A Study on Effective Enhancement of Load Power Factor Using the Load Power Factor Sensitivity of Generation Cost

Byung Ha Lee† and Jung-Hoon Kim*

Abstract - Various problems such as increase of power loss and voltage instability may often occur in the case of low load power factor. The demand of reactive power increases continuously with the growth of active power and restructuring of electric power companies makes the comprehensive management of reactive power a troublesome problem, so that the systematic control of load power factor is required. In this paper, the load power factor sensitivity of generation cost is derived and it is used for effectively determining the locations of reactive power compensation devices and for enhancing the load power factor appropriately. In addition, voltage variation penalty cost is introduced and integrated costs including voltage variation penalty cost are used for determining the value of load power factor from the point of view of economic investment and voltage regulation. It is shown through application to a large-scale power system that the load power factor can be enhanced effectively using the load power factor sensitivity and the integrated cost.

Keywords: generation cost, load power factor, power factor sensitivity, reactive power, voltage variation penalty cost

1. Introduction

The restructuring of KEPCO (Korea Electric Power Corporation) led to the monopolistic company being divided into several companies. As a result, the power system planning section and the operation section of the original company became separated, causing integrated adjustment of reactive power to be difficult because of the structural inharmoniousness of the separated companies. Power loss is increasing as the demand for reactive power rises rapidly with the continuous growth of power demand. Also, deficiency of reactive power supply can cause a voltage stability problem. For these reasons, the importance of load power factor management has been highlighted. As such, it is necessary to investigate under this new circumstance at what level the power factor should be maintained from the point of view of economic operation and planning. Each nation has its own regulations and power rate policy for maintaining power factor within constant bounds and the studies on investment planning of reactive power devices from the point of view of regular voltage maintenance have been performed. However, earnest studies on the model of load power factor and the effects of load power factor to economic operation have not yet been carried out.

Saied [1] discussed the different parameters affecting the economic feasibility of power factor correction.

He performed a study to minimize the sum of the approximate costs of transmission lines, transformers and power loss saved by power factor correction, and the cost of shunt compensating capacitors considering the overall power factor. Nedwick et al. [2] described a Reactive Management Program that Virginia Power developed and implemented on its system with the primary goal of maintaining a reactive reserve at all times so as to operate generating units at or near unity power factor. Costa [3] presented an algorithm for optimal reactive dispatch problems based on Newton's method with an augmented Lagrangian function and considered the penalty terms associated with inequality constraints. Jang [4] presented the optimal condenser position and the proper capacity by Lagrangian function including the transmission line loss, while generation cost was not considered.

In this paper, the load power factor sensitivity of generation cost is derived and it is used for effectively determining the locations of reactive power compensation devices and for enhancing the load power factor appropriately. In addition, we propose the method to convert voltage variation to another cost by introducing penalty cost in exponential function form instead of applying constraint equations since one of the major objectives of enhancing power factor is to maintain bus voltages within

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appropriate bounds. The load power factor sensitivity of generation cost and integrated cost composed of generation cost, voltage variation penalty cost and reactive power compensation cost are used for determining the appropriate value of load power factor from the point of view of economic investment and voltage regulation. The procedures for effectively enhancing load power factor are presented and utilized for the analysis of a practical power system. It is shown through application to a large-scale power system that load power factor can be enhanced successfully using load power factor sensitivity and integrated cost. This is a fundamental study for application to the formulation of a policy pertaining to investment planning and operation of reactive power devices in order to enhance load power factor, and we analyze the effects of load power factor to power system operation by using the load power factor sensitivity of generation cost and the integrated cost.

