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

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

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

Nomenclature

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

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

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

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

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

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

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

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

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

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

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

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I. Introduction

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

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

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

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

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

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

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

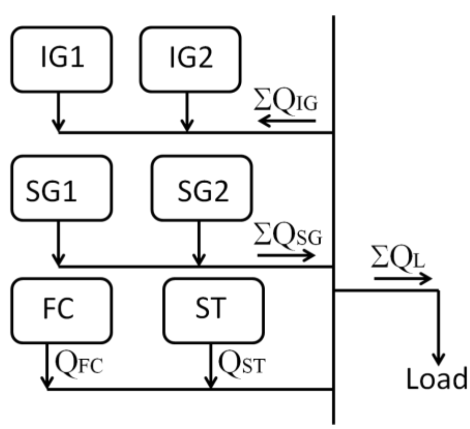

Fig. 1: Reactive power arrangements in multi units HIS

II. System Mathmatical Modelling

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

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

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

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

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

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

Comparing Eq. (2) and (3),

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

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

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

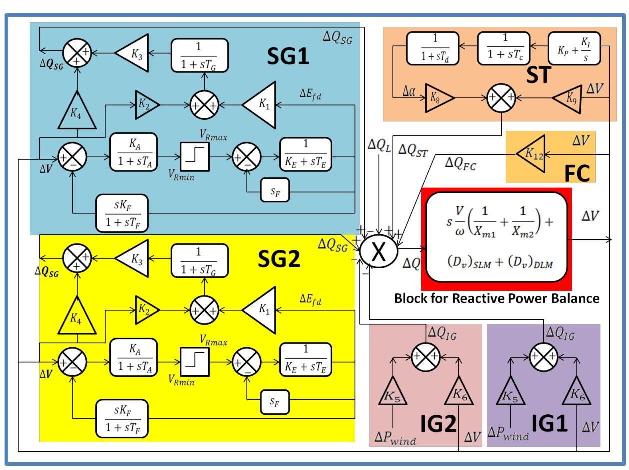

Fig. 2: Simulink block diagram for multi units IHS

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

Table 1: Typical system and components rating used for simulation

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

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

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

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

III. Selection Procedure For Participation Of Static And Dynamic Compensators

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

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

Equality constraints;

$$Q_{demand} = Q_{release} \tag{6}$$

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

$$Q_{release} = Q_{FC}^{ss} + Q_{ST}^{ss} \tag{8}$$

Inequality constraints;

$$0 \le Q_{ST}^{ss} \le Q_{demand} \tag{9}$$

$$0 \le Q_{FC}^{ss} \le Q_{demand} \tag{10}$$

$$V_{min} \le \Delta V \le V_{max} \tag{11}$$

$$settling\ time \le settling\ time_{acceptable} \tag{12}$$

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

IV. Resuts and Discussion

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

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

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

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

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

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

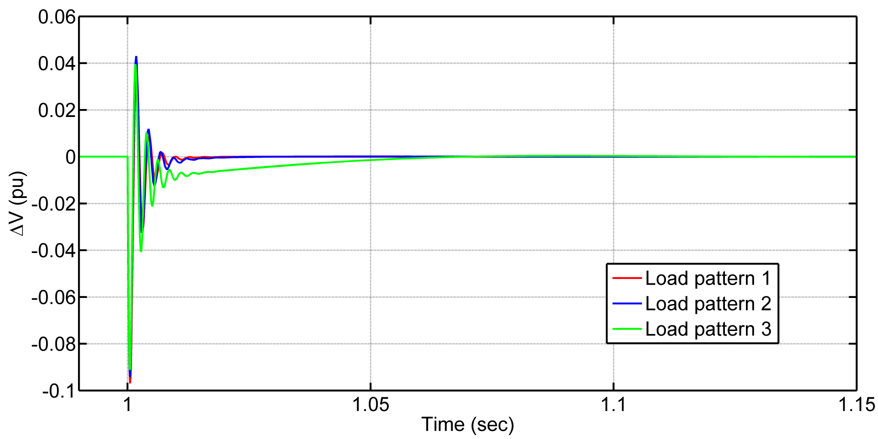

Fig. 3: Comparative study for ΔV for different load patterns

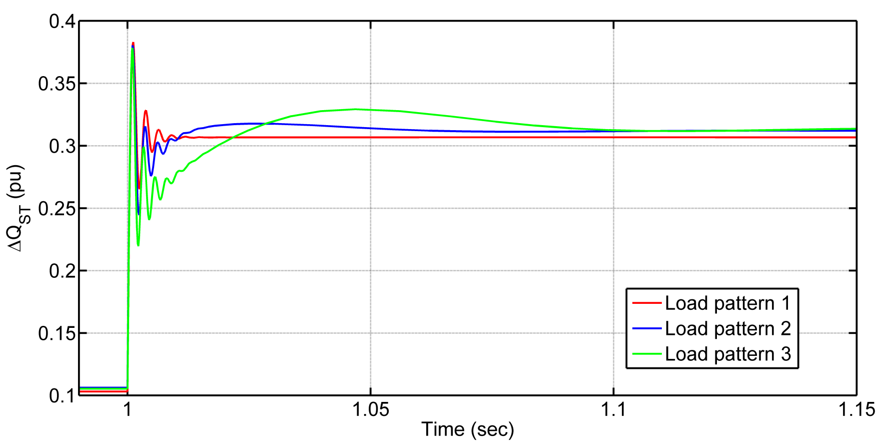

Fig. 4: Comparative study for ΔQ_{ST} for different load patterns

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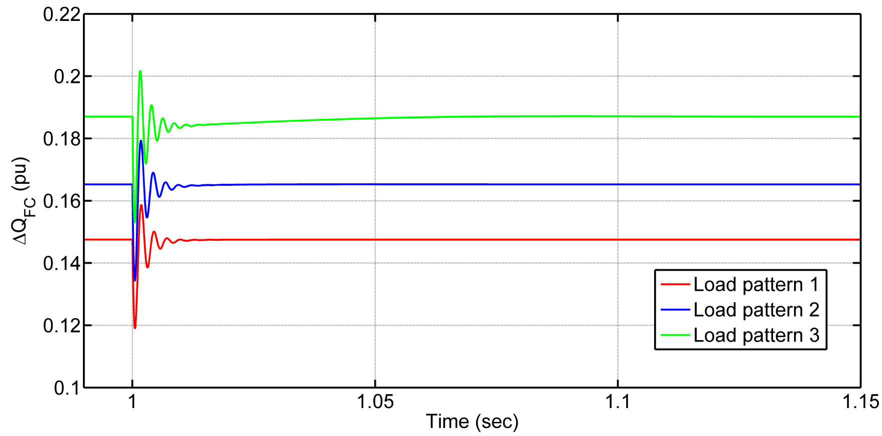

Fig. 5: Comparative study for ΔQ_{FC} for different load patterns

V. Conclusions

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

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Appendix 1

Induction Generator

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

Synchronous Generator

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

Fixed capacitor

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

STATCOM

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

Appendix 2

Constants used in simulink model

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

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

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