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Reactive power pricing using cloud service considering wind energy

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Abstract This paper proposes a transparent and reliable method between the suppliers and consumers for optimal reactive power pricing. The electric power suppliers compute the optimal reactive power using optimal reactive power dispatch problem by considering nodal voltage stability index 'I' as one of the constraints. The computed optimal reactive power of the generator is included in the reactive power pricing. The pricing method to the suppliers based on the opportunity cost method is presented and a detailed analysis using 62 bus Indian utility system has been carried out by considering diverse cases. In this proposed pricing method, the services of the cloud technology have been used to provide transparent pricing based on the demands of the consumers. The power demands at the consumers' site is calculated without the human involvement using the Internet of Things and the same is uploaded in the cloud. In reactive power pricing, the system operator acts as a mediator between the suppliers and consumers. Based on the demand and availability of power, the system operator provides the cost for the service to the consumer through cloud.

Keywords Reactive power price · Stability index · Differential evolution · Optimal dispatch · Opportunity cost · Cloud service

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1 Introduction

Emerging trends towards the deregulation introduces multi-faceted challenges in the power market. Various researches are wheeling to shape the power market. The electricity market provides both real power and reactive power market. The reactive power maintains the voltage and has a profound effect on security of the power system. The analysis of characteristics and cost of the reactive power sources are described in the report submitted by Federal Energy Regulatory Commission (FERC) [1]. Further, a major reason for blackout in the states of USA in 2003 is due to the incapability of the power system to maintain the reactive power [2].

The electric power supply is provided by the suppliers to their customers through the power grid using the interconnected network [3]. This system consists of various generators that produces the electric power that are transmitted through the transmission lines to the place where the demand is available. The cloud computing technology helps in building and automating the smart grid through Internet that offers highly scalable distributed storage and computing platform as services to variety of applications. By hosting the applications, services and data on the cloud, the cost of hardware, software and maintenance can be reduced [4]. Power-aware cloud metering [5] has been proposed for dynamic price calculation in which the tariff for the cloud service is also included in the billing model.

The voltage collapse occurs in the system due to insufficient voltage at system nodes. The effective proximity index for voltage collapse is 'I' index which indicates the current operating status of the system and to identify the vulnerable buses responsible for creating the voltage collapse. This helps the power system operator to take preventive and corrective action in the system. According to the method proposed by

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Sinha [6], even the most popular index, Line voltage stability L_i is not very reliable index to indicate the voltage collapse point. The 'I' index proposed by Sinha observed that with the increase in demand, the diagonal elements $\partial Q/\partial V$ and $\partial P/\partial \delta$ of the Jacobian matrix gets reduced. This reduction is considered as the voltage collapse has reached. The index 'I' is a more proximity indicator for finding the distance to voltage instability of a power system under critical condition. The index 'I' is simple to compute as it is based on the Jacobian matrix which is obtained from Newton Raphson method. This paper introduces the 'I' index as one of the constraints in the optimal reactive power dispatch (ORPD) problem for increased loading condition of the system. Then the reactive power dispatch and generator pricing are analysed for 62 bus Indian utility system (IUS).

The rest of the paper is organised as follows. The Sect. 2 details the literature review. The Sect. 3 presents the reactive power cost model for generators, capacitors and wind farm. The formulation of the optimization problem is explained in the Sect. 4. The overview of the differential evolution to ORPD problem is detailed in the Sect. 5. The Sect. 6 provides the cost model for the generator reactive power service of 62 bus IUS. The simulation results and comparison of reactive power cost of different cases are shown in this section. The final conclusion is given in the Sect. 7.

2 Literature review

Electricity demand and reactive power maintenance are in increasing scenario in the recent years. Most of the loads are inductive in nature. Hence the maintenance of reactive power plays a vital role in the power system. The optimal dispatch of reactive power and reactive power pricing provides an imperative role in the power system.

A few papers considered the system security in the reactive power pricing [7–10]. The reactive power procurement model is proposed in the Ref. [7] by considering the voltage stability in optimization problem. Shuo yang et al. have explained the effect of reactive power compensation in wind plant. This paper proposes ORPD strategy for wind integrated plant [11].

Many researches have been carried for allocating cost of the reactive power. Many of them have assumed that the consumers should pay high cost for the reactive power consumption towards the supplier. Gil et al. have proposed marginal pricing approach to charge for the reactive power services [12]. Marginal pricing method is used to calculate the reactive power cost at each node of the power system [12]. Spot pricing of reactive power at the bus of the power system has been presented by Garcia Roman [13]. These methods does not account the opportunity cost of the reactive power. High volatility in the reactive power pricing leads to unstable price in the power market. The revenue gained by the reactive power seller based on spot pricing may not be sufficient for recovery of the production cost. In Refs. [14,15], the modified power flow tracing method is used to find the contribution of power from the generator to the load and then priced. Wu et al. have detailed the importance of reactive power service in the power market. It has been found that the reactive power service from the generator completes two tasks. The first one is to support the wheeling of real power. The second task is to meet the reactive demand, maintaining the system voltage and thereby improving the power system security. The later task of the generator should be compensated financially in power system which is focussed in this paper. The mean variance model is used to obtain solution for ORPD of the power system incorporating wind plant [16].

