World Applied Sciences Journal 35 (1): 64-74, 2017
ISSN 1818-4952

DOI: 10.5829/idosi.wasj.2017.64.74

Reactive Power Payment for Generator with Wind Farm Incorporating Voltage Stability Index for Practical Power System

[1]D. Danalakshmi, [2]S. Kannan and [3]R. Gnanadass

[1]Department of EEE, Research scholar, Department of EEE,
Kalasalingam University, Krishnankoil, Tamil Nadu, India
[2]Department of EEE, Ramco Institute of Technology, Rajapalayam, Tamil Nadu, India
[3]Department of EEE, Pondicherry College of Engineering, Pondicherry, India

Abstract: The current electric utility system faces challenges to determine the renewable power plant contribution of reactive power towards the reliable operation of electric grid. If the reactive power is not maintained properly, it will lead to voltage collapse that further affects the system security. Hence the pricing for reactive power have become imperative in the power system. In this paper, the amount of reactive power in each node has been computed by optimal reactive power dispatch using Differential Evolution. Due to impact of reactive power flows on the system voltage, the voltage stability index is considered as one of the constraint in the problem. The detailed cost analysis has been carried out with and without nodal voltage stability index 'I' constraint in the problem. With the increasing focus towards wind energy, a unique focus is given on the impact of the wind energy in the reactive power pricing and system stability. It has been shown that the optimal control variables settings and the inclusion of capacitor bank reduce the real power loss and also reduce the generator reactive power cost for 62 bus Indian utility systems.

Key words: Reactive power payment · Stability index · Differential evolution · Optimal dispatch · Opportunity cost

INTRODUCTION

Emerging trends towards the deregulation introduces multifaceted 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 real power does the useful work while 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 are due to the incapability of the power system to maintain the reactive power [2].

The voltage collapse occurs in the system due to insufficient voltage magnitude. 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 A.K. Sinha [3], even the most popular index, Line voltage stability L_i is not very reliable index to indicate the voltage collapse point. The threshold value of Line voltage stability, L_i is 1. It has been noticed that from Ref [3], when $L_i > 1.7$, the voltage collapse does not occur and rarely voltage collapse occurs when $L_i < 0.9$. The 'I' index proposed by A.K.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

Corresponding Author: D. Danalakshmi, Department of EEE, Department of EEE, Kalasalingam University, Krishnankoil, Tamil Nadu, India.

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). A few papers considered the system security in the reactive power pricing [4] [5] [6] [7]. The reactive power procurement model is proposed in [4] considering 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 [8].

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 [9]. Marginal pricing method is used to calculate the reactive power cost at each node of the power system [9]. Spot pricing of reactive power at the bus of the power system has been presented by Garcia Roman [10]. 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 Ref [11] [12], 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 [13].

Researches are actively increasing in the area of reactive power dispatch and pricing. All these researches have not considered the voltage stability index to find the proximity of system voltage instability. In this paper, the relation between the voltage stability index and the reactive power pricing are analysed under normal condition and increased load condition.

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 a constraint 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 'I' index at each bus are obtained and thereby identify the most vulnerable load bus and penalized. We can improve the 'I' index by adding the capacitor at the weak load bus. The optimal dispatch of the generator's reactive power is priced based on the operating region of the synchronous generator. 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, 69.76% of the power production is by the thermal plant. The Hydro plant supplies 14.79% of the total installed capacity. The Nuclear plant supplies 2% of the installed capacity and 13.45% of the power production is by wind energy. So there is an increasing penetration of wind energy technology in India. India is one of the countries which has installed largest wind power capacity in the world. 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. The wind energy technology has various costs such as site cost, commissioning cost, erection cost, operation cost and maintenance cost but has no fuel cost [14]. In this paper, the reactive power pricing is carried out for Indian utility to study the importance of the reactive power. The reactive power contribution of wind plant is analysed and priced accordingly.

The rest of the paper is organised as follows. The section 2 presents the reactive power cost model for generators, capacitors and wind farm. The formulation of the optimization problem is explained in the section 3. The overview of the Differential Evolution (DE) and constraint handling mechanism is detailed in the section 4. The section 5 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 section 6.

