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Real and Reactive Power Nodal Pricing with Hydro Condenser in Pool Based Electricity Market Model

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Abstract

Reactive power procurement has been identified as an important ancillary service. The cost characteristics must be able to recover the lost opportunity cost component of generator reaching the field limits and causes the decrease in its active power when the reactive demand in the system increases. The Synchronous condensers supply reactive power to maintain the voltage and reduce the burden on the synchronous generators. In this paper, the cost characteristics of reactive power support by the generator are proposed based on its capability chart. A non-linear optimization problem formulation is proposed to compute both real and reactive power nodal prices for pool electricity market model with hydro condenser. The marginal prices at each node have been determined for both real and reactive power considering the minimization of fuel cost, reactive power cost, and cost of condenser. The cost characteristics of reactive power have been determined based on the existing methods and the proposed method. The comparison of the results obtained with existing method is also provided. The results have been determined for IEEE 24 bus test system.

***Keywords**: Capability curve, generation costs, condenser fixed and variable costs, reactive power*

1. Introduction

The ISO procure reactive power as an ancillary service provider from the synchronous generators and condensers to maintain voltage profile and thereby the security of the system. Since cost is involved to procure reactive reserve services and to maintain the services, the cost of maintenance and operation is also involved. Therefore the service providers should be remunerated according to their reactive power supply to the system. Therefore, in competitive environment, reactive power cost determination has attracted attention for its impact of economic aspect. Therefore, establishing an equitable and effective reactive power market looking the voltage security issues is very important to provide a reliable restructured power system. The reactive power support is essential in the operation of the system to transmit real power flows and also meeting the reactive power demand of industrial loads comprising electric motors. The reactive power has become essential for proper management of generation and/or transmission companies which is essential responsibilities of the ISO [1]. For the recovery of the cost of reactive power, most of the utilities charge industrial consumers based on KVA demand and penalize the utilities for the poor power factor. This fixed cost recovery of reactive power is insufficient and in the competitive markets may not provide accurate price signal for the ancillary providers [2]. Looking into the limitations of a reactive power price to be charged from the consumers based on power factor penalties authors suggested the use of economic principles based on marginal theory [3-4]. However, the prices of reactive power based on the marginal price theory represent a small portion of the actual reactive power price [5–7]. Reactive power has typical characteristics due to

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reactive power generation equipment and local characteristics of reactive power of loads and transmission system behavior; therefore, it is difficult to access its cost characteristics [8]. For the assessment of reactive power cost, many authors proposed different techniques [10-18]. Dandhachi and Choi *et al*. proposed real time pricing method for reactive power using OPF method [9-11]. The reactive power marginal price is typically less than 1% of the active power marginal price and depends strongly on the network constraints as proposed by Hao and Papalexopoulos [10]. Gill GB *et al*. proposed a conceptual framework for remuneration and charging of reactive power cost [12]. A cost based reactive power dispatch method is proposed for reactive power cost calculation and explicit and implicit cost of reactive support from generator and transmission system is also analyzed [13]. However the method of opportunity cost calculation of reactive support from generators is quite complex. A summary of different methods for reactive power pricing has been discussed using different objective functions for calculation of marginal prices of reactive power using optimal power flow based approach in [14]. A similar approach of generator cost model of reactive power support as discussed in [12] is based on the opportunity cost of generator reactive power dispatch and is presented in [15,16]. Capital cost remuneration of reactive compensators has also been incorporated in an objective function in [16]. Several methods for incorporating reactive power dispatch into nodal pricing and dispatch algorithms were proposed in [17,18]. A method of cost-based reactive power pricing minimizing the cost of reactive power production of generators and capacitors are proposed in [19]. A method of decomposition of spot price using interior point method was proposed in [20]. A non-linear reactive power cost model for deregulated electricity markets was proposed in [21]. A cost allocation for reactive power services in deregulated electricity markets was proposed by Zhao and Erving in [22]. A novel search algorithm for reactive power pricing was proposed in [23]. Ketabi *et al*. in [24] have proposed a pricing technique based on minimization of the generator active and reactive power production and capacitor bank costs using the ant colony algorithm. A tracing based approach for reactive power cost allocation has been proposed in [25]. Nodal real and reactive power price in context to pool and hybrid electricity markets was proposed in [26-27] taking into consideration the impact of FACTS devices on the marginal prices of real and reactive power. Ro has presented the reactive charging scheme composed of recovering capital cost and operational cost [28]. The cost of generator reactive power consists of two components: fixed costs or investment costs and variable costs. Variable costs in turn consist of operating costs (including fuel and maintenance costs) and the opportunity cost. The latter cost results from reduction of its active power generation. The reactive power price has to be charged in such a manner that this cost is able to recover the lost opportunity cost of generator and in case of synchronous condensers is able to recover the capital cost and fuel cost. The proper recovery of reactive power cost with help sustaining the ancillary service providers in the electricity markets. The cost must be decided based on the capability limits of the generators at each operating point due to the load variations and power factor variations.

In this paper, capability limits of the generators have been analyzed and thereafter reactive power cost function has been obtained based on the operating point of the generators. The marginal prices at each node have been determined for both real and reactive power considering the minimization of fuel cost, reactive power cost, and cost of condenser. Three methods are used to determine the reactive power cost are Method1, Method2, and Method3, and using the proposed method the marginal cost comparison have been provided considering the hydro generator as condenser in the system. The results have been determined for IEEE 24 bus test system.