Researches are actively increasing in the area of reactive power dispatch and pricing. In this paper, the security constraints like voltage limit and power flow limits are incorporated in the ORPD problem. The opportunity cost method is used to obtain the reactive power cost of the generator. The differential evolution is used to solve the ORPD problem. Additionally, the stability 'I' index is incorporated as one of the constraints in the ORPD problem for system secure operation. This 'I' index constraint prevents the system from voltage collapse and the reactive power cost are increased by making the system more stable. The fast improvement of wind plant technology encourages its use in the grid and distributed generation. Hence the optimal dispatch of wind farm and its cost are also analysed.

As on February 2016, the Ministry of power announced that the total installed capacity of power is 2,88,665 MW. Out of the total installed capacity, 13.45% of the power production is by wind energy. So there is an increasing penetration of wind energy technology in India. In India, Tamil Nadu is the state which has largest wind power production units. The wind energy is a social and eco friendly power generator [17]. In this paper, the reactive power pricing is carried out for Indian utility to study the importance of the reactive power through cloud service.

The Internet of Things (IoT) is making revolution in the field of power industry [18]. Some of the examples that uses the IoT are smart metering, smart building, industrial automation, automation of lighting in public places, SCADA etc. When using the sensors through IoT in the power equipment, the data related to the health condition of the components can also be posted in the cloud. Based on these information, the condition based maintenance (CBM) scheduling [19] for the power equipment can be done which increases the lifetime of the power equipment. The reactive power contribution of wind plant is analysed and priced accordingly through the cloud service.

Due to the transition towards automating the electrical systems results in adopting the latest technologies like IoT and cloud services. The IoT is used for data acquisition from the electrical devices. The cloud computing is used for data storage and processing services. An European project called as Smart Wind Farm ConTrol (SWiFT) [20] uses these technologies to automate the integration of wind farm in the distribution grid. In this project, the sensor technology is used in the energy monitoring system to collect the data within the factory. Many other researches such as IntelliGrid [21], GridWise [22] were going on for automating the electric power generation and distribution.

3 Cost model of VAR provider

The different reactive power sources used in the power system are generator, synchronous condenser and FACTS device. In power system, most of the generators are of synchronous generator. Determining the cost model for synchronous generator is the basis for reactive power payment mechanism. The relationship between the real and reactive power of the synchronous generator is discussed in Appendix [23]. Another important reactive equipment of electrical power system is capacitor. Most of the equipment and load connected to power system are inductive in nature. The high inductive effect leads to high line losses, poor power factor and poor voltage regulation. Hence the capacitive reactance is used to cancel the inductive effect to improve the system performance. With increasing penetration towards the wind technology [24], the amount of real and reactive power generated by the wind plant have been analysed and priced for 62 bus IUS and the same information is uploaded in the cloud. The pricing scheme for synchronous generator, capacitors and wind plant are made available in the cloud to the customers which are discussed as follows:

3.1 Synchronous generators

Generally synchronous generators are designed to generate real power, generate or absorb the reactive power. The fuel cost functions of generator to generate the real power, $C_{Pi}(P_{Gi})$ are expressed as follows

$$C_{Pi}(P_{Gi}) = a_i + b_i P_{Gi} + c_i P_{Gi}^2 \tag{1}$$

where a_i, b_i and c_i are the cost coefficient of fuel cost curve of i-th generating unit. P_{Gi} is the real power generation at bus i.

Actually, the production of reactive power reduces the real power output of the generator and may leads to financial loss to the generator. This loss due to the reduction of real power sale can be compensated by allocating cost for reactive power production. Reactive power production cost can be evaluated by opportunity cost method [23]. This cost can be approximately evaluated as:

$$C_{qi}(Q_{Gi}) \cong \left[C_{pi}(S_{Gi,\max}) - C_{pi}\sqrt{S_{Gi,\max}^2 - Q_{Gi}^2} \right] K_{Gi} \tag{2}$$

where C_{qi} is the reactive power production cost of the $i-$ th generator, C_{pi} is the real power production cost of the $i-$th generator, P_{Gi} and Q_{Gi} are the real and reactive power of synchronous generator i, $S_{Gi,max}$ is the apparent power of the generator and K_{Gi} is the profit rate of the active power which is usually chosen between 5 to 10%. In this paper, the K_{Gi} is chosen as 10% [25].

3.2 Cloud service

In the smart grid, the IoT technology which includes the sensors and actuators, power electronics controllers, communication and computation platforms are installed in the field [26]. The real power and the reactive power that are generated in distributed manner by the synchronous generators are monitored and the information is uploaded in the Cloud along with the cost. Based on the data, the consumers can choose their appropriate pricing through the system operator. Figure 1 shows the consumer—provider architecture model which is considered in this paper. In this model, the sensors are integrated with IoT devices which are used in both consumer and supplier sites. At the consumer sites, the IoT devices are used to calculate the demand of the electricity. The demand information is made available to the system operator in the cloud through the gateways. At the supplier sites (i.e) in the reactive power generation units, the information about the generated power is smartly calculated with the help of IoT devices. Based on the demand, the suppliers provide their pricing information to the system operators through cloud service. The consumers have been given the flexibility to choose the suppliers based on the pricing information available in the cloud through customized web applications or mobile applications.

