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Evaluation of Generator Reactive Power Pricing Through Optimal Voltage Control under Deregulation

Seung-Wan Jung*, Sung-Hwan Song†, Yong Tae Yoon and Seung-Il Moon****

Abstract - This paper presents the evaluation of reactive power pricing through the control of generator voltages under the assumption that the reactive power market has been transformed into the real power market. By applying the concept of economic dispatch, which minimizes the total cost of real power generation to reactive power generation, the algorithm for implementing reactive power pricing is proposed to determine the optimum voltage profiles of generators. It consists of reactive power voltage equation, the objective function that minimizes the total cost of reactive power generation, and linear analysis of inequality constraints in relation to the load voltages. From this algorithm, the total cost of the reactive power generation can be yielded to the minimum value within network constraints as the range of load voltages. This may provide the fair and reasonable price information for reactive power generation in the deregulated electricity market. The proposed algorithm has been tested on the IEEE 14-bus system using MATLAB.

Keywords: Linear Analysis, Optimization Problem, Power Flow Equation, Reactive Power Pricing

1. Introduction

As the electric power industry undergoes new environment changes in its vertically integrated structure, the operation scheme and control strategy of power systems around the world may be altered as a result.

The primary focus of power system operation has been to adjust the supply and demand balance of active power, and reactive power has been considered as a by-product that is produced during active power generation. Due to this recognition, many generator companies have not received any monetary reward for their role of stabilizing the power system by producing and consuming reactive power. That is, the quantity of reactive power production by controlling generator voltages has been decided by system operators' experience according to the state of the power system based on the database they've accumulated for years, and for this there has been no system of financial compensation.

However, the supply and demand of reactive power is a noteworthy factor in power system operation, especially as the load characteristics are becoming gradually more complex and dynamic. For example, even if the problems related to active power do not occur, voltage instability is observed by dynamic characteristics of the load, and these phenomena can appear in voltage collapse.

Among the recommendations in the final report concerning the North American blackout in 2003 proposed by NERC [1], the strengthening of reactive power and voltage control practices is proposed. This is the evidence that reactive power has been a significant factor in a couple of the outages such as the North American blackout in 2003.

Consequently, reactive power plays an important role for operating power systems stably, keeping the bus voltages within nominal ranges, and supporting the real power transfer. In spite of its importance, the financial compensation scheme for providing generator reactive power is still not well determined compared with that of real power.

Of course, the problem related to reactive power is classified as an ancillary service in some advanced nations that introduce the electricity market mechanism through restructuring and the reactive power pricing system is formed in other structures in each country. New York ISO, California ISO (US), and NEMMCO (Australia) have implemented a pricing system that compensates economic revenue decrease due to decrease in active power output as the concept of Lost Opportunity Cost (LOC) payment. And in case of NGC (United Kingdom), reactive power pricing is calculated through capability component (Price/MVAr) and utilization component (MVAr Price Curve) [2]. Some researches present the methods of power factor based pricing systems [3], marginal nodal pricing [4], incremental average approach [5], reactive flow tracing method [6], and reactive power factor adjustment based zonal charge system [7].

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† Corresponding Author: School of Electrical Engineering and Computer Science, Seoul National University, Korea. (karyman@powerlab.snu.ac.kr)

* Electro-Mechanical Research Institute, Hyundai Heavy Industries Co., LTD. Korea. (jswany@hhi.co.kr)

** School of Electrical Engineering and Computer Science, Seoul National University, Korea.

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Especially, it can be interpreted that the reactive power pricing in most countries is defined by an equivalent system through relation with active power output within the limits of generator capacities.

This paper presents a scheme to compute the actual pricing of reactive power by directly controlling generator voltages under the assumption that a reactive power market has been transformed into a real power market. This contains an algorithm that decides the most suitable voltage profiles of generators to minimize the reactive power production cost. The proposed algorithm is tested using the IEEE 14-bus system and its feasibility and accuracy are verified.