2. The Load Power Factor Sensitivity of Generation Cost

Since load power factor is represented by the equation related to active power and reactive power, reactive power exerts an important effect on power factor. Various problems such as increase of power loss and voltage instability may often occur in the case of low load power factor, causing power system operation to be troublesome. Therefore, at what level the load power factor should be maintained from the point of view of power system stability and economic operation is a subject to be studied intensely and to be investigated considering several aspects simultaneously. The general objective function of optimal power flow calculation for pursuing optimal operation of the power system from the point of view of stability and economics is the production cost of active power, i.e., generation cost. If the load power factor sensitivity of generation cost is obtained, it can be used for determining the locations of reactive power compensation devices and the amounts of compensated reactive power and for drawing up the plan of load power factor enhancement effectively. The generation cost can be expressed as follows:

$$\begin{aligned} F &= \sum_{i\in NTG} F_i(P_{Gi}) \\ &= \sum_{i\in NTG} \{A_i + B_i P_{Gi} + C_i P_{Gi}^2\} \cdot F_{Ci} \end{aligned} \quad , \qquad (1)$$

where F is total generation cost, F_i is the generation cost of i-bus generator, F_{Ci} is the unit fuel cost of i-bus generator, and P_{Gi} is the active power of i-bus generator. NTG is the collection of generator buses, and A, B, C are the coefficients of generation cost.

The power equations in bus i are expressed as follows:

$$\begin{aligned} P_{Gi} - P_{Li} &+ \sum_{j\in N_{Li}} V_i V_j y_{ij} \cos(\delta_i - \delta_j - \theta_{ij}) \\ &- \sum_{j\in N_{Li}} V_i^2 y_{ij} \cos(\theta_{ij}) = 0 \qquad i = 1,2,\cdots,n \end{aligned} \qquad (2)$$

$$\begin{aligned} Q_{Gi} - Q_{Li} &+ \sum_{j\in N_{Li}} V_i V_j y_{ij} \sin(\delta_i - \delta_j - \theta_{ij}) \\ &+ \sum_{j\in N_{Li}} V_i^2 y_{ij} \sin(\theta_{ij}) + \sum_{j\in N_{Li}} \omega C_{lij} V_i^2 / 2 = 0 \\ & \qquad i = 1,2,\cdots,n \end{aligned} \qquad (3)$$

where N_{Li} is the collection of buses connected to bus i by lines, P_{Li}, Q_{Li} are the active power load and the reactive power load, respectively, of bus i, Q_{Gi} is the reactive power of i-bus generator, V_i, δ_i are the voltage magnitude and phase, respectively, of bus i, y_{ij} and θ_{ij} are the magnitude and phase, respectively, of line admittance between buses i and j, C_{lij} is the shunt capacitor between buses i and j, ω is angular velocity, and n is the number of total buses.

In the case of installing the reactive power compensating devices at load bus m, the reactive power equation can be expressed as follows:

$$\begin{aligned} Q_m &= Q_{Cm} - Q_{Lm} \\ &= -\sum_{j\in N_{Lm}} V_m V_j y_{mj} \sin(\delta_m - \delta_j - \theta_{mj}) \\ &\quad - \sum_{j\in N_{Lm}} V_m^2 y_{mj} \sin(\theta_{mj}) - \sum_{j\in N_{Lm}} \omega C_{lmj} V_m^2 / 2 \end{aligned} \quad , \qquad (4)$$

where Q_{Cm} is the amount of controlled reactive power.

Since load power factor enhancement is required to improve load power factor by compensating reactive power, it is assumed that active power load is constant. The active power P_m of load bus m is constant and the reactive power Q_m of load bus m is expressed using the load power factor of load bus m (pf_m) as follows:

$$Q_m = P_m \sqrt{\frac{1}{(pf_m)^2} - 1} \qquad (5)$$

Although the problem may be expressed from the point of view of load power factor, the investment cost and the controlled amount are determined according to the compensation amount of reactive power corresponding to variation of load power factor in the end. Therefore, it is necessary that the load power factor sensitivity of generation cost at load bus m be normalized as $\frac{\partial F}{k_m \cdot \partial(pf_m)}$. Here, k_m is a normalized coefficient expressed by $k_m = \frac{P_m}{(pf_m)^2\sqrt{1-(pf_m)^2}}$.