The cloud service is carried out for power grid of India having 62 cities as intracity network. So the number of virtual machine (VM) [27] is equal to 62. The VM are grouped to model data centre. The data centre can store the data collected from the different cities. The data centre should have high speed and large storage capacity. The speed rate and storage capacity of data centre can be increased as per the demand requirement. The data centre needs the power for all cloud services. In addition, the data centre has running or base cost such as software license cost, hardware cost and maintenance cost. Even the traditional SCADA stores large amount of

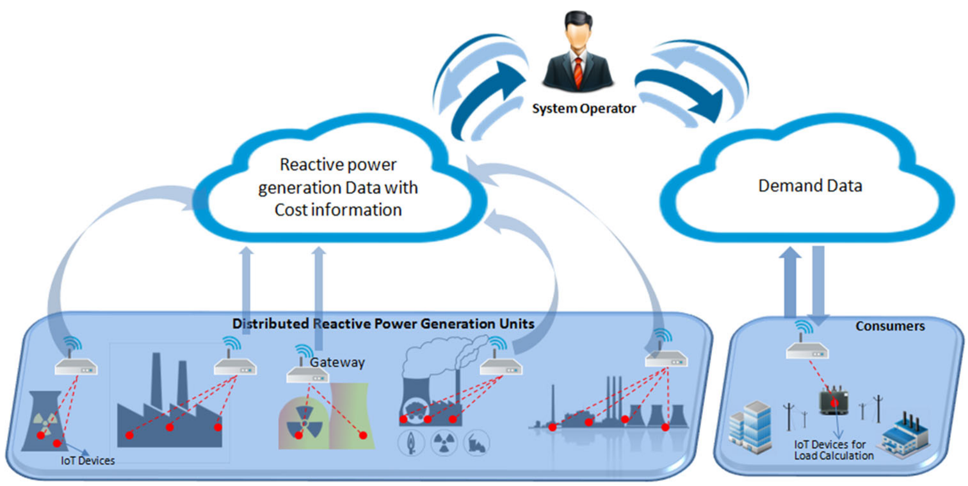


Fig. 1 Interaction between provider and consumer via cloud service

data, the samples taken by the phasor measurement units (PMU) is 30 times/sec which cannot be stored in SCADA. In such case, the cloud-based data storage could be used to store such huge volume of data which will be more cost effective.

3.3 Capacitors

Capacitor supply reactive power at both transmission and distribution levels. It can be connected to the bus bar and tertiary winding of transformer. It can be switched on and off depending on the load change. Capacitor output varies with the square of the voltage. If voltage is reduced, then the reactive power requirement will be high. Capacitor can be switched into a real time system to compensate for the reactive power during heavy load period. Capacitor has high investment cost, less maintenance and operational cost. Hence the capital cost should be considered for modelling the pricing scheme for capacitor. The commonly used reactive power production cost per operating hour of capacitor [14] is as follows:

$$C_Q = \frac{Q_{cap} \times C_{ic}}{\text{lifespan} \times \text{usage}} = 0.1324 \times Q_{cap}; \$/\text{MVAr-h} \quad (3)$$

where C_Q is the cost of 1 MVAr reactive power per hour, Q_{cap} is the capacitor reactive power output in MVAr, C_{ic} is the investment cost of \$11,600/MVAr for lifespan of 15 years with average usage rate of 2/3 [14].

3.4 Wind farm generator

In earlier days, the induction generator used in wind farm (WF) is not self excited. The induction generator absorbs the reactive power from the grid. In order to make the generator to meet the load, a capacitor bank is connected across the terminals of the machine stator [17]. The capacitor bank will supply the reactive power to the generator as well as to the load. Recently the wind turbine is equipped with fixed capacitor bank or static VAR compensator at their grid point. The input parameters for the active power output is 100% for synchronous generators and for wind farm, it is between in the range of 0–100 depending on wind condition. Figure 2 shows the cost model of wind farm that suits the power market.

Variable speed wind turbine with power electronic converter is increasing in the modern power system due to its flexibility in operation. There are various cost associated with the wind farm [24]. They are fixed cost and variable cost. The fixed cost consists of hardware installation cost, operation and maintenance cost, design cost, transportation and installation cost. The variable cost consists of cost of losses and opportunity cost. They are explained as

(a) Cost of losses
The increased real power loss due to production of reactive power from WF to meet the demand should be compensated financially. The reactive demand is met by the grid side converter. The losses associated with the converter should be considered. Peak shaving is another factor to be considered while using WF energy. Jun Dong et al. [28] have discussed about the peak shaving cost for WF power generation using scalable computing methods.

