000	0	0.0001
6	0.0000	0	0.0000
7	0.0000	0	0.0000
8	0.0000	0	0.0000
9	0.0000	0	0.0000
>10	0.0000	0	0.0000

Calculation of Chi-squared value:

$$\chi^2 = \sum\frac{(O-E)^2}{E} = \frac{(5-5.2603)^2}{5.2603} + \frac{(2-1.5030)^2}{1.5030} + \frac{(0-0.2147)^2}{0.2147} + \frac{(0-0.0015)^2}{0.0015}\ldots$$

$$\chi^2 = 0.4139 \quad (7)$$

Degrees of freedom are $k-g-1$. In this case number of classes is $k=11$ (number of faults intensity), and from data we estimate one parameter $g=1$ (in this case one parameter, λ). In the end, degrees of freedom are equal to 11-1-1=9.

Value of significance level is selected to be 0.05. That value means there is a 5% probability that the observed relationship between variables exists by coincidence [22]; in other words, data doesn't follow assumed distribution [23].

Table 6: Table of critical values

Chi-square Distribution Table

d.f.	.995	.99	.975	.95	.9	.1	.05	.025	.01
1	0.00	0.00	0.00	0.00	0.02	2.71	3.84	5.02	6.63
2	0.01	0.02	0.05	0.10	0.21	4.61	5.99	7.38	9.21
3	0.07	0.11	0.22	0.35	0.58	6.25	7.81	9.35	11.34
4	0.21	0.30	0.48	0.71	1.06	7.78	9.49	11.14	13.28
5	0.41	0.55	0.83	1.15	1.61	9.24	11.07	12.83	15.09
6	0.68	0.87	1.24	1.64	2.20	10.64	12.59	14.45	16.81
7	0.99	1.24	1.69	2.17	2.83	12.02	14.07	16.01	18.48
8	1.34	1.65	2.18	2.73	3.49	13.36	15.51	17.53	20.09
9	1.73	2.09	2.70	3.33	4.17	14.68	16.92	19.02	21.67
10	2.16	2.56	3.25	3.94	4.87	15.99	18.31	20.48	23.21

In table 6 for the number of degrees of freedom and significance level of 0.05, the critical value is 16.92. This value shows at which χ^2 value H0 hypothesis is acceptable. [24]

If $\chi^2 < 16.92$ (illustratedin figure 2) than the H0 hypothesis is acceptable, which means there is no evidence that the data doesn't follow Poisson distribution.

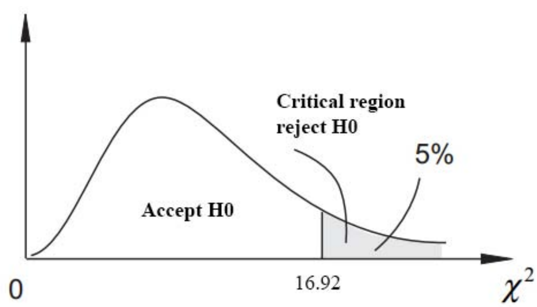

Figure 2: Graphical representation of Chi-squared test

After analyzing faults on all CB's, results are presented in Table 7.

Table 7: Results of Chi-square goodness of fit test

Number of CB's where H_0 hypothesis is accepted (data follow Poisson distribution)	Number of CB's where H_0 hypothesis is rejected
148	19
89 %	11 %

Results are showing that in most cases (89%), data are following Poisson distribution. Analysis of short circuit faults will continue in the future periods to determine will the bigger amount of data increase fit to Poisson distribution.

IV. Conclusion

In this paper, new data are used to check the correctness of methods used in previous research. New data are showing that with an increased number of samples, fit to Weibull distribution becomes greater. Better fit to the Weibull distribution becomes obvious by observing the values of the correlation coefficient of Weibull distribution with old and new data. Shape and scale parameters are showing that survival time is different from previous assessment and that CB's RUL is a little bit greater than in previous research.

Chi-squared Goodness of fit shows that almost 90% of current data of short circuit faults are following Poisson distribution. With Poisson distribution, CB's probability of failure in the next period could be very easily assessed.

This paper proves that it is justifiable to use Weibull and Poisson distribution for CB's remaining useful life estimation. With these two methods, CB's RUL could be calculated very fast and easy which could be later used for other studies such as risk assessment, power station reliability assessment, determining critical points in the power system, or justification of CB replacement.

Research in this field will be continued by gathering data from other power operators in the Power Industry of Serbia to better understand the problem of the CB aging process by using voltage drop values and short circuit faults.

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Global Journal of Researches in Engineering: F
Electrical and Electronics Engineering
Volume 20 Issue 2 Version 1.0 Year 2020
Type: Double Blind Peer Reviewed International Research Journal
Publisher: Global Journals
Online ISSN: 2249-4596 & Print ISSN: 0975-5861

Failure Prediction of Induction Motors: A Case Study using CSLGH900/6-214, 5.8 MW, 11 kV/3ph/50 Hz Sag Mill Motor at Goldfields, Damang Mine

By C. K. Amuzuvi & H. Warden
University of Mines and Technology

Abstract- This paper proposes a generalised feed-forward artificial neural network model that fulfils the failure prediction of a three phase 5.8MW, 11 kV Slip-Ring SAG Mill Induction Motor at Goldfields Ghana Limited, Damang Mine. It provides a general understanding of three phase induction motors, faults associated with induction motors and also emphasizes the use of intelligent systems, particularly artificial neural network, a modern failure prediction technology of induction motors. Site analysis and motor data (Current, Power and Winding Temperatures) collection were conducted at the Damang Mine. Simulation results are presented using MATLAB software (2017a) package to develop the fault prediction model. The proposed feed-forward neural network used the Levenberg-Marquardt and Bayesian Regularisation in training.

Keywords: SAG mill induction motor, feed-forward neural network, multilayer perceptron.

GJRE-F Classification: FOR Code: 090699

FAILUREPREDICTIONOFINDUCTIONMOTORSACASESTUDYUSINGCSLGHMWKVPHSOHZSAGMILLMOTORATGOLDFIELDSDAMANGMINE

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Keywords: SAG mill induction motor, feed-forward neural network, multilayer perceptron.

I. Introduction

Damang Gold Mine, a subsidiary of Goldfields International is a world class mining operation consisting of a 25 MTPA open pit mining and a 5.2 MTPA Carbon in Leach (CIL) metallurgical plant. Located in the south western part of Ghana, 300 km by road from the capital of Ghana, Accra, the mine exploits oxide and fresh hydrothermal mineralization in addition to Witwatersrand – style transitional paleo placer gold. The plant is designed to treat 5.2 MTPA of gold ore from a blend of approximately 20% oxide ore and 80% fresh ore sourced from various open pit mining operations. Process feed for the 12-month period of 2016 comprised 4.3 Mt at a yield of 1.17 g/t for a 148 koz of gold.

The plant has 2×5.8 MW ball mill and sag mill, a 1×600 kW primary gyratory crusher, 1×375 kW pebble crusher, 8×CIL tanks and a secondary crushing plant with a maximum electric power draw of 17.5 MW at peak times. The mine uses a lot if induction motors at the crushing circuit, milling circuit, CIL circuit, elution circuit, tailings, etc., because of its strength, mechanical simplicity and adaptability to a variety of applications [1]. The plant is often faced with issues associated with burnt induction motors. Unfortunately, the exact causes are not clearly known.

Induction motors are the mainstay for every industry. They are widely used in transportation, mining, petrochemical, manufacturing and in almost every other field using electrical power. These motors are simple, efficient, highly robust and rugged, thus, offering a very high degree of reliability. However, like any other machine, they are susceptible to faults, which if left unmonitored, might lead to catastrophic failure of the machine in the long run especially due to heavy duty cycles, poor working environment alongside with installation and manufacturing factors.

In a bid to detect fault and avoid complete breakdown of induction motors with its concomitant production losses, on-line condition monitoring of the induction motors must be implemented for effective operation of these machines. With increasing demands for reliability and efficiency, fault prediction in induction motors has become necessary, particularly in industries that make use of these rotary equipment of which the Damang Gold Mine is no exception [2]. Various fault conditions of induction motors as well as methods of their detection and prediction are presented in this paper.

a) Some Impacts of the Occurrence of Faults

With the mines current maintenance cost of electrical motors on the high, the mine must come up with strategies to bring the overall cost of engineering maintenance down. Figure 1(a) is a graph showing annual motor change-out from 2012 to 2016 and Figure

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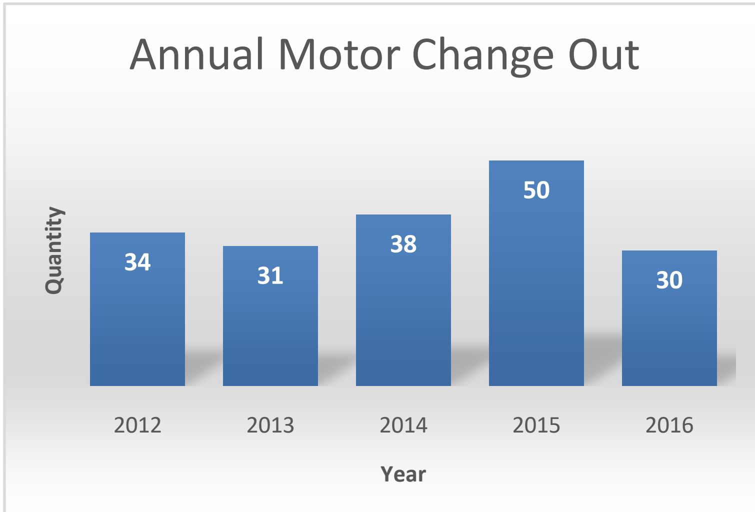
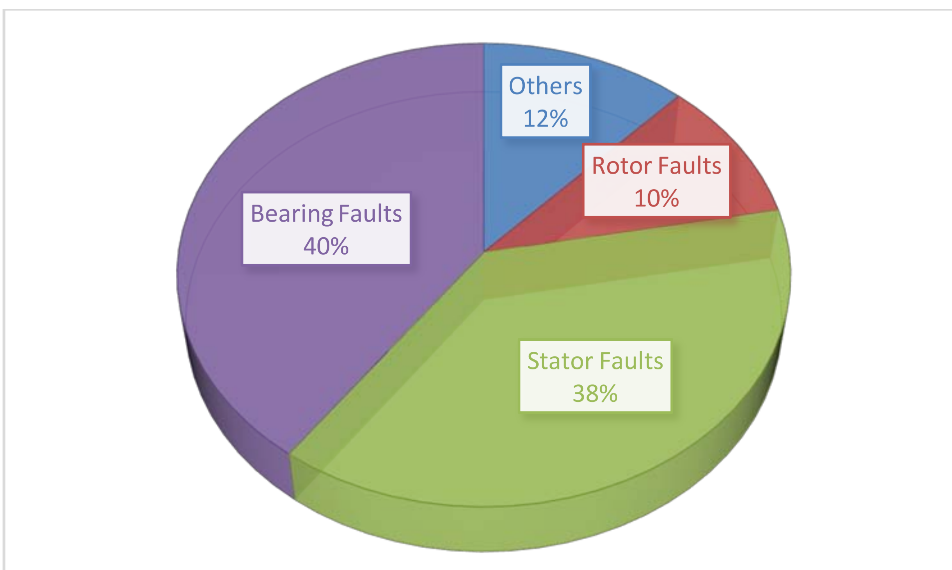
Author σ: Goldfields Ghana Limited, Damang Mine, Damang, Ghana.

1(b) is the probability of occurrence of faults in an operating induction motor [2]. Research has shown that, failures associated with induction motors are often caused by rotor, stator, and bearing failures, etc. [2].

With the current price of gold on the downside, the maintenance department is under intense pressure to efficiently maintain the plant machinery to continue to stay in business. Table 1 show gold prices from 2012 to 2016 respectively. This research work seeks to identify and assess in detail, all the various root causes of induction motor failures in the mine and suggest a means of accurately predicting future failures.



(a)



(b)

Figure 1: (a) Graph Showing Number of Annual Motor Change – Out; and (b) Probability of Occurrence of Faults

Table 1: Gold Price from 2012 to 2016 Year

Year	Closing Price	Year Open	Year High	Year Low	Year Close	% Change
2012	$1,668.86	$1,590.00	$1,790.00	$1,537.50	$1,664.00	5.68%
2013	$1,409.51	$1,681.50	$1,692.50	$1,192.75	$1,201.50	−27.79%
2014	$1,266.06	$1,219.75	$1,379.00	$1,144.50	$1,199.25	−0.19%
2015	$1,158.86	$1,184.25	$1,298.00	$1,049.60	$1,060.20	−11.59%
2016	$1,251.92	$1,075.20	$1,372.60	$1,073.60	$1,151.70	8.63%

(Source: [3])

b) Induction Motor

An induction motor is a type of asynchronous alternating current (AC) motor, where power is supplied to the rotating device (rotor) by means of electromagnetic induction. There are two types, namely wound or slip-ring induction motor and squirrel-cage induction motor.

Squirrel-cage induction motors are the preferred choice for industries due to their low cost, high reliability, absence of slip-rings and brushes, which eliminate the risk of sparking thereby, making them explosion proof with high efficiency over a wide range of power outputs. They also have the ability of speed control. From a constant frequency source, they operate as constant speed drives. For continuous speed control over a wide speed range, a solid-state variable-frequency converter provides an indirect source of supply [4].

c) Induction Motor Failure

Induction motors are rugged, low cost, low maintenance, reasonably small sized, reasonably highly efficient and operating with an easily available power supply. They are reliable in operations but are subject to different types of undesirable faults.

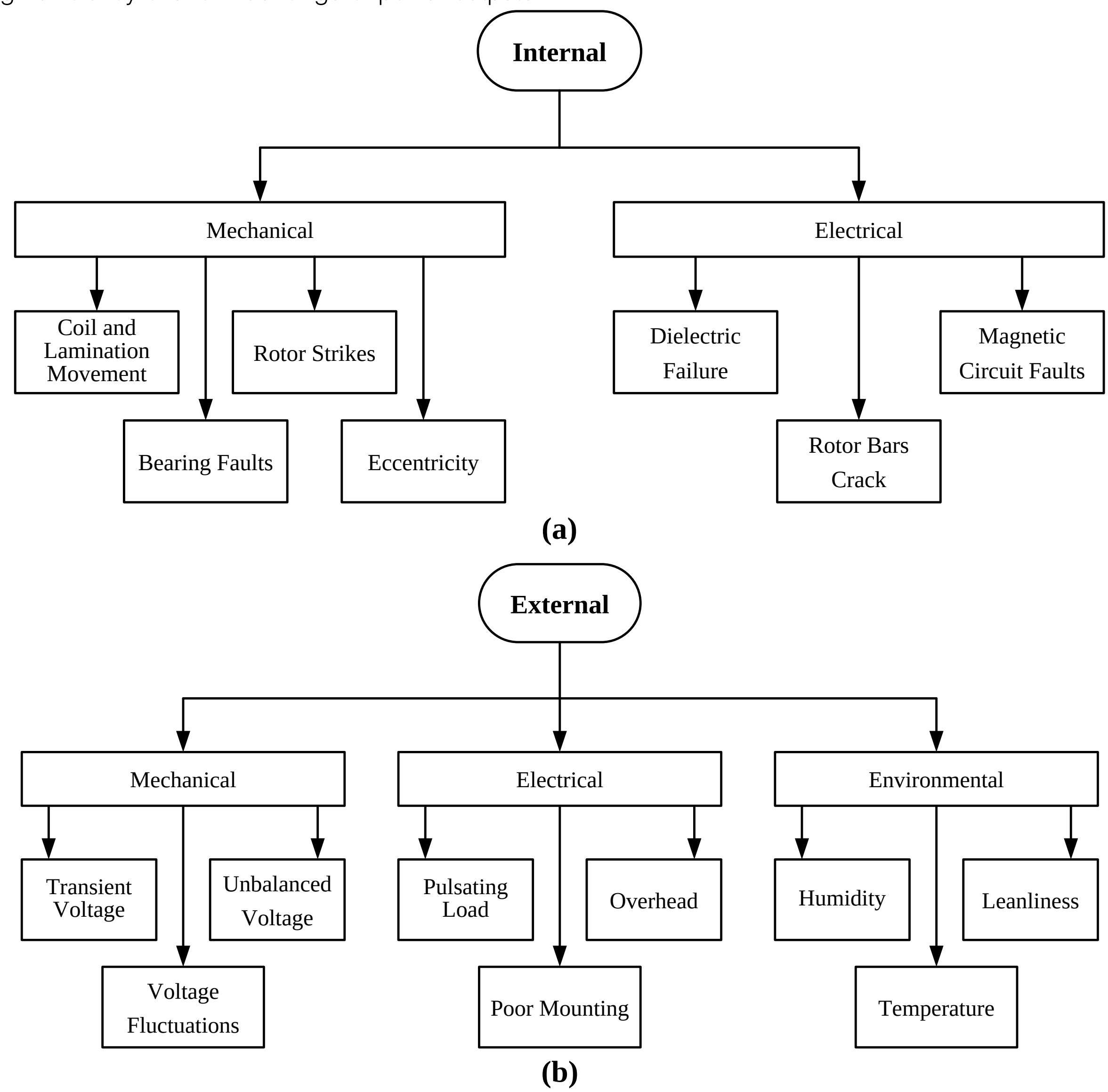
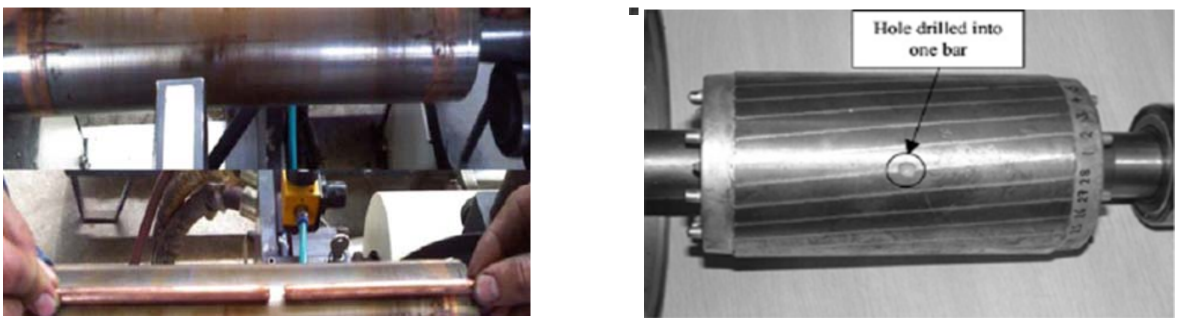


Figure 2: (a) Block Diagram Presentation of Internal Faults; and (b) Block Diagram Representation of External Faults

Sources of induction motor faults may be internal or external. In Figure 2(a) and Figure 2(b) [2], block diagrams of internal and external faults are depicted. The most vulnerable parts for fault in the induction motor are bearing, stator winding, rotor bar, and shaft. Besides, due to non-uniformity of the air gap between stator-inner surface and rotor-outer surface, motor faults occur [5]. Faults in induction motors can be categorized as:

1. Electrical-related faults due to unbalance supply voltage or current, single phasing, under or over voltage or current, reverse phase sequence, earth fault, overload, inter-turn short-circuit fault, and crawling;
2. Mechanical-related faults due to broken rotor bar, mass unbalance, air gap eccentricity, bearing damage, rotor winding failure and stator winding failure; and
3. Environmental-related faults such as ambient temperature, external moisture as well as vibrations of machine due to reasons like installation defect and foundation defect affect the performance of induction motor.

Figure 3(a) [5] show the rotor and parts of a broken rotor bar and Figure 3(b) a rotor with mass unbalance fault, with a hole drilled into one bar.



(a) **(b)**

Figure 3: (a) Photograph of Rotor and Parts of Broken Rotor Bar; and (b) Rotor with Mass Unbalance Fault

Industrial processes make use of a large number of asynchronous motors even in sensitive applications. Consequently, a defect can induce high losses in terms of cost and can be dangerous in terms of security and safety. Motor failures are mostly directly or indirectly caused by insulation breakdown, bearing wear or extensive heating of different motor parts involved in motor operation [6]. Multiple faults may occur simultaneously in an induction motor, which may result in unbalanced stator currents and voltages, oscillations in torque, reduction in efficiency and torque, overheating and excessive vibration. Normally, electric motors do not fail suddenly. It happens over time and regular inspection will detect a problem before a serious situation develops. Three main components of electric motors that experience faults are the stator, rotor and bearings. These faults may be a growing one with only small effects on the operation, a partial non-catastrophic one with emergency operation possible or a catastrophic one with total drive breakdown [6]. Incipient fault detection is preferably done to find faults before complete motor failure in order to avoid service downtime and large losses.

d) Condition Monitoring and Its Necessity

Induction motors are the main workhorse of industrial prime movers due to their ruggedness, low cost, low maintenance, reasonably small size, reasonably high efficiency, and operating with an easily available power supply. About 50% of the total generated power of a nation is consumed by these induction motors[5]. These statistics gives an idea regarding the use of huge number of induction motors, but they have some limitations in their operating conditions. If these conditions are exceeded, then some premature failure may occur in the stator or/and rotor. This failure, in many applications in industry, may lead to a shut down, even, the entire industrial process resulting in loss of production time and money. It is, therefore, an important issue to avoid any kind of failure of an induction motor. Operators and technicians of induction motors are under continual pressure to prevent unscheduled downtime and also to reduce maintenance cost of motors.

Maintenance of electrical motors can be done in three forms: breakdown maintenance, fixed-time maintenance, and condition-based maintenance. In breakdown maintenance, the strategy is 'run the motor until it fails' which means maintenance action is taken only when the motor gets breakdown. In this case, though the motor may run comparatively for a long time before the maintenance is done, when breakdown occurs, it is necessary to replace the entire machine, which is much costlier compared to replacing or repairing the faulty parts of the motor. Also, it causes loss of productivity due to downtime.

In fixed-time maintenance, the motor is required to stop for inspection, which causes long downtime. Also, trained and experienced technical persons are required to recognise each and every fault correctly. All these necessitate the condition-based maintenance of the motor. In this form of maintenance, the motor is allowed to run normally and action is taken at the very first sign of an incipient fault.

In condition monitoring, when a fault has been identified, sufficient data is required for the plant operator for the best possible decision making on the correct course of action. If the data is insufficient, there remains the chance for wrong diagnosis of fault, which leads to inappropriate replacement of components, and if the root of the problem is not identified properly, the replacement or any other action taken already will succumb to the same fate. In condition monitoring, signals from the concerned motor are continuously fed to the data acquisition system and the health of the motor is continuously evaluated during its operation for which it is also referred as online condition monitoring of the motor, and hence, it is possible to identify the faults even while they are developing. The operator/technician can take preparation for the preventive maintenance and can arrange for necessary spare parts in advance, for repairing. Thus, condition monitoring can optimise maintenance schedule and minimise motors downtime and thereby increase the reliability of the motor. Advantages of using condition monitoring can be mentioned point wise as follows:

1. Prediction of motor failure;
2. Optimisation of the maintenance schedule of the motor;
3. Reduction of maintenance cost;
4. Reduction of the downtime of the machine; and
5. Improvement of the reliability of the motor.