The load power factor sensitivity of generation cost at load bus m ($S_{(pf)m}$) can be expressed using chain rule as follows:

$$\begin{aligned} S_{(pf)m} &= -\frac{\partial F}{k_m \cdot \partial(pf_m)} = -\frac{\partial F}{\partial Q_m}\frac{\partial Q_m}{k_m \cdot \partial(pf_m)} \\ &= -\sum_{i\in NTG}\sum_{j=1}^{n}\frac{\partial F}{\partial P_{Gi}}\frac{\partial P_{Gi}}{\partial \delta_j}\frac{\partial \delta_j}{\partial Q_m}\frac{\partial Q_m}{k_m \cdot \partial(pf_m)} \\ &\quad -\sum_{i\in NTG}\sum_{j=1}^{n}\frac{\partial F}{\partial P_{Gi}}\frac{\partial P_{Gi}}{\partial V_j}\frac{\partial V_j}{\partial Q_m}\frac{\partial Q_m}{k_m \cdot \partial(pf_m)} \end{aligned} \tag{6}$$

The equations of partial derivatives in the above equation (6) are expressed as follows:

$$\frac{\partial F}{\partial P_{Gi}} = \{B_i + 2\cdot C_i \cdot P_{Gi}\}\cdot F_{Ci} \tag{7}$$

$$\frac{\partial P_{Gi}}{\partial \delta_j} = -V_i V_j y_{ij}\sin(\delta_i - \delta_j - \theta_{ij}) \tag{8}$$

$$\frac{\partial P_{Gi}}{\partial \delta_i} = \sum_{j\in N_L} V_i V_j y_{ij}\sin(\delta_i - \delta_j - \theta_{ij}) \tag{9}$$

$$\frac{\partial P_{Gi}}{\partial V_j} = -V_i\, y_{ij}\cos(\delta_i - \delta_j - \theta_{ij}) \tag{10}$$

$$\begin{aligned} \frac{\partial P_{Gi}}{\partial V_i} &= -\sum_{j\in N_L} V_j\, y_{ij}\cos(\delta_i - \delta_j - \theta_{ij}) \\ &\quad + \sum_{j\in N_L} 2V_i\, y_{ij}\cos(\theta_{ij}) \end{aligned} \tag{11}$$

$$\frac{\partial \delta_j}{\partial Q_m} = [J^{-1}]_{(j,n+m)} \tag{12}$$

$$\frac{\partial V_j}{\partial Q_m} = [J^{-1}]_{(n+j,n+m)} \tag{13}$$

$$\frac{\partial Q_m}{\partial(pf_m)} = \frac{P_m}{(pf_m)^2\sqrt{1-(pf_m)^2}} \tag{14}$$

where J is the Jacobian matrix in the power flow solution, $[J^{-1}]_{(j,n+m)}$ is the element corresponding to δ_j and Q_m of the inverse matrix of J, and $[J^{-1}]_{(n+j,n+m)}$ is the element corresponding to V_j and Q_m of the inverse matrix of J.

Using this sensitivity equation, the sensitivity values of all the load buses are calculated simultaneously and are compared to one another. Consequently, it can be effectively utilized for power system operation and planning since we can select the bus to install reactive power compensation devices preferentially or improve load power factor preferentially.

3. The Procedures for Effective Load Power Factor Enhancement

3.1 Investment cost

Investment cost can be defined as the sum of installation and maintenance costs of power supply equipments and personnel expenses. The investment cost tends to increase monotonically according to the capacity of installation of compensated equipments and then reinvestment should be made for replacement of the old equipments beyond the expected life span during the investigation period. For simplicity, the expected life spans of equipments are determined assuming that the remainder costs of the equipments are zero. In the case that several costs are paid at different times or at all times of the investigation period, they should be simultaneously converted to the costs considering the worth corresponding to the point of time. The present worth of investment cost including maintenance cost and personnel expenses is C_P, the expected life span of the equipment is L, and discount rate is i. Then, the levelized cost per year can be expressed as follows [8]:

$$C_F = C_P \cdot \frac{i(1+i)^L}{(1+i)^L - 1} \tag{15}$$

This is the value of converting the investment cost to the levelized cost for each year. Since we deal with the problem to enhance power factor by compensating the reactive power, we assume that active power load is constant and consider the investment cost of reactive power compensation devices alone.

