# Proposing a New Method for Calculating Reactive Power Service Charges using the Reactive Power Market

**Kyoung-Soo Ro**† **and Sung-Jin Park***

**Abstract** - With the advent of electric power systems moving from a vertically integrated structure to a deregulated environment, calculating reactive power service charges has become a new and challenging theme for market operators. This paper examines various methods for reactive power management adopted throughout various deregulated foreign and domestic markets and then proposes an innovative method to calculate reactive power service charges using a reactive power market in a wholesale electricity market. The reactive power market is operated based on bids from the generating sources and it settles on uniform prices by running the reactive OPF programs of the day-ahead electricity market. The proposed method takes into account recovering not only the costs of installed capacity but also the lost opportunity costs incurred by reducing active power output to increase reactive power production. Based on the result of the reactive OPF program, the generators that produce reactive power within the obligatory range do not make payments whereas the generators producing reactive power beyond the obligatory range receive compensation by the price determined in the market. A numerical sample study is carried out to illustrate the processes and appropriateness of the proposed method.

**Keywords**: ancillary service, lost opportunity cost, power market, reactive optimal power flow

## 1. Introduction

In the last decade, various developed countries opened their electricity industries to private enterprises and attempted to improve the efficiency of the total power system through a competitive market. As electric power industries have been moving from regional monopolies to globally unbundled competitive structures, there is a necessity for separately pricing such components of electricity production and delivery as power generation, transmission, distribution, and ancillary services.

Transmission service providers need to know the precise operating costs of providing ancillary services to their customers since the costs vary as a function of time, location, and system status. Calculating the costs of the ancillary services has become one of the most challenging areas to research. This paper deals with an ancillary service of reactive power support and control that is essential for system security and voltage control.

The users of transmission networks were traditionally charged for reactive power service based on power factor penalties. Following deregulation, real-time pricing for reactive power support and control became popular due to its ability to provide information regarding the system costs. Real-time reactive power prices are determined from nodal marginal costs in modified OPF programs [1-3]. This real-time pricing of reactive power can be regarded as the extension of real-time pricing of active power, which is developed in [4]. It has been reported that real-time pricing for reactive power has proved superior to the scheme based on power factor penalties since it can provide all customers with accurate signals to reduce their total reactive power consumption [5].

In the majority of real-time pricing methods, the objective is to minimize the total production costs of active power or its variations. Choi et al. attempts a different concept to evaluate the reactive power charge, which employs the objective function of maximizing social benefit rather than minimizing the generation production cost [6]. The marginal cost of reactive power computed from the OPF program represents the sensitivity of generation production cost with respect to reactive power demand. That marginal cost is so slight and therefore so irrelevant to the fuel cost of generators that it cannot account accurately for the actual reactive power costs.

In order to compensate for the above problem, meanwhile, there exist assertions that reactive power charges should be recovered from both the fixed capital costs associated with reactive power facilities and the operational costs related to the reactive power facility utilization [7-9]. It seems reasonable that an appropriate charging structure for reactive power support should not

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only recover the investment capital costs of reactive power supplying equipment but also present an economic signal for real-time operations since the real-time pricing method is insufficient to recover a significant portion of the reactive power capital costs.

An approach by a reactive power market for procuring reactive power service has recently been presented [10, 11]. Gil et al. propose two different reactive power markets; a reactive energy market based on loss minimization spot prices, which are obtained from the solution of optimal reactive dispatch problems; and a reactive capacity market based on a reactive power regulating capacity to ensure system voltage security [10]. Ahmed and Strbac present a similar arrangement that is based on a combined capacity and utilization based reactive power market, to which a security-constrained reactive optimal power flow (OPF) is applied [11].