The remaining organization of this paper is as follows. We first formulate the objective function and analyze linearly the non-linear constraints to obtain the stable convergence. And then we propose the assessment scheme for reactive power pricing, which is based on the power flow equation, the minimization procedure of objective function, and the iterative linearization procedure of inequality constraints. Following that, we demonstrate the proposed algorithm through numerical examples. Finally, we provide a brief summary.

2. Mathematical Formulation

2.1 Reactive Power and Total Cost Formulation

In the power flow equation, the reactive power injected to each bus is as follows.

$$\begin{aligned} Q_i &= \sum_{k=1}^{n} V_i V_k (G_{ik} \sin\theta_{ik} - B_{ik} \cos\theta_{ik}) \\ &\approx -\sum_{k=1}^{n} V_i V_k B_{ik} \cos\theta_{ik} \quad (\because G_{ik} << 1) \end{aligned} \tag{1}$$

where,

Q_i : reactive power injected to the i th bus

n : the number of buses

V_i : voltage of the i th bus

V_k : volage of the k th bus

B_{ik} : line susceptance between the i th bus and the k th bus

θ_{ik} : angle difference between the i th bus and the k th bus, that is, $(\theta_i - \theta_k)$

Assuming that generator voltages are defined as a vector $X = [V_{g1}, V_{g2}, V_{g3}, \cdots V_{gN}]'$, equation (1) can be expressed as a function of both generator voltages and load voltages as in the following,

$$Q_i = g(V_{g1}, V_{g2}, V_{g3}, \cdots V_{gN-1}, V_{gN}, V_{d1}, V_{d2}, V_{d3}, \cdots, V_{dM}) \tag{2}$$

where,

M : the number of load buses

N : the number of generator buses and the n th generator bus is assigned as a slack bus.

Assuming that load buses are defined as a vector $d_j = d_1, d_2, d_3, \cdots d_M$, the reactive power of load buses (Q_{dj}) can be expressed like equation (3). So the reactive power injected to the load buses is a function of the vector(X) and the load voltages ($V_{d1}, V_{d2}, \cdots,\ V_{dM}$).

$$Q_{dj} = g(X, V_{d1}, V_{d2}, V_{d3}, \cdots, V_{dM}) \tag{3}$$

In the power flow equation, the load bus is assumed to be the PQ bus, and the reactive power is a given value at the PQ bus. Therefore, load voltage can be calculated by equation (4) as follows.

$$\begin{aligned} V_{dj} &= h(X\ ; Q_{d1}, Q_{d2}, Q_{d3}, \cdots, Q_{dM}) \\ &= h'(X) \end{aligned} \tag{4}$$

Similarly, assuming that generator buses are defined as a vector $g_i = g_1, g_2, g_3, \cdots g_N$, the reactive power of generator buses (Q_{gi}) can be expressed like equation (5).

$$\begin{aligned} Q_{gi} &= u(X\ ; V_{d1}, V_{d2}, V_{d3}, \cdots, V_{dM}) \\ &= u(X\ ; h'(X)) = u'(X) \end{aligned} \tag{5}$$

Finally, the reactive power at the generator bus becomes formulated by generator voltages.

Using the above equations, the total cost for producing reactive power at the generators can be formulated as follows,

$$\begin{aligned} TC_{gi} &= f(Q_{gi}) \\ &= f(u'(X)) \\ &= f'(X) \end{aligned} \tag{6}$$

The total cost for producing reactive power at the generators can be formulated by vector X , that is generator voltages. And under the assumption that generators are the only reactive power supplier in the power system, the supply and demand of reactive power in the power system can be performed by controlling the generator voltages.

It is noted that $(*)'$ indicates the function expressed by control variables X .

2.2 Objective Function

The total cost for producing reactive power at the generators can be expressed as below.

$$\min_{gi} TC_{gi} = \min_{V_{gi}} \sum_{gi} C_{gi}(Q_{gi}(X)) \qquad (7)$$

where,

TC_{gi} : Total cost for reactive power at the generator i

Load voltages should be kept within rated range in the power system. If load voltage escapes rated range, damage may occur to consumer's electrical appliances.