(b) Opportunity cost component
Due to production of reactive power, the active power is reduced to fulfil the needs of reactive power service of Independent system operator (ISO). Then the wind farm should receive Lost Opportunity Cost (LOC) for this service similar to generator concept.
The reactive power structure, C is as follows

$$C = a_0, \forall 0 \le Q \le Q_R$$
$$C = a_0 + m_2(Q - Q_R), \forall Q_R \le Q \le Q_{av}$$
$$C = a_0 + m_2(Q_{av} - Q_R) + m_3(Q - Q_{av})^2, \forall Q_{av} \le Q$$

m_0 is the fixed cost (\$/h), m_2 is the cost of loss offer (\$/MVAr-h), m_3 is the LOC offer (\$/MVAr^2-h).

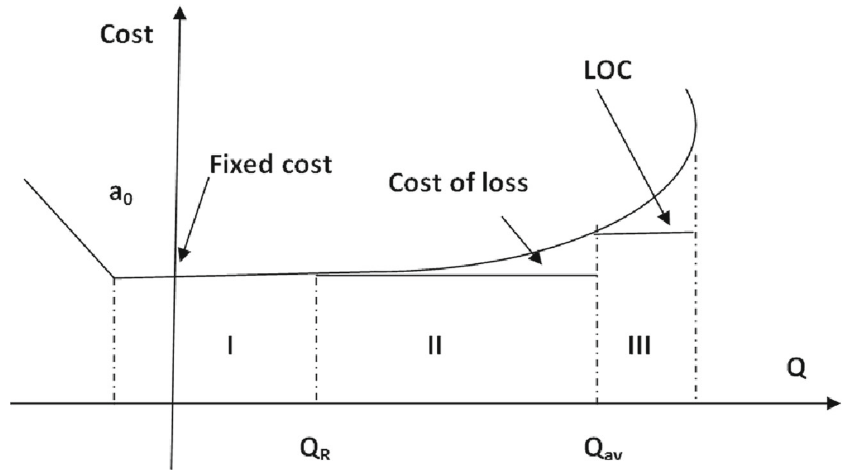


Fig. 2 Cost model of wind farm

4 Problem formulation

Generally the ORPD problem aims to determine the set of control variables that will manage the voltage and reactive power under normal and increased load condition. The ORPD involves the optimization of nonlinear real power loss minimization subject to linear and nonlinear constraint. The objective function can be represented as follows [29].

$$F_{loss} = \sum_{k=1}^{nl} g_k((t_k v_a)^2 + v_b^2 - 2t_k v_a v_b \cos(\delta_a - \delta_b)) \quad (4)$$

where g_k is the conductance of the k-th line, v_a and v_b are the voltage magnitude at the end buses a and b of the k-th line, nl is the number of lines, t_k is the k-th transformer tap ratio and δ_a and δ_b are the phase angles of voltage at the end buses a and b of the k-th line.

The objective function is to be fulfilled along with the constraints [29] such as active and reactive power load flow equations, active and reactive power limits of Generator and WF, Bus voltage limits and Power limits of transmission line.

The inequality constraints on security variable [6,30] are given by

$$I_i \geq I_i^{spec} \quad (5)$$

where $I_i = \dfrac{\partial P_i/\partial \delta_i}{\sum\limits_{\substack{j=1 \\ j \neq i}}^{N} B_{ij} V_j}$,

N is the total number of system buses, V_j is the magnitude of voltage at j-th bus; δ_i is the angle of bus voltage at i-th bus and B_{ij} is the imaginary part of Y $_{bus}$ at (i, j)-th entry. I_i is the stability index of load buses. I_i^{spec} is the specified index value for secure operation. If the load is increased at the load bus i, then the value of $\partial P_i/\partial \delta i$ and $\partial Q_i/\partial V_i$ gets deviate from no load to any load condition. This index is helpful for finding the stability of voltage at the load bus i. The restrictions on transformer tap setting, bus voltage and reactive power of shunt compensation are used as control variables and expressed as follows.

$$V_{Gi}^{\min} \leq V_{Gi} \leq V_{Gi}^{\max} \qquad i \in N_G \quad (6)$$

$$t_i^{\min} \leq t_i \leq t_i^{\max} \qquad i \in N_t \quad (7)$$

$$Q_{ci}^{\min} \leq Q_{ci} \leq Q_{ci}^{\max} \qquad i \in N_c \quad (8)$$

V_{Gi} is the generator bus voltage magnitude at i-th bus. Q_{ci} is the generation of reactive power at i-th shunt VAR compensation and t_i is the tap ratio of transformer. $N_{G,}$ N_t and N_c represent the number of generators, transformer and shunt compensation respectively. Superscripts min and max represent the minimum and maximum value of particular variables respectively.

