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무효전력시장을 이용한 무효전력서비스 요금 산정방법의 비교 및 새로운 방안

(Comparison of Methods for Calculating Reactive Power Service Charge and Proposing a New Method using Reactive Power Markets)

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요 약

전력산업이 수직독점적인 구조에서 규제완화의 경쟁체제로 전환됨에 따라 무효전력서비스의 요금산정이 전력시장 운영자에게는 새로운 이슈가 되고 있다. 본 논문은 몇몇의 선진국과 국내에서 채용되는 무효전력서비스에 대한 요금산정방법을 검토하고, 무효전력시장을 이용하는 새로운 요금산정방법을 제안한다. 무효전력시장은 무효전력 발전원이 제시하는 입찰값을 바탕으로 하루전 전력시장 후에 무효전력 최적조류계산을 거쳐 단일가격으로 결정된다. 제안하는 방법은 무효전력 설치용량에 대한 투자비뿐만 아니라 무효전력 생산량을 늘리기 위해 발전기가 줄이게 되는 유효전력에 대한 기회비용을 함께 고려하고 있다. 26모선 모델계통에서의 사례연구를 통하여 제안하는 방법의 효용성을 입증하고 있다.

Abstract

As electric power systems have been moving from a vertically integrated structure to a deregulated environment, calculating reactive power service charges is a new challenging theme for market operators. This paper examines various methods for reactive power management adopted in some deregulated foreign and domestic markets and then proposes a new method to calculate reactive power service charges using a reactive power market. The reactive power market is operated based on bids from the generating sources and is settled on uniform prices by running reactive OPF programs after 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. A numerical sample study is carried out to illustrate the processes and appropriateness of the proposed method.

Key Words : Reactive power market, Reactive optimal power flow, Lost opportunity cost

1. Introduction

As electric power industries have been moving

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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.

The users of transmission networks were traditionally charged for reactive power service based on power factor penalties. After deregulation, real-time pricing for reactive power support and control became popular due to its ability to provide information about the system cost. Real-time reactive power prices are determined from nodal marginal costs in modified OPF programs[1]. This real-time pricing of reactive power can be regarded as the extension of real-time pricing of active power, which is developed in[2].

In most of the 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 uses the objective function of maximizing social benefit instead of minimizing the generation production cost[3].

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[4-5]. It seems reasonable that an appropriate charging structure for reactive power support should not only recover the investment capital costs of reactive power supplying equipment but also present an economic signal for real-time operations since real-time pricing method is not enough to recover the large portion of reactive power capital costs.

An approach of a reactive power market for procuring reactive power service has recently been presented[6]. Gil et al. propose two different reactive power markets such as a reactive energy market based on losses minimization spot prices, which are obtained from the solution of optimal reactive dispatch problem and a reactive capacity market based on a reactive power regulating capacity to ensure system voltage security[6].

This paper examines various methods for reactive power management adopted in some deregulated foreign and domestic markets such as California, England and Wales, and KPX, and then proposes a new method to calculate reactive power service using a reactive power market.

2. Comparison of some utility cases

This section describes examinations of various methods for reactive power service charges adopted in some deregulated markets such as California, England and Wales, and Korea KPX and then presents a comparison of those methods.

2.1 California ISO

The total payments for reactive power service by generators are the sum of the short-term procurement payments and the payments under long-term contracts[7].

Short-term payments are made for compensating generators for providing reactive energy output outside 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 after 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 the minimum power factor range.

2.2 England and Wales

According to the Grid Code, all generating units more than 50[MW] capacity are required to provide a mandatory reactive power service. This minimum obligation makes the generators enter into a Default Payment Mechanism (DPM) or participate in the tender market as their choices. The DPM started with two components like a capability and utilization based payments and now is compensated based only on the reactive power utilization[8-9].

Instead of 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 of capability component ($/MVAr) and utilization component ($/MVArh). The capability component submarket gets two types of bid price curves of synchronized capability price and available capability price curve, normally synchronized one having higher prices. The utilization component submarket has similar structure as the capability component except it has one price curve.

2.3 Korea KPX

Reactive power of contracted generating units will be scheduled and dispatched by 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 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[10].

$$FC = MVARG*(MTG - MMCG)/12 \qquad (1)$$

Or when the contracted generating unit is available to absorb reactive power it is as follows.

$$FC = MVARA*(MTA - MMCA)/12 \qquad (2)$$

where MVARG/MVARA is the availability price per MVar of reactive power generation/absorption capability, MTG/MTA is the maximum reactive power generation/absorption capability, and MMCG/MMCA is the minimum capability for MVar generation/absorption required.