Condition monitoring and fault detection are usually carried out by investigating the corresponding anomalies in the machine current, voltage and leakage flux. Other methods include monitoring the core temperature, bearing vibration level and pyrolysed products. Fault conditions such as insulation defects and bearing degradation may also be diagnosed [2].

e) Failure Prediction Methods or Techniques

According to [7], online failure prediction aims to identify situations that will evolve into a failure. Classification of failure prediction methods are usually based on the type of input data used, namely: data from failure tracking, symptom monitoring, detected error reporting and undetected error auditing. System monitoring, however, is mostly used as it is effective and offers reliable data based on analysis of time series and/or type of symptoms. In order to build high availability systems based on failure prediction, methods are developed not only to capture, select, or interpret essential data and predict future system states but also to provide proactive recovery and failure avoidance schemes, which build on these predictions and help to self-manage the system.

Thus, it has become necessary to diagnose motor faults for effective maintenance plans by management, so as to avoid complete failure of systems or machines in the future. Using baseline characteristics of a healthy motor as a reference data, any deviation in motor operating characteristics obtained from system monitoring may be used to perform fault detection and diagnosis, irrespective of unavoidable manufacturing defects in the system. Depending on the region of fault occurrence, five main categories of faults, namely: stator faults, eccentricity faults, rotor faults, bearing faults and vibration faults are diagnosed based on various failure prediction methods [2].

i. *Vibration Spectrum Analysis*

This technique is used to detect bearing faults. High frequency components of vibration are created due to friction or forces occurring in the rolling element bearing in electrical machines under normal conditions. In case of a defect in the bearings or breaks in the lubrication layer between the friction surfaces, shock pulses are produced.

The method analyses the vibration spectrum of an induction machine using piezoelectric accelerometer, which works on Fast Fourier Transform to extract from a time domain signal, the frequency domain representation. In diagnosing bearing fault, the harmonic vibration spectrum of the healthy motor and that with defective bearing is analysed individually. Upon comparison, it is realized that the vibration amplitude for faulty motor is larger than that of a healthy motor. Dynamic simulation of motor running with bearing fault to analyse frequency spectrum of electromagnetic torque produced by the faulty motor may provide similar result when compared with its vibration spectrum.

ii. *Park Vector Approach and Complex Wavelets*

Park vector transformation approach is used to diagnose stator faults on a three-phase induction motor due to the impact of fault on the machine current. This technique uses Park's Transform to derive a two-dimensional Park's current vector components, which are expressed as functions of the phase currents of the three-phase induction motor. Thus, the locus of instantaneous spatial vector sum of the measured three phase stator currents forms the basis for Park's vector.

This maps a circle, which has its centre at the origin of the coordinates. This locus is distorted by stator winding faults and thus provides easy fault diagnosis. In other words, a graphical representation of the Park's current vector for a faulty motor gives an elliptical shape, which is a distortion of the circularly shaped Park's current vector representation of a healthy motor. The amount of distortion of the circular shape depends on the level of stator fault of the motor. Simulation and experimental results are finally analysed using complex wavelets.

iii. *Motor Current Signature Analysis (MCSA)*

This technique can be used to detect rotor faults and eccentricity. In case of a fault, current harmonics in the stator current, caused by a backward rotating field in the air gap, are analysed by MCSA. This requires only one current sensor, whose function is based on signal processing techniques like the Fast Fourier Transform (FFT).

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An equipment set-up, which comprises current transformer, signal conditioning unit, data collector/analyser and computer, is used for measuring the motor current. Data is acquired by performing FFT on the stator current. The data obtained, is analysed after FFT is normalized as a function of the first harmonic amplitude. Conversely, harmonic contents or percentage amplitude for harmonics, increase with increase in the level of faults, like the number of broken rotor bars and eccentricity.

iv. *Intelligent Techniques*

Several intelligent techniques like Fuzzy logic systems, Artificial Neural Networks and Neuro-Fuzzy Systems usually have three prime steps for induction motor condition monitoring. These are: i) Signature extraction; ii) Fault detection; and iii) Fault severity estimation.

Apart from the above-mentioned techniques, some other methods for incipient fault detection of induction motors are the finite element method, vibration testing and analysis, Concordia transform, external magnetic field analysis, multiple reference frames theory, power decomposition technique, zero crossing time method and modal analysis method. This work, however, makes use of the artificial neural network for failure prediction of induction motors.

f) Artificial Neural Network

According to [8], Artificial Neural Network (ANN) is a non-linear mapping structure inspired by observed process in natural network of neurons in the human brain. It consists of highly interconnected simple computational units called neurons. It imitates the learning process of the human brain and can process problems, which involve complex, non-linear, imprecise and noisy data. It is ideally suited for modelling and predicting the outcome of new independent input data after training.

ANNs are parallel computational models consisting of densely interconnected adaptive processing units. They are used for a wide variety of applications where statistical methods are traditionally employed. ANN is therefore being recognised as a powerful tool for data analysis. By their adaptive nature, "learning by example" replaces "programming" in solving problems. This feature makes such computational models very appealing especially in application domains, where a problem to be solved is not understood fully but training data is readily available. Back propagation algorithm is the most widely used learning algorithm in an ANN. Various types of ANN include Multilayered Perceptron, Radial Basis Function and Kohonen networks. In fact, majority of the networks are more closely related to traditional mathematical and/or statistical models, such as non-parametric pattern classifiers, clustering algorithms, non-linear filters, and statistical regression models than they are to neurobiology models.

ANNs are constructed with layers of units. All units in a particular layer perform similar tasks. The first and last layers of a multilayer ANN consist of input units (independent variables) and output units (dependent or response variables) respectively. All other units (hidden units) make up the hidden layer. The behaviour of a unit is governed by an input function and an output or activation function. These functions are normally the same for all units within the whole ANN. Input into a node is a weighted sum of outputs from nodes connected to it. There exists a threshold term, which is a baseline input to a node in the absence of any other inputs. A weight is termed inhibitory if it is negative as it decreases net input, otherwise it is called excitatory.

Each unit takes its net input and applies an activation function to it. In instances where the inputs and outputs are binary encoded, the threshold function becomes very useful. The activation function mainly maps the outlying values of the obtained neural input back to a bounded interval. The activation function shows a great variety. However, the most common choice is the sigmoid function since it maps a wide domain of values into the interval.

i. *Development of an ANN Model*

A neural network forecasting model is developed by the following steps:

1. Variable selection;
2. Formation of training, testing and validation sets;
3. Neural network architecture; and
4. Model building.

Suitable variable selection procedures are used to select the input variables, important for modelling or forecasting variable(s) under study in the first step. This is followed by the formation of three distinct data sets called training, testing and validation sets. These data sets are used by the neural network not only to learn current data patterns (training set) and evaluate the overall ability of the supposedly trained network (testing set), but also to check the performance of the trained network using the validation set. The third step defines the network structure, which includes a number of hidden layers and hidden nodes as well as the number of output nodes and the activation function. The next step involves model building.

The model of a very popular and frequently used multilayer feed-forward neural network (FFNN) or multilayer perceptron (MLP) learned by back propagation algorithm is constructed based on supervised procedure or on examples of data with known output. The examples presented are assumed to implicitly contain the information necessary to establish the relation for building the model. An MLP allows prediction of an output object for a given input object. Its non-linear elements or neurons are arranged in successive layers with a unidirectional flow of information from input layer to output layer through hidden layer(s). With adequate data, only one hidden layer is always sufficient for an MLP as it can learn to approximate virtually any function to any degree of accuracy. MLPs are therefore also known as universal approximates. Generally, learning methods in neural networks are classified into three basic types, namely; supervised learning, unsupervised learning or reinforced learning. A neural network learns off-line if the learning phase and the operation phases are distinct. On-line learning occurs when it learns and operates at the same time. Supervised learning is usually performed off-line based on training data, whereas unsupervised learning is performed on-line based on given data. In reinforced learning, data is usually not given, but generated by interactions with the environment.

ii. *Architecture of Neural Networks*

The two most widely used ANN architecture are the feed-forward networks and the feedback or recurrent networks. Other types of ANN architecture include stochastic network, physical network, bi-directional network, Elman and Jordan network, Hopfield network, self-organising map and long short-term memory networks. Feed-forward networks have no feedback loops and are extensively used in pattern recognition. Thus, signals are allowed to travel one way only; from input to output. The output layer does not affect that same layer. In feedback networks however, signals do not travel in one way only due to the presence of a feedback loop. In addition, their state changes continuously (dynamic) until an equilibrium point is reached. They remain at this point until the input changes and a new equilibrium needs to be found.

The MLP network is trained using a supervised learning algorithm like the backpropagation algorithm. The backpropagation algorithm uses data to adjust the network's weights and thresholds so as to reduce the error in its prediction on the training set. It computes how fast the error, which is the difference between the actual and the desired activity, changes due to an alteration in:i) the activity of an output unit; ii) the total input received by an output unit; iii) weight on the connection into an output unit; and iv) the activity of a unit in the previous layer.

According to [9], some of the uses and applications of Artificial Neural Networks are for; classification, pattern matching, pattern completion, optimisation; control, function approximation/times series modelling, and data mining.

g) Related Works

Lizarraga-Morales *et al.* [10] proposed a novel FPGA-based methodology for early broken rotor bar (BRB) detection and classification through homogeneity estimation. Obtained results demonstrated the high efficiency of the proposed methodology as a deterministic technique for incipient BRB diagnosis in induction motors, which can detect and differentiate among half, one, or two BRBs with very high accuracy.

Kayri [11] did a comparative study on the predictive ability of Bayesian regularization with Levenberg-Marquardt artificial neural networks. Analysis were done by sum squared error (SSE), sum squared weight (SSW) and correlation of regression and concluded that the Bayesian regularization training algorithm shows better performance than the Levenberg-Marquardt algorithm.

Araujo *et al.* [12] provides an analysis about early incipient and recurring failures in three-phase induction motor bearings when driven by pulse width modulation inverters, focusing on a real industrial process. Over the investigation, it was concluded that the presence of common-mode currents at the verified levels could cause damages to the motor bearings, which was confirmed when the machine stopped working due to another bearing failure.

Yu *et al.* [13] developed a model-based remaining useful life (RUL) prediction method for induction motor with stator winding short circuit fault. The induction motor model with stator winding short circuit fault is introduced based on reference frame transformation theory. A particle filter method is used to realize unknown parameter estimation and RUL prediction. Simulation results were provided to validate the proposed method.

Kraleti *et al.* [14] presented a paper on model-based diagnostics and prognostics of three-phase induction motor for vapour compressor applications. Faults under consideration were incipient electrical faults: insulation degradation and broken rotor bars. Two online approximators were used to discover the system parameter degradation and facilitate fault isolation, or root-cause analysis, and a time to failure (TTF) prediction before the occurrence of a failure.

Ghate and Dudul [15] developed the radial-basis- function- multilayer- perceptron cascade connection neural-network based fault detection scheme for the small and medium sizes of three-phase induction motors. Simple statistical parameters of stator current were considered as input features and experimental results showed ability of the proposed classifier for detecting faults such as stator winding inter-turn short and/or rotor eccentricity. The network was tested for good classification accuracy with enough robustness to noises. The classifier was then found to be suitable for real world applications.

The use of ANN's in predicting failure of the 5.8 MW 11 kV motor on nominal load provides a new area of research. The network is a generalised feed-forward network and the input data samples are current, winding temperatures and power all in the time domain.

II. Methods Used

In designing a model for the failure prediction of a 3 phase 5.8 MW, 11 kV slip-ring SAG Mill induction motor at Goldfields Ghana Limited, Damang mine, Artificial Neural Networks was employed in modelling and simulations on the data collected (power, current and winding temperatures) from the company. The materials used in this research for the collection of the motor data was the Citect and Laptop computer with MATLAB software (2017a) for modelling and simulation of the data.

a) Designing and Programming of ANN Models

Figure 4(a) [15] shows a generalized flow chart of ANN–based fault classification of induction motors. Designing ANN models follows a number of systemic procedures. In general, there are five basics steps: (1) collecting data, (2) pre-processing data, (3) building the network, (4) train, and (5) validate and test the performance of model as shown in Figure 4(b).

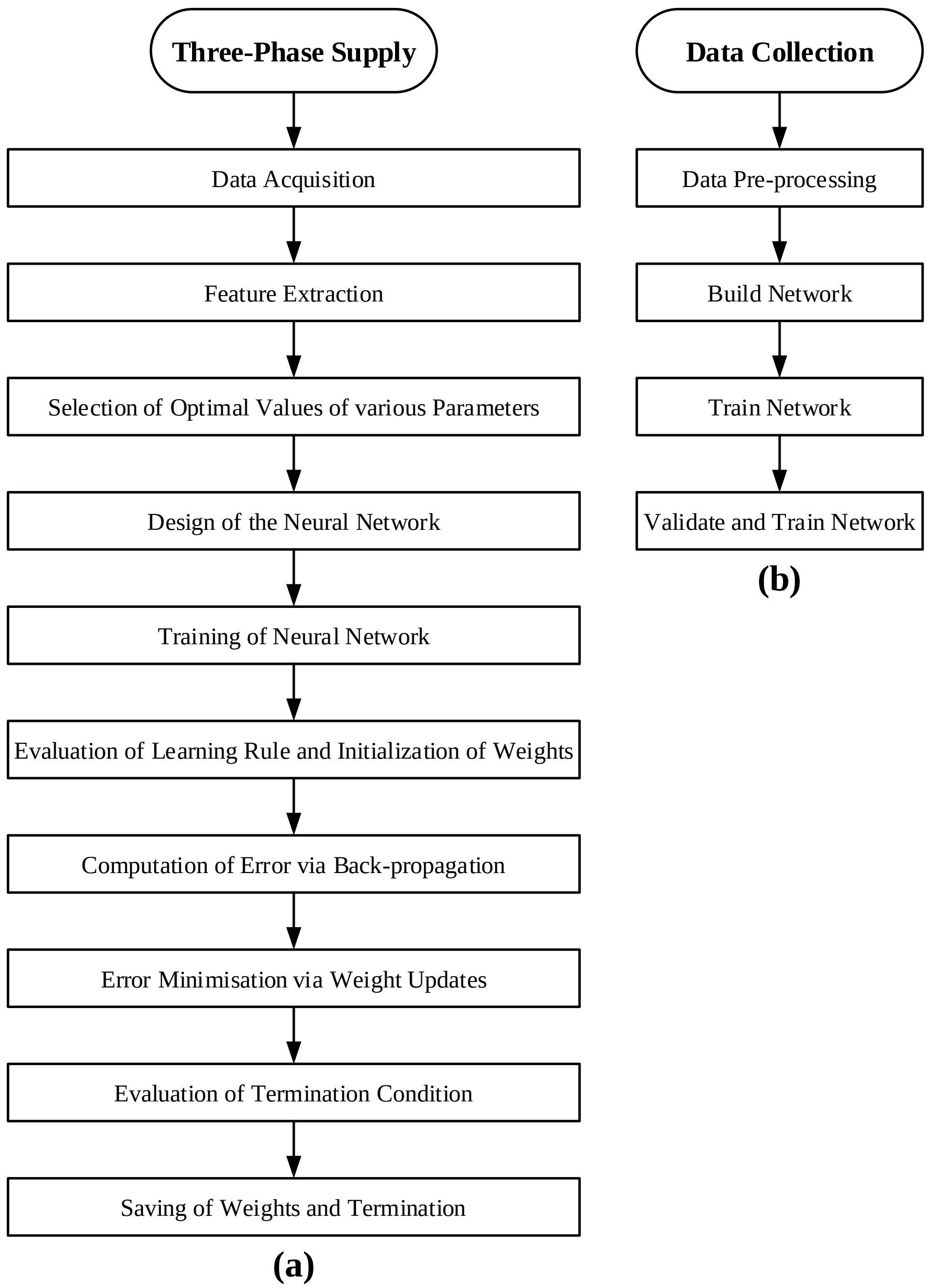
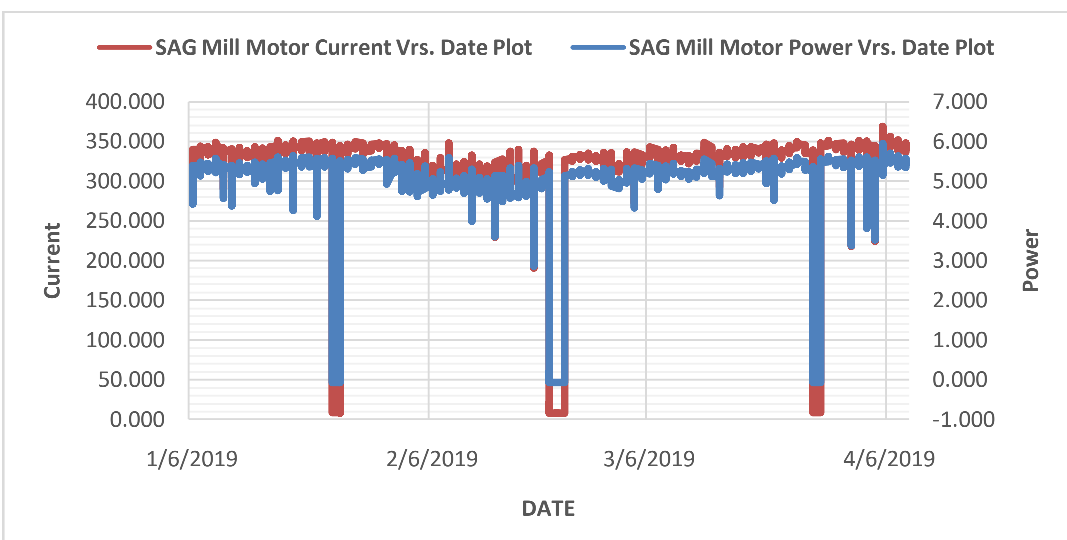


Figure 4: (a) General Flow of ANN–Based Fault Classification of Induction Motors; and (b) Basic Flow Chart for Designing Artificial Neural Network Model

b) Data Collection

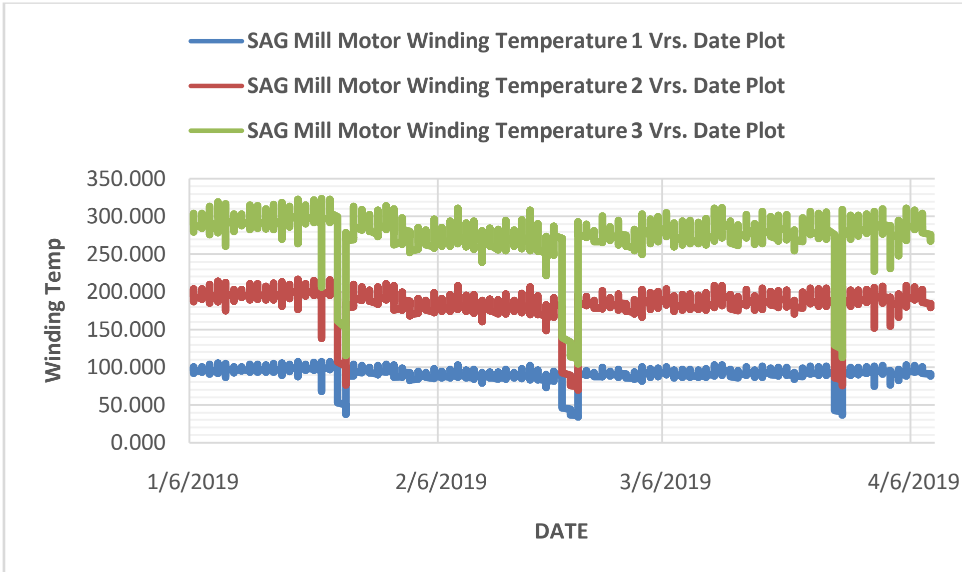
Collecting and preparing sample data is the first step in designing ANN models. As it is outlined in Figure 4(b), measurement data of the SAG Mill motor power (MW), motor current (A), and winding temperatures (°C) with the corresponding motor condition i.e. motor healthy or motor faulty (MH/MF) for the Damang mine for a 93-day period from 6th January, 2019 to 8th April, 2019 was collected through the Citect as shown in Figure 5 (a). A total of 5×879 data samples were collected. Figure 5(b) show graphs of trends of the SAG Mill motor current and power.

(a)

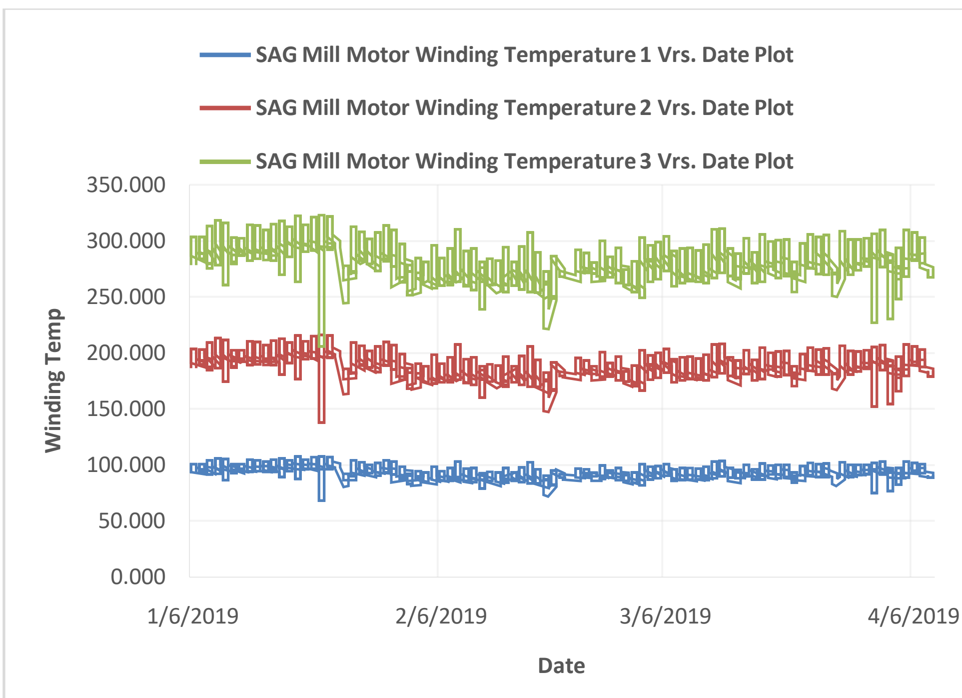


(b)

Figure 5: (a) Trends of SAG Mill Motor Current, Power and Winding Temperatures; and (b) Graph Showing Trends of SAG Mill Motor Current and Power



(a)



(b)

Figure 6: (a) Graph Showing Trends of SAG Mill Motor Winding Temperatures; and (b) Graph Showing Trends of SAG Mill Motor Winding Temperatures after Normalisation

c) Data Pre-Processing

After data collection, data pre-processing procedures are conducted to train the ANNs more efficiently. The procedure is normalisation of data. Normalization procedure before presenting the input data to the network is generally a good practice, since mixing variables with large magnitudes and small magnitudes will confuse the learning algorithm on the importance of each variable and may force it to finally reject the variable with the smaller magnitude [16]. Figure 6(a) and Figure 6(b) are graphs showing SAG Mill motor winding temperatures and winding temperatures after normalisation. A total of 5×837 data samples were considered healthy after normalisation.