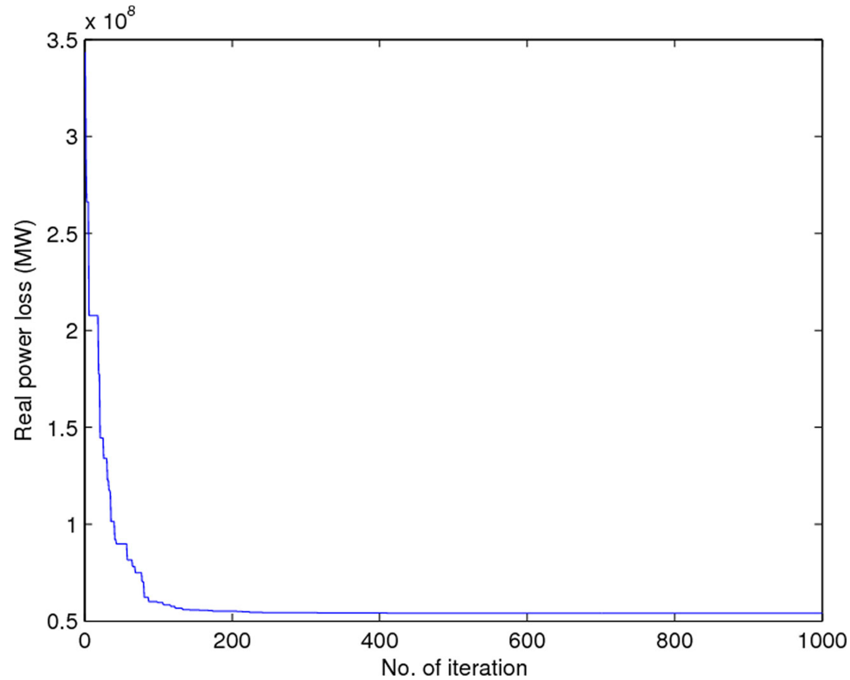
The optimization problem with state variable and control variable can be solved by various global searching based techniques. In this paper, we have used differential evolution for solving the optimization problem due to its more flexibility and simplicity.

5 Differential evolution to ORPD problem

The algorithm of differential evolution (DE) for solving the ORPD and reactive power cost allocation problem are summarized as follows [31]

Step 1 Input the data such as generator, line and bus data of the 62 bus Indian utility system.
Step 2 Select the DE parameters such as population size (N_p), number of control variables (D), mutation factor (F), crossover probability (CR) and maximum iteration or generations.

Fig. 3 The convergence curve of loss minimization for base case system



Step 3 Set iteration count G = 0 and randomly choose the initial population of control variable within the operating bounds.
Step 4 Calculate the fitness function of individuals and check the constraints.
• The power balance constraints are tested by the Newton Raphson (NR) method.
• The inequality constraint is restricted between the operating limits by the algorithm.
Step 5 Set iteration count G = 1
Step 6 Perform mutation and crossover to introduce new offspring from the parents. Perform selection operation which compares the parents and offspring. Then select the vectors which provide best solution. This produces the population in the next iteration.
Step 7 Find the fitness value of new population and check the constraints including stability constraint.
Step 8 Choose the best fitness value by comparing solution of the current with the previous iteration.
Step 9 Check for stopping criteria. If the stopping criteria and solutions are not reached, then go to step 5 for repeating the process to find the best solutions. Once the best solutions and the stopping criteria are obtained, then go to the next step.
Step 10 The output gives the optimal control variable settings and the generator reactive power dispatch is obtained. Then generator reactive powers are priced using the opportunity cost method. The dispatch information of power and pricing are hosted in the cloud.

6 Reactive power pricing model

The optimal dispatch of the generator reactive power for 62 bus IUS is obtained by differential evolution. The one line diagram is referred from Ref. [32] which consists of 19 generators, 43 loads and 89 transmission lines. The input data is on 100 MVA base apparent powers. The generator, load characteristics and line data are taken from [32]. The power flow is calculated using MATPOWER package [33]. The opportunity cost method is used to price the generator reactive power for different cases. The first case is increasing the demand at bus 62 and finds the cost of generator reactive power considering I index as a constraint in ORPD problem. The second case is analysing the cost of the generator reactive power considering the capacitor with increased load at the bus 62. The third case is the inclusion of wind farm in the system and analysing the generator reactive power cost.

The differential evolution is used to analyse the different cases with N_P = 65, F = 0.6, CR = 0.8, D = 29 and the maximum iteration = 1000. Figure 3 shows the convergence curve of loss minimization for base case system. Table 1 shows the bounding limits of control variables for 62 bus IUS.

Base Case The base case system has the load of 3028 MW and 1320 MVAr. With the objective of the minimization of real power loss, the generator optimal real and reactive power dispatch is shown in Table 2. Most of the generators are operating in the over excitation region. The generators 32, 50 and 57 are operating in under excitation region which are shown in the Table 2. The total reactive power generation

Table 1 Control variables of 62 bus IUS

Variable	Bus/branch no.	Minimum limit	Maximum limit
Generator bus voltage	Bus 1(slack),2,4,5,8,17, 23,25,32,33,34,37,49,50,51,52,54,57,58	0.9 p.u	1.1 p.u
Transformer tap settings	Branch 1–14, 14–15, 4–14, 13–14, 12–13, 14–19, 14–18, 14–16, 48–54, 48–50,49–48	0.9 p.u	1.1 p.u
Capacitor (case 4)	Bus 62	0 MVAr	500 MVAr