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2. Capability Curves of Synchronous Generator

Synchronous generators capability to generate the real power is limited by the field current, armature current, and the end region heating limits. The generation of rated real power requires field current and the corresponding power requirements of the field circuit. To control the reactive power, the field or excitation current of the synchronous machine is varied by the exciters. The current is limited as well, due to the heating of the windings [29] [30]. The locus of the excitation current is a circle with centre on the Q axis. The capability chart of the generator is obtained utilizing the eqns. (1-4) and is shown in Figure 1 region (i) and region (ii) operated as generator mode, region (iii) and (iv) operated as condenser mode.

$$E_q = E_t + jI_a X_s \text{ Or } E_q = X_{ad} I_f \tag{1}$$

$$P = \frac{X_{ad}}{X_s} |E_f||I_f| \sin\delta \tag{2}$$

$$Q = \frac{X_{ad}}{X_s} |E_f||I_f| \cos\delta - \frac{|E_t|^2}{X_s} \tag{3}$$

For maximum reactive power generation limit δ =0

$$Q = \frac{X_{ad}}{X_s} |E_f||I_f| \cos\delta - \frac{|E_t|^2}{X_s} \tag{4}$$

Where,

I_{fd} field current

P=active power Pu. δ =load angle

Q=reactive power in pu

E_t =terminal voltage pu , X_s =synchronous reactance pu

E_q=no load generator voltage pu , X_{ad} =effective reactance (0.2 to 0.4 X_s)

For the cylindrical rotor synchronous generator, the synchronous reactance X_s=X_d and nominal power factor taken is 0.95.

Based on the capability chart, the reactive power to be supplied by the generator can be obtained at any operating point and accordingly a cost function can be obtained for reactive power supply. In the next section, a method is proposed based on capability chart to recover reactive power cost and the cost is also determined based on the existing methods.

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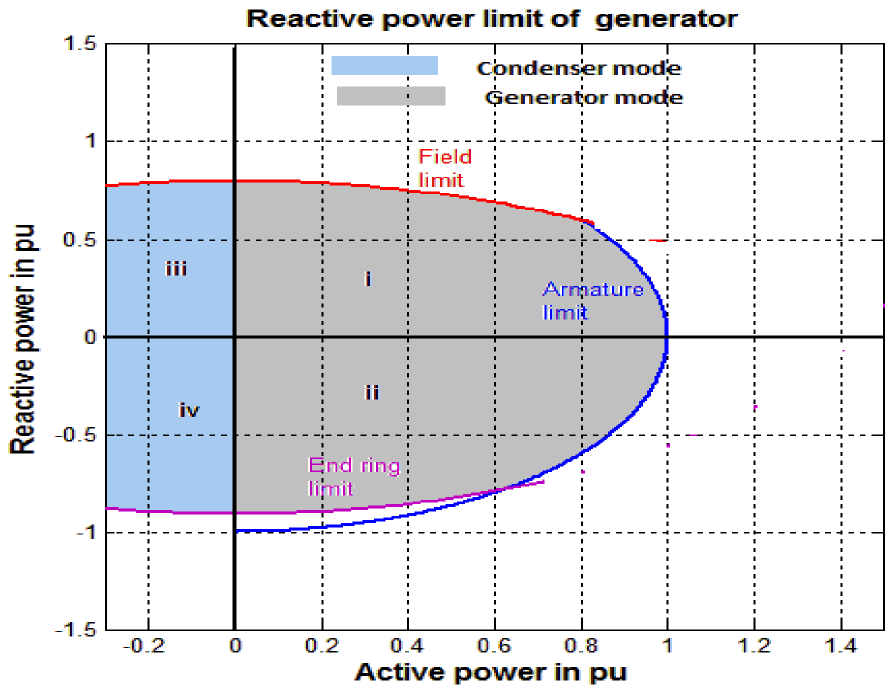

Figure 1. Capability Chart of Synchronous Generator

3. Reactive Power Cost Model for Generator Reactive Power Support

Three methods have been considered to evaluate the cost of reactive power of generators

3.1. Method-1: Triangular Approach [22]

This method of reactive power cost calculation is based on the formulation for active power cost, in which the active power is replaced by reactive power using the triangular relationship.

$$Cost(Q) = a_q Q_g^2 + b_q Q_g + c_q \quad (5)$$

Where

$a_q = a_p \sin^2 \delta;\ \ b_q = b_p \sin\delta;\ \ c_q = c_p$

The cost of reactive power will lead to calculation of wrong fixed costs for reactive power and do not concern to the operating power factor of the generator.