3.2 Model of voltage variation cost

Since one of the major objectives of enhancing power factor is to maintain bus voltages within appropriate bounds, economic operation must not be considered. Therefore, we reflect its effect by including another cost corresponding to voltage variation in the process of formulating in order to obtain the optimal power factor. In general methods, we conclude that if all bus voltages are within the permitted limits of the bus voltage, the optimal solution of power equations is appropriate and if not so, it is not appropriate. However, when the solutions near permitted limits are dealt with, it is not reasonable to determine the solution as suitable or unsuitable by the infinitesimal difference. Also, when a solution with 1.0 p.u. voltage magnitude and a solution with 0.9 p.u. voltage magnitude within 10% permitted limit are considered, it is not reasonable to deal with both solutions equally because the solutions are different in quality. Considering these respects, we introduce the penalty function instead of voltage constraint conditions and convert voltage variation to another cost. The following C_V is the function of voltage variation penalty cost to convert voltage variation to another cost.

$$C_V = k_a \sum_{i \in Nload} \frac{\exp[k_b \mid V_i - V_{ri} \mid] - 1}{N_l} \cdot F \quad , \tag{16}$$

where N_{load} is the collection of load buses, N_l is the number of load buses, k_a, k_b are positive constants, V_i is the voltage magnitude of bus i in per unit, V_{ri} is the desired voltage magnitude of bus i in per unit, F is total generation cost, and exp represents an exponential function. The value of this function is zero if the voltage magnitude is equal to the desired value, but it has the characteristics to increase exponentially if the voltage magnitude deviates from the desired value. It corresponds to an average value of the values of all the buses by dividing the summation of the values of all the load buses by the number of load buses (N_l). The values of constants k_a, k_b are appropriately determined by the decision maker of power system operation and planning.

The summation of generation cost, investment cost of reactive power compensation devices and voltage variation penalty cost considered above is defined as integrated cost. If we solve the minimum value of the integrated cost, the optimal power factor can be determined considering voltage variation from the point of view of power system planning.

3.3 Procedures of enhancing load power factor using the load power factor sensitivity and the integrated cost

The load power factor sensitivity of generation cost and the integrated cost composed of generation cost, voltage variation penalty cost and reactive power compensation cost can be used for determining the locations and the amounts of reactive power compensation and selecting the plan of improving load power factor. We consider all the costs mentioned above in order to reflect both economical aspect and voltage regulation. After solving the optimal generation allocation by executing the OPF program, we calculate the load power factor sensitivity of generation cost and determine the locations and the order of reactive power compensation. We make reactive power compensation and then calculate the integrated cost including generation cost, voltage variation penalty cost and reactive power compensation cost. Since the integrated cost decreases to some degree according to the compensation amount and increases in excess of a certain compensation amount convexly, we can determine the minimum point with ease. By repeating the above procedures until the integrated cost does not decrease any further, we can determine the optimal plan of improving load power factor. Then, it is unnecessary to calculate the load power factor sensitivity of generation cost per each iteration step, since the load power factor sensitivity of generation cost varies slightly according to each iteration step. The procedures for effectively enhancing the load power factor are shown in the following Fig. 1.

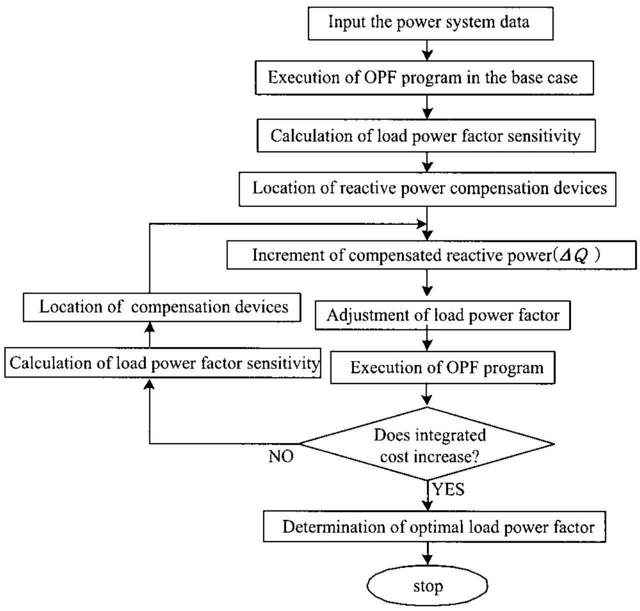

Fig. 1 Flow chart of load power factor adjustment using sensitivity cost and integrated cost