Therefore, the inequality constraints condition, as in equation (8) exists. Load voltages are the function of generator voltages, so load voltages can be kept within desirable voltage range by controlling reactive power at the generators.

$$V_{dj}^{\min} \le V_{dj}(X) \le V_{dj}^{\max} \qquad (8)$$

where,

V_{dj} : load voltage

$V_{dj}^{\max}$: maximum load voltage

$V_{dj}^{\min}$: minimum load voltage

2.3 Linear Analysis of Inequality Constraints

The objective function in (7) has inequality constraints such as in (8). In these inequality constraints, uncertainty of convergence can exist in the process that finds the optimized total cost of the objective function. Therefore, linearization analysis procedure is needed for the stable convergence as follows.

Load voltages are the function of generator voltages as follows,

$$\overline{V_{dj}} = f(\overline{V_{gi}}) \qquad (9)$$

The deviation of load voltages can be expressed as below.

$$\overline{\Delta V_{dj}} = \left[\frac{\partial f}{\partial V_{gi}} \bigg|_{V_{gi},V_{dj}} \right] \overline{\Delta V_{gi}} \qquad (10)$$

And the reactive power at the load bus is a function of generator voltages and load voltages as in the following,

$$\overline{Q_{dj}} = g(\overline{V_{gi}}, \overline{V_{dj}}) \qquad (11)$$

Using the above equations, the deviation of reactive power at the generator bus and load bus can be linearized by the deviation of generator voltage and load voltage.

$$\begin{bmatrix} Q_{gi} + \Delta Q_{gi} \\ Q_{dj} + \Delta Q_{dj} \end{bmatrix} = \begin{bmatrix} u(V_{gi}, V_{dj}) \\ g(V_{gi}, V_{dj}) \end{bmatrix} + \begin{bmatrix} J_{gg} & J_{gd} \\ J_{dg} & J_{dd} \end{bmatrix} \begin{bmatrix} \Delta V_{gi} \\ \Delta V_{dj} \end{bmatrix} \qquad (12)$$

where,

$$J_{gg} = \left[\frac{\partial Q_{gi}}{\partial V_{gi}} \right], \quad J_{gd} = \left[\frac{\partial Q_{gi}}{\partial V_{dj}} \right],$$

$$J_{dg} = \left[\frac{\partial Q_{dj}}{\partial V_{gi}} \right], \quad J_{dd} = \left[\frac{\partial Q_{dj}}{\partial V_{dj}} \right]$$

Equation (12) can be simplified by the following procedure.

$$\begin{bmatrix} Q_{gi} + \Delta Q_{gi} \\ Q_{dj} \end{bmatrix} = \begin{bmatrix} u(V_{gi}, V_{dj}) \\ g(V_{gi}, V_{dj}) \end{bmatrix} + \begin{bmatrix} J_{gg} & J_{gd} \\ J_{dg} & J_{dd} \end{bmatrix} \begin{bmatrix} \Delta V_{gi} \\ \Delta V_{dj} \end{bmatrix}$$

$$(\because \Delta Q_{dj} = 0) \qquad (13)$$

$$\begin{bmatrix} \Delta Q_{gi} \\ 0 \end{bmatrix} = \begin{bmatrix} J_{gg} & J_{gd} \\ J_{dg} & J_{dd} \end{bmatrix} \begin{bmatrix} \Delta V_{gi} \\ \Delta V_{dj} \end{bmatrix}$$

From (13), we finally attain the ΔV_{dj} and ΔQ_{gi} like (14) and (15).

$$\Delta V_{dj} = -(J_{dd}^{-1} J_{dg}) \Delta V_{gi} \qquad (14)$$

$$\begin{aligned} \Delta Q_{gi} &= J_{gg} \Delta V_{gi} + J_{gd} \Delta V_{dj} \\ &= (J_{gg} - J_{gd} J_{dd}^{-1} J_{dg}) \Delta V_{gi} \end{aligned} \qquad (15)$$

Equations (14) and (15) mean that the deviation of load voltages and the reactive power of generators can be linearized by the deviation of generator voltages.