3.2. Method-2: Real Power Based Approach [27]

If a generator produces its maximum active power (P_{max}), then its cost for generating active power equals to cost (P_{max}). In such a situation, no reactive power is produced and therefore, S equals P_{max}. To generate reactive power Q_i by generator which has been operating at its nominal power (P_{max}), it is required to reduce its active power to Pi such that:

$$P_i = \sqrt{P_{max}^2 - Q_i^2} \text{ and } \Delta P = P_{max} - P_i \quad (6)$$

ΔP represents the amount of active power that will be reduced as a result of generating reactive power, Cost(P_{max}) : cost of producing active power equal to P_{max} in one hour,

Cost(P_{max}−ΔP) : cost of generator when producing both active and reactive power with the amounts Pi and Qi , respectively. Cost(Pmax) − Cost(Pmax −ΔP) : Reduction in the

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cost of active power due to compulsory reduction in active power generation (ΔP) which happens due to generating reactive power with the amount of Qi .

$$Cost(Q_i) = \frac{P_{\max} - \Delta P}{P_{\max}} \cos t(P_{\max}) - \cos t(P_{\max} - P_i) \tag{7}$$

The cost of reactive power by this method is not accurate because of the factor in P_{max} cost which is depends on the operating point ,at higher generation of Q_g ,P_i will reduce due to this P_{max} cost will reduce .another demerit is even the generator deliver reactive power below rated reactive power consumer is penalized unnecessary.

3.3. Method-3: Proposed Method

To determine the cost function of reactive power, the two operating conditions have been considered based on the power factor of operation. When the power factor of operation is within the rated power factor or at higher than the rated power factor, there will be no cost of reactive support as generator is operating at its rated active power and providing the base case reactive power. When the generator is operated at a power factor below its rated value due to more reactive power requirements, the active power generation will decrease and reactive power generation will increase to meet the reactive power demand and the reactive power generation must follow the maximum reactive power generation limits. The reduction in active power generation due to the reactive power supply can be obtained by eqn. (9). The cost difference due to decrease in the active power from the rated value can be obtained from the fuel cost characteristics of the generator at any operating point and this difference must be recovered from the reactive power generation. Thus, the obtained capability curve of each generator has been traced at each operating point to obtain the cost of the reactive power recovering the reduced cost of active power. The cost of real power is obtained based on the fuel cost function. The reduction in the cost of active power must be recovered from the cost of reactive power as eqn. (10).

$$Cost(P_i) = a_p P_i^2 + b_p P_i + c_p \tag{8}$$

$$P_i = \sqrt{S_i^2 - Q_i^2} \tag{9}$$

$$Cost(Q_i) = \begin{cases} 0 & if Q_i \le Q_{rated} \\ Cost(P_{rated}) - Cost(P_i) & if Q_i > Q_{rated} \end{cases} \tag{10}$$

Where

P_{rated}=S.cos(Φ), Q_{rated}=S.sin(Φ)

Φ is rated power factor angle

4. Algorithmic Steps for Determination of Cost of Reactive Power

Step 1. Read data for the system and run the base case load flow.

Step 2. Obtain the capability curves for each generator in the system using the eqns. (1-4).

Step 3. Increase the reactive power requirement on the each generator up to Qmax limit and obtain the real power and reactive power supplied by generator in the system tracing the capability chart at every change in the operating point.

Step 4. Find out reduced real power by eqn. (9) to meet higher reactive power demand and obtain the power factor and check the power factor.

Step 5. If power factor is at rated value or higher than the rated value, take the cost of reactive power as zero, otherwise calculate the cost of reactive power using eqn. (10).

Step 6. Knowing the cost of reactive power at each operating point following the capability chart of each generator, obtain the cost data corresponding to reactive power operating point on the curve. Use curve fit toolbox in MATLAB to obtain quadratic cost curve for each generator.

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Step 7. To obtain the reactive power cost characteristic from the derive cost function in Table 2 for different generators use eqn. (11).From eqn. (11), at rated or below rated reactive power generation cost become negative *i.e*. maximum is zero and above the rated reactive power cost will become positive

Step 8. Stop

The capability chart of the generators have been obtained for the IEEE 24 bus system, there are ten generators synchronous reactance(Xs) and fuel cost function are given in Table I. and the Reactive power cost function has determined by the above procedure is given in Table 2.From drive quadratic reactive power cost function the cost will be

$$Cost(Q_{gi}) = Max\left(0, a_q \mid Q_{gi} \mid^2 + b_q \mid Q_{gi} \mid + c_q\right) \tag{11}$$

Table 1. Generators Cost Function Data

Generators	**MVA**	**Xs(pu)**	**a**	**b**	**c**
G1	192	0.15	0.2917	35.07	3591.39
G2	192	0.15	0.2917	35.07	3591.39
G3	300	0.2	0.0	64.96	306.7
G4	591	0.897	0.0322	19.18	1940.98
G5	215	1.0	0.0322	19.18	649.99
G6	155	1.0	0.0628	27.22	1829
G7	400	1.58	0.0191	14.86	552.8
G8	400	1.58	0.0086	30	1992.36
G9	300	0.20	0.0086	30	1992.36
G10	660	1.72	0.0112	14.17	927.15

Table 2. Generators Reactive Power Cost Function

Generators	**a_q**	**b_q**	**c_q**
G1	0.4	-1.7	-1341.5
G2	0.4	-1.7	-1341.5
G3	0.1324	-3.5081	-832.848
G4	0.055	-2.6	-1401.3
G5	0.0975	-2.851	-245.93
G6	0.1913	-4.0462	-250.244
G7	0.0492	-3.2493	-353.182
G8	0.0544	-1.6201	-646.997
G9	0.0697	-1.6201	-460.093
G10	0.0289	-3.2792	-536.269

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5. Hydro Condenser Reactive Power Cost Analysis

Hydro Synchronous generators can be operated as a hydro condenser mode [9]. In a standstill condition if a machine is started in condenser mode then it has to be started as a synchronous generator till it synchronizes with grid and then changes to condenser mode. For the operation in condenser mode either the turbine is decoupled by clutch or remains in connected with turbine which will act as a small load on the hydro condenser. Machine is operating in condenser mode without any water in the turbine. During clutch changeover, complete water should be removed from turbine and pressurized air is forced inside the turbine to remove complete water particles. In Figure 1 region (iii) and region (iv) are in a condenser mode region which has negative real power which is taken from the grid.