Data samples which were out of range after normalisation were taken to be faulty data samples. This data samples totalled 5×42 faulty data samples. Figure 7 is a graph showing faulty data samples.

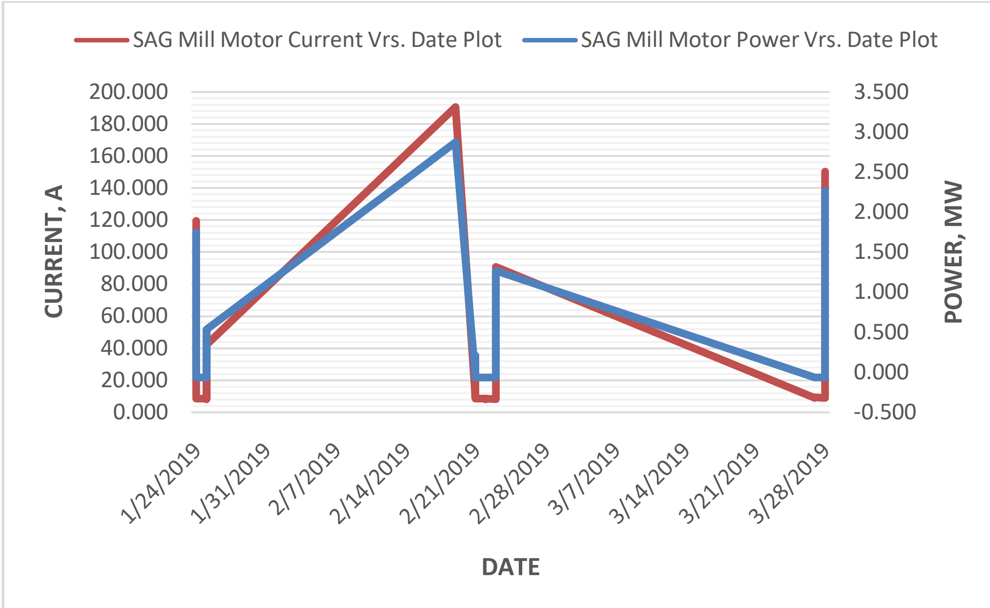


Figure 7: Graph Showing Trends of Faulty SAG Mill Motor Current and Power

d) Building the network

At this stage, the designer specifies the number of hidden layers, neurons in each layer, transfer function in each layer, training function, weight/bias learning function, and performance function. In this work, the generalised feed-forward neural network was used.

Feed-Forward Neural Network with Backpropagation Algorithm

In feed-forward neural networks, otherwise known as multilayer perceptrons, the input vector of independent variables is related to the target (SAG Mill motor condition) using the architecture depicted in Figure8. This figure shows one of the commonly used networks, namely; the layered feed-forward neural network with one hidden layer. Here, each single neuron is connected to those of a previous layer through adaptable synaptic weights. Knowledge is usually stored as a set of connection weights, and then, the weights are adjusted so that the network attempts to produce the desired output. The weights after training contain meaningful information, whereas before training they are random and have no meaning.

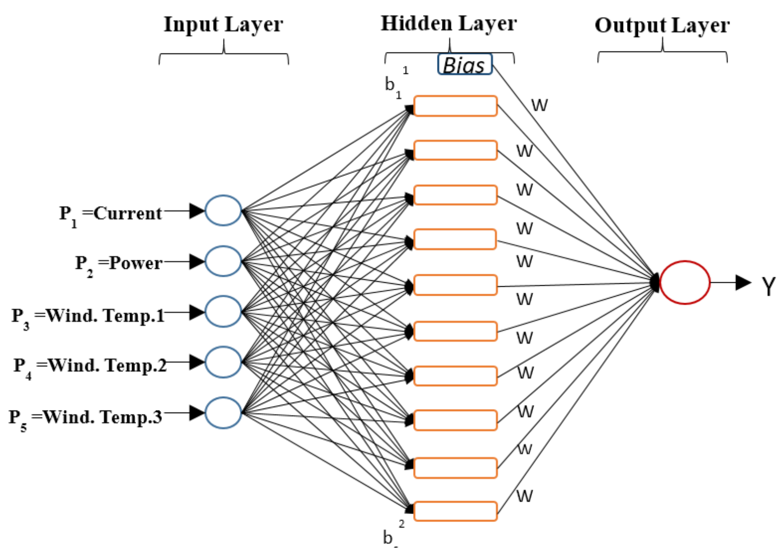


Figure 8: Architecture of Feed-Forward Network

e) Training the network

Training is the process of modifying the network using a learning mode, in which an input is presented to the network along with the desired output. During the training process, the weights are adjusted in order to make the actual outputs (predicated) close to the target (measured) outputs of the network. In this study, 70% of the data was used for training. Two different types of training algorithms were investigated for developing the feed-forward network. These are Levenberg-Marquardt algorithm and Bayesian Regularisation algorithm. MATLAB provides built-in transfer functions, which are used in this study; Linear (purelin), Hyperbolic Tangent Sigmoid (tansig) and Logistic Sigmoid (logsig).

f) Validating and Testing the Network

The next step is to validate and test the performance of the developed model. At this stage, unseen data are fed to the model. For this case study, 15% of SAG Mill motor data was used for validating and another 15% used for testing the ANN models. Validation data generalise the network validation and stops training before overfitting, which occurs when a network memorises the training data but not learn to generalise new inputs.

In order to evaluate the performance of the developed ANN models quantitatively and verify whether there is any underlying trend in performance of ANN models, statistical analysis involving mean squared error were conducted. MSE provides information on the short-term performance, which is a measure of the variation of predicated values around the measured data. The lower the MSE, the more accurate is the estimation. The expressions for the aforementioned statistical parameter is:

$$MSE=\frac{1}{n}\sum_{i=1}^{n}\left(I_p-I_i\right)^2 \quad (1)$$

where
I_p denotes the predicted power of SAG Mill motor in MW;
I_i denotes the measured power of SAG Mill motor in MW; and
n denotes the number of observations.

On the other hand, regression is a statistical analysis assessing the correlation between two variables. The regression line equation can be written as:

$$y = a + bx \quad (2)$$

$$b = \frac{N\sum XY - (\sum X)(\sum Y)}{\left(N\sum X^2 - \sum X\right)^2} \quad (3)$$

$$a = \frac{\sum Y\text{-}b(\sum X)}{N} \quad (4)$$

where
a = the y intercept when x = 0;
b = the slope/gradient of the line;
N = number of data samples;
X = first group; and
Y = second group and regression coefficient.

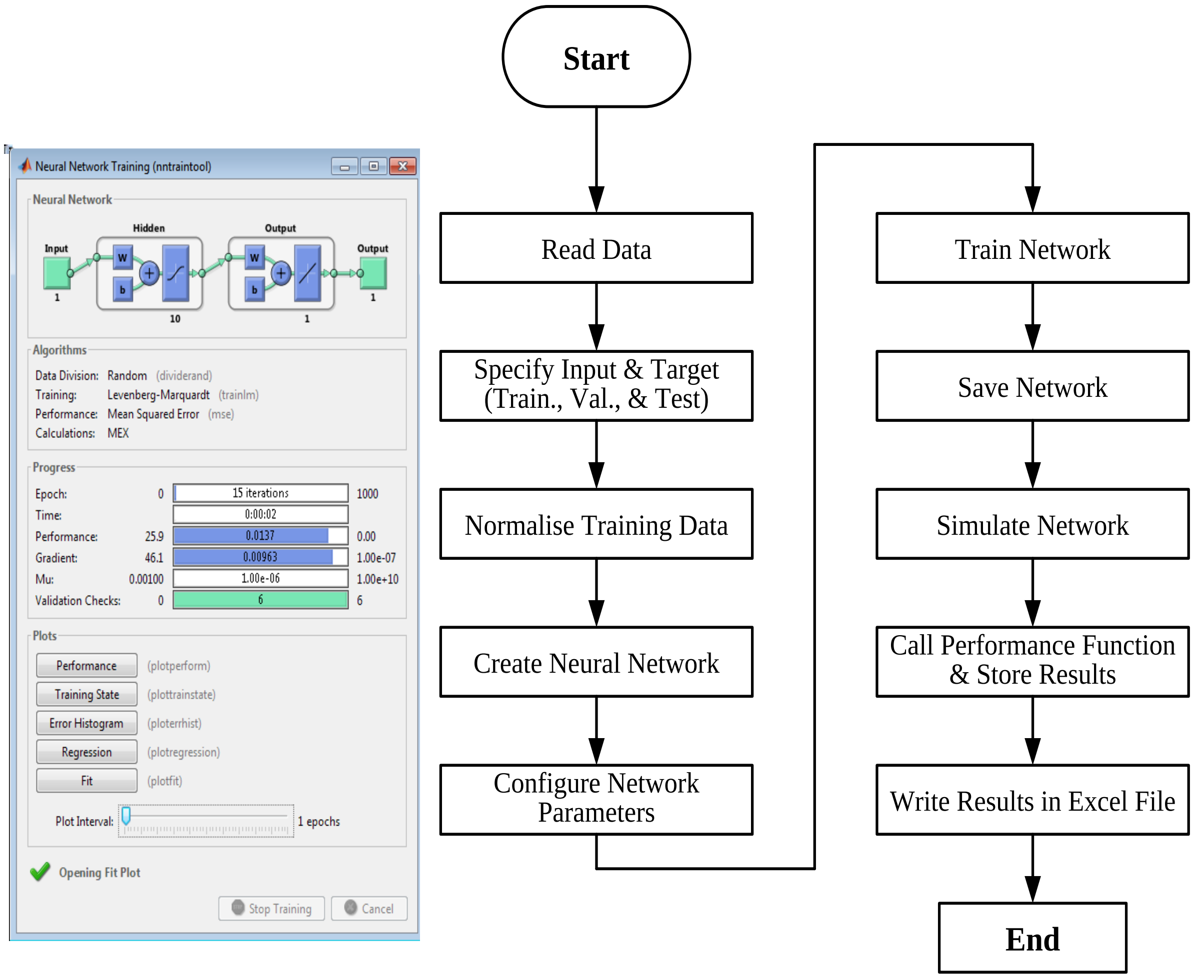
R is the correlation coefficient and is given as:

$$R = \frac{\sum XY \frac{\sum X \sum Y}{N}}{\sqrt{\left(\sum X \frac{(\sum X)^2}{N}\right)\left(\sum Y \frac{(\sum Y)^2}{N}\right)}} \quad (5)$$

g) Programming the Neural Network Model

MATLAB is a numerical computing environment and also a programming language. It allows easy matrix manipulation, plotting of functions and data, implementation of algorithms, creating user interfaces and interfacing with programs in other languages. The Deep Learning Toolbox (formerly Neural Network Toolbox) provides a framework for designing and implementing deep neural networks with algorithms, pretrained models, and apps. Apps and plots help you visualize activations, edit network architecture, and monitor training progress (The Math Works, 2019).

Figure 9(a) show the screen captions of the FFNN ANN training window obtained using the "nntraintool" GUI toolbox in MATLAB. Figure 9(b) show the flow chart for the development of the feed forward network using MATLAB.



(a) (b)

Figure 9: (a) FFNN Network Training Window; and (b) Flow Chart for Developing the Feed-forward Networks Using MATLAB

h) Implementation of Proposed Methodology

The proposed methodology is implemented using a microprocessor to achieve online failure detection. In addition to the cost–effectiveness of the microprocessor implementation, it is flexible and its re-configurability allows changes and refinements while in operation.

Figure 10 show the block diagram of the proposed methodology implementation. The data acquisition system receives current, power and three winding temperature signals from the sensors connected to the power supply to the stator windings of the motor. Signal processing is performed by the microprocessor and the result further analysed by a postprocessor decision-making block that simply states the motor condition in two possible values, i.e., MH (a healthy motor) and MF (a faulty motor), making the process online with no expert technician required for the diagnosis.

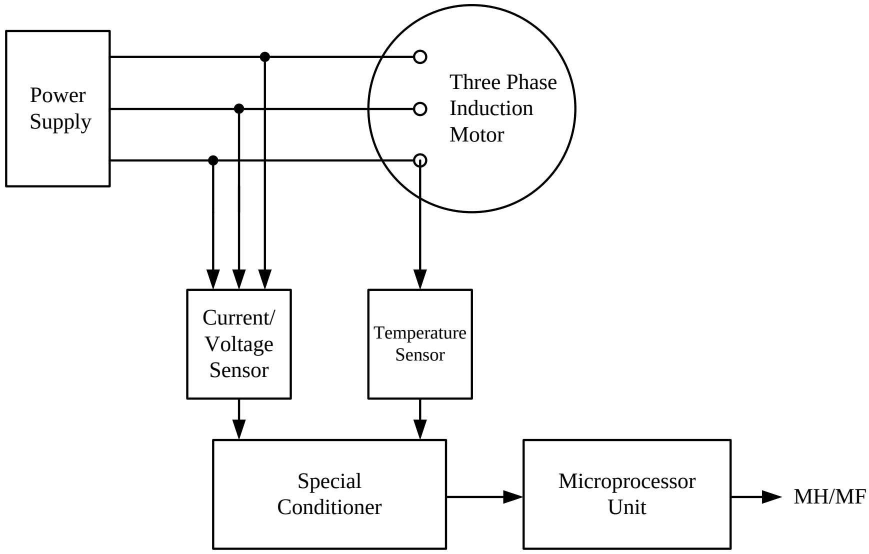


Figure 10: Overall Block Diagram of Implementation of Proposed Methodology

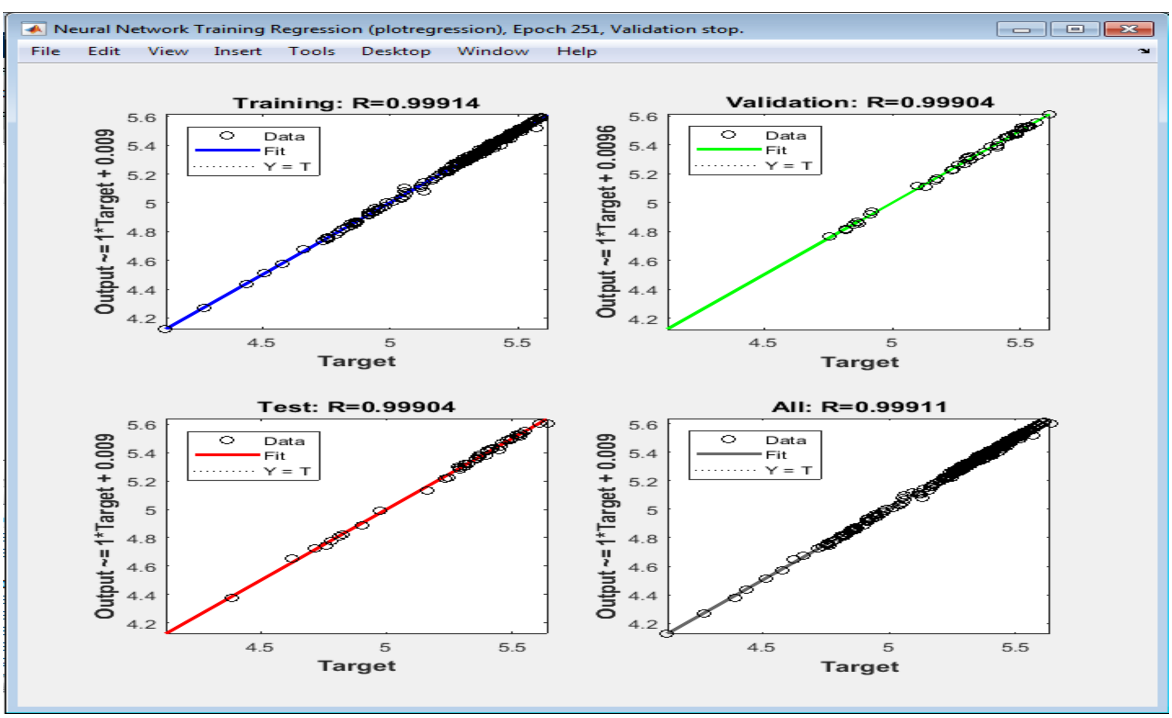
III. Results and Discussion

The results of MATLAB simulations using Artificial Neural Network tool box of SAG Mill motor current, temperature and power data from Goldfields Damang Mine are presented here.

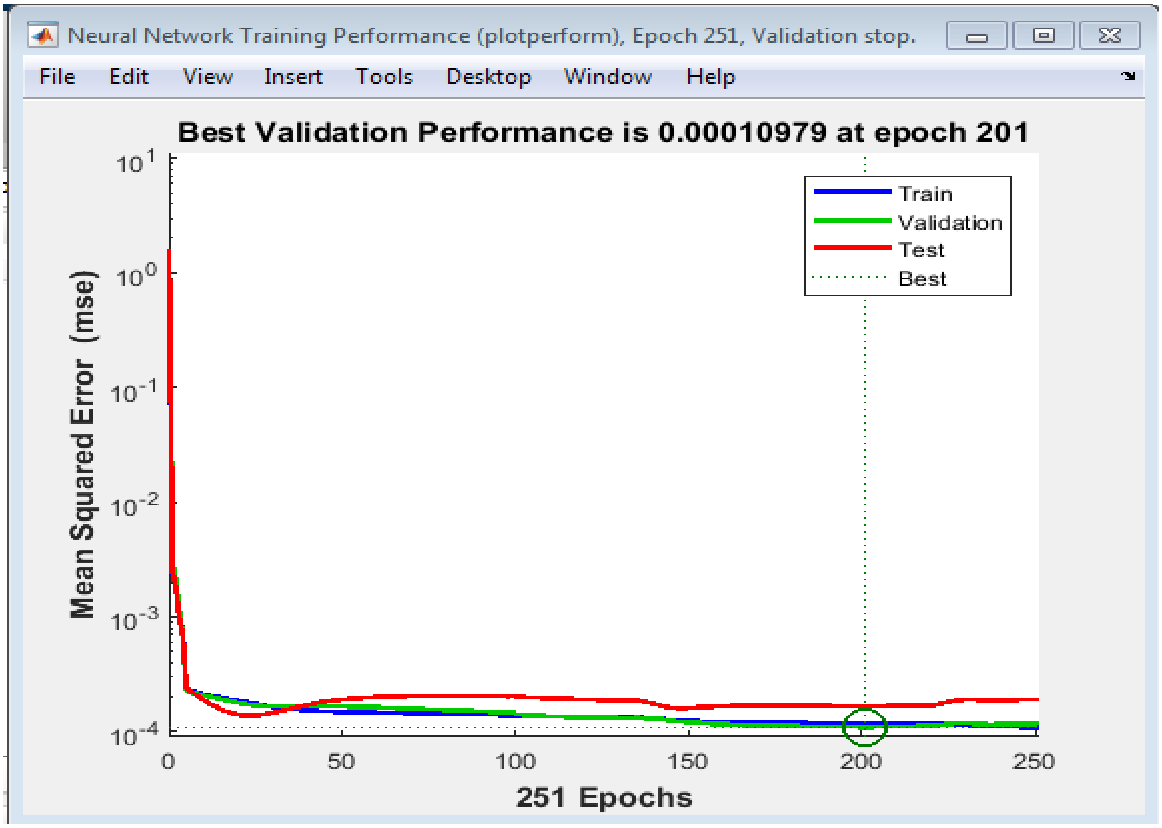
a) Simulation Results using Feed-Forward Network

In this section, results of using current and winding temperature readings representing three sides of the SAG Mill motoris used as the input to the network with Mill motor power as the target of the network. Two training algorithms i.e. Levenberg-Marquardt (LM) and Bayesian Regularization (BR) were used in training the network. Simulation results of correlation coefficient for network performance (R), mean squared error (MSE) against epochs, error histograms and training state plot for model validation are presented here.

i. *Simulation Results of FFNN Using Levenberg-Marquardt Training Algorithm*

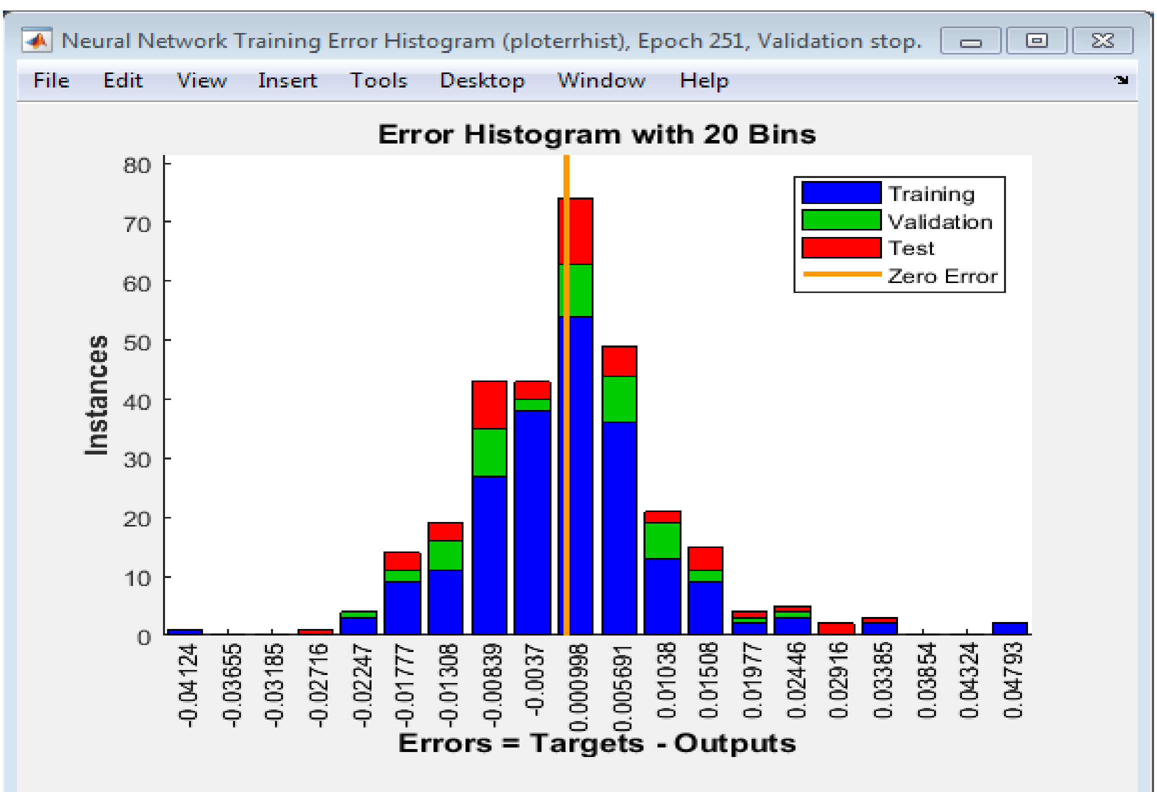


(a)