4. Simulation and Results

The developed tool was applied to the practical power system of KEPCO during the summer of 2004. The practical power system includes the following:

Buses: 1550, Generators: 249, Lines: 2592,
Transformers: 165 bank, Maximum load: 52,812 MW

A 345kV and above transmission system of KEPCO is shown in Fig. 2. The load power factor sensitivity of generation cost was calculated using the PSS/E package with IPLAN and the calculation of optimal power flow was performed using the Power World program. The Power World program has the compatible function of converting the data into appropriate form mutually with the PSS/E program.

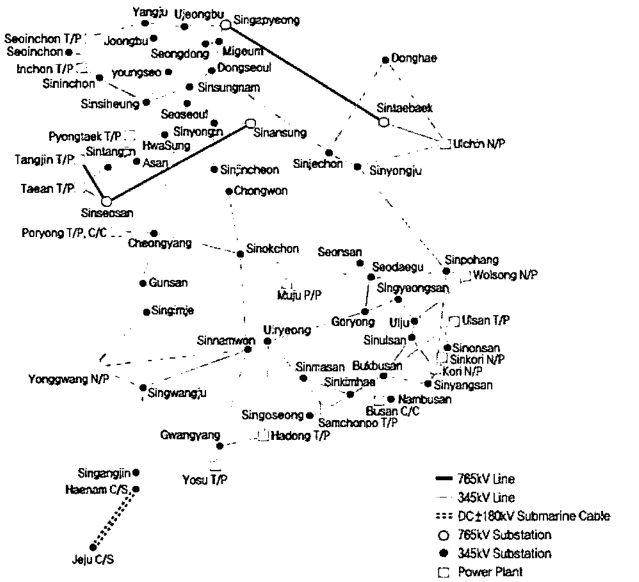

Fig. 2 The 345kV and above transmission system of KEPCO (2004)

It is assumed that the expected life span of reactive power compensation devices is 30 years, and that the discount rate is 8%. Since high quality electricity is gradually being required more and more by consumers, voltage variation penalty cost is considered and it is assumed that the values of constants are $k_a = 2.5 \cdot 10^{-4}$, $k_b = 30.0$. It is also assumed that the present worth of investment cost of reactive power compensation devices per kVA is 30.0[$/kVA] in the main investigation. In addition, the simulation results are compared with the cases of 20.0[$/kVA] and 40.0[$/kVA] costs per kVA. We consider the power system of KEPCO for the summer of 2004 as a base case and it is assumed that the investment cost of reactive power compensation devices is zero in this base case. The load power factor in the base case is 0.908. Although the analysis of load power factors of all the loads should be synthesized through analyzing the numerous cases of different load models, it is assumed that this base case is the case of a representative load model for the sake of simplicity and that the power demand level is sustained continually. We determine the locations of reactive power compensation using the load power factor sensitivity of the generation cost and enhance the power factor by making reactive power compensation in the order of the sensitivity. Then, the effects of load power factor are analyzed using the trajectories of the costs according to the compensation amount.

Variations of generation cost per year and investment cost of reactive power compensation devices in case of increasing load power factor in the order of the sensitivity are shown in Fig. 3 and Fig. 4, respectively. Then, the trajectory of voltage variation penalty cost is shown in Fig. 5. The integrated cost including generation cost, investment cost and voltage variation penalty cost is shown in Fig. 6. From Fig. 6, the optimal value of load power factor when the present worth of investment cost of reactive power compensation devices per kVA is 30.0[$/kVA] is 0.918. The system power factor can be defined as the ratio of the summation of active powers to the summation of apparent powers of all the generators. The trajectory of the annual integrated cost corresponding to variation of system power factor is shown in Fig. 7. The optimal value of system power factor is 0.97 from Fig. 7. The value of system power factor is higher than the load power factor because the power system in the base case is operated running many reactive power compensation devices including the shunt capacitors. The trajectory of the annual integrated cost corresponding to variation of the reactive power compensation amount is shown in Fig. 8. In this case, the optimal reactive power compensation amount is 1600[MVar] from Fig. 8.