Cost Model of VAR Providers: The different reactive power sources used in the power system are generator, static var compensator, 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 are discussed in Appendix and shown in Fig. A1 [15]. 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 [16]. The amount of real and reactive generated by the wind plant have been analysed and priced for 62 bus IUS. The pricing scheme for synchronous generator, capacitors and wind plant are discussed as follows

Synchronous Generators: Generally synchronous generators are designed to generate real power, generate or absorb the reactive power. A synchronous generator operating in over excitation mode generates reactive power. Synchronous generator operating in under excitation mode absorb reactive power.

Real power production cost functions are expressed as follows;

$$F\left(P_{Gi}\right) = a_i + b_i P_{Gi} + c_i {P_{Gi}}^2$$

where a_i, b_i and c_i are the fixed cost coefficient, cost coefficient of the linear term and cost coefficient of quadratic term of the variable cost function of i-th generating unit.

Actually, the production of reactive power reduces the active 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 [15]. This cost can be approximately evaluated as:

$$C_{qi}(Q_{Gi}) = \left[C_{pi}(S_{Gi,\max}) - C_{pi}\sqrt{S^2{}_{Gi,\max} - Q^2{}_{Gi}}\right] K_{Gi} \quad (2)$$

where C_{qi} is the reactive power production cost of the i-th generator, C_{pi} is the active 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 0.05~0.1. In this paper, the K_{Gi} has been chosen as 0.1.

Capacitors: 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 pricing for capacitor [11] is as follows:

$$C_Q = \frac{Q_{cap} \times C_{ic}}{lifespan \times usage}; \$/MVArh \quad (3)$$

where C_q is the cost of 1 MVAr reactive power per hour, $Q_{cap,}$ $C_{ic,}$ *lifespan* and *usage* are the capacitor reactive power capacity in MVAr, investment cost ($/MVAr), lifespan (hours) and the fraction of capacitors lifetime to supply the reactive power.

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 [14]. The capacitor bank will supply the load 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. Fig. 1 shows the cost model of wind farm that suits the power market.

Variable speed wind turbine with power electronic converter are increasing in the modern power system due to its flexibility in operation. There are various cost associated with the wind farm [16]. They are as follows;

Fixed cost: The fixed cost component are

- Hardware installation cost (51%)
- Operation and maintenance cost (29%)
- Transportation cost (5%)
- Installation cost (5%)
- Design of wind farm (10%)

Variable cost: The variable cost components are;

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.

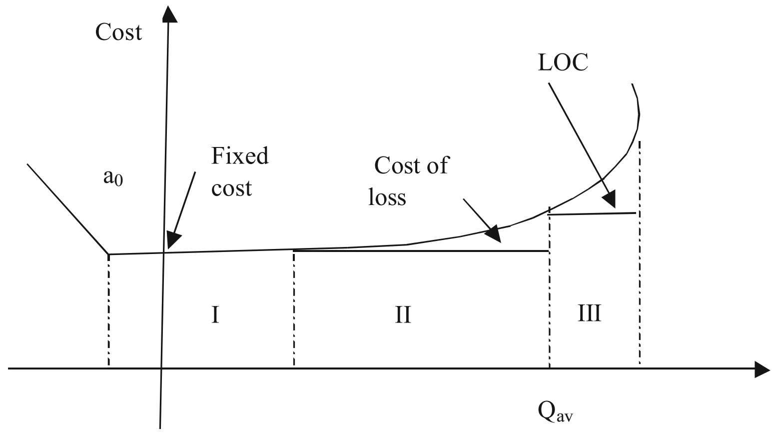

Fig. 1: Cost model of Wind farm

Opportunity Cost Component: Due to production of reactive power, the active power is reduced to fulfil the needs of reactive power service of ISO. Then the wind farm should receive LOC for this service similar to generator concept.

The reactive power structure 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($/hr), m_2 is the cost of loss offer , m_3 is the LOC offer.

Problem Formulation: Generally optimization problem are used to compute the optimum control variable to achieve the certain goal such as fuel cost or real power loss minimization subject to various constraints. 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 ORPD gives the solution of optimal control variable and generator optimal power. The objective function can be represented as follows [17].