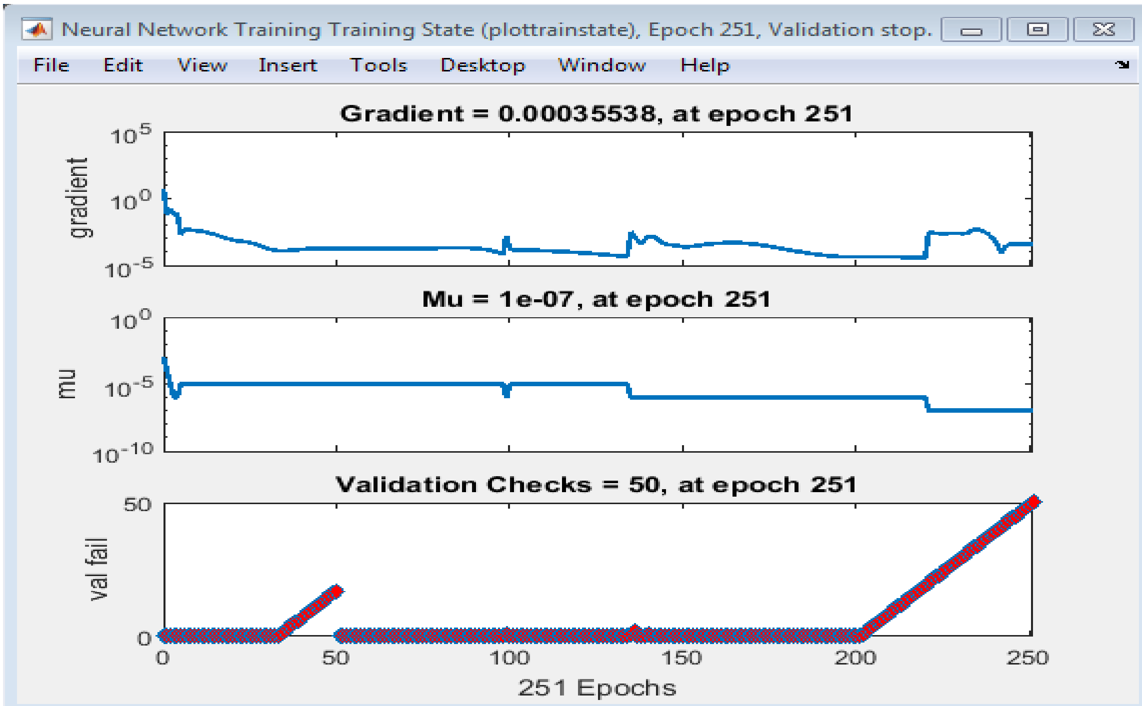


(b)

Figure 11: (a) Correlation Coefficient for Network Performance, R (LM); and (b) Mean Squared Error (MSE) against Epochs (LM)



(a)



(b)

Figure 12: (a) Error Histogram (LM); and (b) Training State Plot for Model Validation (LM)

ii. *Simulation Results of FFNN Using Bayesian Regularisation Training Algorithm*

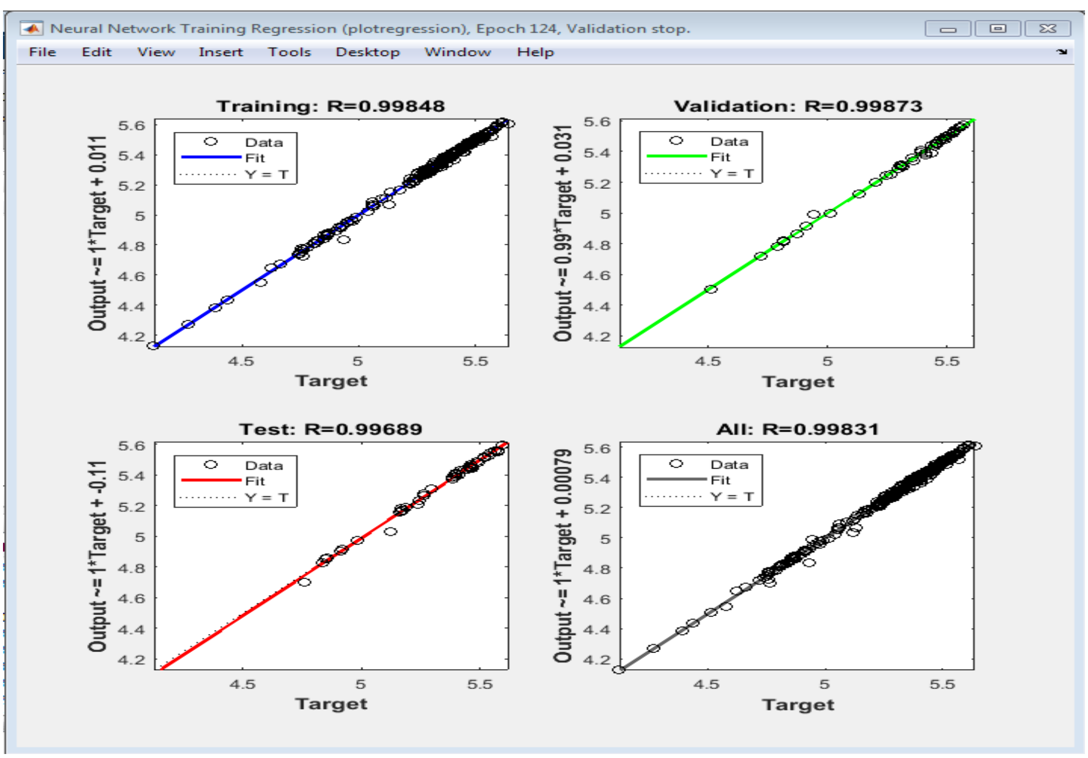
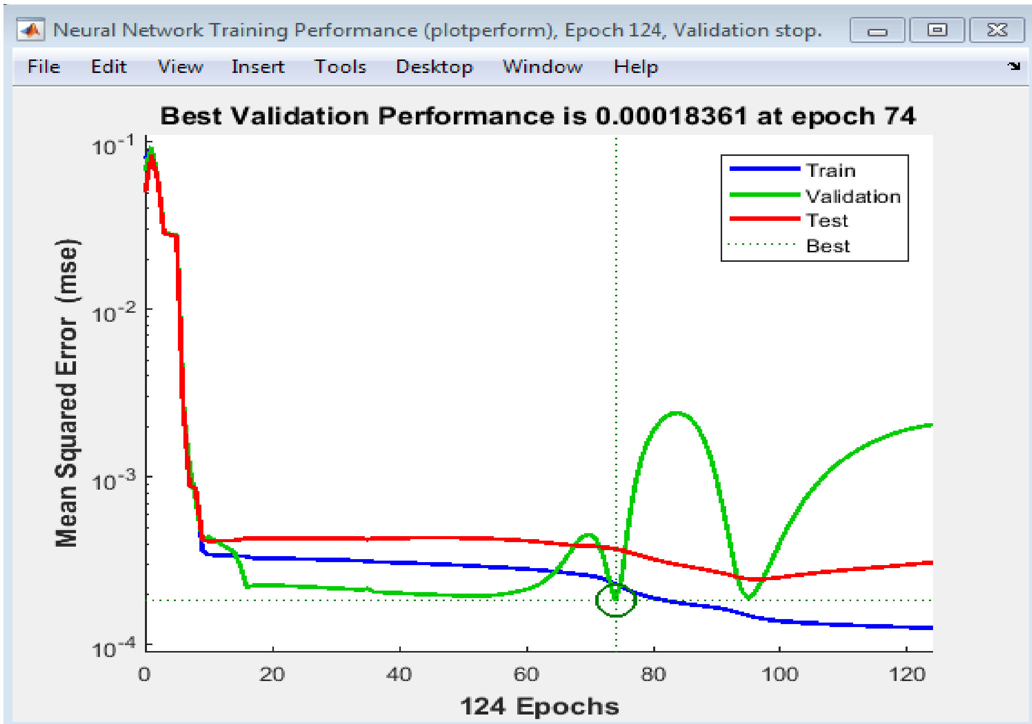
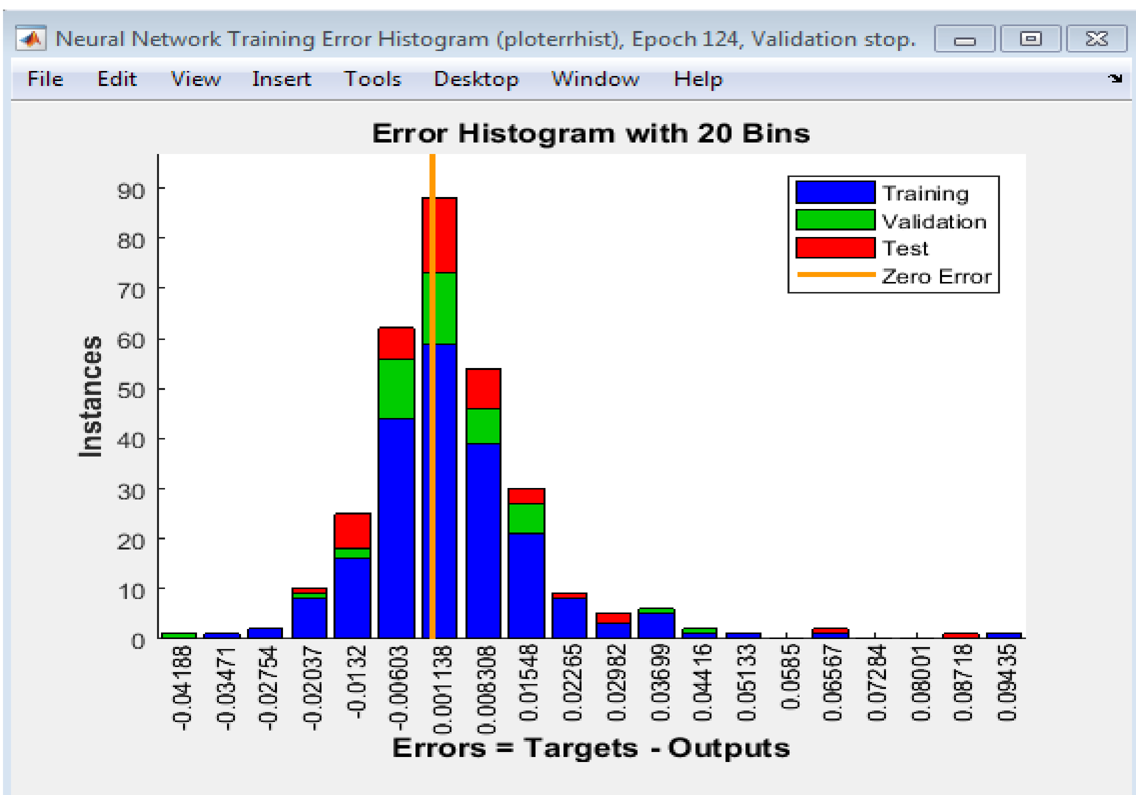


Figure 13: Correlation Coefficient for Network Performance, R (BR)



(a)



(b)

Figure 14: (a) Mean Squared Error (MSE) against Epochs (BR); and (b) Error Histogram (BR)

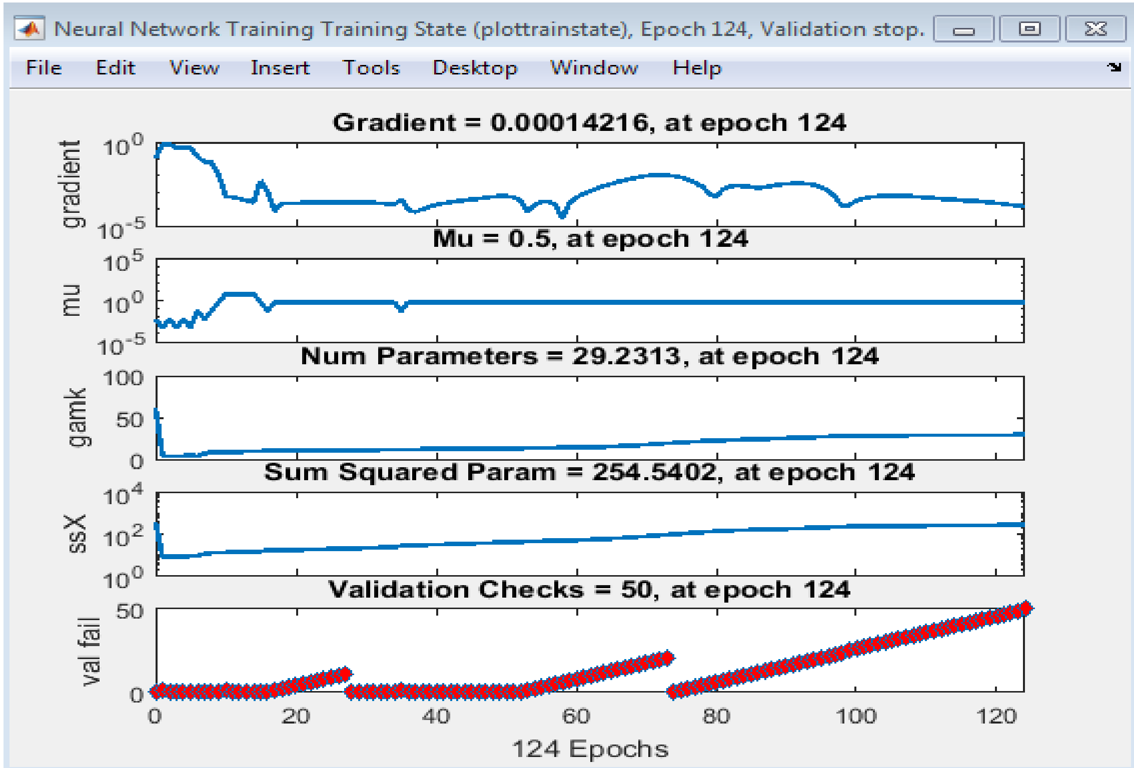


Figure 15: Training State Plot for Model Validation

b) Discussion of Simulation Results

This section also presents discussions of the MATLAB simulated results using FFNN. Table 2 shows the computed values of mean squared error MSE and correlation coefficient of network performance, R. It shows values of MSE and R for different number of data samples for training, validation and testing of the generated FFNN. The data samples range from 100, 200, 300, 400 and 500.

Table 2: Statistical Error Parameters of Developed FFNN Models for Different Data Sample Size

Number of Data Samples	Levenberg - Marquardt Algorithm				Bayesian Regularisation Algorithm			
	A/F – LOGSIG		A/F – TANSIG		A/F - LOGSIG		A/F - TANSIG	
	MSE	R	MSE	R	MSE	R	MSE	R
100	1.48E-04	0.99724	2.48E-04	0.99842	2.55E-04	0.99702	2.32E-04	0.99668
200	1.03E-04	0.99894	2.76E-04	0.99751	1.87E-04	0.99812	1.67E-04	0.99843
300	1.33E-04	0.99904	1.74E-04	0.99911	3.70E-04	0.99831	3.03E-04	0.99701
400	8.93E-04	0.99565	4.46E-04	0.99685	5.50E-03	0.9755	5.41E-04	0.99738
500	0.0064	0.96889	6.40E-03	0.96977	6.50E-03	0.96807	6.40E-03	0.96863

In this study, the network was decided to consist of one hidden layer with 10 neurons. The criterion R and MSE were selected to evaluate the networks to find the optimum solution. The complexity and size of the network was also an important consideration and therefore smaller ANN's had to be selected. A regression analysis between the network response and the corresponding targets was performed to investigate the network response in more detail. Thus, LM and BR were selected. The R-values in Table 3 represent the correlation coefficient between the outputs and targets. The R-values did not increase beyond 10 neurons in the hidden layer. Consequently, the network with 10 neurons in the hidden layer would be considered satisfactory. From all the networks trained, few ones could provide the low error condition, from which the simplest network was selected. The results showed that, the training algorithm of LM was sufficient for predicting SAG Mill motor failures. There is a high correlation between the predicted values by the ANN model and the measured values collected from normal real time running of 5.8 MW, 11 kV SAG Mill motor, which imply that the model succeeded in prediction of SAG Mill motor failures.

It can be observed in Figs. (11a, b, 12a, b and 13) that, the ANN provided the best accuracy in modelling induction motor failures with correlation coefficients of 0.999 and 0.998 for LM and BR respectively. Generally, the ANN offers the advantage of being fast, accurate and reliable in the prediction or approximation affairs, especially when numerical and mathematical methods fail. There is also a significant simplicity in using ANN due to its power to deal with multivariate and complicated problems.

The measured values collected from real time, on load running of the 5.8 MW, 11 kV SAG Mill motor showed some linearity between the current, temperatures and the power. The power of the SAG Mill motor at nominal load ranges from 4 MW – 5.6 MW with the current and temperatures reading 300 A – 349 A and 80ºC – 109ºC respectively.

From Table 2, it can be seen that, the ANN showed good R and MSE values when data samples of 300 was used. This was the same for LM and BR, while using log-sigmoid and tan-sigmoid as transfer functions for the hidden layer. The results for R-values for data samples of 300 were 0.99904, 0.99911, 0.99831 and 0.99701 respectively, while MSE values were 1.33E-04, 1.74E-04, 3.70E-04 and 3.03E-04 respectively. This simulation was repeated for data samples of 100, 200, 400 and 500. It was observed that, increasing the number of data samples resulted in bad R-values. Data samples of 100 gave better results than 200, 200 than 400 and 400 than 500 in that order.

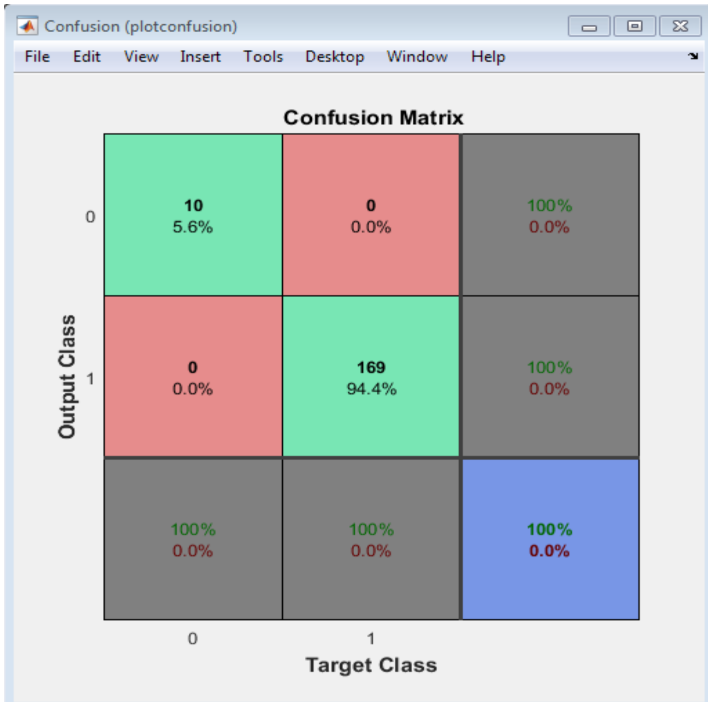
Training stops after 251 iterations. At this position, performance of network, 150×10^{-4}, gradient decrease to 3.55×10^{-4} and also the value of mu $= 10^{-7}$ as shown in Figure 12(b). Validation performance reached the minimum at epoch 201. The training continued for 51 more iterations and stopped at epoch 251. The gradient and mu increased gradually as shown in Figure 12(b).

From the error histogram shown in Figure 12(a), most errors occurred between –0.04 to +0.05. Errors also occurred at 0.065, 0.087 and 0.094 of the training data on the histogram, and also represents the point for which output 4.5 – target value 4.6, output 4.8 – target 4.9 and output 5.1 – target 5.2 on the training correlation coefficient for network performance, plot shown in Figure11(a).

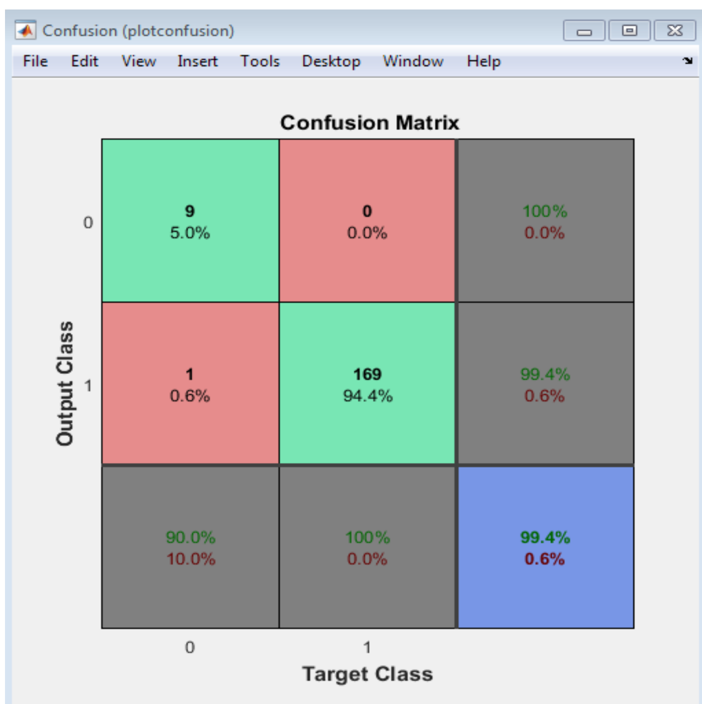
c) *Discussions on Using the Network for Prediction*

Two matrices of 5×669 and 5×31 constructed by power, current and three winding temperature values normalised sample data of SAG Mill motor at healthy and faulty on load condition respectively as input are used to analyse network performance. Among them, 70%, 15% and rest data are used as training, cross validation and testing data. The target of the network is 1 or 0, with 1 indicating healthy motor condition and 0 indicating faulty motor condition. For any output value between 1 and 0 represents the probability of fault condition, in training the network, there was 1 hidden layer with 10 neurons and tansigmoid as the transfer function. The output layer had 1 neuron and the transfer function was logsigmoid.