This paper examines various methods for reactive power management adopted in several deregulated foreign and domestic markets such as New York, California, England and Wales, and KPX, and then proposes a new method to calculate reactive power service charges using a reactive power market in a wholesale electricity market. Reactive power serving entities will bid for recovering two cost components of the generators supplying reactive power. One is extra costs related to utilize the capacity beyond the obligatory reactive power supply range (0.9 lagging - 0.95 leading) and the other is lost opportunity costs of generators incurred by reducing active power output in order to increase reactive power production. The reactive OPF program is performed to achieve optimal reactive power procurement. Based on the result of the reactive OPF program, the generators that produce reactive power within the obligatory range do not make payments whereas the generators producing reactive power beyond the obligatory range receive compensation by the price determined in the market.

## 2. Foreign and Domestic Cases

### 2.1 New York ISO

Suppliers of reactive power service obtain payments for providing both capacity-related costs and lost opportunity costs (LOC). The embedded cost calculation is used to calculate the capacity-related costs on a resource-specific basis [12]. Suppliers that meet the requirements in the ISO procedures and are under contract to supply installed capacity receive one-twelfth the annual embedded cost payment. Suppliers that are not under contract to provide installed capacity receive one-twelfth the annual embedded cost payment pro-rated by the number of hours that the resources were operated during that month. The annual embedded cost payment includes the annual fixed charge rate associated with resource capital investment, current capital investment of the resource allocated for supplying reactive power service, and the operating and maintenance expenses for supervision and engineering allocated for supplying the service.

A supplier of reactive power service receives a payment for any LOC when the ISO directs him to reduce its actual power output below its schedule to allow production or absorption of additional reactive power. Fig. 1 illustrates the calculation of the LOC and the value is described as follows.

$$LOC = P_{RT}(D_2 - D_1) - \int_{D_1}^{D_2} Bid \tag{1}$$

$P_{RT}$ = real-time market price for electricity
$D_1$ = new dispatch point
$D_2$ = original dispatch point
$Bid$ = bid curve of generator supplying reactive power service

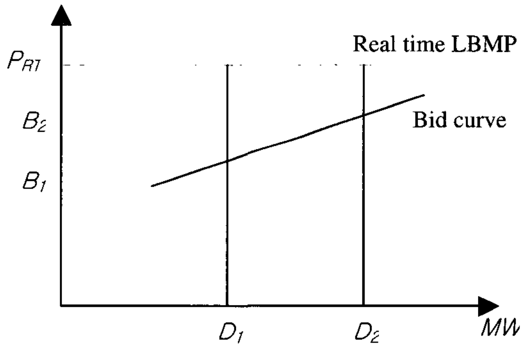

**Fig. 1** Calculation of LOC for a synchronous generator [12]

### 2.2 California ISO

The total number of payments for reactive power service by generators is the sum of the short-term procurement payments and the payments under long-term contract [13].

Short-term payments are made for compensating generators for providing reactive energy output outside of the reactive power support obligation. Generators receive no compensation for operating within the minimum power factor range of 0.9 lagging and 0.95 leading. The ISO determines, on a day-ahead basis, the quantity and location of reactive power support required to maintain voltage levels and reactive margins using a power flow study once the active power market is settled. The short-term payments include the opportunity cost of reducing active power output to enable reactive energy production.

The ISO contracts for long-term reactive power support service with owners of reliability must-run units and the long-term payments are made if the ISO has decreased the output of the must-run units outside of the minimum power factor range.

### 2.3 England & Wales

According to the Grid Code, all generating units greater than 50MW in capacity are required to provide a mandatory reactive power service. This minimum obligation obliges the generators to enter into a Default Payment Mechanism (DPM) or participate in the tender market as per their choice. The DPM initially began with two components such as capability and utilization based payments and is now compensated based only on reactive power utilization [14, 15].

Rather than entering into the DPM, the generators can bid for reactive power service through the tender market. In this market the generators submit bids that are composed of two components; a capability component (\$/MVAr) and a utilization component (\$/MVArh). The capability component submarket receives two types of bid price curves, which are synchronized capability price and available capability price curve, with the synchronized one normally having the higher prices. The utilization component submarket has a similar structure to the capability component except that it has one price curve.