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

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 following constraint [17]. The equality constraint of power balance equation are represented as follows;

$$P_{Gi} = V_i \sum_{j=1}^{N} V_j (G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij}) + P_{Di} \quad (5)$$

$$Q_{Gi} = V_i \sum_{j=1}^{N} V_j (G_{ij} \sin\theta_{ij} - B_{ij} \cos\theta_{ij}) + Q_{Di} \quad (6)$$

where N is the number of buses; P_{Gi} and Q_{Gi} are the active and reactive power in i-th bus, respectively; P_{Di} and Q_{Di} are the active and reactive power demand in i-th bus; G_{ij} and B_{ij} are the real and imaginary part of Y-bus at (i, j)-th entry.

The inequality constraints on security and control variable [18] are given by;

$$P_{Gi}^{\min} \le P_{Gi} \le P_{Gi}^{\max} \quad (7)$$

$$Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max} \quad (8)$$

$$P_{li}^2 + Q_{li}^2 \le S_{li,\max}^2 \quad (9)$$

$$V_{Li}^{\min} \le |V_{Li}| \le V_{Li}^{\max} \quad (10)$$

$$I_i \ge I_i^{spec} \quad (11)$$

where, $I_i = \dfrac{\partial P_i / \partial \delta_i}{\sum_{\substack{k=1 \\ K \ne i}}^{N} B_{ij} V_k}$

where $P_{Gi,}^{min}$ and $P_{Gi,}^{max}$ are the operating limits of the active power at i-th generator bus; $Q_{Gi,\ min}$ and $Q_{Gi,}^{max}$ are the operating limits of the reactive power at i-th generator bus; $S_{li,\ max}$ is the maximum apparent power at i-th transmission line; $V_{Gi,}^{min}$ and $V_{Gi,}^{max}$ are the operating limits of the voltage at i-th bus; V_k is the magnitude of bus voltage at k-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. 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 control variable limits are the inequality constraints which are given as follows;

$$V_{Gi}^{\min} \le V_{Gi} \le V_{Gi}^{\max} \qquad k = 1..............PVbuses \tag{12}$$

$$t_i^{\min} \le t_i \le t_i^{\max} \qquad i = 1................Transformers \tag{13}$$

$$Q_{ci}^{\min} \le Q_{ci} \le Q_{ci}^{\max} \qquad k = 1...............Shuntdevices \tag{14}$$

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.

The above optimization problem involves inequality constraint is difficult to be handled by mathematical method. 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 simple.

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 [19].

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), population Dimension(D), mutation factor (F), crossover probability (CR), maximum iteration or generations, the number of constraint variables and constraint limits.

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. The control variable should be checked and restricted by the following Eq. 15.

$$U_i = \begin{cases} U_i^{\max} \, if \, U_i > U_i^{\max} \\ U_i^{\min} if \, U_i > U_i^{\min} \\ U_i \, otherwise \end{cases} \tag{15}$$

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 and 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 shows the generator reactive power dispatch model to achieve objective. Then generator reactive powers are priced using the opportunity cost method.

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 shown in Fig. A2 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 [20]. The opportunity cost method is used to price the generator reactive power for different cases. The first case is the base case system with objective of transmission loss minimization (Eq.4). The second case is increasing the demand at bus 62 and finds the cost of generator reactive power (Eq.2) without considering I index as a constraint in ORPD problem. The third case is increasing the demand at bus 62 and finds the cost of generator reactive power with I index as one of the constraint in ORPD problem. The fourth case is analysing the cost of the generator reactive power considering the capacitor with increased load at the bus 62. The fifth case is the inclusion of wind farm in the system and analysing the generator reactive power cost.

Table 1: Parameters of DE algorithm

Parameter	Value
No. of population	65
Scaling factor	0.6
Crossover ratio	0.8
Dimension	29
Maximum number of iterations	1000

Table 2: 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 3: Generators Real and Reactive powers using DE