Fresh data samples consisting of 5×169 and 5×10 healthy and faulty on load power, current and three winding temperatures of the SAG Mill motor were fed into the network to detect health. Table 3, Figure 16(a) and 16(b) show the detection efficiency and confusion plot of network using LM and BR algorithm respectively. Out of the 169 healthy data samples, using LM training algorithm could rightly predict them as true detection (TD) and false detection (FD) of 0. The network could also predict a TD of 10 out of 10 faulty data fed into it. This shows the network with LM training algorithm can detect healthy and faulty conditions of the SAG Mill motor with 100% accuracy. BR training algorithm could detect 169 healthy samples as TD and 9 out of 10 faulty data samples as TD and 1 FD, therefore, network with BR could detect healthy and faulty conditions of the SAG Mill motor with 99.4% efficiency.



(a)



(b)

Figure 16: (a) Plot of Confusion Matrix Using Levenberg-Marquardt Algorithm; and (b) Plot of Confusion Matrix Using Bayesian Regularization Algorithm

Table 3: Detection Accuracy

TOTAL NUMBER DATA SAMPLES	HEALTHY		FAULTY		ACCURACY
	TD	FD	TD	FD	
Levenberg-Marquardt	169/169	0/169	10/10	0/10	100%
Bayesian Regularization	169/169	0/169	9/10	1/10	99.4%

d) Summary of Findings

The findings as regards simulations of data samples measured on the 5.8 MW, 11 kV SAG Mill motor at the Goldfields Ghana Ltd., Damang Mine from 6th January, 2019 to 8th April, 2019 are summarised as follows:

1. A smaller Feed-Forward Neural Network size of 4-10-1 provides optimum performance for prediction of SAG Mill motor failures;
2. Though Bayesian Regularisation training algorithm has not been extensively used in failure prediction of three phase slip-ring induction motor as compared to Levenberg-Marquardt, yet it gives acceptable results in terms of accuracy but at a relatively low efficiency;
3. Data samples of 100, 200, 300, 400 and 500 were used in this work. Data samples of 300 with Levenberg-Marquardt training algorithm and tansigmoid activation function of the hidden layer provided the best results for R-values and MSE;
4. The network stopped training at 251 iterations, a network performance of 150×10^{-4} at this position. The gradient decreases to 3.55×10^{-4} and mu = 10^{-7}. Validation performance reaches minimum at epoch 201; and
5. The network with Levenberg-Marquardt training algorithm can detect healthy and faulty conditions of the SAG Mill motor with 100% accuracy and 99.4% using Bayesian Regularization as the training algorithm.

IV. Conclusions and Recommendations

a) Conclusions

From the results and discussions, the following conclusions can be drawn:

1. The proposed Feed-Forward Neural Network with Levenberg-Marquardt training algorithm is capable of predicting imminent faults ofon load 5.8MW, 11 kV SAG Mill three phase slip-ring induction motor at Goldfields Ghana Ltd., DamangMine with 100% accuracy;
2. Correlation coefficient of network performance, R and mean squared error, MSE proved to be very good statistical tools for artificial neural network model analysis; and
3. Bayesian Regularisation training algorithm proved to be a good alternative to Levenberg-Marquardt algorithm in failure prediction networks.

b) Recommendations

The following are recommended based on the conclusions drawn:

1. Similar research could be carried out on the Ball Mill motor and other important motors at the plant;
2. Since it will be very difficult to set up a prototype for the 3 phase 5.8 MW, 11 kV slip-ring induction motor taking into consideration the size and cost, MATLAB/SIMULINK and Finite Element Method Magnetics could be considered in generating signals for this research; and
3. Wavelet techniques and Fuzzy logic could be used to find exact location of fault, identification and evaluation of fault severity.

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Global Journal of Researches in Engineering: F
Electrical and Electronics Engineering
Volume 20 Issue 2 Version 1.0 Year 2020
Type: Double Blind Peer Reviewed International Research Journal
Publisher: Global Journals
Online ISSN: 2249-4596 & Print ISSN: 0975-5861

MONSDA: - A Novel Multi-Objective Non-Dominated Sorting Dragonfly Algorithm

By Pradeep Jangir

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Keywords: non-dominated; crowing distance; NSDA algorithm; multi-objective algorithm; economic constrained emission dispatch.

GJRE-F Classification: FOR Code: 290901p

MONSDAANOVELMULTIOBJECTIVENONDOMINATEDSORTINGDRAGONFLYALGORITHM

Strictly as per the compliance and regulations of:

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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 based stochastic 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 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 consider two objectives, first cost and second comfort level. So we go for sole objective of minimum cost possible then we

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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.

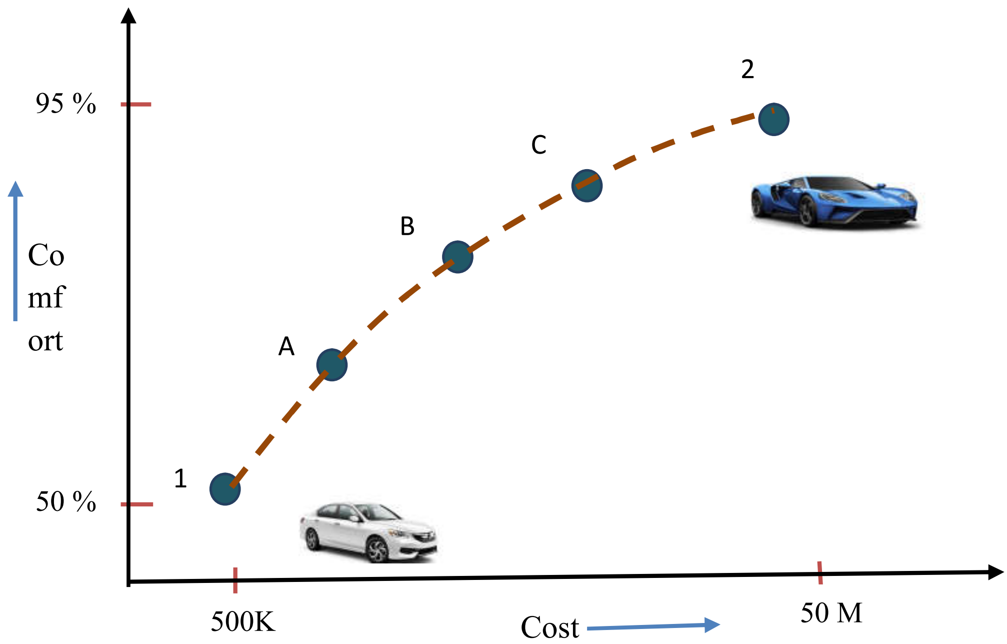

Fig. 1: Car-buying decision-making problem (Hypothetical Optimal solutions)

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 dragonfly algorithm (DA) [17]. In this paper non-sorted DA (NSDA) is tested on the standard un-constraint and constraint test 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 NSDA algorithm; 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 handles simultaneously multiple objectives. Mathematically minimize/maximize optimization problem can be written as follows:

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

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

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

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

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:

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

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

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

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

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

These equations show 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.

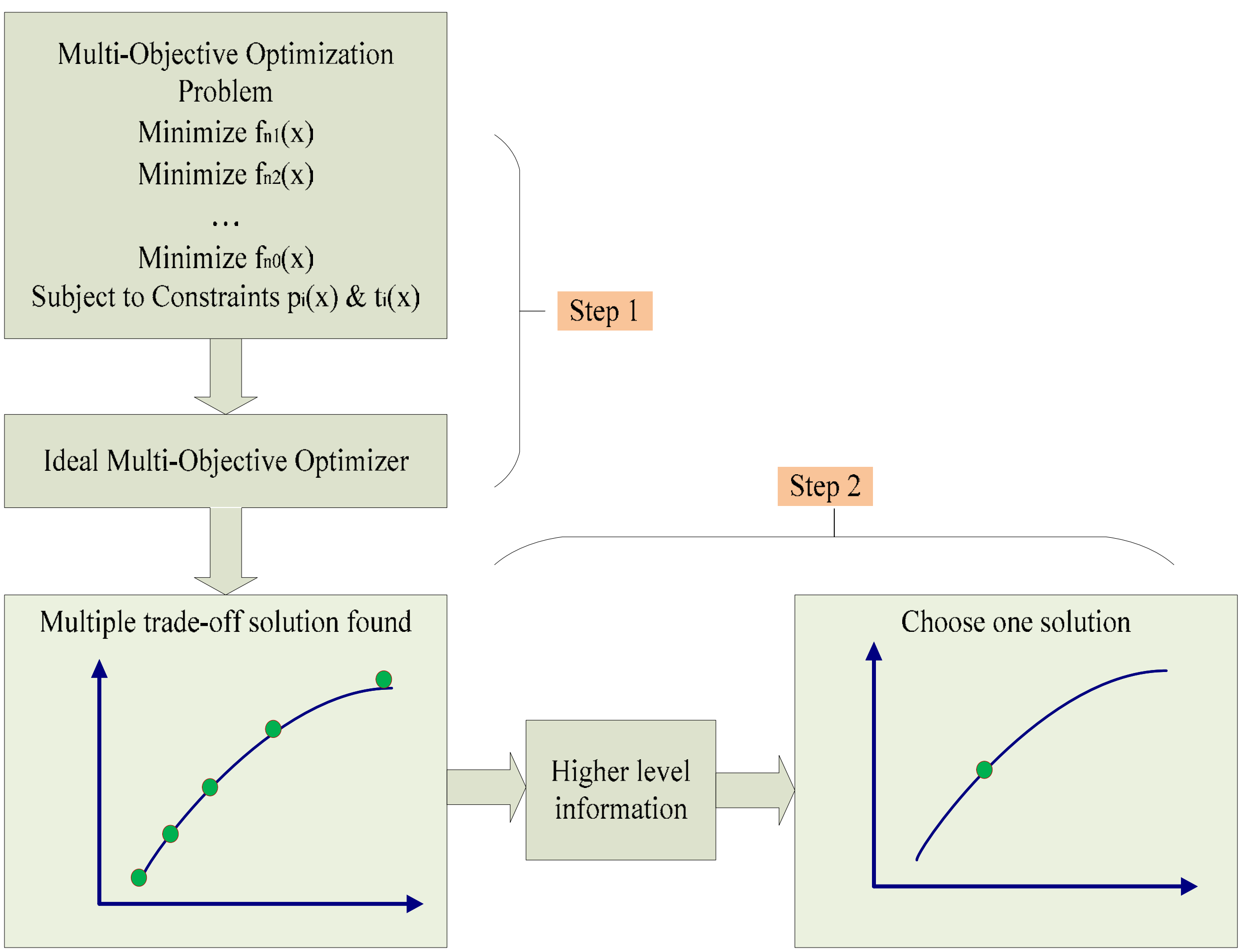

Fig. 2: Multi-objective optimization (Ideal) procedure.

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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 NSDA 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] and Multi-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 NSDA 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 Dragonfly Algorithm (NSDA)

Dragonfly Algorithm (DA) with sole objective was proposed by Mirjalili Seyedali in 2015 [17]. It is basically a stochastic population based, nature inspired algorithm. In this algorithm the basic strategy based on swarming nature of dragonflies for exploration and exploitation. DA algorithm originated from the static and dynamic swarming behaviors of dragonflies. These two swarming behaviors are similar to the basic stage of working of any optimization algorithm in all meta-heuristic algorithms as: exploration and exploitation. Dragonflies build small number of group and fly in different directions in search of food is known as static swarm, this function is very similar to exploration phase in meta-heuristic techniques. Whereas, dragonflies make a big group and fly in only direction for either attacking to prey or migration to other place is known as dynamic swarm, this function is very similar to exploitation phase.

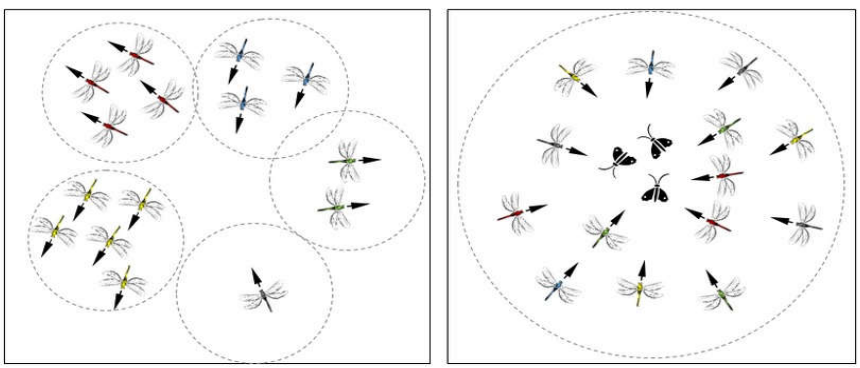

Fig. 3: Representation of static and dynamic swarming behavior of Dragonflies

Mathematical modelling of Dragonfly Algorithm:

Each portion of Dragonfly Algorithm is formulated by algebraic equations are:

1. For Separation part formulating equation:

$$\text{SEP.}_{\,j} = -\sum_{i=1}^{N} L - L_i \quad (3.1)$$

2. For Alignment part formulating equation:

$$\text{Alig.}_{\,j} = \frac{\sum_{i=1}^{N} L_i}{N} \quad (3.2)$$

3. For cohesion part formulating equation:

$$\text{Coh.}_{\,j} = \frac{\sum_{i=1}^{N} L_i}{N} - L \quad (3.3)$$

4. For Attraction towards a food source part formulating equation:

$$F_j = L^{+} - L \tag{3.4}$$

5. For Attraction towards a food source part formulating equation:

$$E_j = L^{-} + L \tag{3.5}$$

6. Step vector is formulating equation:

$$\Delta L_{t+1} = \left(sSep._j + aAlig._j + cCoh._j + fF_j + eE_j\right) + w\Delta L_t \tag{3.6}$$

7. Position vector is calculated using equation

$$L^{d}{}_{t+1} = L_t + \Delta L_{t+1} \tag{3.7}$$

8. Position of dragonfly updated using equation

$$L_{t+1} = L_t + \text{Levy}(L) * L_t \tag{3.8}$$

Where:

L=Location of the current individuals, N= Neighboring individuals, L^{+}=positions of food source, L^{-}=positions of enemy, s=separation weight, a=alignment weight, c=cohesion weight, f=food weight, e=enemy weight, w=inertia weight, t=iteration counter and d=dimension of position vectors that levy flight step calculated.

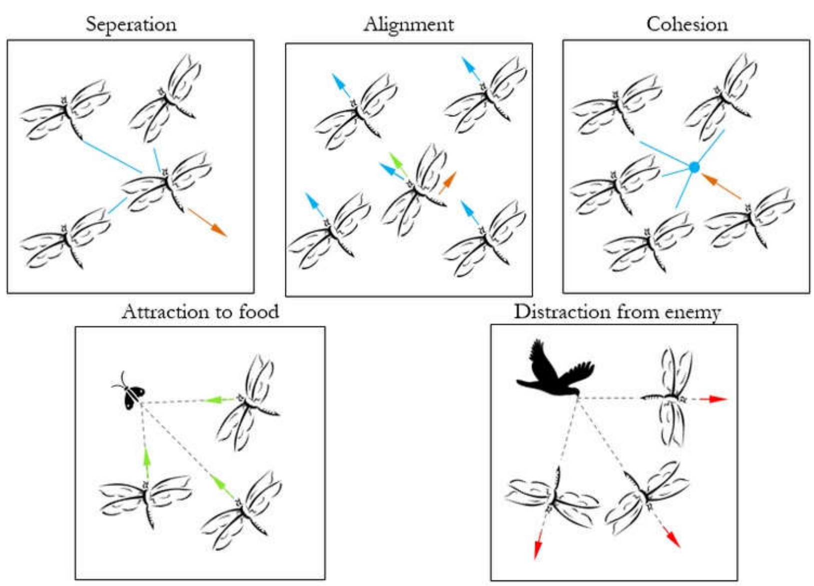

Fig. 4: Dragonfly Algorithm principle

Basic working of NSDA algorithm is as follows:

- Stage 1
  - First of all, initialize the population of dragonflies
  - Randomly generated sets of dragonflies & position vectors are represented in matrix for convenience to understand
  - Then fitness of step vector & position vectoris calculated on an according as objective function
- Stage 2
  - Position of dragonflies are updated as a function of levy flight motion and so as value of position vector is decided
  - The value of absolute distance is achieved which is basically a distance between the current best solution to the final optimal solution
  - Step vector is a function of both static and dynamic swarming behavior of dragonflies where some constant weight is assigned to the step vector function according to their swarming nature
- Step 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 dragonflies are updated towards the optimal one via a Levy function or position vector equation for each iteration

➢ Step 4

- Likewise, multi-objective optimization the NSDA algorithm is made to capable to store the pare to optimal solutions in a collection set 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 nature are 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 NSDA is very similar to that of DA, in which solutions are improved using step vectors. Due to the existence of multiple best solutions, however, the best dragon flies 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 NSDA 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 subsection proposes multi-objective version of the DA algorithm called NSDA 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 DA algorithm. In the NSDA algorithm, solutions are updated with the same equations presented in equation 3.9. In every iteration, however, the solutions to have optimal position of dragonflies are chosen using the following equation:

$$P_i = {}^{c}/_{Rank_i} \quad (3.9)$$

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 NSDA algorithm. Flow chart of NSDA algorithm is represented as Fig. 5.

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 NSDA 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 dragonflies) from archive is selected to get desired solution.

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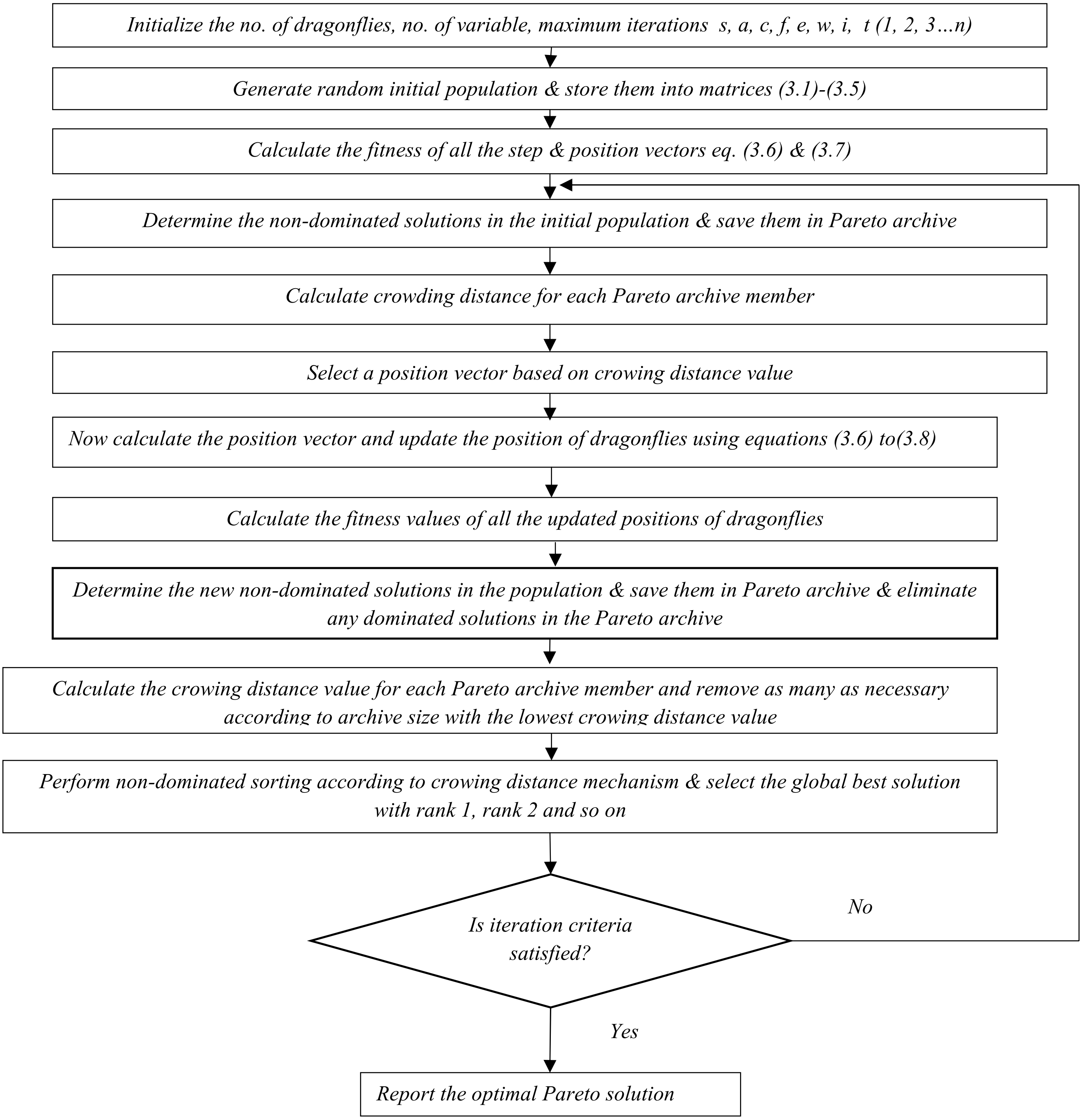


Fig. 5: Flow chart of NSDA algorithm

IV. Results Analysis on Test Functions

For determine the performance of proposed NSDA 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 formulation of economic constrained emission dispatch (ECED) with stochastic integration of wind power (WP) in the next section

NSDA 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 are 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 NSDA algorithm. To deal with real world engineering design problem is really a typical task with unknown search space, in this article we includes 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 pareto front with respect to their original or true pareto fronts.

For numeric as well as qualitative performance of purposed NSDA 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 pareto front and obtained pareto 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:

$$GD = \frac{\sqrt{\int_{i=1}^{n_{PFs}} (d_i)^2}}{n} \tag{4.1}$$

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.

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

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 pareto front and obtained pareto front. n_{PFs} and 'd' are the total number of achieved Pareto optimal solutions and averaged distance of all solutions.

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

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

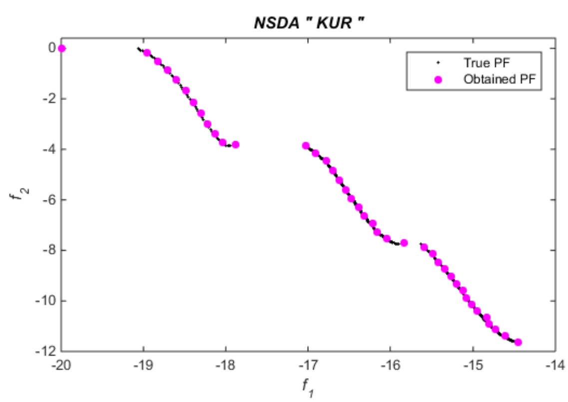
Like as above mentioned, the first set of test problems consist of unconstrained standard test functions. All the standard unconstrained test functions mathematical formulation is shown in Appendix A. Later, the numeric results are represented in Table 1 and best optimal pareto front is shown in Fig. 6.