3. Algorithm for Reactive Power Pricing

This paper presents an algorithm for the purpose of evaluating the total cost for reactive power at the generators. The proposed solution method has the following algorithm in the procedure of cost minimization.

The proposed algorithm is divided into 3 procedures. Initial values for optimization are obtained in Stage I, and total cost for reactive power is minimized in Stage II by the iterative method. Iteration steps are performed to correct the error occurred by linear analysis of nonlinear constraints in Stage III.

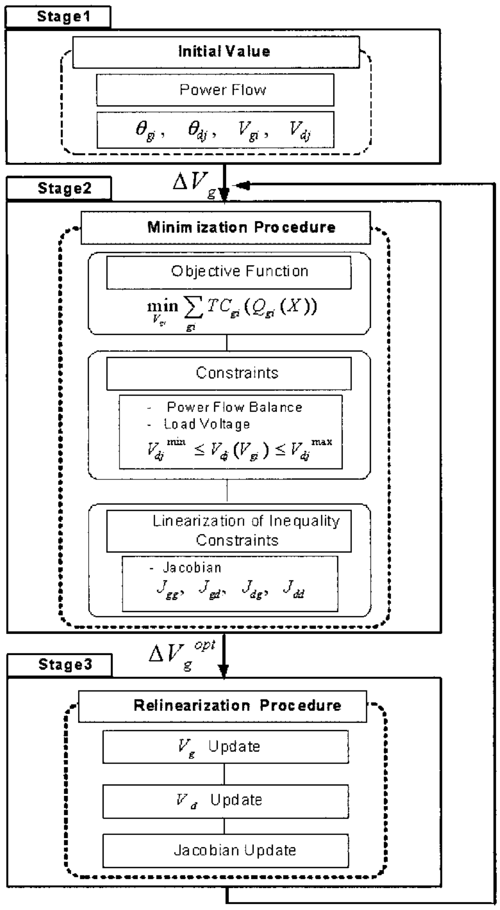

Fig. 1 Algorithm for reactive power pricing

The detailed algorithm can be explained as follows.

- Stage I:

1. Input system data
2. Construct Y matrix
3. Solve power flow, and set initial condition $(\theta_{gi},\ \theta_{dj},\ V_{gi},\ V_{dj})$

- Stage II:

4. Set the deviation of generator voltages (ΔV_g) as control variables
5. Linearize inequality constraints using Jacobian matrix
6. Calculate the total cost for reactive power generation
7. Check the following convergence condition $\left|TC^{k+1} - TC^{k}\right| < \varepsilon_1$
8. If converged, then proceed to Stage III with ΔV_g^{opt}, which is the voltage variation after optimization process, otherwise repeat from step 4

- Stage III:

9. Check the following convergence condition $\left|V_g^{k+1} - V_g^{k}\right| < \varepsilon_2$
10. If converged, then terminate, otherwise update V_g with ΔV_g^{opt}
11. Solve Q-V flow, and update V_d.
12. Update Jacobian (J_{gg}, J_{gd}, J_{dg}, J_{dd}) with the updated V_g and V_d.
13. Repeat from Stage II.

The minimum total cost for reactive power through generator voltages control can be yielded from the proposed algorithm including consideration of power flow balance and load voltage constraints.

4. Case Study

The proposed algorithm has been tested on the IEEE-14 bus system, which has 5 generator buses (bus #1-slack bus) and 9 load buses. In this paper, the following conditions and assumptions are utilized to demonstrate the numerical solutions.