5.1. Cost Component for Hydro Condenser

The costing structure of reactive power price by the hydro condenser power plant consisting of various cost components in condenser mode operation is presented in the paper [8]. The various cost components are described below: -

5.1.1. Capital Cost Component (CF)

It is the reactive power capital cost which signifies the capacity of a synchronous machine used as a synchronous condenser. It can be calculated as: -

$$CF_i = \frac{A_i}{P_{rated}.lf.af.n.8760}\tan\left(\cos^{-1}\left(pf\right)\right)=5.36\,\frac{\$}{MVAr/hr} \quad (12)$$

Where A_i is capital cost of condenser, pf is power factor, lf is load factor, af is available factor, and n is expected life of machine

5.1.2. Changeover Cost Component (Cc)

The machine can operate in condenser mode either from standstill mode or from generator mode. During this operation two cost component is associated (i) Cost of water loss. (ii) Cost of wear and tear of mechanical and electrical system.

5.2. Cost of Water Lost (cw)

During every changeover to condenser mode, there is a loss of water, as complete water inside turbine needs to be spilled out. Therefore cost of water should be accounted for during the condenser mode. Two cases may be considered for changeover

5.2.1. Case-1 Cost of Water Lost When A Changeover from Standstill to Condenser Mode [28]

No load turbine discharge = q= 4.5 m^3/s.

Time taken from standstill to rated speed in generator mode ts = 50 s.

Rate of water discharge is assumed to be constant from zero speed to no load synchronization. Therefore, water discharge for running a machine up to rated speed is

q = 4.5*50 = 225 m^3

Let cost of water R = $ 0.002/m^3

Cost of water lost (C_w) = q * R= 225 *0.002=0.45 $/Changeover

5.2.2. Case-2 Change Over From On Load Generator Mode to Condenser Mode

The turbine discharge more water at the generator mode as compare condenser mode .discharge should be reduce up to no load discharge. However during this period, just

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before change over. The generator supply active power to the grid .hence loss of water can be neglect.

5.3. Cost of Wear and Tear of Mechanical System (Ct)

The mechanical seals of servomotor of main spherical valves are replaced frequently. This is due to increase in mechanical stresses during changeover. Records show that changeover operations of units have caused early replacement of these seals much before their normal life span. The main valve is controlled by two servomotors. Two seals are provided for each servomotor. Cost calculation of this component is carried out on the basis of reduction in life of the mechanical seals. The cost component is given in Table III.

Cost of seals per hour without changeover operation C_b =0.09 $/hr

Cost of seals per hour with 300 changeover operations per year C_c = 0.24 $/hr

Cost of wear and tear of seals per hour c = C_c - C_b=0.15 $/hr

Reduction in life (hr) = 28(hr/changeover) approx

C_t = c ($/hr)* Reduction in life (hr/changeover)= 0.15 * 28= 4.2 $/changeover

Table 3. Changeover Cost Component

Sr. No.	Changeover cost component (Cc)	Cost($/changeover)
1	Cost of water lost (c_w)	0.45
2	Cost of wear and tear(c_t)	4.2
total	Changeover cost(Cc)	4.65

5.4. Cost of Energy Consumed in Condenser Mode (Ce)

Synchronous machine consume Electrical energy to run the unit in condenser mode operation required about 2-3% of the rated power from the grid. As per load flow the consume power will fulfill by the slack bus generator. That consume electrical power cost is determined by the slack bus fuel cost function. Cost of energy consumed

$$C_e = a_p\left(0.03P_{rated}\right)^2 + b_p\left(0.003P_{rated}\right) + c_p \tag{13}$$

Where

a_p, b_p and c_p are slack bus fuel cost function

P_{rated} is hydro machine rated power

Total reactive power price by the hydro condenser

$$Cost\left(Q_{hc}\right) = CF.|Q_g| + C_c.No.ofchangeover + C_e \tag{14}$$

6. Mathematical Model to Obtain Real and Reactive Power Price

The real and reactive power nodal prices, fuel cost, cost components of reactive power with Hydro condenser device, generation schedule of real and reactive power have been obtained solving an optimization problem of minimizing total cost subject to equality and inequality constraints for a pool model based electricity market. The objective function can be represented as:

Objective function

$$\min(F) = \sum_{i=1}^{N_g} Cost(P_{gi}) + Cost(Q_{gi}) + Cost(Q_{hc}) \tag{15}$$

Where

$Cost(P_{gi})$ is active power cost which is determine by the fuel cost function

$Cost(Q_{gi})$ is generators reactive power price which will be determine by the drive quadric cost function

$Cost(Q_{hc})$ is hydro condenser reactive power price

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Equality constraints:power flow equation