			Increased Loading at bus 62					
	Base case		Without I index constraint		With I index constraint		With capacitor and I index constraint	
Gen	P (MW)	Q (MVAr)	P (MW)	Q (MVAr)	P (MW)	Q (MVAr)	P (MW)	Q (MVAr)
G_1	349.86	11.0173	799.3	10	659	450	350.1962	23.0163
G_2	100	10	100	63.3137	100	429.6076	100	10
G_4	100	146.6452	100	491.8822	100	-50	100	141.8816
G_5	20	10	20	10	20	10	20	10
G_8	120	52.2224	120	105.5338	120	300	120	69.2677
G_{17}	300	70.5522	300	-50	300	112.226	300	80.4468
G_{23}	100	120.1676	100	250	100	250	100	120.4292
G_{25}	500	58.9879	500	270.0088	500	141.7082	500	89.8657
G_{32}	200	-9.103	200	426.3052	200	550	200	-4.0276
G_{33}	30	10	30	10	30	10	30	10
G_{34}	100	40.9078	100	-50	100	-50	100	36.2856
G_{37}	50	14.2542	50	75	50	10	50	10
G_{49}	120	0.7485	120	-30.6233	120	-50	120	-25.8428
G_{50}	50	-24.3779	50	-50	50	200	50	12.0155
G_{51}	125	37.3131	125	296.6298	125	101.3988	125	37.4973
G_{52}	55	46.4668	55	200	55	200	55	53.1769
G_{54}	55	10	55	10	55	10	55	10
G_{57}	150	-31.9023	150	400	150	-50	150	-34.72
G_{58}	550	50.253	550	426.96	550	600	550	68.46
Ploss (MW)	54		76.6		82.5		54.4	
Cost ($/MVAr)			14029.64		18222.31		1409.66	

The DE parameter settings are summarized in Table 1. Table 2 shows the bounding limits of control variables for 62 bus IUS.

Case 1: The first case is the base case system with demand 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 3. 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 4. The total reactive power generation are 694.43 MVAr and the reactive power absorption is 65.38 MVAr. The I index value for the load buses are shown in the Fig. 2 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 and without *I* index as a constraint. Fig. 2 shows the *I* index value of different load buses for four cases.

Table 4: Results of generators optimal generation (Increased load condition)

		With *I* constraint	
Total cost	Without / constraint	Without Capacitor	With Capacitor
Cost of reactive power	14029.64 $/Hr	18222.50$/Hr	1252.66 $/Hr