Table 2 Generators real and reactive powers using DE

Gen	Base case		Increased loading at bus 62			
			Case 1: with I index constraint		Case 2: with capacitor and I index constraint	
	P (MW)	Q (MVAr)	P (MW)	Q (MVAr)	P (MW)	Q (MVAr)
G_1	349.86	11.0173	659	450	350.1962	23.0163
G_2	100	10	100	429.6076	100	10
G_4	100	146.6452	100	−50	100	141.8816
G_5	20	10	20	10	20	10
G_8	120	52.2224	120	300	120	69.2677
G_{17}	300	70.5522	300	112.226	300	80.4468
G_{23}	100	120.1676	100	250	100	120.4292
G_{25}	500	58.9879	500	141.7082	500	89.8657
G_{32}	200	−9.103	200	550	200	−4.0276
G_{33}	30	10	30	10	30	10
G_{34}	100	40.9078	100	−50	100	36.2856
G_{37}	50	14.2542	50	10	50	10
G_{49}	120	0.7485	120	−50	120	−25.8428
G_{50}	50	−24.3779	50	200	50	12.0155
G_{51}	125	37.3131	125	101.3988	125	37.4973
G_{52}	55	46.4668	55	200	55	53.1769
G_{54}	55	10	55	10	55	10
G_{57}	150	−31.9023	150	−50	150	−34.72
G_{58}	550	50.253	550	600	550	68.46
Ploss (MW)	54		82.5		54.4	
Cost ($/h)			18222.31		1409.66	

are 689.54 MVAr and the reactive power absorption is 65.38 MVAr. The I index value for the load buses are shown in the Fig. 4 and it is found all values are greater than 0.5 and utility system is operating in secure condition. The real power loss is 54 MW.

Increased load Single load change either real load alone or reactive load alone is changed in any one bus. The I index is obtained for all the load bus. The 'I' index >0.5 is added as a constraint in the problem for more secure operation. Here the reactive demand at the load bus 62 is increased to 650 MVAr, then the generator reactive power price are analysed with 'I' index as a constraint. Figure 4 shows the 'I' index value of different load buses for different cases.

Case 1: Here the 'I' index is added as a constraint in ORPD problem with increased load at bus 62. Because of the addition of 'I' index as one of the constraint in the problem, the reactive power generation of the generators are increased and it is shown in the fifth column of Table 2. The sum of opportunity cost of generator reactive power are 18222.5 $/h. The reactive power generation is improved and the security of the system is maintained. Here the reactive power loss is 82.5 MW.

The real power loss is low for base case. Static changes in real bus power affect the bus phase angle and not the bus voltage magnitudes. This change affects the real line flows. Hence the 'I' value is increased at bus 62 when the 'I' index