- The cost function is given in the form of quadratic curve in order to compensate for the region of supply and demand like the capability price structure and utilization price structure in NGC (United Kingdom) [8]. So, the total cost can be calculated with the cost curve coefficient product reactive power at the generator. The total cost equation is as follows,

$$TC = \sum_{gi} a_{gi} Q_{gi}^{2}$$

Where, a_{gi} : cost curve coefficient

- It is assumed that the reactive power at the generator is defined in reactive capability curves including field current limit, armature current limit, and under-excitation limit [9].
- The voltage limits at load buses, $V_{dj}^{\min}$ and $V_{dj}^{\max}$ are 0.98 [pu] and 1.02 [pu], respectively.

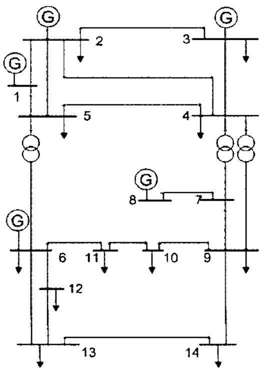

Fig. 2 IEEE 14 bus system

Two cases are considered in this paper. One is that all generators have the identical cost curve coefficient, and the other is that one generator has a different cost curve coefficient.

4.1 Case 1: Identical cost curve coefficient

Table 1 shows the identical cost curve coefficient at each generator.

Table 1 Cost curve coefficient of generators

Bus	# 1	# 2	# 3	# 6	# 8
Cost curve Coefficients	1	1	1	1	1

Table 2 presents the initial and final values of voltage, reactive power and cost at each bus when all generator buses have 1.02[pu] as their initial voltages. All the voltages at the load buses should be maintained within the network constraints ($0.98[pu] \le V_d \le 1.02[pu]$). The left table indicates the initial value given as a power flow result, and the right table reveals the final values following the optimization process with 16 iterations. All the generator voltages except bus 8 have been decreased below 1.0[pu] to reduce the total cost for reactive power generation. However, bus 8 has a unique characteristic in terms of its network topology, that is, it is located close to several load buses and it plays an important role in maintaining the load voltages within the load voltage constraints ($0.98[pu] \le V_d \le 1.02[pu]$). As shown in this table, the voltage values from bus 10 to bus 13 are close to 0.98[pu] and bus 14 has a lower bound constraint voltage. Therefore, the generator at bus 8 must increase its voltage to support load voltages within the constraints.

The reactive power at each generation bus has also been decreased, except for bus 8 as shown in Table 2. So the total cost has been decreased from 158.33 to 6.43 through the proposed algorithm.

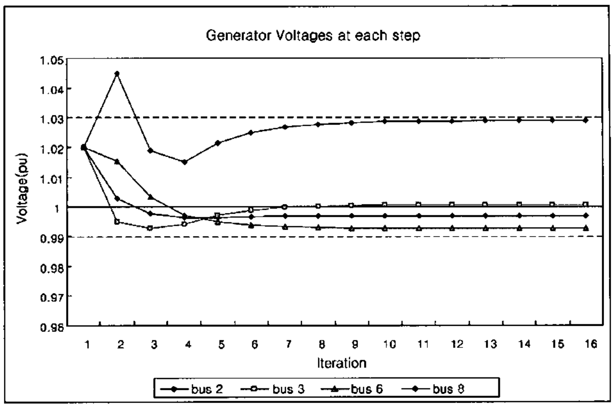

Fig. 3 Generator Voltages at each step

Fig. 3 shows generator voltages at each iteration step. During iteration steps 1 through 3, the voltage at bus 8 has a rapid increase and decrease. Following that, the value is converged stably to 1.028[pu]. That is why the minimum total cost is computed by the linearization process. Therefore, the voltage resulted from the linearization process has an error compared to the voltage resulted from the original nonlinear equation. The same explanation can be applied to the case of bus 3.