Finally, variations of annual generation cost and annual investment cost of reactive power compensation devices when the present worth of the investment cost of reactive power compensation devices per kVA is 20.0[$/kVA] and 20.0[$/kVA] are shown in Fig. 9 ~ Fig. 12, respectively. The optimal value of load power factor when the present worth of the investment cost of reactive power compensation devices per kVA is 20.0[$/kVA] is 0.926 and it is 0.915 in case of 40.0[$/kVA], showing that the optimal load power factor rises according to the decrease of the investment cost of reactive power compensation devices per kVA. However, the optimal load power factor does not vary proportionally to variation of the investment cost of reactive power compensation devices per kVA because voltage variation penalty cost is included and annual generation cost does not vary linearly with load power factor.

Besides the present worth of the investment cost of reactive power compensation devices per kVA, the trajectories change greatly according to the values of the constants of voltage variation penalty cost and the characteristics of the power system. The values of constants k_a, k_b are appropriately determined from the point of view of voltage regulation and economical aspects by the decision maker of the power system operation and planning. Through the above simulation results, it is shown that the load power factor can be enhanced effectively by using load power factor sensitivity and integrated cost.

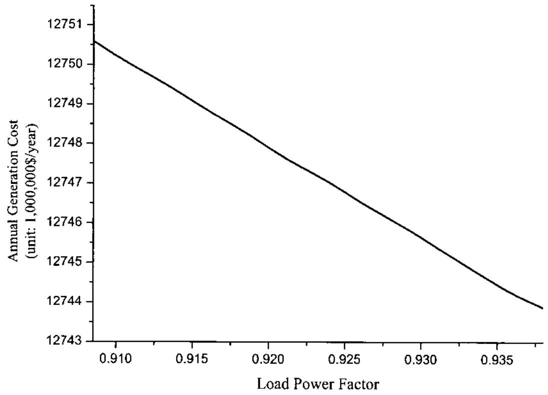

Fig. 3 Variation of generation cost according to load power factor

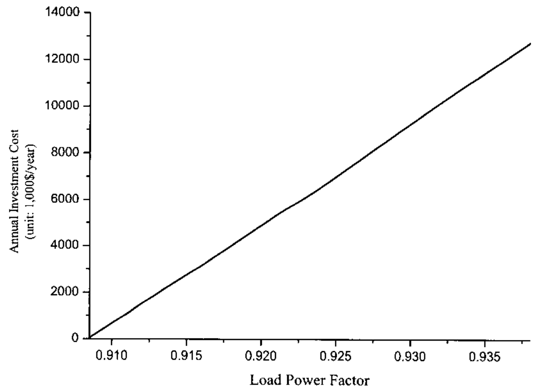

Fig. 4 Variation of investment cost of compensation devices according to load power factor

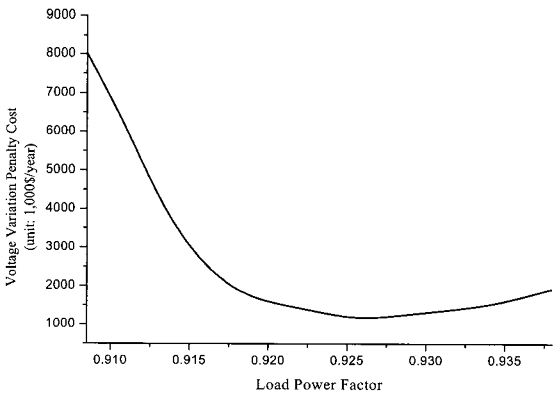

Fig. 5 Variation of voltage variation penalty cost according to load power factor