The real and reactive power flow equations from bus-*i* to bus-*j* can be written as:

$$P_{ij} = V_i^2 G_{ij} - V_i V_j \left(G_{ij}\cos\delta_{ij} + B_{ij}\sin\delta_{ij}\right) \tag{16}$$

$$Q_{ij} = -V_i^2 \left(B_{ij} + B_{sh}\right) - V_i V_j \left(G_{ij}\sin\delta_{ij} - B_{ij}\cos\delta_{ij}\right) \tag{17}$$

The real and reactive power flow equations from bus-*j* to bus-*i* can be written as:

$$P_{ji} = V_j^2 G_{ij} - V_i V_j \left(G_{ij}\cos\delta_{ij} - B_{ij}\sin\delta_{ij}\right) \tag{18}$$

$$Q_{ji} = -V_j^2 \left(B_{ij} + B_{sh}\right) + V_i V_j \left(G_{ij}\sin\delta_{ij} + B_{ij}\cos\delta_{ij}\right) \tag{19}$$

Power injection at buses

$$P_{gi} - P_{di} - \sum_{j \varepsilon N_b} |V_i||V_j||Y_{ij}|\cos(\theta_{ij} + \delta_j - \delta_i) = 0 \tag{20}$$

$$Q_{gi} - Q_{di} - \sum_{j \varepsilon N_b} |V_i||V_j||Y_{ij}|\sin(\theta_{ij} + \delta_j - \delta_i) = 0 \tag{21}$$

Power balance equation

$$\sum_{i=1}^{ng} P_{gi} - P_{di} - Losses = 0 \tag{22}$$

$$\sum_{i=1}^{ng} Q_{gi} - Q_{di} - Losses = 0 \tag{23}$$

inequality constraints:Power generation limit

$$P_{gi\min} \le P_{gi} \le P_{gi\max} \tag{24}$$

$$Q_{gi\min} \le Q_{gi} \le Q_{gi\max} \tag{25}$$

Transmission line limits

$$P_{ij\min} \le P_{gi} \le P_{ij\max} \tag{26}$$

Bus voltage and angle limits

$$V_{i\min} \le V_i \le V_{i\max} \tag{27}$$

$$\delta_{gi\min} \le \delta_{gi} \le \delta_{gi\max} \tag{28}$$

7. Results and Discussions

The results have been determined for IEEE-24 bus system using OPF with cost minimization based approach for a pool electricity market model. The results have been determined for both the test systems in three cases considering the different methods for the incorporation of reactive power cost model.

Case 1: Comparison of Result between Method1, Method2 and proposed Method method3 at base case

Case 2: Comparison of Result between Method1, Method2 and method3 with increase in reactive power load at all buses by 1.5 per unit.

Case 3: With Hydro condenser for supplying the reactive power

From the optimal power flow (OPF) solution three methods have been considered *i.e*. Method1, Method2 and Method3 and the results of real and reactive power generation and the cost of reactive power obtained for the generators at the respective buses in case-1 is given in Table IV. From Table IV It can be observed that for Method1 and Method2, there is cost of reactive power for generators based on their reactive power supply however, for method 3, there is no cost component for generators as, and generators are generating the reactive power within their base case values. In the method-1 and method-2 reactive power cost is considered while in method-cost is neglected because of operating point of generator. The marginal cost of real and reactive power has obtained is shown in Figure 2 and Figure 3. With three methods .In case-2 the results of real and reactive power generation and the cost of reactive power obtained for the generators at the respective buses is given in

Table V. From Table V, it can be observed that for Method1 and Method2, there is cost of reactive power for generators based on their reactive power supply. While using the method-3 reactive power cost is considered for the generators at bus 7, 15 and 18 which are operating above the rated reactive power of generators. The marginal cost of real and reactive power obtained is shown in Figure 4 and Figure 5 .In case-3, the voltage profile for case 2 is shown in Figure 6. , on the basis of voltage profile of the system bus number 3 is chosen as a candidate node for placement of hydro condenser. The rating is taken as 2 per unit MVAr. On the basis of it the hydro condenser reactive power cost is considered and the results obtained for real and reactive power generation and the cost is given in Table VI. From Table VI, it is observed that due to hydro condenser, generators deliver reactive power below rated reactive power and therefore the cost of reactive power is zero. There is only the cost of reactive power for hydro condenser. The cost of reactive power has reduced and the total cost with hydro condenser is lower compared to the total cost without hydro condenser. With hydro condenser, the marginal cost of both the real power and the reactive power has reduced due to improvement in voltage profile and reduction in the losses. It is observed that the marginal cost of reactive power is both positive and negative. The negative reactive power marginal cost represent that the Lagrange multiplier is negative at that bus. With the presence of hydro condenser voltage profile has improved as shown in Figure 7.