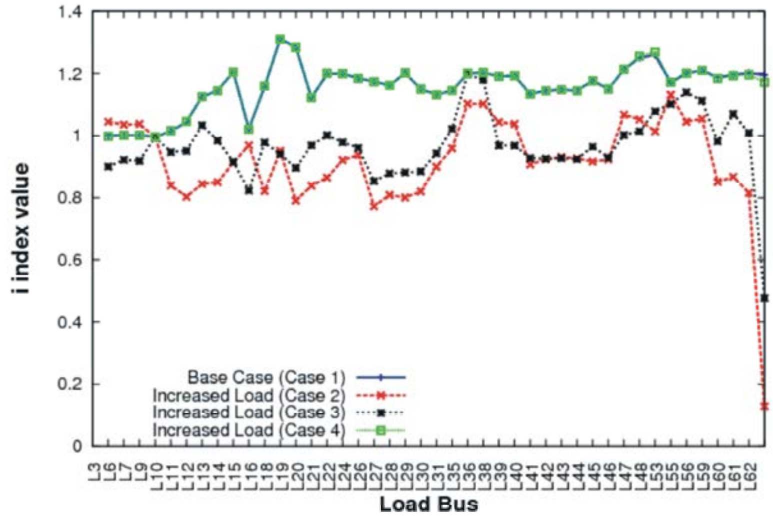

Fig. 2: Stability index value of load buses

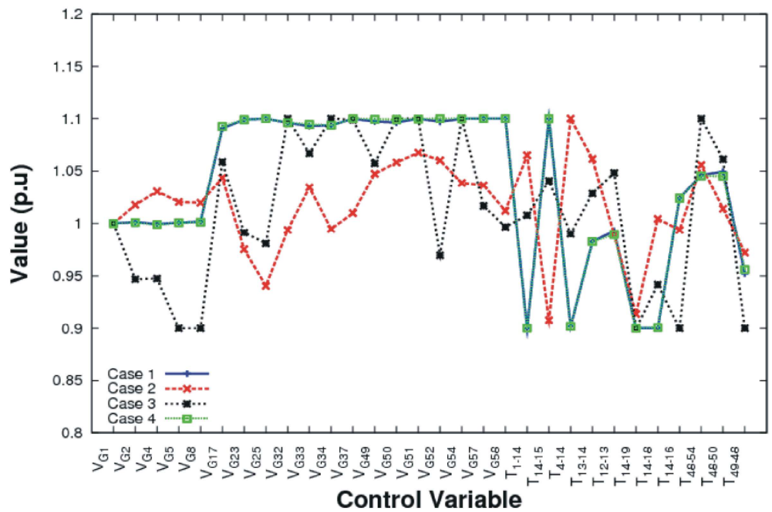

Fig. 3: Operating value (p.u) of control variable

Case 2: The load at bus 62 is increased to 650 MVAr. The fifth column in Table 3 shows the reactive power of the generator. The generator provides reactive power of 3045.634 MVAr and absorbs the reactive power of 180 MVAr. The sum of the opportunity cost of generator reactive power are 14029 $/MVAr. The *I* index value for the load bus 62 is very less and it is found as 0.1288. The security of the system is lost and therefore capacitor should be incorporated to increase the security index. The real power loss is 76.7 MW. Fig.2 shows that the *I* index value is less for load buses for this case.

Case 3: 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 seventh column of Table 3. The sum of opportunity cost of generator reactive power are 18222.5 $/MVAr. But still *I* index value is at margin and the system is not in secure state and it is in alert state. Hence the capacitor should be located at the bus where the *i* index value is less than 0.5 and thereby 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. When the load is increased at bus 62, the real power loss is high when '*I'* constraint is not considered. 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 is considered as one of the constraint in case 3. Thus the real power loss is high

Case 4: 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 ninth column in Table 3 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 $/MVAr. This is less compared to remaining cases. 500 MVAr is injected at bus 62 by the capacitor. The cost of capacitor reactive power is 157 $/MVAr should be added with generator cost which gives 1409.66 $/MVAr. Fig. 2 shows that the case 4 have increased stability index value at load buses similar to base case system.

Fig. 3 shows the optimal control variable settings of the generator and transformers under different cases. Case 1 has higher voltage magnitude at the generator. The graph shows the voltage magnitude of different generators for different cases. It will be found that the voltage magnitude is higher in 4th case and also lower transmission loss even when the load is higher at bus 62. The real power loss is 54.4 MW and it is less, compared to case 2 and case 3 even when the load at bus 62 is increased.

Table 4 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=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$/Hr 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 $/Hr 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.

Case 5: 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 $/MVAr which is low when compared to case 3.

Fig. 4 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 $/MVAr. However the reactive power of 60 MVAr from wind farm equipped with capacitor bank should charge 18.744$/MVAr. Thus the total reactive power cost is 2268.61 $/MVAr. 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.

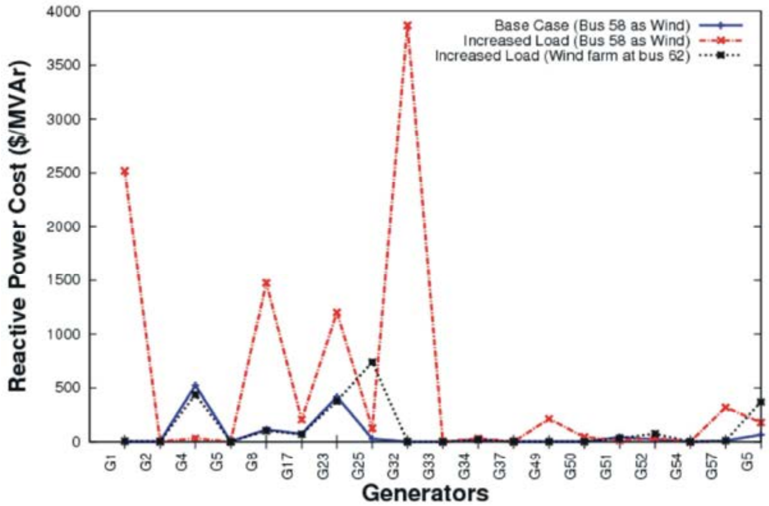

Fig. 4: Generator reactive power cost incorporating wind plant

CONCLUSION

The ORPD with the transmission loss minimization as its 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 test results with 62 bus Indian utility system validate that to achieve the objective of transmission loss minimization, the reactive power need to be reduced but at the same time it has to be maintained in the system to maintain the system voltage stability. The optimal reactive power of the generator to maintain the voltage stability are priced using opportunity cost method. This analysis has been performed for five diverse cases. From the analysis of the first three 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 the capacitor bank in the fourth 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. Good reactive power pricing can be possible for the ISO by adapting this method.