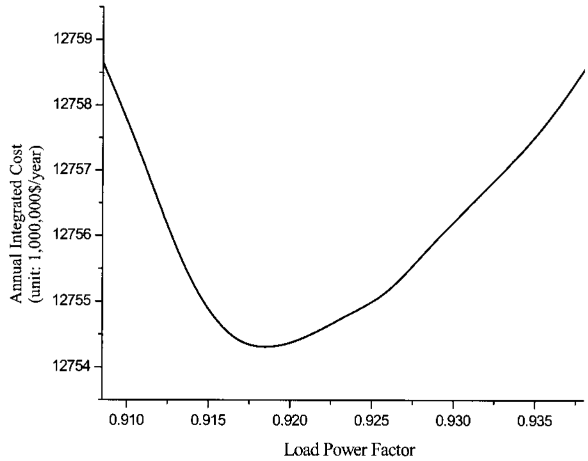

Fig. 6 Variation of integrated cost according to load power factor

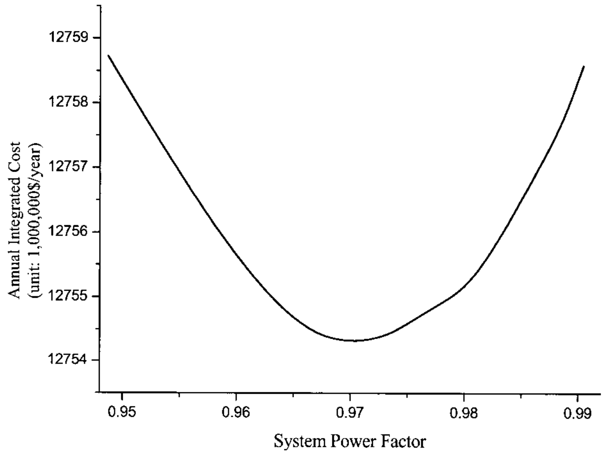

Fig. 7 Variation of integrated cost according to system power factor

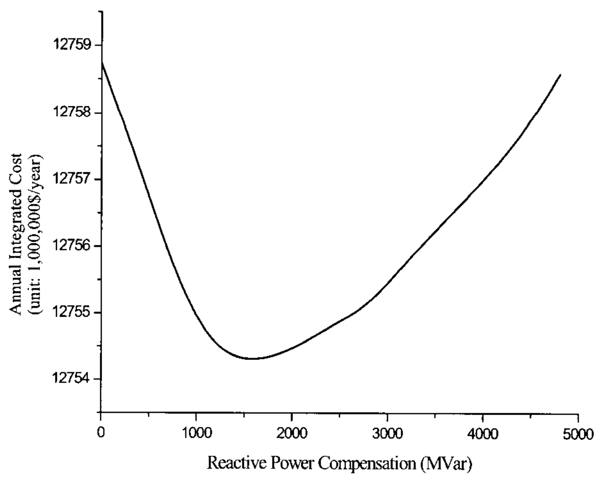

Fig. 8 Variation of integrated cost according to the compensation amount of reactive power

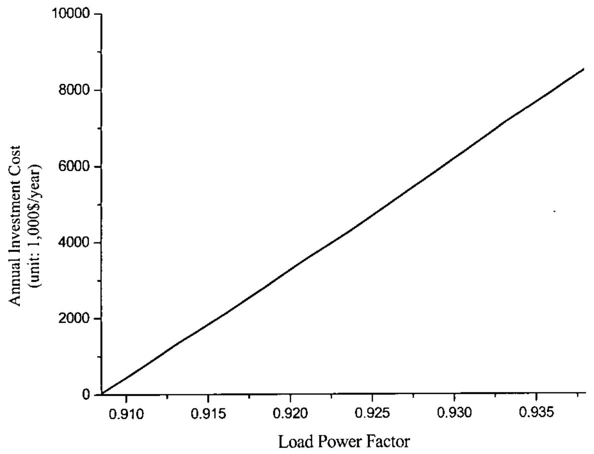

Fig. 9 Variation of investment cost of compensation devices according to load power factor(present cost of installation: 20.0 [$/kVA])