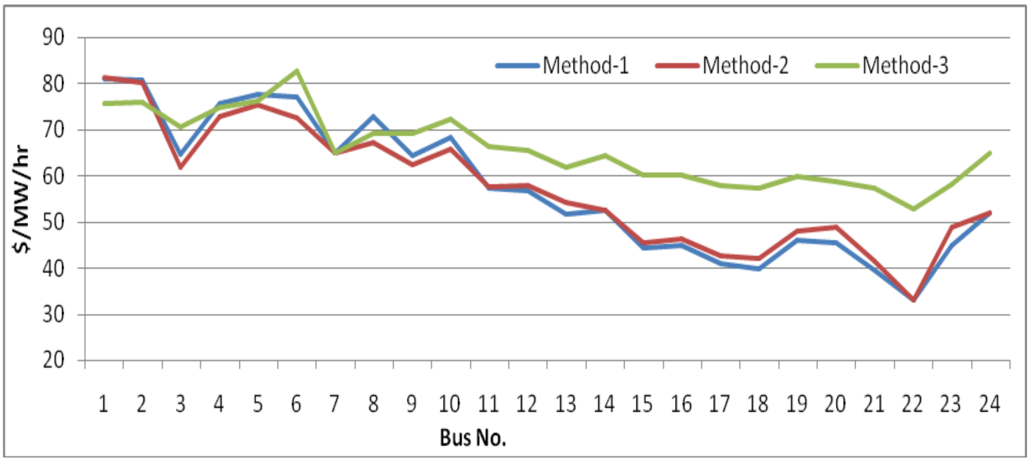

Figure 2. Marginal Cost of real power (Case-1)

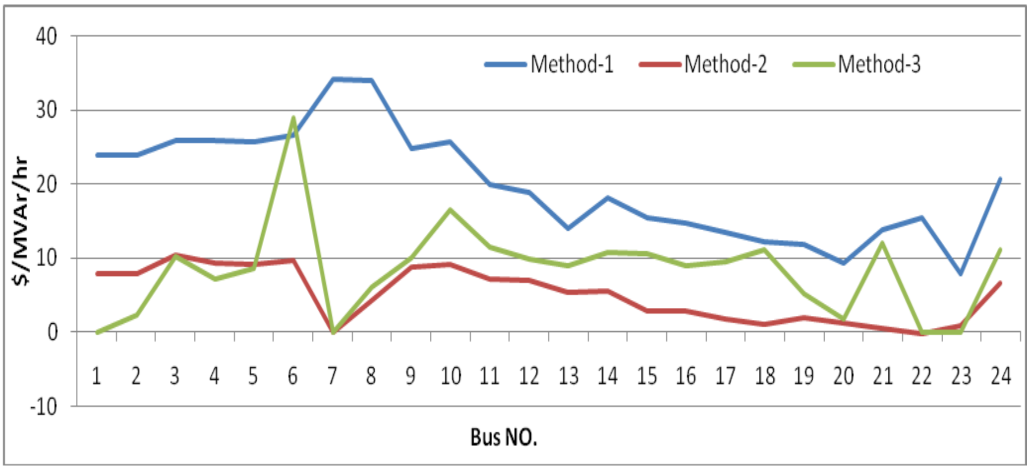

Figure 3. Marginal Cost of Reactive Power (Case-1)

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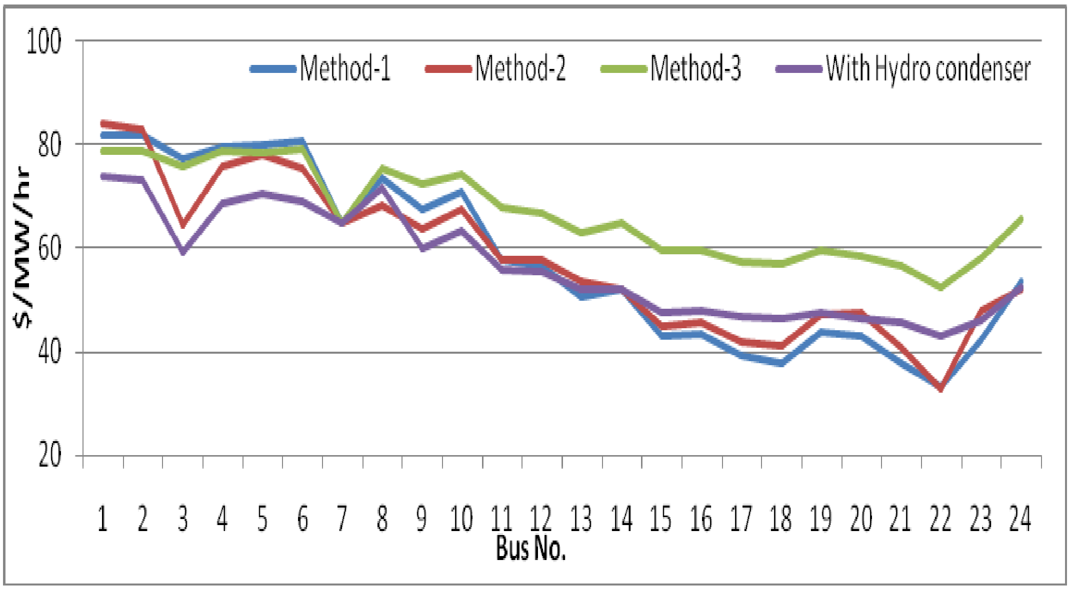

Figure 4. Marginal Cost of Real Power (Case-2 and Case-3)