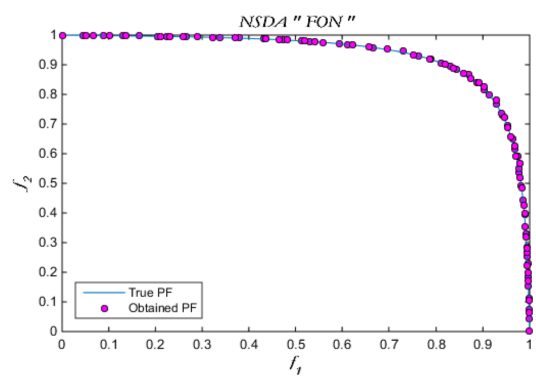
All the statistical results are shown Table 1 suggests that the NSDA algorithm effectively outperforms with most of the unconstraint test functions compare to the MOSOS, MOCBO, MOPSO and NSGA-II algorithm. The effectiveness of proposed non-dominated version of DA (NSDA algorithm) can be seen in the Table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

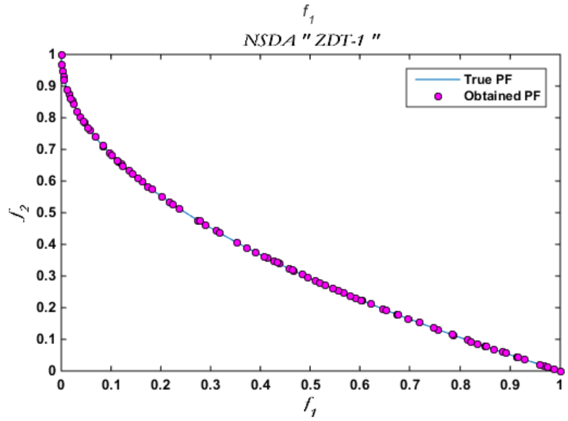
Table 1: Results of the multi-objective NSDA algorithms (using GD, Δ, CT) on the unconstrained test functions employed

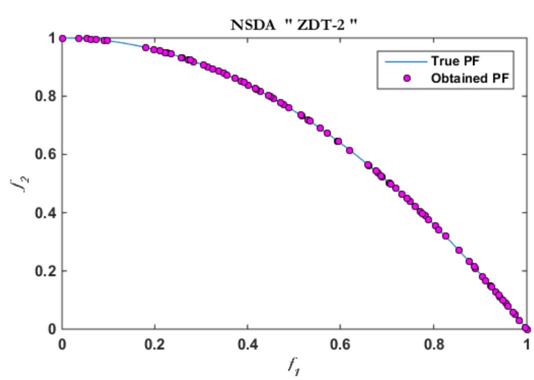
Algorithm→ Function ↓	PFs	NSDA MEAN±SD	MOSOS MEAN±SD	MOCBO MEAN±SD	MOPSO MEAN±SD	NSGA-II MEAN±SD
	GD	0.00729±0.00241	0.0075±0.0042	0.0083±0.0062	0.015±0.0075	0.0301±0.0043
KUR	Δ	0.02704±0.01025	0.0295±0.0122	0.0357±0.0236	0.0991±0.031	0.0362±0.0240
	CT	7.65853±0.44369	10.7413±0.822	7.9531±0.5823	8.0532±0.621	20.4368±3.102
	GD	0.00173±0.00032	0.0019±0.0002	0.0022±0.0003	0.0042±0.000	0.0026±0.0003

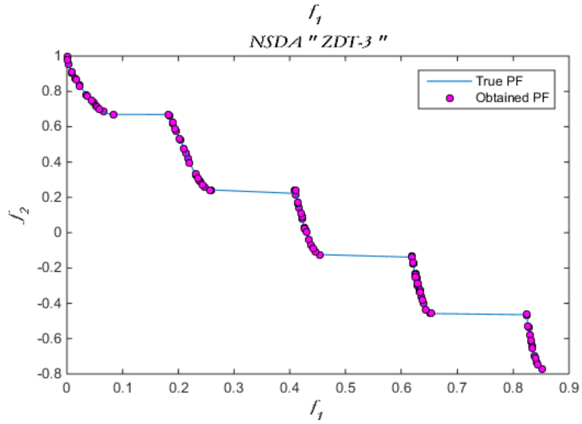
FON	Δ	0.29805±0.03758	0.3875±0.0062	0.3955±0.0068	0.4158±0.008	0.3987±0.0082
	CT	09.6681±0.55567	11.4013±1.140	8.6606±0.8862	8.732±0.9134	22.0323±4.522
	GD	0.32751±0.06748	0.3325±0.0256	0.3337±0.0319	0.3348±0.035	0.3352±0.038
ZDT-1	Δ	0.35589±0.00875	0.3803±0.0122	0.3825±0.0125	0.3876±0.024	0.3905±0.0220
	CT	6.59987±0.00381	8.2351±0.0204	3.1435±0.0193	3.7533±0.006	11.2681±0.364
	GD	0.07104±0.00066	0.0731±0.0010	0.0729±0.0005	0.0733±0.001	0.0725±0.0004
ZDT-2	Δ	0.04239±0.06687	0.4307±0.0007	0.4316±0.0007	0.4321±0.001	0.431±0.00075
	CT	4.66875±0.02005	8.2345±0.0457	3.1502±0.0130	3.6113±0.014	11.2811±0.024
	GD	0.07146±0.03847	0.1022±0.5187	0.0982±0.5007	0.1235±0.009	0.1147±0.0039
ZDT-3	Δ	0.69874±0.23568	0.6537±0.0052	0.65325±0.002	0.8234±0.108	0.7386±0.0474
	CT	8.78546±0.34789	13.4567±0.129	6.2846±0.1059	8.3764±0.231	14.3406±0.144
	GD	0.49878±0.00020	0.5015±0.0006	0.5078±0.0013	0.5146±0.001	0.5204±0.0019
ZDT-4	Δ	0.35879±0.01478	0.4585±0.0073	0.4795±0.0079	0.6543±0.024	0.7003±0.0089
	CT	7.87956±0.12275	13.9022±0.121	6.6922±0.1440	8.8203±0.218	14.8102±0.170
	GD	0.00904±0.00070	0.0028±0.0024	0.0031±0.0032	0.0032±0.003	0.0034±0.0042
SCHN-1	Δ	0.50078±0.01578	0.5295±0.1312	0.5302±0.1356	0.8582±0.164	0.5502±0.1360
	CT	11.7805±1.23254	8.2135±1.121	5.4845±1.1320	5.5721±1.133	17.9121±2.162
	GD	0.04478±0.00189	0.0705±0.0215	0.0932±0.0228	0.1497±0.022	0.3096±0.0217
SCHN-2	Δ	0.66587±0.02458	0.7821±0.0512	0.801±0.08326	0.8652±0.060	0.9562±0.0921
	CT	5.79974±0.14058	8.7015±0.4532	5.9751±0.2821	6.0272±0.582	18.421±2.1802

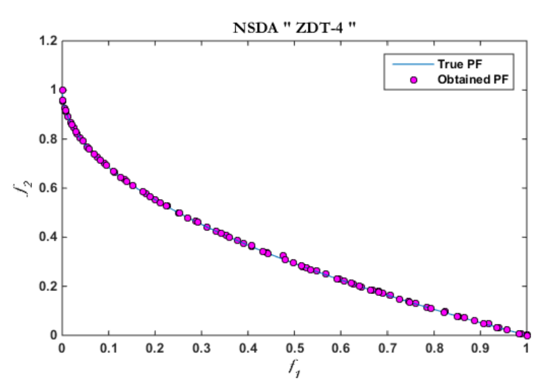












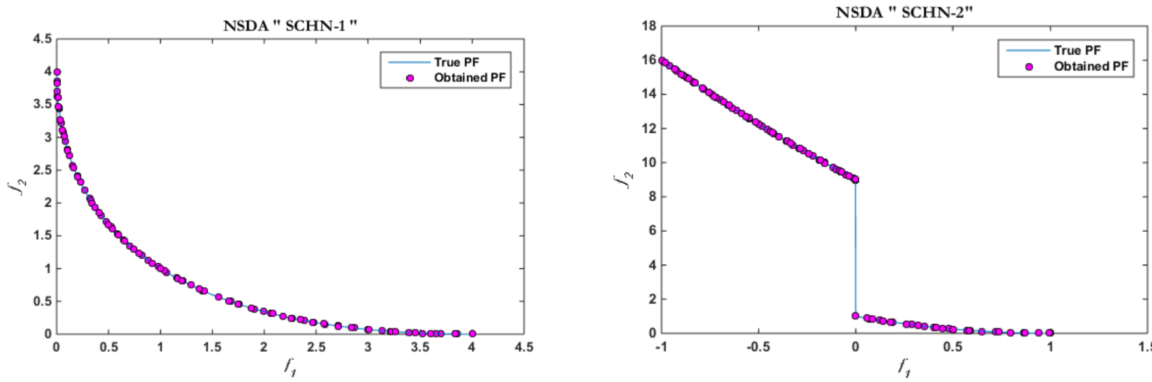


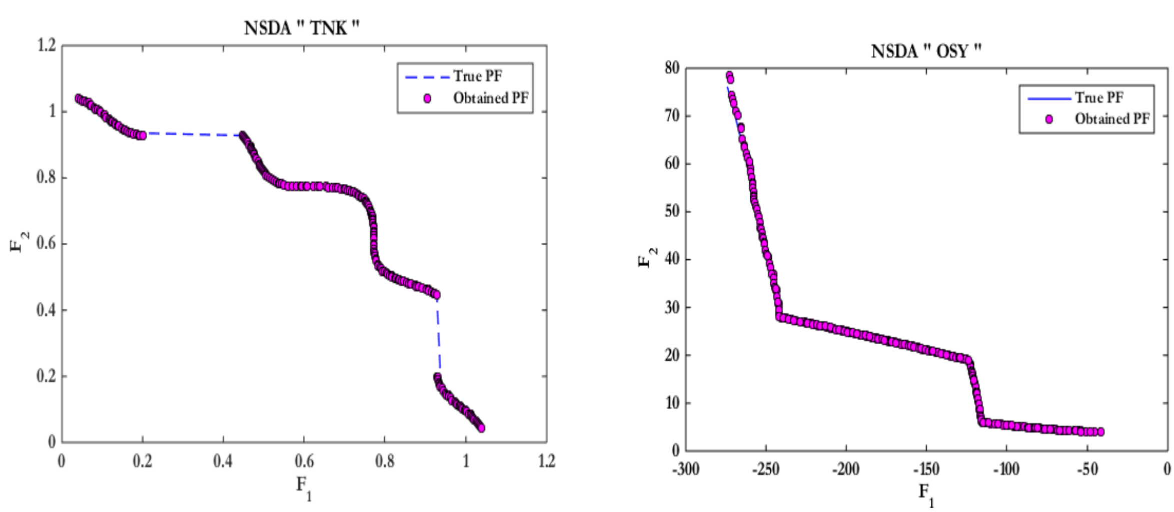
Fig. 6: Best Pareto optimal front of KUR, FON, ZDT1, ZDT2, ZDT3, ZDT4, SCHN1 and SCHN2 obtained by the NSDA algorithm

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 NSDA 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 NSDA algorithms on constrained test problems

Algorithm→ Function ↓	PFs	NSDA MEAN±SD	MOSOS MEAN±SD	MOCBO MEAN±SD	MOPSO MEAN±SD	NSGA-II MEAN±SD
	GD	0.14466±0.00210	0.1508±0.0040	0.1528±0.0051	0.1576±0.0062	0.1542±0.0072
TNK	Δ	0.57896±0.05587	0.1206±0.0423	0.1242±0.0512	0.1286±0.0522	0.126±0.06242
	CT	10.7895±0.04748	15.1286±0.063	11.0104±0.052	12.0212±0.054	17.4204±0.055
	GD	0.10054±0.00020	0.1196±0.0031	0.1210±0.0041	0.1282±0.0042	0.1242±0.0043
OSY	Δ	0.54789±0.05679	0.5354±0.0616	0.5422±0.0712	0.5931±0.0721	0.5682±0.0751
	CT	15.5578±0.02047	20.2124±0.032	12.2104±0.030	14.6420±0.042	24.2204±0.039
	GD	0.14458±0.00375	0.1436±0.0062	0.1498±0.0076	0.1644±0.0078	0.1566±0.0042
BNH	Δ	0.44587±0.03789	0.4288±0.0625	0.4798±0.0721	0.4975±0.0632	0.4892±0.0832
	CT	07.5254±0.04587	16.2664±0.054	9.1544±0.0420	9.7452±0.0464	19.652±0.0511
	GD	0.05001±0.01478	0.0988±0.0014	0.1018±0.0015	0.1125±0.0026	0.1024±0.0032
SRN	Δ	0.20458±0.00090	0.2295±0.0017	0.2352±0.0019	0.2730±0.0023	0.2468±0.0018
	CT	7.24456±0.00102	12.3254±0.012	7.3251±0.0082	9.2134±0.0083	17.0231±0.023
	GD	0.32145±0.04002	0.5162±0.0021	0.5202±0.0034	0.5854±0.0036	0.5532±0.0041
CONST	Δ	0.7056±0.000706	0.7122±0.0072	0.7235±0.0083	0.7344±0.0084	0.8126±0.0087
	CT	16.8556±0.00054	10.0112±0.003	5.2252±0.0028	6.4766±0.0035	14.0892±0.003



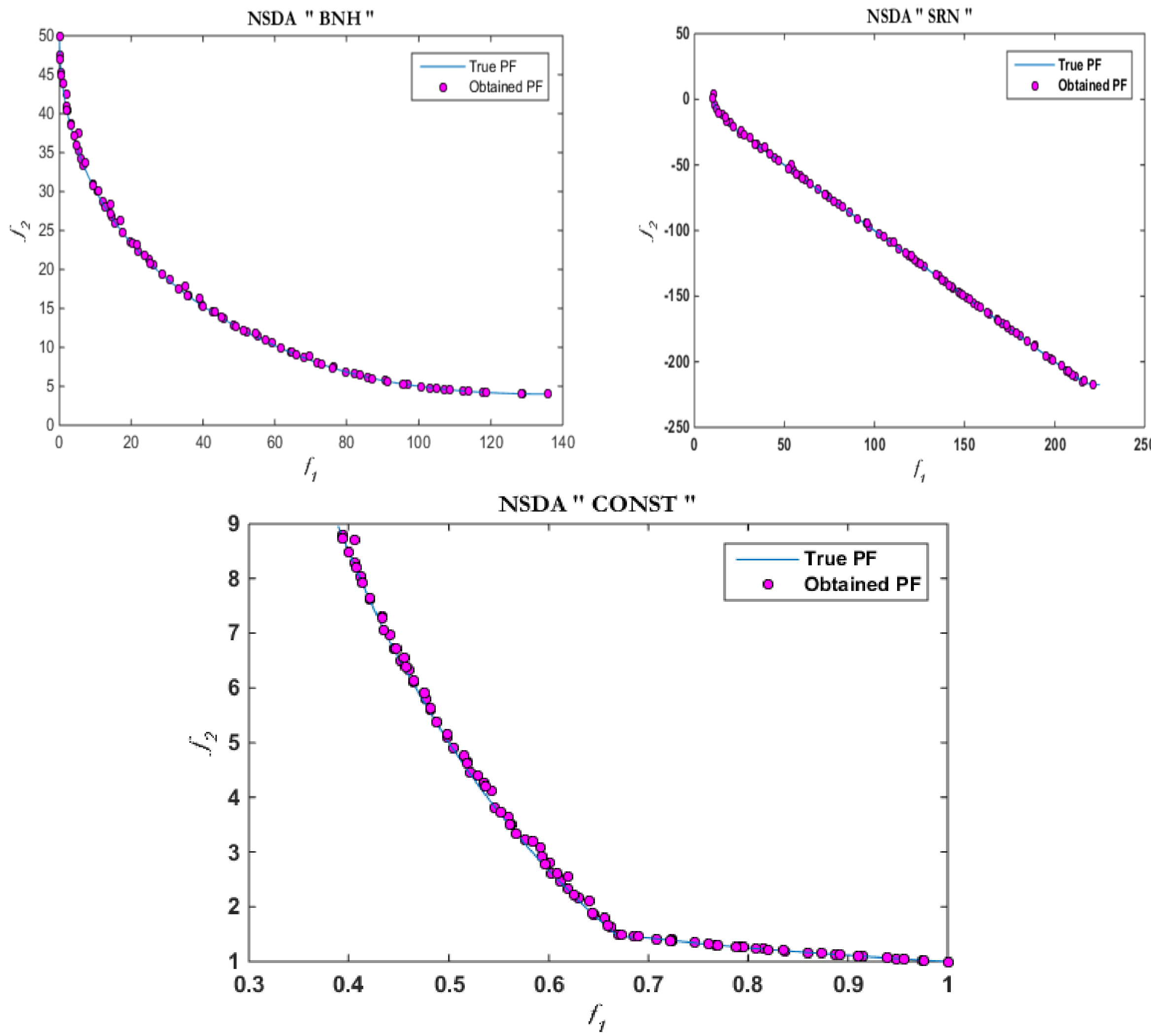


Fig. 7: Best Pareto optimal front TNK, OSY, BNH, SRN and CONST obtained by NSDA algorithm

Table 2 suggests that the NSDA algorithm comparatively performs better than other four algorithms for most of the standard constrained test functions employed. The best Pareto optimal fronts in Fig. 7 also helps in proving since all the Pareto optimal solutions exactly follow the true pareto fronts obtained from by NSDA 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 NSDA 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 NSDA 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 NSDA 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. 8. 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 NSDA algorithm on four-bar truss design problem in terms mean and standard deviation

PFs→ Methods ↓	GD	S
	MEAN±SD	MEAN±SD
NSDA	0.1756±0.0235	1.8717±0.1205
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

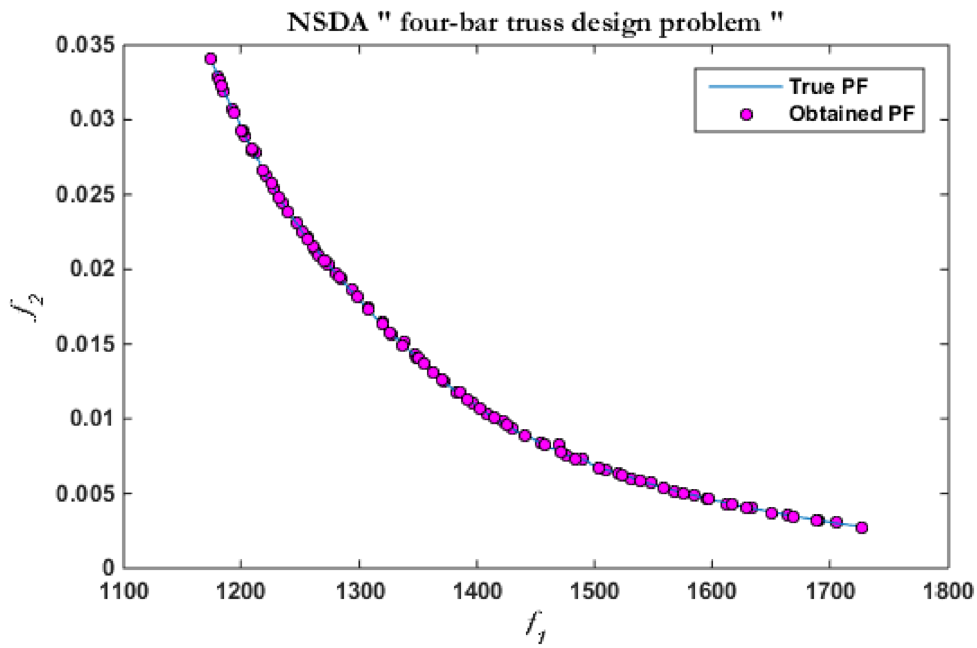


Fig. 8: Pareto optimal front obtained by the NSDA Algorithm for "Four –bus truss design problem"

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. 9. 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 NSDA algorithm on speed-reducer design problem in terms mean and standard deviation

PFs→ Methods ↓	GD	S
	MEAN±SD	MEAN±SD
NSDA	0.95578±0.32458780	1.578354±05.947475
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

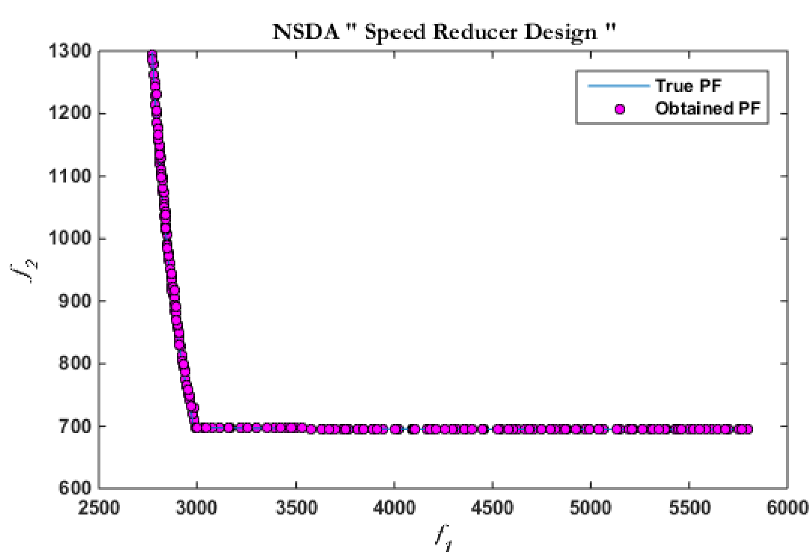


Fig. 9: Pareto optimal front obtained by the NSDA Algorithm for "Speed Reducer design problem"

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. 10. 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 NSDA algorithms on welded-beam design problem in terms mean and standard deviation

PFs→ Methods ↓	GD	Δ
	MEAN±SD	MEAN±SD
NSDA	0.03325±0.01693	0.75844±0.03770
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