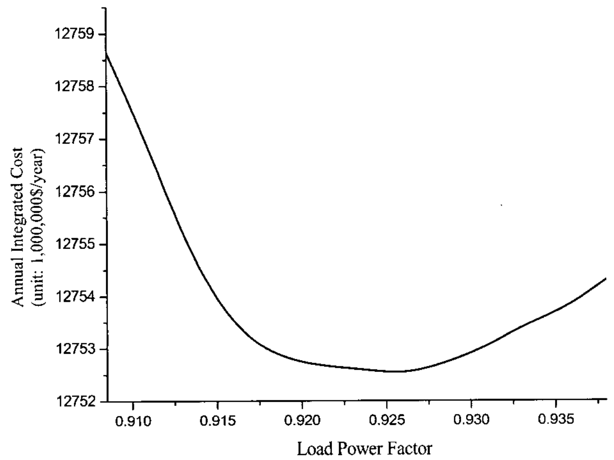

Fig. 10 Variation of integrated cost according to load power factor(present cost of installation: 20.0 [$/kVA])

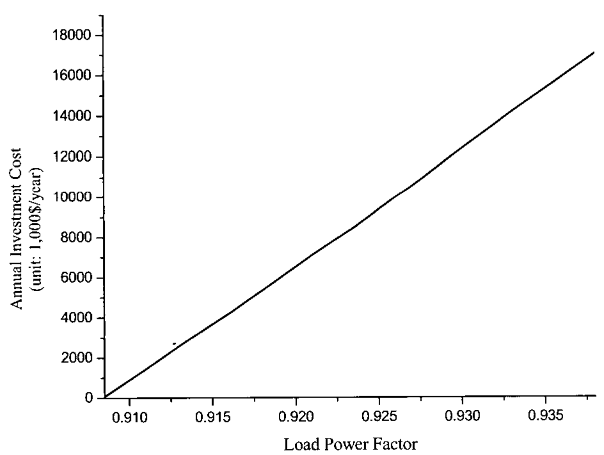

Fig. 11 Variation of investment cost of compensation devices according to load power factor(present cost of installation: 40.0 [$/kVA])

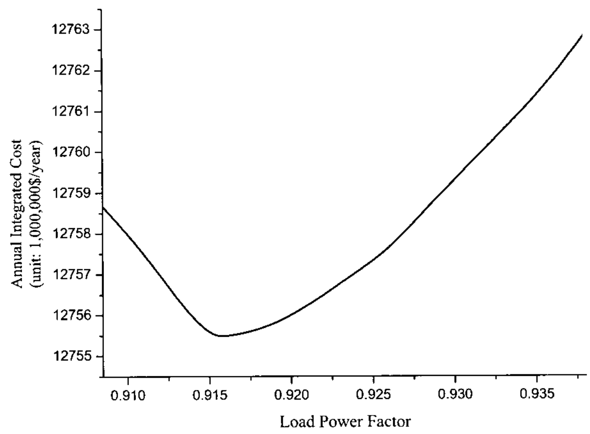

Fig. 12 Variation of integrated cost according to load power factor(present cost of installation: 40.0 [$/kVA])

5. Conclusion

The load power factor sensitivity of generation cost is derived and it has been shown that it can be effectively used for determining the locations of reactive power compensation devices and for enhancing the load power factor appropriately. Since one of the major objectives of enhancing the power factor is to maintain bus voltages within appropriate bounds, we propose the method to convert voltage variation to another cost by introducing the penalty cost in exponential function form instead of applying constraint equations. The procedures for successfully enhancing load power factor by using the load power factor sensitivity of generation cost and the integrated cost composed of generation cost, voltage variation penalty cost and reactive power compensation cost are presented and utilized for analyzing the variations of annual generation cost and integrated cost according to variation of load power factor in the practical power system of KEPCO. The cases where the present worth of the investment cost of reactive power compensation devices per kVA varies are also analyzed. This is a fundamental study for application to the formulation of a policy pertaining to investment planning and operation of reactive power devices in order to enhance load power factor. In the future the studies on load power factor enhancement should be performed more intensely in order to determine the definite policy planning of load power factor.

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