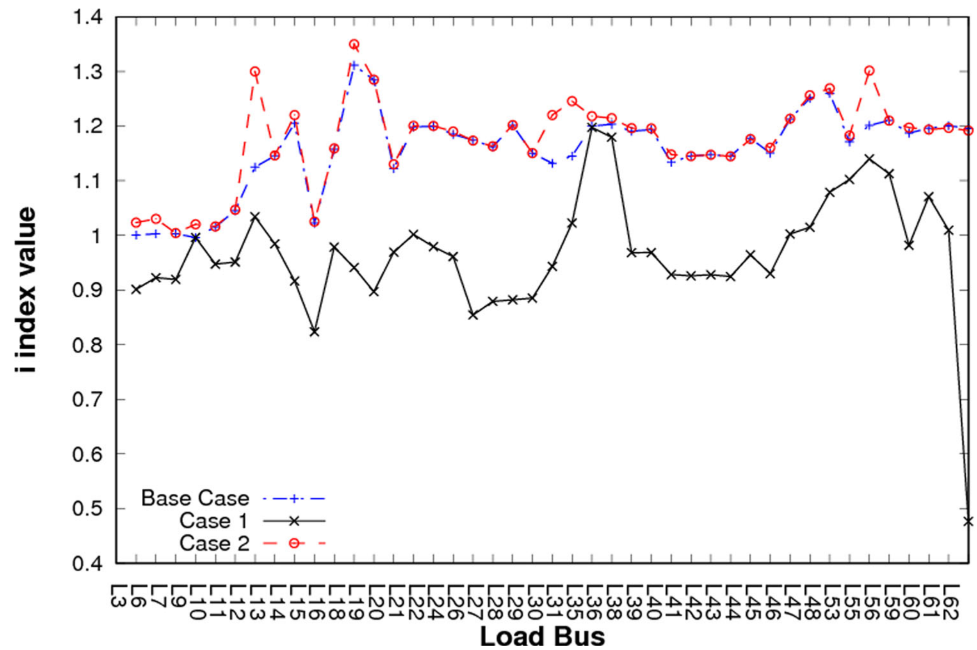


Fig. 4 Stability index value of load buses

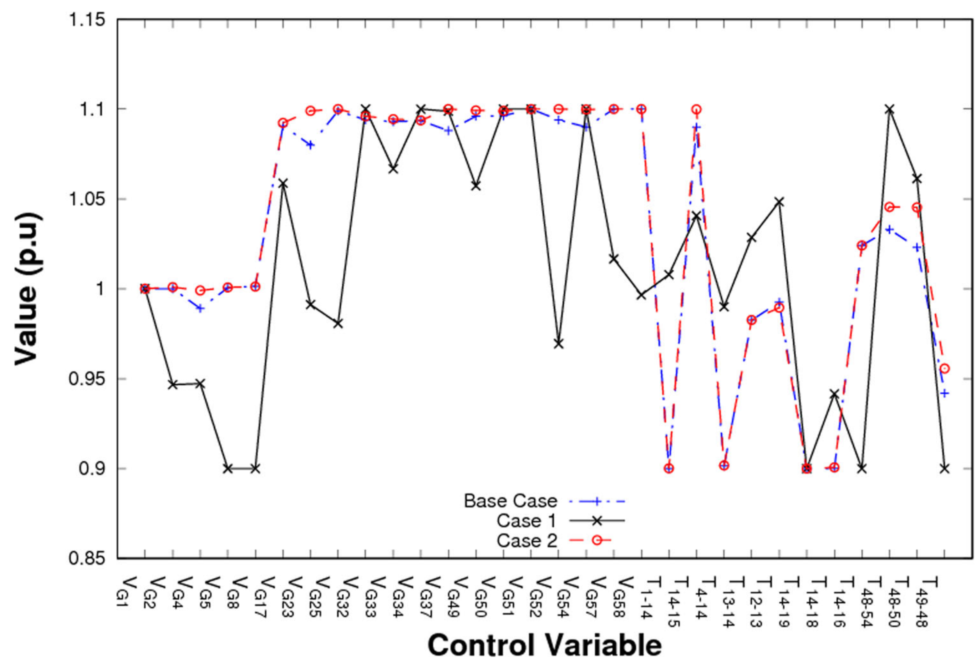


Fig. 5 Operating value of control variable

is considered as one of the constraint. Thus the real power loss is high

Case 2: Here the ‘I’ index at load buses are calculated for the increased loading condition. It will be found that load 62 has very low ‘I’ value. Hence the capacitor whose operating capacity is between 0 to 500 MVAr is located at bus 62. The seventh column in Table 2 shows the reactive power generation under this case. It will found that the generator reactive power is improved to maintain the system secure. The sum of opportunity cost of generator reactive power are 1252.66 \$/h. This is less compared to first case. 500 MVAr is injected at bus 62 by the capacitor. The cost of capacitor reactive power is 157 \$/h should be added with generator cost which gives 1409.66 \$/h. In Fig. 4, it is evident that the case 2 have increased stability index value at load buses similar to base case system.

Figure 5 shows the optimal control variable settings of the generator and transformers under different cases. The graph shows the voltage magnitude of different generators for two cases. It will be found that the bus voltage magnitude is higher in case 2 and also lower transmission loss even when the load is higher at bus 62. The real power loss is 54.4 MW and it

Table 3 Results of generators optimal generation (increased load condition)

Total cost	With I constraint	
	Without capacitor	With capacitor
Cost of reactive power	18222.50 \$/h	1252.66 \$/h

is less, compared to case 1 even when the load at bus 62 is increased.

Table 3 shows the results of generator reactive power for increased load. In node 62, the reactive load is varied from its base value to 650 MVAr. With the addition of constraint 'I' > 0.5 in the ORPD problem, the stability of the system is managed but the losses is very high. Hence the capacitor should be located at bus 62, so that the stability of the system can be managed with minimum transmission loss.

The stability index 'I' $\geq$ 0.5 can be managed either by increasing the generator reactive power at the expense of real power or by introducing the capacitor at the weak load bus.

Thus the stability of the system is managed by including capacitor at the weak bus. The total reactive power cost saving of 16969.84 \$/h is possible with the introduction of 500 MVAr capacitor at bus 62.The total generator reactive power cost considering the capacitor at bus 62 is found to be 1252.66 \$/h which is low as compared to the total reactive power cost without capacitor. Thus the introduction of capacitor at the weak load bus improves the system stability and reduces the generator reactive power cost. This makes benefit on the generator not to expense the real power for producing the reactive power to meet the increased loading condition. Thus power system is operated economically.

Thus the consumer has two options for utilising the reactive power service. One of the options is getting all the dynamic reactive power from the generator itself. The other option is by including the capacitor in particular bus which has low I index value and thereby providing static reactive power supply. The bus which has low I index value affects the stability of the power system. Through IoT and cloud service, the providers collect the data of power requirement and calculate the I index value at all the bus and suggest the possible cases for reactive power service. Through the system operator, the required case is selected by the consumer based on pricing and power supply continuity. Due to recent focus towards the wind energy, the following case is analysed by incorporating the wind plant at particular bus.

Case 3: Due to fluctuation in the wind, the maximum output power of the wind plant is fixed at fifty percentage of the power. The generator 58 is considered as wind plant. Then the optimal reactive power dispatch is found for this case, it can be found that all the remaining online generator have increased their reactive power output. The wind plant has supplied the reactive power of 60 MVAr even though the maximum real power output is reduced. If the generator 58 is considered as wind farm, then for the base load condition, the reactive power cost is high compared to case with all generators as synchronous generator. But if the load is increased at bus 62, and with introduction of this wind farm, there will be improvement in 'I' index value at all the generator buses. The reactive power cost to satisfy the increased demand along with stability is 10097.24 \$/h which is low when compared to case 1.