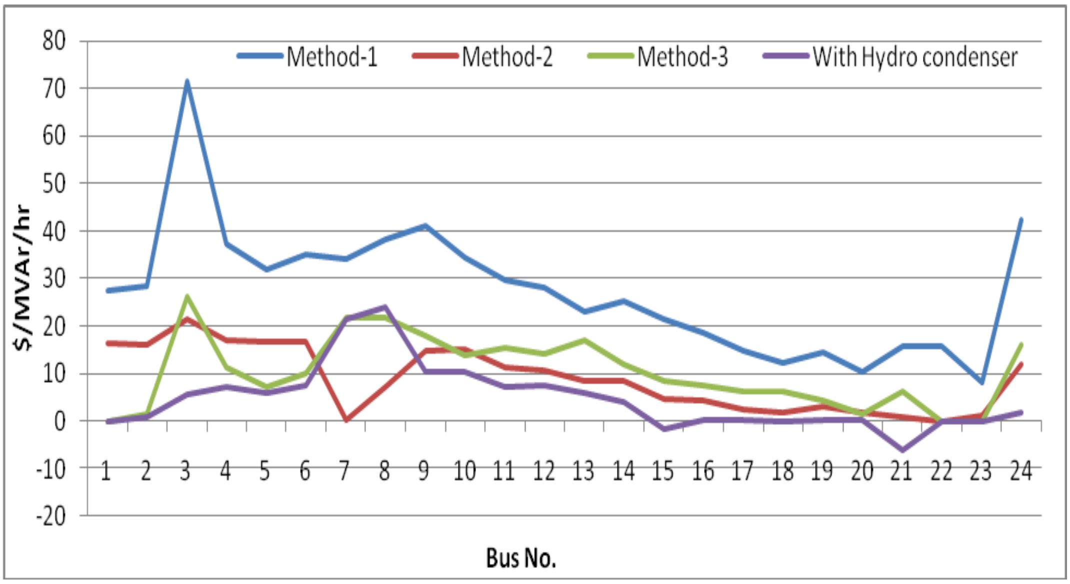

Figure 5. Marginal Cost of Reactive Power(Case-2 and Case-3)

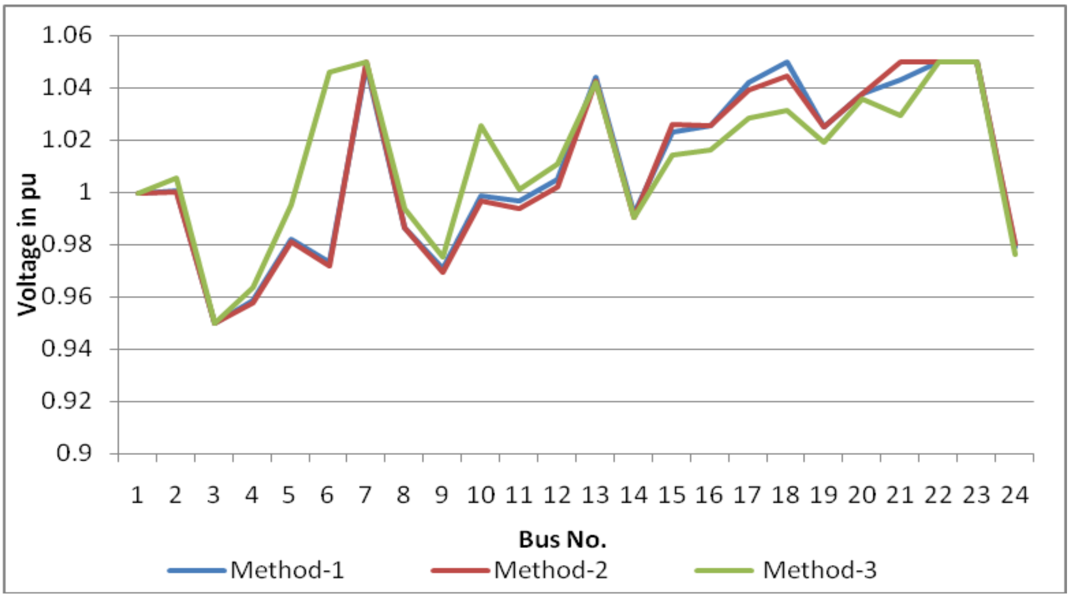

Figure 6. Bus Voltage Profile (Case-2)

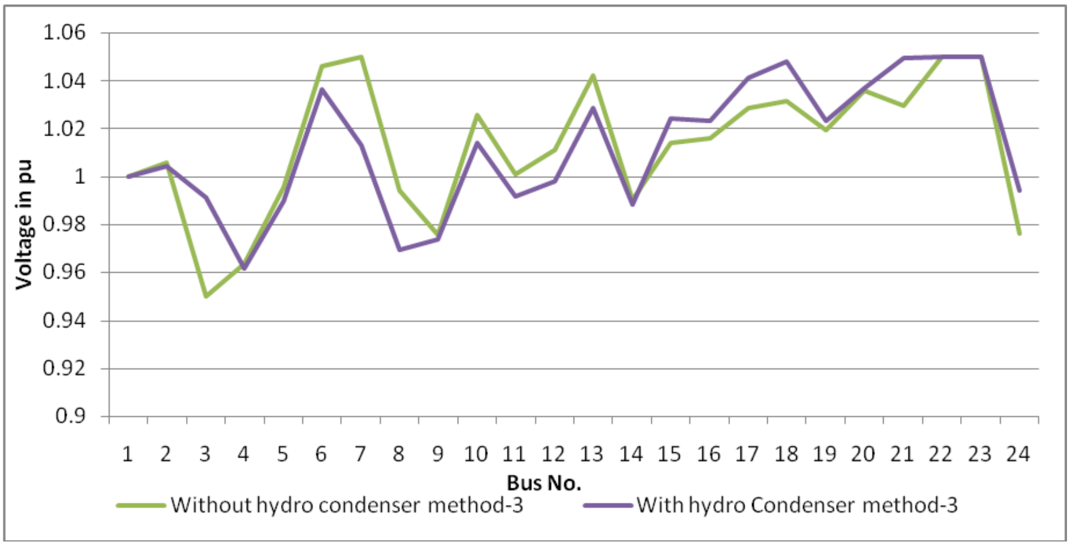

Figure 7. Bus Voltage Profile With Hydrocondenser (Case-3)