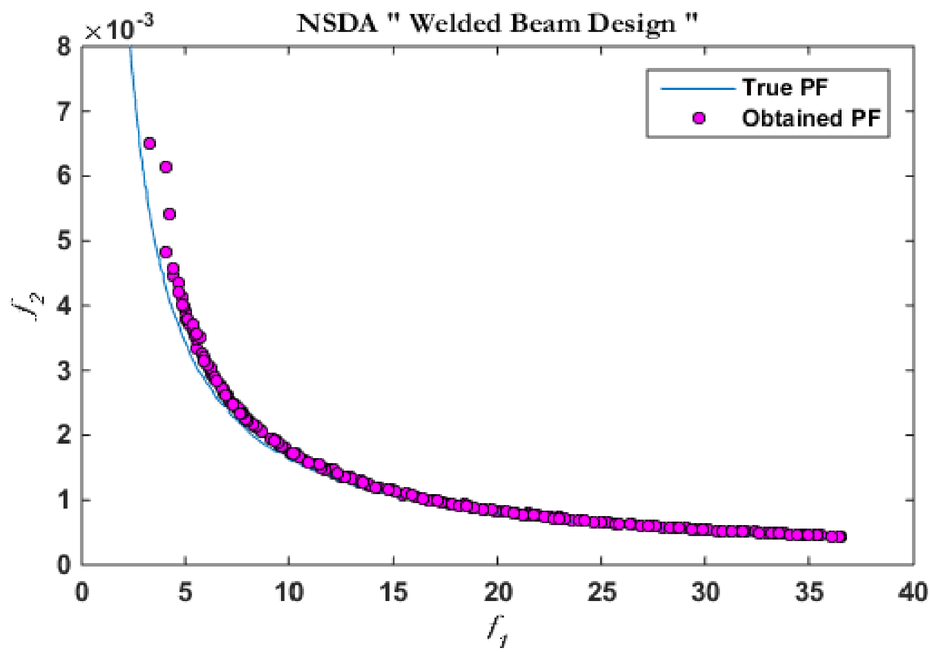


Fig. 10: Pareto optimal front obtained by the NSDA Algorithm for "Welded Beam Design problem"

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. 11. 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 NSDA algorithms on the Disk brake design problem in terms mean and standard deviation

PFs→ Methods ↓	GD	Δ
	MEAN±SD	MEAN±SD
NSDA	0.0587±0.27810	0.43551±0.08237
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

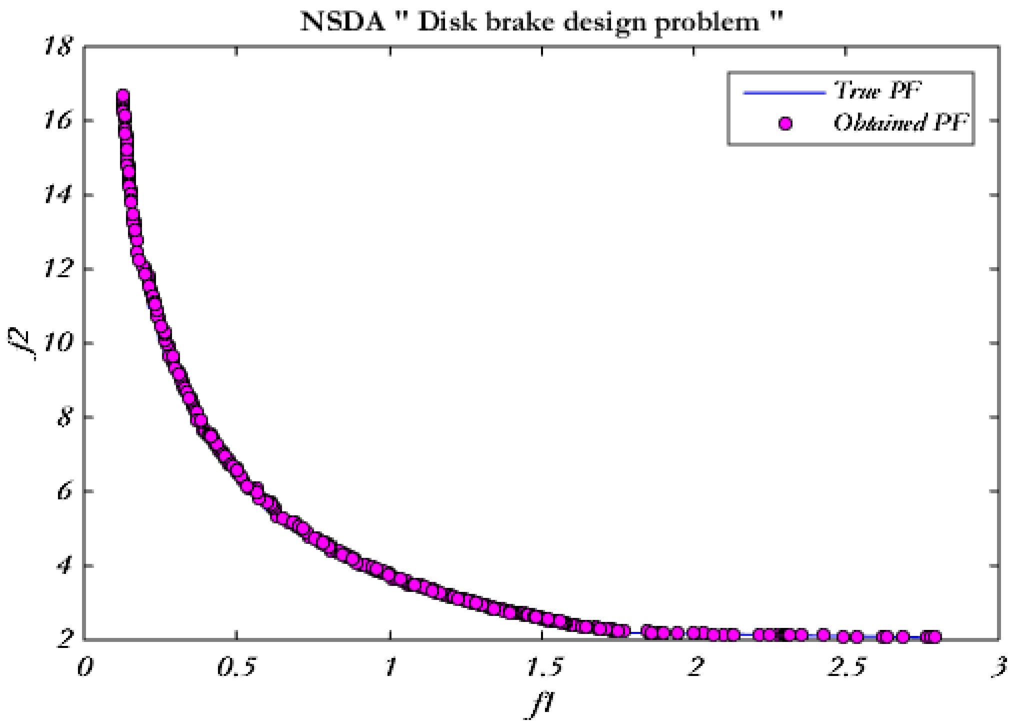


Fig. 11: Pareto optimal front obtained by the NSDA Algorithm for "Disk brake design problem"

Due to high complexity of engineering design problem it is really hard to gain results alike true pareto front but we can clearly see that optimal pareto obtained by NSDA 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 NSDA 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 there 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:

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

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

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:

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

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:

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

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:

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

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:

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

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.

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

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:

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

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

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

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

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

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:

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

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

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:

$$P_i^{Minimum} \leq P_i \leq P_i^{Maximum} \tag{4.13}$$

V. 40-Operational Thermal Generating Unit

a) 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 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 NSDA algorithm is added to table 7 and best pareto front obtained by NSDA algorithm is represented in Fig. 12.

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

Case Study I	SMODE [45]			NSGAII [45]			MBFA [46]			NSDA		
	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	127,568	119,310	124,830
Emission (tons/h)	66,799	377,560	96,578	93,002	153,560	99,671	176,682	356,424	188,963	87,124	408,025	94,450

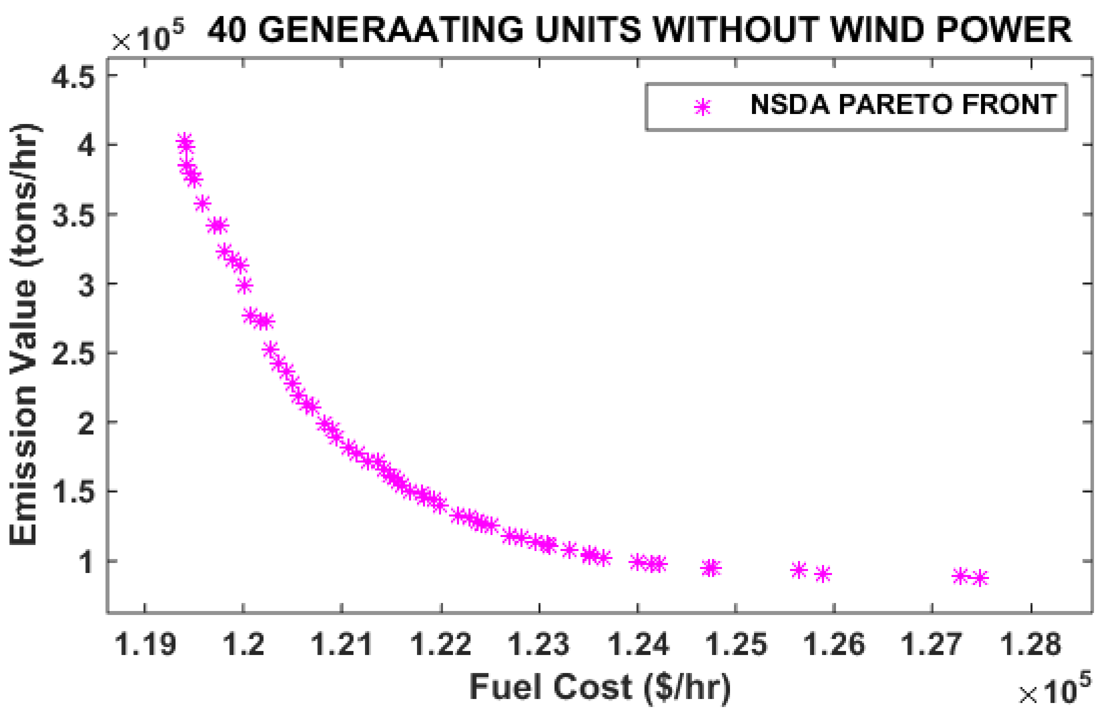


Fig. 12: Pareto optimal front obtained by the NSDA Algorithm for "40 thermal-generator lossless system without wind power"

b) *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 NSDA algorithm is reported in Table 8 and best optimal front is represented in Fig. 13.

Table 8: Results of the multi-objective NSDA algorithms for case study II- 40 thermal-generator lossless system with wind power

Case Study-II	SMODE[45]			NSGAII [45]			MOEA/D[51]			NSDA		
	Best emission	Best cost	Best Compromise point	Best emission	Best cost	Best Compromise Point	Best emission	Best cost	Best Compromise	Best emission	Best cost	Best Compromise Point
$\sum P_G$ P_W Cost Emission	10,245.76 254.24 153,830 54,055	10,177.55 322.45 116,430 385,770	10,225.71 274.29 123,590 68,855	10,241.72 258.28 132,410 73,894	10,242.09 257.91 122,610 121,850	10,241.63 258.37 126,240 78,860	10,244.43 255.568 154,0 0 0 55,754	10,242.71 257.294 115,770 440,240	10,242.8 257.156 120,950 79,485	10,242.7 257.321 146,685 56,509	10,224.18 275.82 118,689 179,099	10,236.58 263.42 123,459 68,801

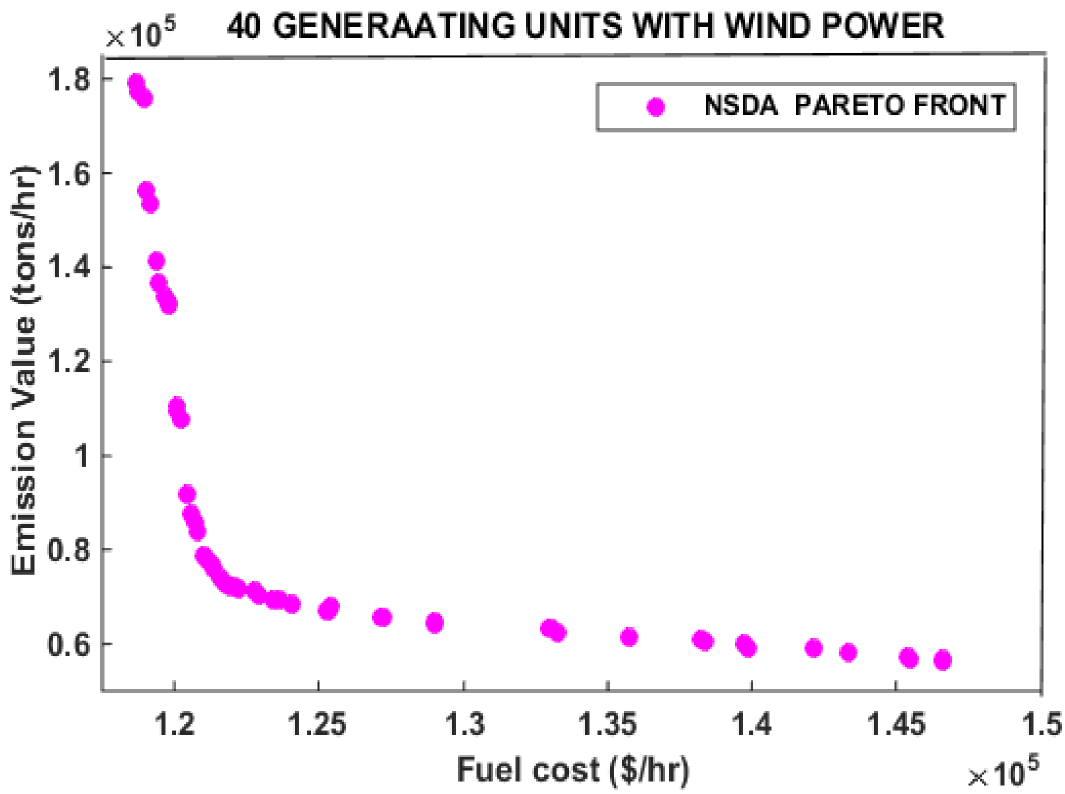


Fig. 13: Pareto optimal front obtained by the NSDA Algorithm for "40 thermal-generator lossless system with wind power"

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

		NSDA	NSGAII [45]			NSDA	NSGAII [45]
Case Study I Cost	Best Worst Mean Wilcoxon test (H/P) Simulation speed (s)	119310 127568 124830 1/ 5.40e −10 11.89	124,380 147,760 131,710	Case Study II Cost	Best Worst Mean Wilcoxon test (H/P) Simulation speed (s)	118,689 146,685 123,010 1/ 5.77e −10 09.785	122,610 173,060 134,880
Case Study I Emission	Best Worst Mean Wilcoxon test (H/P) Simulation speed (s)	87,124 408.025 189,284 1/ 5.55e −10 20.57	93,002 194,830 141,800 154.78	Case Study II Emission	Best Worst Mean Wilcoxon test (H/P) Simulationspeed (s)	56,509 179,099 104,258 1/ 5.63e −10 40.04	73,894 158,250 102,120 127.57

VI. Result Discussion

In almost all the cases that we consider in this article where NSDA algorithm proves its effectiveness in both prospective quantitative and qualitative. From plots also evident that NSDA algorithm follows the exact pareto front similar to the true pareto 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 Wilcoxon 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 NSDA algorithm performs superior to other algorithms that are considered for comparative purpose. NSDA algorithm shows good performance in both coverage and convergence as main mechanism that guarantee convergence in DA and NSDA algorithms are continuously shrink its virtual limitation using Levy strategy in the movement of dragonflies 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 NSDA algorithm has a little effect of slow convergence at all.

NSDA algorithm has an advantage of high coverage, which is the result of the selection of position of dragonflies and archive selection procedure. All the position are 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 pareto optimal front obtained during the optimization process.

VII. Conclusion

In this paper the non-dominated sorting dragonfly algorithm-multi-objective version of recently proposed dragonfly algorithm (DA) is proposed known as NSDA algorithm. This paper also utilizes the static and dynamic swarming strategy for exploration purpose used in its parent DA version. NSDA algorithm is developed with equipping dragonfly algorithm with crowding distance criterion, an archive and dragonflies position (accordance to ranking) selection method based on Pareto optimal dominance nature. The NSDA algorithm is first applied on 17 standard test functions (including eight unconstraint, five constraint and four engineering design problem) to prove its capability in terms of qualities and quantities showing numerical as well as convergence and coverage of pareto optimal front with respect to true pareto front. Then after NSDA 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 pareto 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 NSDA algorithm is able to find pareto optimal front of any kind of shape. Finally, the result of complex real world ECEDWP problem validates that NSDA 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 DA 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 NSDA 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:

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

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

$$-5 \le x_i \le 5$$

$$1 \le i \le 3$$

FON:

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

$$-4 \le x_i \le 4$$

$$1 \le i \le n$$

ZDT1:

Minimise: $f_1(x) = x_1$

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

Where:

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

$$0 \le x_i \le 1, 1 \le i \le 30$$

ZDT2:

Minimise: $f_1(x) = x_1$

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

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

$$0 \le x_i \le 1, 1 \le i \le 30$$

ZDT3:

Minimise: $f_1(x) = x_1$

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

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

$$0 \le x_i \le 1, 1 \le i \le 30$$

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: $f_1(x) = x_i^2$

$f_2(x) = (x-2)^2$ Where: value of can be from 10 to 10^5.

$$-A \le x \le A$$

SCHN-2 :

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

$$-5 \le x \le 10$$

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

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

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

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

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

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

$g_2(x) = 7.7 - (x_1 - 8)^2 - (x_2 + 3)^2$

$0 \leq x_1 \leq 5, 0 \leq x_2 \leq 3$

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: $g_1(x) = 2 - x_1 - x_2$

$g_2(x) = -6 + x_1 + x_2$

$g_3(x) = -2 - x_1 + x_2$

$g_4(x) = -2 + x_1 - 3x_2$

$g_5(x) = -4 + x_4 + (x_3 - 3)^2$

$g_6(x) = 4 - x_6 - (x_5 - 3)^2$

$0 \leq x_1 \leq 10, 0 \leq x_2 \leq 10, 1 \leq x_3 \leq 5, 0 \leq x_4 \leq 6, 1 \leq x_5 \leq 5, 0 \leq x_6 \leq 10$

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

$g_2(x) = x_1 - 3x_2 + 10$

$-20 \leq x_1 \leq 20, -20 \leq x_2 \leq 20$

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: $g_1(x) = 6 - (x_2 + 9x_1)$, $g_2(x) = 1 + x_2 - 9x_1$

$0.1 \leq x_1 \leq 1, 0 \leq x_2 \leq 5$

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: $f_1(x) = 200 * (2 * x(1) + sqrt(2 * x(2)) + sqrt(x(3)) + x(4))$

Minimise: $f_2(x) = 0.01 * (\left(\frac{2}{x(1)}\right) + \left(\frac{2*sqrt(2)}{x(2)}\right) - ((2 * sqrt(2))/x(3)) + (2/x(1)))$

$$1 \le x_1 \le 3{,}1.4142 \le x_2 \le 3{,}1.4142 \le x_3 \le 3{,}1 \le x_4 \le 3$$

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:

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

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

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

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

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

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

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

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

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

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

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

$2.6 \le x_1 \le 3.6{,}0.7 \le x_2 \le 0.8{,}17 \le x_3 \le 28{,}7.3 \le x_4 \le 8.3{,}7.3 \le x_5 \le 8.3{,}2.9 \le x_6 \le 3.9$

$5 \le x_7 \le 5.5$

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: $f_1(x) = 1.10471 * x(1)\hat{}2 * x(2) + 0.04811 * x(3) * x(4) * (14.0 + x(2))$

Minimise: $f_2(x) = 65856000/(30 * 10\hat{}6 * x(4) * x(3)\hat{}3)$

Where:

$g_1(x) = tau - 13600$

$g_2(x) = sigma - 30000$

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

$$g_4(x) = 6000 - P$$

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

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

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

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

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

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

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

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

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

Global Journal of Researches in Engineering: F
Electrical and Electronics Engineering
Volume 20 Issue 2 Version 1.0 Year 2020
Type: Double Blind Peer Reviewed International Research Journal
Publisher: Global Journals
Online ISSN: 2249-4596 & Print ISSN: 0975-5861

Research on Smooth Control of Wind Power Fluctuation with Hybrid Energy Storage

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GJRE-F Classification: FOR Code: 090607

RESEARCHONSMOOTHCONTROLOFWINDPOWERFLUCTUATIONWITHHYBRIDENERGYSTORAGE

Strictly as per the compliance and regulations of:

Research on Smooth Control of Wind Power Fluctuation with Hybrid Energy Storage

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Abstract- The output fluctuation of wind power system has brought huge hidden dangers to the grid. In recent years, the application of energy storage devices to stabilize the fluctuation has been greatly developed. In this paper, a control strategy for wind power fluctuation based on hybrid energy storage of battery and super-capacitor is proposed. Due to the performance characteristics of battery and super capacitor, a low-pass filter is designed to separate the output into low frequency for battery, and high frequency for super-capacitor. A voltage and current double closed-loop coordination controller is further designed to realize the frequency division mixed energy throughput of the battery and the super capacitor. The simulation results show that the proposed hybrid energy storage system effectively suppresses the power fluctuation of wind power system and prolongs the service life of the battery.

Keywords: wind power generation, hybrid energy storage, power fluctuation, smooth control.

I. Introduction

In order to alleviate energy crisis and improve ecological environment, the development and utilization of new energy has been worldwide concerned, among which the wind power generation technology has been rapidly developed. However, wind energy, as a natural clean energy, has great volatility and randomness under the influence of weather. Large-scale wind power grid connection has a certain impact on the safe and stable operation of the power system. At present, matching corresponding energy storage devices is usually adopted in the wind power generation system to effectively smooth the power fluctuation of wind energy [1-3].

At present, the energy storage system based on battery and super capacitor is mainly used to smooth the wind power fluctuation. Literature[4] proposed an energy storage structure of dual battery pack that separated charging and discharging processes, and designed a control strategy for power fluctuation to keep the battery running within the optimum discharge depth, thus prolonging the service life of the battery. Sun G W[5] utilized storage battery to suppress the power fluctuation of the wind farm, and realized real-time system adjustment by studying the space vector modulation algorithm of PWM converter. However, a single energy storage device cannot fully meet the comprehensive performance requirements of the system, and the combination of super capacitors and battery can improve the power regulation capacity of the energy storage system[6]. In literature[7], super capacitor voltage low-frequency suppression method is adopted to distribute the smoothing power required by super-capacitor and battery respectively. The battery set is divided into three independent units to alleviate the current imbalance and reduce the loop current ripple. In literature[8], the sliding average filtering algorithm is adopted to separate the power required by the flat suppression of the battery, which effectively reduces The Times of charging and discharging of the battery and improves the operation economy of the energy storage system. Literature[9] proposed an energy storage technology based on wavelet packet decomposition to smooth power fluctuations. Power fluctuation signals are decomposed at multiple scales by wavelet packet decomposition theory. Low-frequency fluctuations are directly connected to the grid, while high-frequency fluctuations are further decomposed to different energy storage devices through wavelet packet decomposition for smoothing.

In this paper, for the combined wind storage system, a control strategy based on hybrid energy storage to smooth out wind power fluctuations is studied. Through a low-pass filter the fluctuation of power is separated into high frequency and low frequency, complying with the super capacitor and battery characteristics respectively, to enhance the control capacity and the service life of the battery energy storage system, proposing a voltage and current double closed-loop coordination controller where two kinds of energy storage devices share the voltage outer loop. Finally the validity of the proposed control strategy is validated by computer simulation.

II. Structure of the Wind Storage System

The energy storage system can cut the peak load, fill the valley load and reduce the power fluctuation when wind power is connected to the power system, which is conducive to large-scale access of wind power, improving the stability of the grid, and carrying out planned dispatching of wind power generation[10]. For

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the current mainstream doubly fed induction generator, adopting a centralized hybrid energy storage system which is directly connected to the ac bus in parallel. Its structure is shown in figure 1.

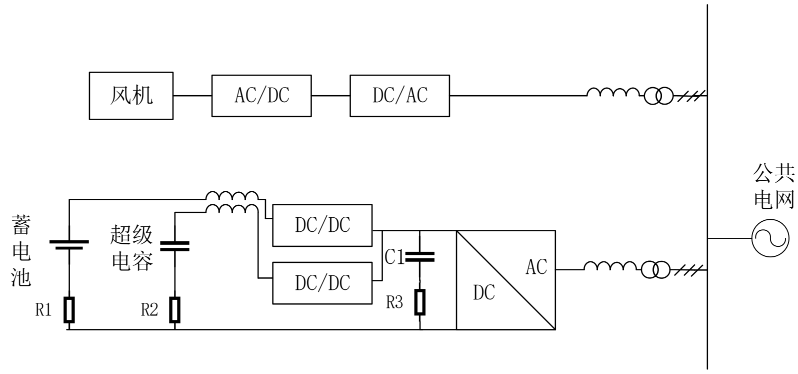

Fig. 1: Structure of wind turbine-energy storage system

The energy storage devices are all connected to the dc bus of the energy storage converter through bi-directional DC-DC Converter, as shown in figure 2.The circuit has a Boost state and a Buck state. When the wind energy is insufficient, the energy storage device is required to provide energy. Energy flows from the energy storage device to the dc bus. When there is surplus of wind energy, the energy storage device is required to absorb energy. Energy flows from the dc bus to the energy storage device. Meanwhile T1 tube is turned on and T2 tube is turned off, the converter works in Buck state, and the energy storage device is charged.