### 2.4 Korea KPX

The reactive power of contracted generating units will be scheduled and dispatched by the KPX (Korea Power Exchange) to ensure that system voltages are maintained within the limits and adequate reactive power reserves are available. Thus, the provision of reactive power will be determined by the availability of reactive power reserve rather than by actual reactive power generation.

The payment for a generating unit providing reactive power service will be based on availability of reactive power reserve while providing active power to the system. This availability charge for each dispatch period is determined by the following equation when the contracted generating unit is available to generate reactive power [16].

$$FC = MVARG*(MTG - MMCG)/12 \qquad (2)$$

When the contracted generating unit is available to absorb reactive power, the equation is as follows.

$$FC = MVARA*(MTA - MMCA)/12 \qquad (3)$$

where MVARG and MVARA are the contracted availability prices per MVAr of reactive power generation and absorption capabilities, MTG and MTA are the maximum MVAr generation and absorption capabilities, and MMCG and MMCA are the minimum capabilities for MVAr generation and absorption required by the Grid Code, respectively.

## 3. Proposed Method using the Reactive Power Market

A new method is proposed to calculate the costs of reactive power service using a reactive power market. Reactive power serving entities will bid for recovering two cost components of the generators supplying reactive power. One is the extra costs related to using the capacity beyond the obligatory reactive power supply range (0.9 lagging - 0.95 leading) and the other is the lost opportunity costs of generators incurred by reducing active power output in order to increase reactive power production.

Fig. 2 shows the typical reactive power capability region of a synchronous generator, surrounded by capability curves. The curves *a-b* and *b-d* represent field winding current limit and armature winding current limit, respectively, and the curve *d-e* denotes field under-excitation limit. According to the figure, the limit of reactive power production depends on its active power output.

This study simplifies the capability curves into the linearized ones so they can be applied easily to market operation. Points *a* and *e* are maximum lagging and leading reactive powers, respectively when producing minimum active power. The other points are intersections of the above capability curves. Point *c* is the maximum active power corresponding to zero reactive power production.

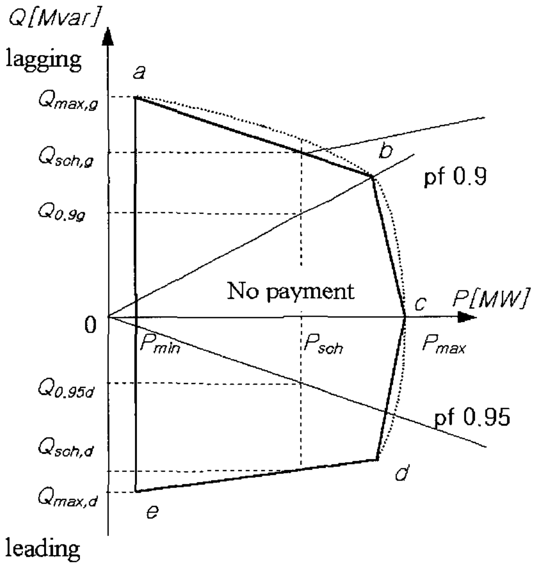

**Fig. 2** A typical reactive power capability region of a generator

All generators producing contracted active power should be equipped with automatic voltage regulators and have a duty to provide reactive power without compensation when operating power factors are within the obligatory range. The cone-shaped region in Fig. 2 represents reactive power output having no payment.

All generators willing to provide reactive power beyond the obligatory range should bid to the system operator and the generators that provide extra reactive power capability receive payment proportional to the reactive power generation.

Next, LOC incurred by generators depends on the result of the day-ahead electricity market. Since basic active power outputs of generators are determined in the day-ahead market, reactive power procurement from generators is also made in the day-ahead electricity market. In this process, any reduction of active power outputs determined in the day-ahead market for increase of reactive power provokes calculation of LOC, as presented in Fig. 1.

The reactive OPF program is performed to achieve optimal reactive power procurement. Fig. 3 demonstrates the cost functions related to reactive power procurement to be applied to the reactive OPF program.