4.2 Case 2: Different cost curve coefficient

Table 3 indicates the different cost curve coefficient at generator 8. The reactive power coefficient at bus 8 is assigned to be 5 times as large as the other generators, and it can be expected for the voltage at bus 8 to be changed

Table 2 Initial and final voltages, reactive power and cost

Initial values				Final values			
Bus	V(pu)	Q(pu)	Cost	Bus	V(pu)	Q(pu)	Cost
1	1.0000	-0.9247	85.51	1	1.0000	0.1692	2.86
2	1.0200	0.7000	49.00	2	0.9969	0.0300	0.09
3	1.0200	0.4037	16.30	3	1.0007	0.0516	0.27
4	0.9996	0.0390		4	0.9981	0.0390	
5	0.9997	-0.0160		5	0.9953	-0.0160	
6	1.0200	0.2603	6.78	6	0.9926	0.1124	1.26
7	1.0050	0		7	1.0050	0	
8	1.0200	0.0868	0.75	8	1.0289	0.1397	1.95
9	0.999	0.0240		9	0.9951	0.0240	
10	0.9956	-0.0580		10	0.9892	-0.0580	
11	1.004	-0.0180		11	0.9887	-0.0180	
12	1.004	-0.0160		12	0.9854	-0.0160	
13	0.9986	-0.0580		13	0.9827	-0.0580	
14	0.9803	-0.0500		14	0.9800	-0.0500	
Total Cost			158.33	Total Cost			6.43

differently compared to the case in which all generators have the identical cost curve coefficients.

Table 3 Cost curve coefficient of generators

Bus	# 1	# 2	# 3	# 6	# 8
Cost curve Coefficients	1	1	1	1	5

Table 4 Initial and final voltages, reactive power and cost

Initial values				Final values			
Bus	V(pu)	Q(pu)	Cost	Bus	V(pu)	Q(pu)	Cost
1	1.0000	-0.9247	85.51	1	1.0000	0.1474	2.17
2	1.0200	0.7000	49.00	2	0.9981	0.0475	0.23
3	1.0200	0.4037	16.30	3	1.0041	0.0804	0.65
4	0.9996	0.0390		4	0.9978	0.0390	
5	0.9997	-0.0160		5	0.9962	-0.0160	
6	1.0200	0.2603	6.78	6	1.0006	0.1781	3.17
7	1.0050	0		7	0.9954	0	
8	1.0200	0.0868	0.75	8	1.0036	0.0466	0.22
9	0.999	0.0240		9	0.9904	0.0240	
10	0.9956	-0.0580		10	0.9867	-0.0580	
11	1.004	-0.0180		11	0.9912	-0.0180	
12	1.004	-0.0160		12	0.9927	-0.0160	
13	0.9986	-0.0580		13	0.9889	-0.0580	
14	0.9803	-0.0500		14	0.9800	-0.0500	
Total Cost			158.33	Total Cost			7.30

Table 4 shows the initial and final values of voltage, reactive power and cost at each bus and all the generator voltages are assigned to be 1.02[pu] as their initial voltages. All the voltages at the load bus are maintained within the inequality constraints ($0.98[pu] \le V_d \le 1.02[pu]$) as indicated. The left table presents the initial value as a result of power flow, and the right table indicates the final value after 15 iterations. All the generator voltages have been decreased from 1.02[pu] to around 1.0[pu]. But compared to the case in which all generators have the identical cost curve coefficients, the voltage at bus 8 has been decreased from 1.0289[pu] to 1.0036[pu] as shown in Table 4. This is why the coefficient of bus 8 changed from 1 to 5 and it is 5 times more expensive than other generators, so the generator at bus 8 has to drop its voltage as low as possible to reduce the cost to produce reactive power within the load voltage constraints ($0.98[pu] \le V_d \le 1.02[pu]$).

The reactive power at each generator bus has also been decreased. And the total cost has been decreased from 158.33 to 7.30 by the proposed algorithm. The total cost has been increased because of the change of cost curve coefficient at bus 8.

Fig. 4 shows generator voltages at each iteration step. At iteration step 3, the voltage at bus 3 showed the minimum voltage and after that, it increased to 1.0041[pu] stably. That is why the linearization process caused an error compared to the actual value resulted from the nonlinear constraints.