2.4 Comparison of above methods

Table 1 shows a summary of comparison of the methods for calculating reactive power service charges presented in the previous clauses. First of all, the units applied to the reactive power ancillary service are almost same for the three cases, but the computation principles are entirely different. California ISO pays them for long-term contracts with reliability must-run units and short-term reactive power market on a day-ahead basis. On the other hand, in the case of England and Wales the all generating units should enter into a DPM based on reactive power utilization or participate in the tender markets for capability and

Table 1. Comparison of several methods for reactive power service charges

	California	England/Wales	KPX
applied units	generators and synchronous condensers	generators and synchronous condensers	generators and synchronous condensers determined by availability of reactive power reserve
computation principle	long-term contract + day-ahead reactive power market	payment based on reactive utilization or tender market for capability and utilization	capacity availability of reactive power reserve
PF range of no compensation	0.9 lagging - 0.95 leading	none	0.484Pmax lagging - 0.329Pmax leading

utilization components. In Korea KPX, the service charge is capacity-related, so the contracted units are paid based on the availability of reactive power reserve.

Next, such markets as England/Wales have no descriptions for power factor range of compensation for operating units whereas California ISO and KPX designate the power factor range and reactive power production range of no compensation, respectively.

3. Proposed method using reactive power market

A new method is proposed to calculate 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 extra costs related to use the capacity beyond the obligatory reactive power supply range (0.9 lagging - 0.95 leading) and the other is lost opportunity costs (LOC) of generators incurred by reducing active power output in order to increase reactive power production.

Fig. 1 shows a typical reactive power capability region of a synchronous generator, surrounded by capability curves. The curve 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.

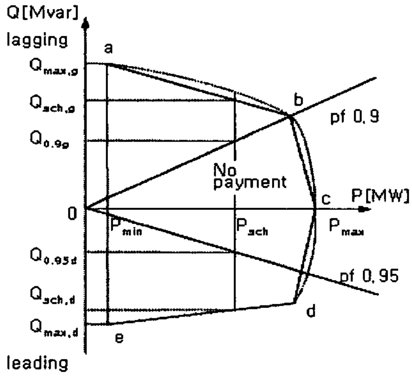

Fig. 1. A typical reactive power capability region of a generator

This study simplifies the capability curves into the linearized ones to 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.

All generators producing contracted active power should equip with automatic voltage regulators and have a duty to provide reactive power without compensation when power factors are within the obligatory range. The cone-shaped region in Fig. 1 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 get received payment proportional to the reactive power generation.

Next, LOC incurred by generators depends on the result of a day-ahead electricity market. Since basic active power outputs of generators are determined in the day-ahead market, reactive power procurement from generators is made after 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.

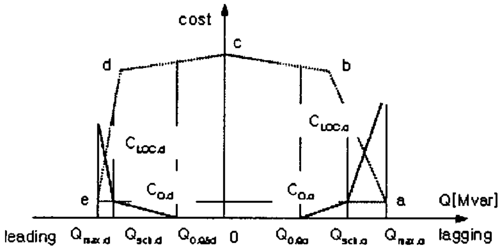

Fig. 2. Reactive power cost curve

Reactive OPF program is performed to achieve optimal reactive power procurement. Fig. 2 shows cost functions related to reactive power procurement to be applied to the reactive OPF program. The slopes CQ and CLOC are determined by each generator and are its bids. Based on the result of the reactive OPF program, the generators that produce reactive power within the obligatory range do not have payment whereas the generators producing reactive power beyond the obligatory range get compensation by the price determined in the market.

4. Case study

The proposed algorithm is tested on a 26-bus sample system, which is shown in Fig. 3. The system has 6 generators and 46 branches. The total active and reactive loads are 1263MW and 702Mvar, 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 given in Table 2.

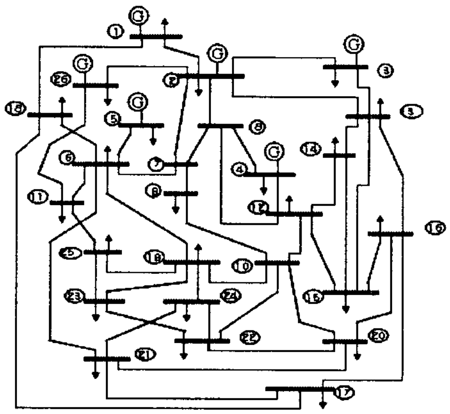

Fig. 3. 26-bus sample power system

Table 2. Generation range of generators

Gen	P(MW)		Q(Mvar)	
	min	max	min	max
Gen. 1	100	500	-300	375
Gen. 2	50	250	-150	187.5
Gen. 3	80	300	-180	225
Gen. 4	50	220	-132	165
Gen. 5	70	300	-180	225
Gen.26	20	150	-90	112.5

In order to get the outcome of a day-ahead electricity market, the result of optimal power flow calculations are used in this study.

The used cost function of individual generator for active power generation has the form of equation (3) and their coefficients are shown in Table 3.

$$C_i = \alpha_i + \beta_i P_i + \gamma_i P_i^2 \quad (\$/\text{hr}) \tag{3}$$

Table 3. Coefficients of generator cost function

Gen	α_i	β_i	γ_i
Gen. 1	1045.11	43.054	0.02112
Gen. 2	927.95	48.621	0.03704
Gen. 3	994.88	47.354	0.03016
Gen. 4	887.92	51.241	0.03828
Gen. 5	950.00	44.547	0.02955
Gen.26	833.33	52.791	0.04078

As a result of the day-ahead electricity market, Table 4 lists generator schedules and locational marginal costs.