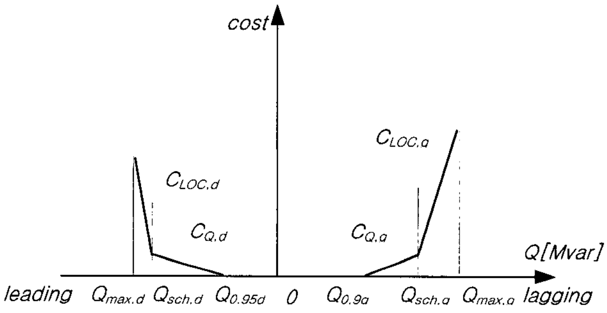

**Fig. 3** Reactive power cost curve for a generator

The slopes $C_Q$ and $C_{LOC}$ are determined by each generator and are its bids. The system operator runs the reactive OPF program using the objective costs of Fig. 3 and constraints of the conventional OPF algorithm. Based on the result of the reactive OPF program, the generators that produce reactive power within the obligatory range do not make payments whereas the generators producing reactive power beyond the obligatory range receive compensation by the price determined in the market.

## 4. Case Study

The proposed algorithm is tested on a 6-bus sample system, which is shown in Fig. 4. The system has 3 generators and 11 branches. The total active and reactive loads are 380MW and 213.71Mvar, respectively, and it is assumed that every generator shall participate in the reactive power market. The lower and upper limits of active and reactive power output at each generator are provided in Table 1.

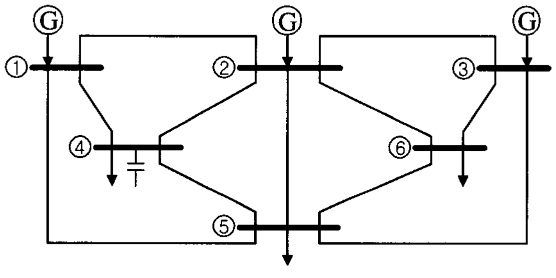

**Fig. 4** 6-bus sample system

**Table 1** Generation range of generators

| Gen | P(MW) | | Q(Mvar) | |
|---|---|---|---|---|
| | min | max | min | max |
| Gen. 1 | 50 | 200 | -100 | 150 |
| Gen. 2 | 37.5 | 170 | -100 | 150 |
| Gen. 3 | 45 | 180 | -100 | 150 |

In order to find the outcome in a day-ahead electricity market, the result of optimal power flow calculations are used in this study. The used cost function of individual generators for active power generation has the form of equation (4) and their coefficients are shown in Table 2.

$$C_i = \alpha_i + \beta_i P_i + \gamma_i P_i^2 \quad (\$/\text{hr}) \qquad (4)$$

As a result of the day-ahead electricity market, Table 3 lists generator schedules and locational marginal costs.

**Table 2** Coefficients of generator cost function

| Gen | $\alpha_i$ | $\beta_i$ | $\gamma_i$ |
|---|---|---|---|
| Gen.1 | 1065.5 | 58.345 | 0.02665 |
| Gen.2 | 1000 | 51.665 | 0.04445 |
| Gen.3 | 1200 | 54.165 | 0.03705 |

Fig. 2 illustrates a typical reactive power capability region and the 6 points of the vertical axis for each generator are calculated and provided in Table 4. Then, the reactive power cost curve shown in Fig. 3 can be constructed using the data from Tables 3 and 4. Reactive capacity costs of 2.4, 2.1 and 2.2 $/Mvar are assumed to be compensating generators 1, 2 and 3, respectively for their reactive power production beyond the reactive obligation. Table 5 lists the coordinates of reactive power cost curves of generators, which reflects both the costs related to additional reactive power production beyond reactive obligation and the lost opportunity costs. For calculating the slope of $C_{LOC}$, active power bid prices of 60, 63 and 64 \$/MW are used for calculating the LOC of generators 1, 2 and 3, respectively.