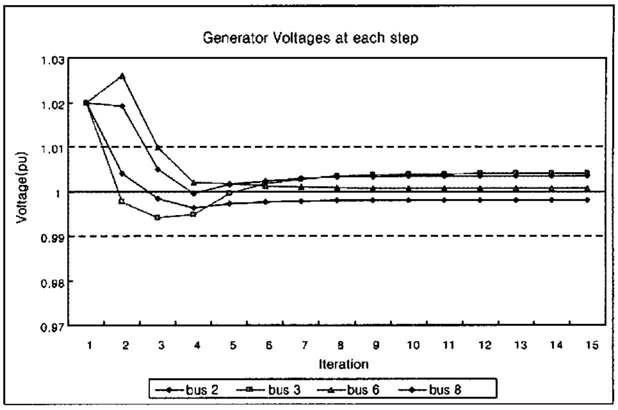

Fig. 4 Generator Voltages at each step

5. Conclusion

This paper suggests an algorithm that computes the actual pricing of reactive power by directly controlling generator voltages and optimum generator voltage profiles that can minimize the reactive power costs that are determined from the proposed algorithm. The summary is as follows.

- The proposed algorithm is divided into 3 stages. Stage I is the step to yield the initial value for the minimization of total reactive power cost, and the optimized values of the reactive power of generators are obtained in Stage II by the minimization process. Stage III is the step to update voltage values and Jacobian in each bus to reduce the error caused by linearization analysis.
- In the case that the cost curve coefficients of all generators are identical, the optimal voltage profiles of generators can be decided to minimize reactive power cost within the voltage range at load buses, which is the network constraint.
- In the case that the cost curve coefficients of all generators are not identical, generator voltages are adjusted in order that the most expensive generator produces as few as possible. This can be similar to the economic dispatch concept into reactive power allocation.

In some countries, like Korea, the ISO (Independent System Operator) receives bids only pertaining to the active power. Furthermore, it offers reactive power as an ancillary service according to system situations and its pricing system is not yet defined reasonably.

Therefore, it is necessary that the reactive power market systems be constructed not through ancillary service but through bids similar to active power. If these systems are established, the proposed algorithm can be applied as the fundamental principle for deciding reactive power and assessing its cost under the deregulation environment.

Furthermore, it may provide the fair and reasonable price information for reactive power, since it sets up a scheme to compute the actual pricing of reactive power by directly controlling generator voltages.

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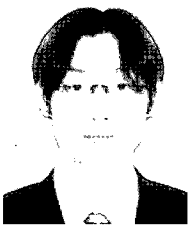

Seung-Wan Jung

He was born in Korea on May 31, 1979. He received his B.S. degree from Korea University, Korea in 2003 and his M.S. degree from Seoul National University, Korea in 2005. Currently, he is a Researcher at the Electro-Mechanical Research Institute, Hyundai Heavy Industries Co., LTD. His research field of interest includes power system operation in IPS ships and the online partial discharge diagnosis algorithm using fuzzy and neural-network.

Sung-Hwan Song

He was born in Korea on May 30, 1978. He received his B.S. degree from Busan National University, Korea in 2001 and his M.S. degree from Seoul National University, Korea in 2003. Currently, he is a Ph.D. student with Seoul National University, Korea. His research field of interest includes the power system operation in a deregulated environment, electric power economics and FACTS operation.

Yong Tae Yoon

He was born in Korea on April 20, 1971. He received his B.S. degree, M.Eng. and Ph.D. degrees from M.I.T., USA in 1995, 1997 and 2001, respectively. Currently, he is an Assistant Professor in the School of Electrical Engineering at Seoul National University, Korea. His special field of interest includes electric power network economics, power system reliability, and the incentive regulation of independent transmission companies.

Seung-Il Moon

He was born in Korea on February 1, 1961. He received his B.S. degree from Seoul National University, Korea in 1985 and his M.S. and Ph.D. degrees from Ohio State University in 1989 and 1993, respectively. Currently, he is an Associate Professor at the School of Electrical Engineering at Seoul National University, Korea. His special field of interest includes analysis, control and modeling of power systems, FACTS and power quality.