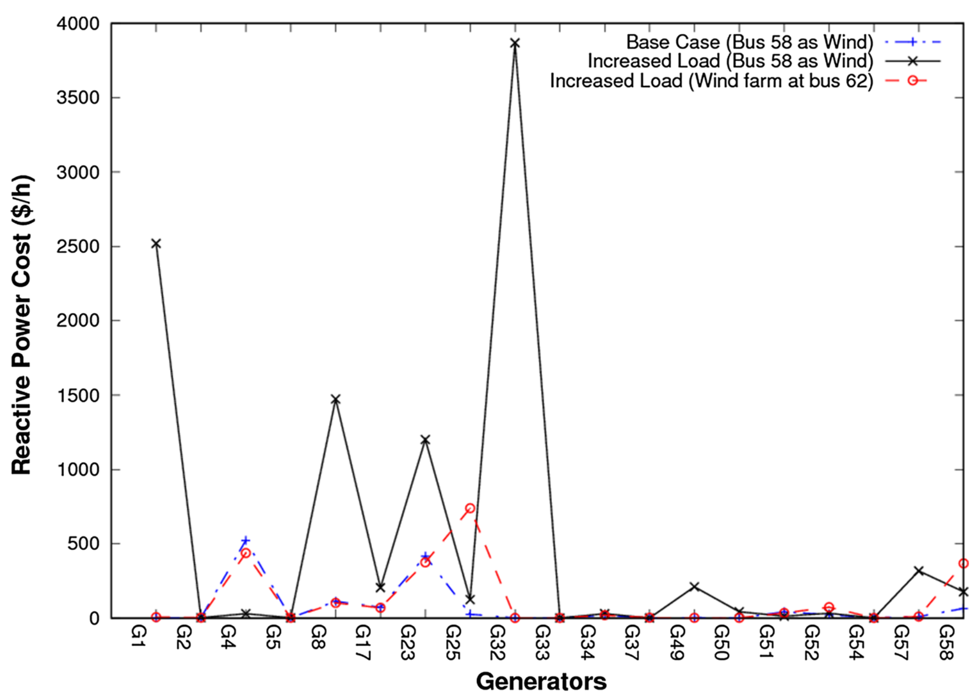


Fig. 6 Generator reactive power cost incorporating wind plant

Figure 6 shows the generator cost towards reactive power production for different cases. In the base case 62 bus IUS, the system is expanded by adding the wind farm at the bus 62 to meet the increased load condition. It will be found that the wind farm has able to meet the fifty percent of load demand. Also the total reactive power cost of the remaining generator are 2249.87 \$/h. However the reactive power of 60 MVAr from wind farm equipped with capacitor bank should charge 18.744 \$/h. Thus the total reactive power cost is 2268.61 \$/h. Also the I index value at all the load buses are improved even with the increased reactive load at bus 62. Thus, when the wind plant is added at the distribution side, there will be improvement in the 'I' index value and also meets the real power demand of the load at that bus. There will be saving in the reactive power cost of the remaining synchronous generator but of course there will be investment cost for the wind plant installation.

7 Conclusion

The consumers seek for the secure power service for city inhabitants. The consumers requirements are fulfilled only by maintaining the reactive power in the power system. The prime objective of the system operator is to provide reactive power with minimum transmission loss. The objective with its stability and security constraints are solved by DE algorithm. The ISO settles the cost for generator reactive power using opportunity cost method. The analysis of the proposed pricing method has been performed for diverse cases. From the analysis of the different cases, the generator reactive power cost is increased with the introduction of stability index as one of the constraint in ORPD problem. With the introduction of capacitor bank in the second case, it has been identified that the real power loss is minimized and also the generator reactive power cost is reduced. By introducing the wind farm at the weak bus, the wind plant can supply the load at the bus and thereby maintain the power system stability in economic manner by reducing the generator reactive power cost. The providers provide the information on reactive power cost for possible cases. The consumers choose the appropriate case of reactive power pricing. The method which is chosen by most of the consumers will be cleared by the system operator. The proposed method provides a smart and flexible environment for the system operators for reactive power pricing by considering the wind energy. With the emerging trends based on the IoT technology, the consumer demands are sensed strongly using sensors and the same is uploaded in the cloud. The providers use the demand information available in cloud and offer optimal reactive power dispatch and price to the customers. The advantages of this method are that it increases the wind energy penetration and reliable power supply with reduced operational cost. This method also provides transparent communication between the providers and consumers.

Appendices

Synchronous generator The generator reactive power output is limited by its MVA rating. In order to generate the reactive power, a generator has to sacrifice the cost associated with the real power sale [23]. The capability curve of synchronous generator is referred from [23].

This is called the opportunity cost. The operating region of the synchronous generator is defined using the capability curve. Q_{base} is the amount of the reactive power essential for the generator to maintain its technical requirements.

Regions The generator reactive power output operates in three regions. They are:

- Over excitation (above Q_{base}) region.
- Under excitation region.
- Lost opportunity cost region.

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