Fig. 1 illustrated a typical reactive power capability region and the 6 points of the vertical axis for each generator are calculated and given in Table 5. Then, reactive power cost curve shown in Fig. 2 can be constructed using the data of Tables 4 and 5. Reactive capacity costs of 2.5, 2.2, 2.3, 2.4, 2.1 and 2.3 $/Mvar are assumed to be compensating generators 1, 2, 3, 4, 5 and 26, respectively for their reactive power production beyond the reactive obligation. Table 6 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 CLOC, active power bid prices of 60, 61, 63, 62, 59 and 60 $/MW are used for calculating the LOC of generators 1, 2, 3, 4, 5 and 26, respectively.

A reactive OPF program is executed using the data of Table 6 and the program results are listed in Table 7. The table gives the market price of reactive service, day-ahead reactive power schedules and reactive service costs of generators.

Table 4. Generator schedules after day-ahead electricity market

Gen	Psch(MW)	locational marginal price ($/MW-hr)
Gen. 1	394.06	59.699
Gen. 2	149.59	59.703
Gen. 3	258.68	62.958
Gen. 4	135.53	61.617
Gen. 5	239.49	58.701
Gen.26	96.98	60.701

Table 5. Reactive values describing reactive power capability regions of generators

Gen	Qmax,d	Qsch,d	Q0.95d	Q0.9g	Qsch,g	Qmax,g
Gen.1	-300	-231.06	-129.52	190.85	243.05	375
Gen.2	-150	-126.65	-49.17	72.45	142.81	187.5
Gen.3	-180	-133.70	-85.02	125.28	136.38	225
Gen.4	-132	-111.14	-44.55	65.64	125.06	165
Gen.5	-180	-138.28	-78.72	115.99	145.14	225
Gen.26	-90	-73.52	-31.88	46.97	80.96	112.5

Table 6. Coordinates of reactive power cost curves of generators

Gen	Qmax,d	$/h	Qsch,d	$/h	Q0.95d	$/h	Q0.9g	$/h	Qsch,g	$/h	Qmax,g	$/h
Gen. 1	-300	3620.06	-231.06	253.85	-129.52	0	190.85	0	243.05	130.49	375	3654.23
Gen. 2	-150	952.57	-126.65	170.46	-49.17	0	72.45	0	142.81	154.79	187.5	983.85
Gen. 3	-180	1185.15	-133.70	111.96	-85.02	0	125.28	0	136.38	25.52	225	1196.05
Gen. 4	-132	634.62	-111.14	159.81	-44.55	0	65.64	0	125.06	142.62	165	663.19
Gen. 5	-180	2103.89	-138.28	125.08	-78.72	0	115.99	0	145.14	61.22	225	2120.12
Gen.26	-90	694.79	-73.52	95.79	-31.88	0	46.97	0	80.96	78.18	112.5	711.82

Table 7.Reactive power schedule of generators

Gen	Qsch (Mvar)	service cost ($/h)	market price ($/Mvar-h)
1	190.85	-	2.3
2	142.81	161.83	2.3
3	136.38	25.53	2.3
4	65.64	-	2.3
5	120.45	10.26	2.3
26	56.44	21.78	2.3
Total	712.57	219.4	

5. Conclusion

This paper dealt with an ancillary service of calculating reactive power service charges. First, we have examined various methods for reactive power management adopted in some deregulated foreign and domestic markets such as California, England and Wales, and KPX. Next, a practical method based on a reactive market for calculating charges of reactive power service is proposed.

The reactive power market is operated based on bids from the generating sources and is settled on uniform prices by running reactive OPF programs after 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.

References

[1] A. A. El-keib, X. Ma, Calculating Short-Run Marginal Costs of Active and Reactive Power Production, IEEE Trans on Power Systems 12 (1997) 559-565.
[2] M. C. Caramanis, R. E. Bohn, F. C. Schweppe, The Costs of Wheeling and Optimal Wheeling Rates, IEEE Trans on Power Systems 1 (1986) 63-73.
[3] J. Y. Choi, S. H. Rim, J. K. Park, Optimal Real Time Pricing of Real and Reactive Powers, IEEE Trans on Power Systems 13 (1998) 1226-1231.
[4] K. Ro, S. Park, A Method to Calculate Charge for Reactive Power Service under Competition of Electric Power Utilities, KIEE International Trans on Power Engineering 11A (2001) 39-44.
[5] J. W. Lamont, J. Fu, Cost Analysis of Reactive Power Support, IEEE Trans on Power Systems 14 (1999) 890-898.
[6] J. B. Gil, T. G. San Roman, J. J. Alba Rios, P. S. Martin, Reactive Power Pricing: A Conceptual Framework for Remuneration and Charging Procedures, IEEE Trans on Power Systems 15 (2000) 483-489.
[7] California Independent System Operator Corporation, Ancillary services requirement protocol, FERC Electricity Tariff (2000).
[8] National Grid Company, An introduction to reactive power: Ancillary Services (1998).
[9] National Grid Company, NGC reactive market report (2000).
[10] Korea Power Exchange, Ancillary Services Agreement-Technical Schedules (2002).

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