REFERENCES

1. Federal Energy Regulatory Commission and others, "Principles for efficient and reliable reactive power supply and consumption, "FERC Staff Reports, Docket No. AD05-1-000, pp: 161-162, 2005.
2. Task Force, Final Report on the August 14 th Blackout in the United States and Canada: Causes and Recommendations, 2004.
3. Sinha, A.K. and D. Hazarika, 2000. "A comparative study of voltage stability indices in a power system, "International Journal of Electrical Power & Energy Systems, 22: 589-596.
4. Mala De and Swapan K. Goswami, 2014. "Optimal reactive power procurement with voltage stability consideration in deregulated power system, "IEEE Transactions on Power Systems, 29: 2078-2086.
5. Javad Saebi, Hassan Ghasemi and Saeed Afsharnia, 2014. "Reactive power procurement model in electricity markets based on normalized effective reactive power reserve, " International Transactions on Electrical Energy Systems, 24: 858-874.
6. Hamed Ahmadi and Asghar Akbari Foroud, 2014. "Joint energy and reactive power market considering coupled active and reactive reserve market ensuring system security," Arabian Journal for Science and Engineering, 39: 4789-4804.
7. Ismael El-Samahy, Kankar Bhattacharya, Claudio Cañizares, Miguel F. Anjos and Jiuping Pan, 2008. "A procurement market model for reactive power services considering system security, "IEEE Transactions on Power Systems, 23: 137-149.
8. Shuo, Y.A.N.G., W.A.N.G. Weisheng, L.I.U. Chun and Yuehui Huang, 2015. "Optimal reactive power dispatch of wind power plant cluster considering static voltage stability for low-carbon power system, "Journal of Modern Power Systems and Clean Energy, 3: 114-122.

9. Barquin J. Gil San, Gómez, Tomás Román, J.J. Alba Rios and P. Sanchez Martin, 2000. "Reactive power pricing: a conceptual framework for remuneration and charging procedures, " *IEEE Transactions on Power Systems*, vol. 15, pp. 483-489, 2000.
10. Garcia-Román, J.I., 2012. "Analysis and decomposition of the electricity market active and reactive power spot price under centralized management, " International Journal of Electrical Power & Energy Systems, 43: 1179-1184.
11. Mala De and Swapan K. Goswami, 2012. "Reactive power cost allocation by power tracing based method, "Energy Conversion and Management, 64: 43-51.
12. Susithra, M. and R. Gnanadass, 2014. "Power Flow Tracing Based Reactive Power Ancillary Service (AS) in Restructured Power Market, "World Academy of Science, Engineering and Technology, International Journal of Electrical, Computer, Energetic, Electronic and Communication Engineering, 8: 1603-1610.
13. Yuanzheng, L.I., L.I. Mengshi and W.U. Qinghua, 2014. "Optimal reactive power dispatch with wind power integrated using group search optimizer with intraspecific competition and lévy walk," Journal of Modern Power Systems and Clean Energy, 2: 308-318.
14. Zhe Chen, 2005. "Issues of connecting wind farms into power systems," in 2005 IEEE/PES Transmission & Distribution Conference & Exposition: Asia and Pacific, 2005, pp: 1-6.
15. John W. Lamont and Jian Fu, 1999. "Cost analysis of reactive power support, "IEEE transactions on Power Systems, 14: 890-898.
16. Nayeem Rahmat Ullah, Kankar Bhattacharya and Torbjörn Thiringer, 2009. "Wind farms as reactive power ancillary service providers—technical and economic issues, " IEEE Transactions on Energy Conversion, 24: 661-672.
17. Ramesh Subramanian, Kannan Subramanian and Baskar Subramanian, 2009. "Application of a fast and elitist multi-objective genetic algorithm to reactive power dispatch, "Serbian Journal of Electrical Engineering, 6: 119-133.
18. Wu, H., C.W. Yu, N. Xu and X.J. Lin, 2008. "An OPF based approach for assessing the minimal reactive power support for generators in deregulated power systems, "International Journal of Electrical Power & Energy Systems, 30: 23-30.
19. Varadarajan, M. and K.S. Swarup, 2008. "Differential evolution approach for optimal reactive power dispatch, "Applied Soft Computing, 8: 1549-1561.
20. Gnanadass, R., 2010. "Optimal, Power Dispatch and Pricing for Deregulated Power Industry.

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 [15].