Table IV. Reactive Power Price In Case-1

Gen. bus	Q rated in pu	Method-1			Method -2			Method-3		
		Generated P in pu	Generated Q in pu	Cost Q in $/hr	Generated P in pu	Generated Q in pu	Cost Q in $/hr	Generated P in pu	Generated Q in pu	Cost Q in $/hr
1	0.599	0.789	0.342	4319.02	0.793	0.2695	105.417	0.709	-0.1043	0
2	0.599	0.781	0.342	4321.09	0.773	0.2698	105.69	0.702	0.5131	0
7	0.936	2.406	0.321	1404	1.948	0.919	0	2.92	0.755	0
13	1.84	5.064	2.23	4637.	5.458	1.76	491.74	5.91	0.0005	0

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	5			72						
15	0.671	2.15	1.1	1869.204	2.15	0.9896	148.31	2.15	0.669	0
16	0.484	1.419	0.095	1967.91	1.532	0.4826	71.281	1.55	0.066	0
18	1.249	4	2	2329.941	4	0.555	29.304	4	-0.5	0
21	1.249	4	-0.5	1208.335	4	0.5491	12.906	2.340	1.249	0
22	0.9367	1.778	-0.553	1124.56	1.744	-0.2764	3.279	2.035	0.2326	0
23	2.0608	6.6	0.67	1463.74	6.6	0.6776	25.646	6.6	1.84	0

Table V. Reactive Power Price In Case-2

Gen. bus	Q rated in pu	Method-1			Method -2			Method-3		
		Generated P in pu	Generated Q in pu	Cost Q in $/hr	Generated P in pu	Generated Q in pu	Cost Q in $/hr	Generated P in pu	Generated Q in pu	Cost Q in $/hr
1	0.599	0.799	0.552	4859.338	0.837	0.58845	492.58	0.7508	0.0627	0
2	0.599	0.798	0.605	5006.238	0.818	0.574	469.83	0.7536	0.599	0
7	0.936	2.610	1.105	4088.98	2.072	1.243	0	2.889	0.9604	51.66
13	1.845	4.889	2.4	4879.74	5.342	2.4	885.607	5.91	1.95	0
15	0.671	2.15	1.1	1869.204	2.15	1.1	180.42	2.15	1.1	620.2
16	0.484	1.288	0.8	3088.043	1.469	0.8	185.42	1.55	0.4594	0
18	1.249	4	2	2329.941	4	0.83988	66.60	4	1.258	8.05
21	1.249	4	-0.35	1429.406	4	0.8928	33.83	2.342	-0.231	0
22	0.9367	1.861	-0.189	1695.572	1.718	-0.2529	2.746	2.003	0.147	0
23	2.0608	6.6	0.964	1676.194	6.6	1.013	57.221	6.6	1.086	0

Table VI. Reactive Power Price in Case-3

Gen Bus	**Q rated in pu**	**Hydro condenser placed at bus-3 and OPF by Method-3**		
		Generated P in pu	Generated Q in pu	Cost Q in $/hr
1	0.599	0.666	0.0514	0
2	0.599	0.6514	0.6007	0
3*	2		0.7817	449.16
7	0.936	1.869	0.9365	0
13	1.845	5.123	1.852	0
15	0.671	3.225	0.546	0

16	0.484	2.325	0.403	0
18	1.249	4.248	1.239	0
21	1.249	1.524	0.784	0
22	0.9367	1.258	-0.2318	0
23	2.0608	8.1325	1.28	0

8. Conclusions

In this paper, real and reactive power marginal price using three different methods of reactive power cost calculations have been determined for IEEE 24 bus test system. The results have been obtained with and without hydro condenser. The impact of hydro condenser has been observed on nodal prices of real and reactive power. Reactive power price in all the cases has been obtained and it is observed that the cost of reactive power is higher with method1 and method2 for both the cases case1 and case2 as these methods do not account actual operating point of the system at base case and at higher reactive power requirements. However, for case 3 the cost of reactive power is dependent on actual operating point on the capability chart of each generator. In case when the reactive power is above the base case reactive power generation, only then reactive power cost is to be remunerated. For case1, with method3, there is no reactive power requirement above the base case and hence the reactive power cost is zero. But when the reactive power requirement is more as for case 2, the reactive power for generators at buses 7, 15, and 18 are more than their base case generation and hence in this case generators are to be remunerated for their additional reactive power support. For case 3 with hydro condenser, all generators reactive power is within their base case limits and there is reactive power remuneration only hydro condenser at bus 3 needs to be remunerated for its reactive power support. With hydro condenser, reactive power cost reduces and the voltage profile is also better.

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