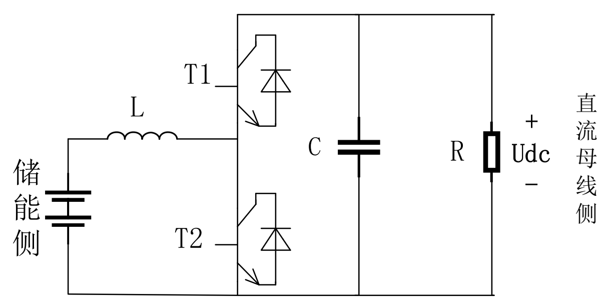

Fig. 2: Bidirectional DC-DC convertor

The energy storage converter is connected between the dc bus and the common ac bus, and PQ control is adopted to obtain the active power and reactive power required by the system (where the reference value of reactive power is set as 0). When there is surplus of wind energy, the energy storage system absorbs energy, and the energy storage converter is in the rectifying state. When there is short of wind energy, the energy storage system releases energy, and the energy storage converter is in the state of inverter. Its circuit structure diagram is shown in figure 3.

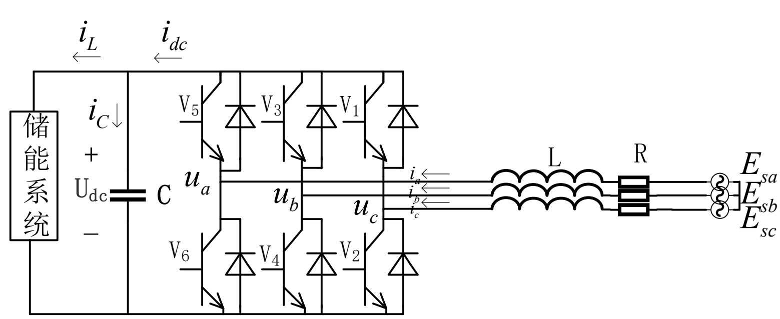

Fig. 3: Equivalent circuit model energy storage convertor

The expressions of active power and reactive power of the energy storage converter are as follows [11]

$$P = E_{sd} i_d$$
$$Q = -E_{sd} i_q \qquad (1)$$

Where i_d 、 i_q is the component of the three-phase current on the ac side in the d and q axis, and is the component of the three-phase voltage on the ac side in the d axis. Active power and reactive power can be

Global Journal of Researches in Engineering (F) Volume XX Issue II Version I Year 2020

controlled by controlling i_d and i_q. When the energy storage converter is connected to the grid, the phase and frequency of the ac side can be obtained through the phase-locked loop. Through the energy storage system to specify the throughput active power P_{HESS} and reactive power Q_{HESS}, the reference value of the current loop i_{dref} and i_{qref} can be obtained after calculation. u_d、u_q can be obtained by comparing and controlling the current loop with i_d、i_q, and u_{ref} can be obtained by Park transform in version, and then generating SVPWM wave to control the on and off of the switch tube.

III. Power Fluctuation Restrain based on Hybrid Energy Storage System

Current specification standards of wind power fluctuations is in accordance with Technical Provisions for Wind Farm Access to Power System issued by State Grid Corporation of China, in February 2009, This document clearly specifies the maximum variation of output power when the wind farm is connected to the grid, including the variation of 1min and 10mins. The specific data are shown in table 1 below.

Table 1: The recommendation value of the maximum variation rate of the wind farm

Capacity of Wind Farms(MW)	Maximum Change in 1 min(MW)	Maximum Change in 10 mins (MW)
<30	6	20
30-150	capacity/5	capacity/1.5
>150	30	100

a) Energy flow of wind storage system

The main output power of the wind storage system comes from the power generated by the draught fan, so the main factor affecting the wind storage system is wind speed. The power balance relationship of wind storage system is as follows

$$\begin{aligned} P_o &= P_w - P_{HESS} \\ P_{HESS} &= P_b + P_c \end{aligned} \tag{2}$$

Where P_{HESS} is the throughput power of the hybrid energy storage system, P_b and P_c is the throughput power of the battery and ultra-capacitor respectively, and P_o is the grid-connected power of the whole system. When the wind speed is relatively high, the energy storage system needs to absorb power to smooth the fluctuating power, while the wind speed is relatively low, the energy storage system emits power to stabilize the power fluctuation.

b) Low pass filter for frequency division

The first order low-pass filter is designed to separate the power frequency of the energy storage system into low frequency for battery and high frequency for super-capacitor. The circuit schematic diagram is shown in figure 4, where U_1 is the input signal, U_2 is the output signal, R is the filter resistance, and C is the filter capacitor.

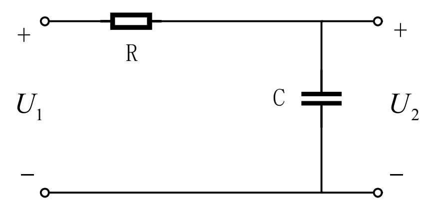

Fig. 4: Circuit diagram of one-order low pass filter

The differential equation of the circuit is shown in equation (3).

$$RC\frac{dU_2}{dt} + U_2 = U_1 \tag{3}$$

The transfer function is

$$H(s) = \frac{1}{1+\tau s} \tag{4}$$

Where s is the filter operator, τ is the filter time constant, $\tau = 1/2\pi f_c$, and f_c is the filter cut-off frequency.

When the filter is applied to the power distribution of the energy storage system, the input signal U_1 is the expected power value of the energy storage through put P_{HESS}^*, and the output signal U_2 is the reference power value of the battery throughput P_b^*. The expressions are

$$P_b^* = \frac{1}{1+\tau s} P_{HESS}^* \tag{5}$$

$$P_c^* = P_{HESS}^* - P_b^* = \frac{\tau s}{1+\tau s} P_{HESS}^* \tag{6}$$

In the expression, P_c^* is the reference value of the power suppressed by super-capacitor. According to the characteristics of each energy storage device, the battery response time is the key factor. The power with a frequency higher than 0.1Hz and the power with a frequency lower than 0.1Hz is designed to be absorbed by a super-capacitor and a battery respectively, so take $f_c = 0.1Hz$, $\tau = 1.6s$.

c) *Coordinated control strategy of voltage and current double closed loop*

The following voltage and current double closed-loop frequency division coordination control strategy is further proposed, as is shown in fig 5. The super-capacitor and the battery share a voltage outer loop. The current inner loop reference value I_{ref} is obtained by the PI controller, and is subsequently divided into high frequency part and low frequency part, as the reference value of the battery current loop and the reference value of the super-capacitor current loop respectively.

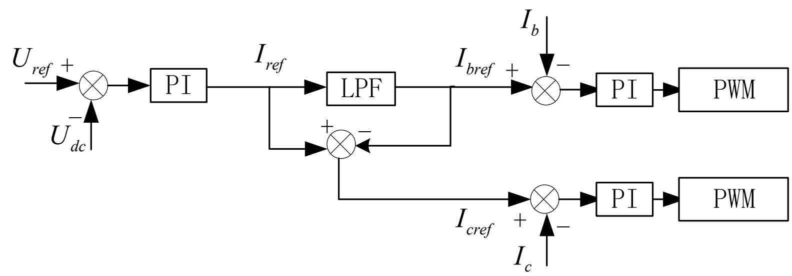

Fig. 5: Voltage and current double closed-loop coordination control strategy

When the circuit is in Boost state, T1 tube is turned off and T2 tube is working. The DC voltage is controlled by adjusting its duty cycle D, where $D = T_{on} / T$, and T_{on} is the conduction time of T2 tube in one cycle. Provided that the DC bus voltage is U_{dc}, the terminal voltage of the energy storage device is U_{bar}, and the current flowing into the energy storage side is I, when the T2 tube is working, the state equation can be obtained as follows:

$$\frac{d}{dt}\begin{bmatrix} I \\ U_{dc} \end{bmatrix} = \begin{bmatrix} 0 & \frac{-1(1-D)}{L} \\ \frac{1-D}{C} & \frac{-1}{RC} \end{bmatrix} \begin{bmatrix} I \\ U_{dc} \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} U_{bar} \tag{7}$$

Thus, the circuit's current loop control equation and duty cycle adjustment equation under Boost state are:

$$L\frac{dI}{dt} = U_{bar} - (1-D)U_{dc} \tag{8}$$

$$D = \frac{(K_p + K_i / s)(I_{ref} - I) - U_{bar} + U_{dc}}{U_{dc}} \tag{9}$$

Where K_p and K_i are the proportional and integral current loop parameters of the PI controller.

Similarly, when the circuit is in Buck state, the current loop control equation and duty cycle expression are:

$$L\frac{dI}{dt} = -U_{bar} + D * U_{dc} \quad (10) \tag{10}$$

$$D = \frac{(K_p + K_i / s)(I_{ref} - I) + U_{bar}}{U_{dc}} \tag{11}$$

IV. Simulation Results

Based on Matlab / Simulink, an integrated wind and energy storage grid-connected system is established. The external system uses a single-machine infinite system. The main parameters of the fan are 100kW fan capacity and 690V rated voltage, and the main parameters of the energy storage system are 300Ah battery capacity, 0.5R battery internal resistance, 70F super-capacitor capacity and 800V DC bus reference voltage.

Assume that the active power output expectation of the system, namely the grid dispatch value, is constant within a second time scale, the reactive power is zero, and the wind speed is variable. The output power of the wind turbine and the power to the grid stabilized by the energy storage system are shown in Fig 6, which verifies that the power to the grid remains basically unchanged after smoothed by the designed hybrid energy storage stabilization system, meeting the grid dispatching requirements.

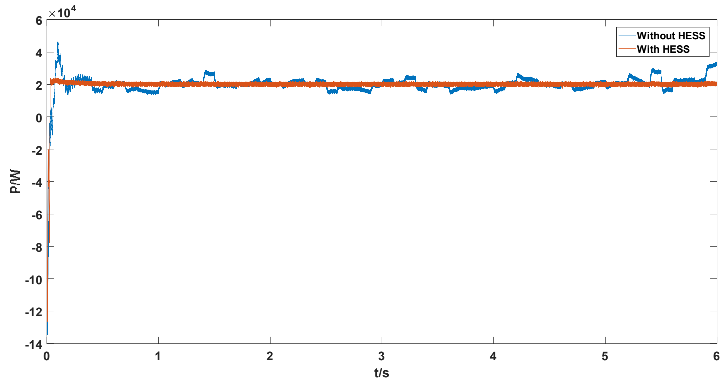

Fig. 6: Comparison of suppressing power under variable wind speed

Figures 7 and 8 compare the actual power and reference power of the battery and super-capacitor, illustrating that the energy storage device can be charged and discharged according to the reference value of power distribution, and the proposed hybrid energy storage system can well suppresses wind power fluctuations.

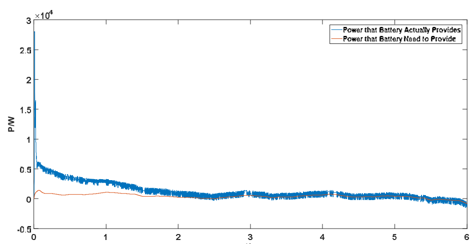

Fig. 7: Actual and reference power of battery

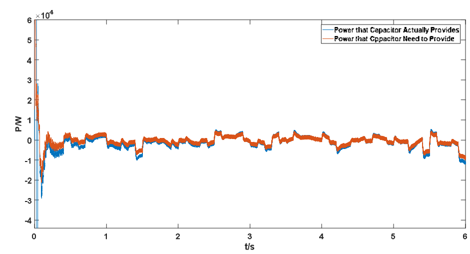

Fig. 8: Actual and reference power of capacitor

Fig 9 and 10 show the changes of SOC values of the battery and super-capacitor when the system is connected to the grid. It shows that the smooth battery SOC curve has a small amplitude variation range without repeated charge and discharge. The super-capacitor SOC changes rapidly with repeated charge and discharge for many times, and the charge and discharge depth is also larger than that of the battery. Therefore, the effectiveness of the hybrid energy storage control strategy is verified, which can effectively reduce the charging and discharging times of the battery and prolong its service life.

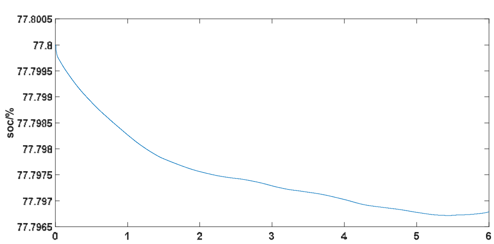

Fig. 9: SOC curve of battery

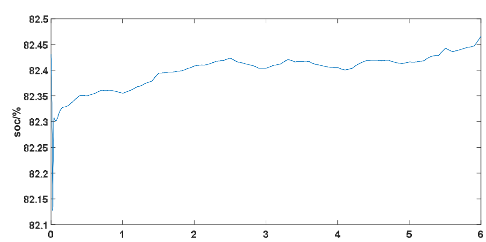

Fig. 10: SOC curve of super capacitor

V. Conclusion

In this paper, a wind power grid-connected system based on hybrid storage of battery and super-capacitor is established, and a power fluctuation smoothing strategy based on voltage and current double closed-loop frequency division coordinated control is proposed. The actual power characteristics and SOC change curve of the battery and super-capacitor are observed in the simulation under the conditions of constant wind speed and variable wind speed. The results verify that the control strategy can effectively smooth the fluctuation of wind power, reduce charging and discharging times of the battery, and prolong its service life.

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17. Never copy others' work: Never copy others' work and give it your name because if the evaluator has seen it anywhere, you will be in trouble. Take proper rest and food: No matter how many hours you spend on your research activity, if you are not taking care of your health, then all your efforts will have been in vain. For quality research, take proper rest and food.

18. Go to seminars: Attend seminars if the topic is relevant to your research area. Utilize all your resources.

19. Refresh your mind after intervals: Try to give your mind a rest by listening to soft music or sleeping in intervals. This will also improve your memory. Acquire colleagues: Always try to acquire colleagues. No matter how sharp you are, if you acquire colleagues, they can give you ideas which will be helpful to your research.

20. Think technically: Always think technically. If anything happens, search for its reasons, benefits, and demerits. Think and then print: When you go to print your paper, check that tables are not split, headings are not detached from their descriptions, and page sequence is maintained.

21. Adding unnecessary information: Do not add unnecessary information like "I have used MS Excel to draw graphs." Irrelevant and inappropriate material is superfluous. Foreign terminology and phrases are not apropos. One should never take a broad view. Analogy is like feathers on a snake. Use words properly, regardless of how others use them. Remove quotations. Puns are for kids, not grunt readers. Never oversimplify: When adding material to your research paper, never go for oversimplification; this will definitely irritate the evaluator. Be specific. Never use rhythmic redundancies. Contractions shouldn't be used in a research paper. Comparisons are as terrible as clichés. Give up ampersands, abbreviations, and so on. Remove commas that are not necessary. Parenthetical words should be between brackets or commas. Understatement is always the best way to put forward earth-shaking thoughts. Give a detailed literary review.
22. Report concluded results: Use concluded results. From raw data, filter the results, and then conclude your studies based on measurements and observations taken. An appropriate number of decimal places should be used. Parenthetical remarks are prohibited here. Proofread carefully at the final stage. At the end, give an outline to your arguments. Spot perspectives of further study of the subject. Justify your conclusion at the bottom sufficiently, which will probably include examples.
23. Upon 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 for 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 of 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 criteria peer reviewers will use for grading the final paper.

Final points:

One purpose of organizing a research paper is to let people interpret your efforts selectively. The journal requires the following sections, submitted in the order listed, with each section starting on a new page:

The introduction: This will be compiled from reference matter and reflect the design processes or outline of basis that directed you to make a study. As you carry out the process of study, the method and process section will be constructed like that. The results segment will show related statistics in nearly sequential order and direct reviewers to similar intellectual paths throughout the data that you gathered to carry out your study.

The discussion section:

This will provide understanding of the data and projections as to the implications of the results. The use of good quality references throughout the paper will give the effort trustworthiness by representing an alertness to 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 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 avoid:

- Insertion of a title at the foot of a page with subsequent text on the next page.
- Separating a table, chart, or figure—confine each to a single page.
- Submitting a manuscript with pages out of sequence.
- In every section of your document, use standard writing style, including articles ("a" and "the").
- Keep paying attention to the topic of the paper.

- Use paragraphs to split each significant point (excluding the abstract).
- Align the primary line of each section.
- Present your points in sound order.
- Use present tense to report well-accepted matters.
- Use past tense to describe specific results.
- Do not use familiar wording; don't address the reviewer directly. Don't use slang or superlatives.
- Avoid use of extra pictures—include only those figures essential to presenting results.

Title page:

Choose a revealing title. It should be short and include the name(s) and address(es) of all authors. It should not have acronyms or abbreviations or exceed two printed lines.

Abstract: This summary should be two hundred words or less. It should clearly and briefly explain the key findings reported in the manuscript and must have precise statistics. It should not have acronyms or abbreviations. It should be logical in itself. Do not cite 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 approaches 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. Use comprehensive sentences, and do not sacrifice readability for brevity; you can maintain it succinctly by phrasing sentences so that they provide more than a 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 limit the initial two items to no more than one line each.

Reason for writing the article—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 for this; results of any numerical analysis should be reported. Significant conclusions or questions that emerge from the research.

Approach:

- o Single section and succinct.
- o An outline of the job done is always written in past tense.
- o Concentrate on shortening results—limit background information to a verdict or two.
- o Exact spelling, clarity 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 of comprehending and calculating the purpose of your study without having to refer to other works. The basis for the study should be offered. Give the most important references, but avoid making a comprehensive appraisal of the topic. Describe the problem visibly. If the problem is not acknowledged in a logical, reasonable way, the reviewer will give no attention to your results. Speak in common terms about techniques used to explain the problem, if needed, but do not present any particulars about the protocols here.

The following approach can create a valuable beginning:

- o Explain the value (significance) of the study.
- o Defend the model—why did you employ this particular system or method? What is its compensation? Remark upon its appropriateness from an abstract point of view as well as pointing out sensible reasons for using it.
- o Present a justification. State your particular theory(-ies) or aim(s), and describe the logic that led you to choose them.
- o Briefly explain the study's tentative purpose and how it meets 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 for every section. If you make the four points listed above, you will need at least four paragraphs. Present surrounding information only when it is necessary to support a situation. The reviewer does not desire to read everything you know about a topic. Shape the theory specifically—do not take a broad view.

As always, give awareness to spelling, simplicity, and correctness of sentences and phrases.

Procedures (methods and materials):

This part is supposed to be the easiest to carve if you have good skills. A soundly written procedures segment allows a capable scientist to replicate 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 to give the least amount of information that would permit another capable scientist to replicate 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 section, mention the specific item describing the way, but draw the basic principle while stating the situation. The purpose is to show 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:

Materials may be reported in part of a section or else they may be recognized along with your measures.

Methods:

- Report the method and not the 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—detail how procedures were completed, not how they were performed on a particular day.
- If well-known procedures were used, account for the procedure by name, possibly with a reference, and that's all.

Approach:

It is embarrassing to use vigorous voice when documenting methods without using first person, which would focus the reviewer's interest on the researcher rather than the job. As a result, when writing up the methods, most authors use third person passive voice.

Use standard style in this and 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 as 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. Use statistics and tables, if suitable, to present consequences most efficiently.

You must clearly differentiate material which would usually be incorporated in a study editorial from any unprocessed data or additional appendix matter that would not be available. In fact, such matters should not be submitted at all except if requested by the instructor.

Content:

- Sum up your conclusions in text and demonstrate them, if suitable, with figures and tables.
- In the manuscript, explain each of your consequences, and point the reader to remarks that are most appropriate.
- Present a background, such as by describing the question that was addressed by creation of an exacting study.
- Explain results of control experiments and give 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 manuscript.

What to stay away from:

- Do not discuss or infer your outcome, report surrounding information, or try to explain anything.
- Do not include raw data or intermediate calculations in a research manuscript.
- Do not present similar data more than once.
- A manuscript should complement any figures or tables, not duplicate information.
- Never confuse figures with tables—there is a difference.

Approach:

As always, use past tense when you submit 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 section.

Figures and tables:

If you put figures and tables at the end of some details, make certain that they are visibly distinguished from any attached appendix materials, such as raw facts. Whatever the position, each table must be titled, numbered one after the other, and include a heading. All figures and tables must be divided from the text.

Discussion:

The discussion is expected to be the trickiest segment to write. A lot of papers submitted to the journal are discarded based on problems with the discussion. There is no rule for how long an 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 implications of the study. The purpose here is to offer an understanding of your results and support all of your conclusions, using facts from your research and generally accepted information, if suitable. The implication of results should be fully 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 the prospect, and let it drop at that. Make a decision as to whether each premise is supported or 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.

- You may propose future guidelines, such as how an experiment might be personalized to accomplish a new idea.
- Give details of all of your remarks as much as possible, focusing on mechanisms.
- Make a decision as to whether the tentative design sufficiently addressed the theory and whether or not it was correctly restricted. Try to present substitute explanations if they are sensible alternatives.
- One piece of 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 other available information. Present work done by specific persons (including you) in past tense.

Describe generally acknowledged facts and main beliefs in present tense.

The Administration Rules

Administration Rules to Be Strictly Followed before Submitting Your Research Paper to Global Journals Inc.

Please read the following rules and regulations carefully before submitting your research paper to Global Journals Inc. to avoid rejection.

Segment draft and final research paper: You have to strictly follow the template of a research paper, failing which your paper may get rejected. You are expected to write each part of the paper wholly on your own. The peer reviewers need to identify your own perspective of the concepts in your own terms. Please do not extract straight from any other source, and do not rephrase someone else's analysis. Do not allow anyone else to proofread your manuscript.

Written material: You may discuss this with your guides and key sources. Do not copy anyone else's paper, even if this is only imitation, otherwise it will be rejected on the grounds of plagiarism, which is illegal. Various methods to avoid plagiarism are strictly applied by us to every paper, and, if found guilty, you may be blacklisted, which could affect your career adversely. To guard yourself and others from possible illegal use, please do not permit anyone to use or even read your paper and file.

Criterion for Grading a Research Paper (Compilation) by Global Journals

Please note that following table is only a Grading of "Paper Compilation" and not on "Performed/Stated Research" whose grading solely depends on Individual Assigned Peer Reviewer and Editorial Board Member. These can be available only on request and after decision of Paper. This report will be the property of Global Journals.

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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ISSN 9755861