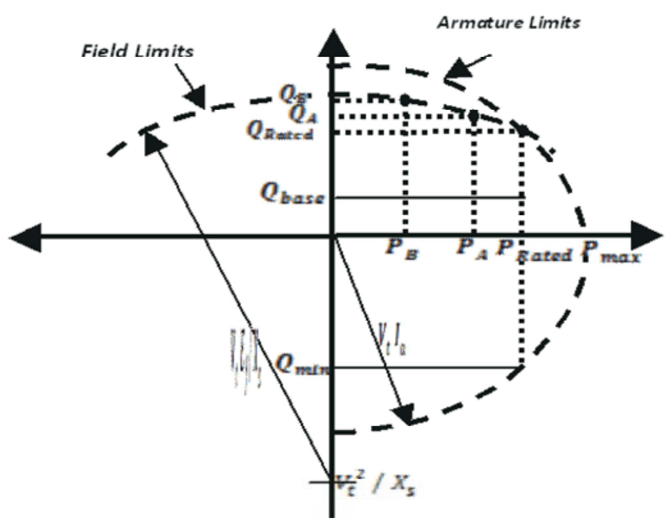

Fig. A1: Synchronous generator capability curve

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 in three different region

- Over excitation (Q_{base} up to Q_A) region
- Under excitation region (0 to Q_{min})
- Lost opportunity cost region (Q_A to Q_B)

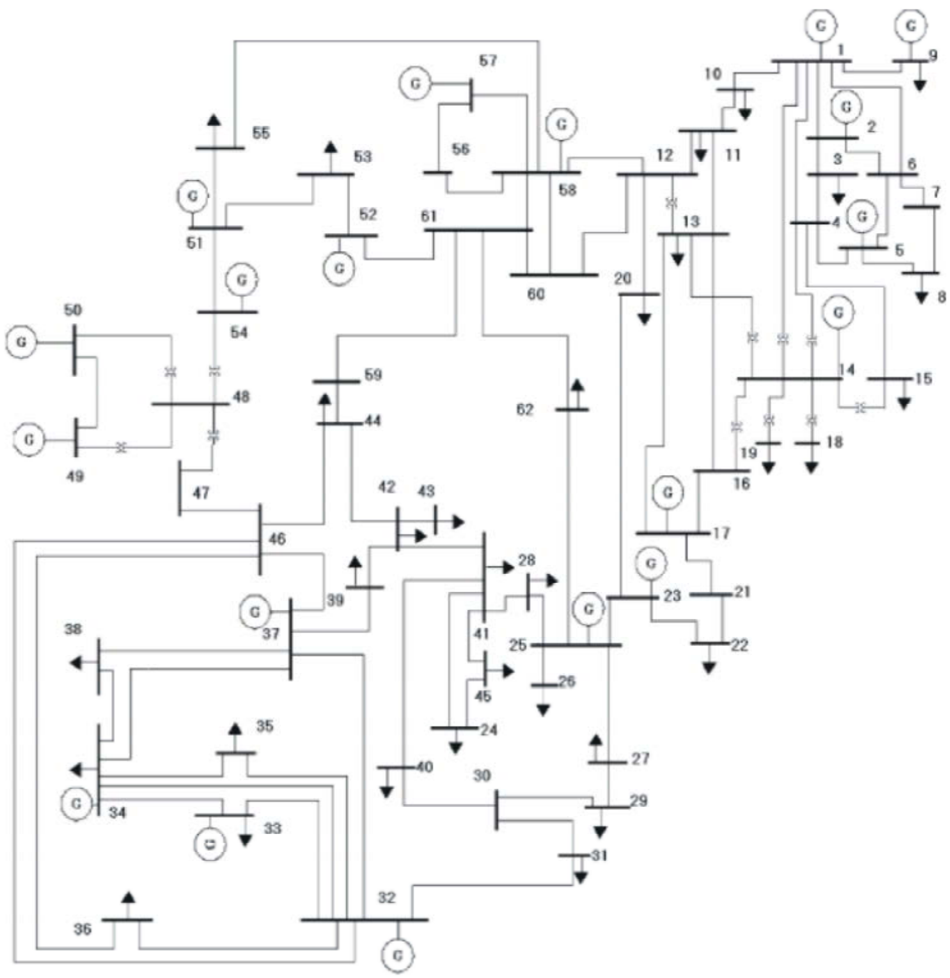

Fig. A2: Oneline diagram of 62 bus Indian utility system