**Table 3** Generator schedules of the day-ahead electricity market

| Gen | $P_{sch}$(MW) | locational marginal price (\$/MW-hr) |
|---|---|---|
| Gen.1 | 109.14 | 64.162 |
| Gen.2 | 144.15 | 64.480 |
| Gen.3 | 141.50 | 64.650 |

**Table 4** Reactive values describing reactive power capability regions of generators

| Gen | $Q_{max,d}$ | $Q_{sch,d}$ | $Q_{0.95d}$ | $Q_{0.9g}$ | $Q_{sch,g}$ | $Q_{max,g}$ |
|---|---|---|---|---|---|---|
| Gen.1 | -100 | -94.17 | -35.87 | 52.86 | 121.42 | 150 |
| Gen.2 | -100 | -76.09 | -47.38 | 69.82 | 79.92 | 150 |
| Gen.3 | -100 | -82.23 | -46.51 | 68.53 | 90.99 | 150 |

A reactive OPF program is executed using the data in Table 5 program results of which are listed in Table 6. The service costs for generators are calculated by multiplying ($Q_{sch}$-$Q_{0.9g}$) by the market price. The table provides the market price of reactive service, day-ahead reactive power schedules and reactive service costs of generators.

**Table 5** Coordinates of reactive power cost curves of generators

| Gen | $Q_{max,d}$ | *\$/hr* | $Q_{sch,d}$ | *\$/hr* |
|---|---|---|---|---|
| Gen.1 | -100 | 478.88 | -94.17 | 139.91 |
| Gen.2 | -100 | 697.14 | -76.09 | 60.28 |
| Gen.3 | -100 | 431.33 | -82.23 | 78.60 |
| Gen | $Q_{0.95d}$ | *\$/hr* | $Q_{0.9g}$ | *\$/hr* |
| Gen.1 | -35.87 | 0 | 52.86 | 0 |
| Gen.2 | -47.38 | 0 | 69.82 | 0 |
| Gen.3 | -46.51 | 0 | 68.53 | 0 |
| Gen | $Q_{sch,g}$ | *\$/hr* | $Q_{max,g}$ | *\$/hr* |
| Gen.1 | 121.42 | 164.55 | 150 | 558.11 |
| Gen.2 | 79.92 | 21.21 | 150 | 755.03 |
| Gen.3 | 90.99 | 49.42 | 150 | 492.88 |

**Table 6** Reactive power schedules of generators

| Gen | $Q_{sch}$(Mvar) | service cost (\$/hr) | market price (\$/Mvar-hr) |
|---|---|---|---|
| 1 | 52.86 | - | 2.2 |
| 2 | 71.45 | 3.586 | 2.2 |
| 3 | 77.36 | 19.426 | 2.2 |

## 5. Conclusion

With electric power industries moving from regional monopolies to competition modes, it has become necessary to calculate accurate costs of ancillary services. This paper dealt with an ancillary service of calculating reactive power service charges. First, we examined various methods for reactive power management adopted in some deregulated foreign and domestic markets such as New York, California, England and Wales, and KPX. Next, a practical method based on a reactive market for calculating charges of reactive power service is proposed.

Only synchronous generators and synchronous condensers are entitled to provide reactive power ancillary service, and all generators are required to be equipped with automatic voltage regulators. The reactive power market is operated based on bids from generating sources and determines uniform prices by running reactive OPF programs emulating the day-ahead electricity market. The proposed method takes into account recovering not only the costs of installed capacity but also the lost opportunity costs incurred by reducing active power output to increase reactive power production. The settlement of this reactive power market is dependent on the day-ahead electricity market and this is well-suited with the nature that reactive power is a supplement to active power transmission. A numerical sample study is carried out to illustrate the processes and appropriateness of the proposed method.

The proposed method contributes the system operators to calculate an ancillary service cost of reactive power management and makes power markets active in offering reactive power charges under power system deregulation.

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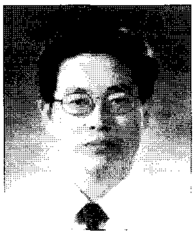

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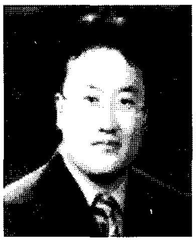

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