A Pricing Mechanism for Network Reactive Power Devices in Competitive Market

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***Abstract*— In this paper, a pricing mechanism is proposed for network reactive power compensation devices in competitive markets. The cost components of network devices are examined in the paper. In the proposed market, network device owners offer the prices for supplying or absorbing reactive power. The market model is settled on uniform market prices. In the study cases, the issues of market power are analyzed and some useful conclusions are obtained for the consideration of establishing a market mechanism for network reactive power devices.**

***Index Terms*—Electricity market, market power, network reactive power devices, reactive power, reactive power pricing.**

I. INTRODUCTION

IN power systems, sufficient reactive power need to be provided in order to maintain the power flow limits on transmission lines and voltage limits at bus bars. Unable to meet the demand of reactive power may cause the drop of voltages. The reactive power supply, as well as active power, is important and there is a cost associated with this supply. The issues about reactive power pricing mechanisms have been discussed since a long time ago. Among existing reactive power pricing methods, approach considering nodal marginal costs are proposed in [1,2,3]. In the approach, the nodal marginal cost is defined as the sensitivity of the generation cost to the reactive power demand. This pricing instrument represent operating cost – that associated with fuel costs of real power. Nodal pricing methods can motivate new reactive power investment in high-demand areas. In [4], authors have provided a comprehensive analysis of various costs incurred by providing reactive power. The costs include capital costs, variable costs and opportunity costs. In [5], the authors presented some factors that will affect the management and pricing of reactive power. Two pricing structures are proposed base on performance requirements and local market concept, respectively.

In the current deregulated electricity markets, reactive power management and payment mechanisms vary for different markets. However, a fully competitive reactive power market has yet to emerge. At the current stage, reactive power provided by generators is financially compensated in some electricity markets. To establish a competitive reactive power market, it is required that both generators and network devices are included in the market as market participants for reactive power provision. As well as reactive power provided by generators, the reactive power provided by network devices should also be financially compensated for their services.

From the technical point view, since reactive power cannot be transmitted over a long distance, it should be provided locally according to the availability of reactive power support devices. In most systems, network devices are used for maintaining voltages and the responsibility for managing reactive power lies with individual local network companies. The network reactive power devices are usually not paid for their reactive power provision. A good pricing mechanism reflecting the investment costs and operating costs of these devices would encourage network companies to put more efforts on maintaining bus voltages.

From the market point view, limited reactive power service providers in a control area may lead to the market power problem. A few generators located at strategic locations may have the power for gaming in the market. The market power in a reactive power market can be mitigated or eliminated by extending the number of participants in the reactive power market. A well-designed reactive power pricing mechanism for network devices will help to attract more participants to reactive power market. A good pricing mechanism will also encourage independent transmission companies to plan, install and operate reactive power compensation devices.

In this paper, we will examine the cost components of network devices and propose a pricing mechanism for the reactive power services provided by network devices. In Section II the cost components for different reactive power devices are analyzed. In Section III, a reactive power settlement model is proposed to procure reactive power support service from both network devices and generators at uniform market prices. In Section IV, a case study with Cigre-32 bus system is presented to test the market settlement, and the market power problems are also analyzed for the test system. Some conclusions are given in Section V.

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II. COSTS OF REACTIVE POWER SUPPORT

Generating equipment and transmission network devices are the two sources of reactive power support. Generation sources include synchronous generators and synchronous condensers. Transmission network sources include capacitor banks, reactors, static VAr compensators (SVCs), etc. In some systems, reactive power supplied by generators is classified as one of the ancillary services provided by generation companies, while the reactive power supplied by transmission devices is classified as one of the transmission services provided by network companies.

Reactive power equipment in a power system have different characteristics in terms of dynamics and speed of response, ability of voltage changes, capital costs, operating costs and opportunity costs. For example, synchronous generators are very fast reactive power support devices, but have high operating and opportunity costs. Capacitor banks are slow and have poor performance but are cheap to install and operate. Static VAR compensators have fast response speed, but the ability to support voltages is poor and drops with the square value of voltage. The cost for Static VAR compensators is between that for generators and capacitors. Usually, capacity banks provide base requirement of reactive power, and the capacities of other fast equipment are reserved for further reactive power needs. In the following subsections, we will analysis the costs of reactive power provided from different sources.

A. Costs of reactive power support from generators

The cost for a generator to provide reactive power can be divided into three cost components: availability cost, operating cost and opportunity cost.

The capacity of a generator is used to produce not only active power, but also reactive power. Therefore, the capital cost of a generator should be considered in reactive power cost analysis as well as in real power cost analysis. Here, the term *availability cost component* of reactive power represents the capital cost of the generator capacity used to produce reactive power.

When a generator provides or absorbs reactive power, the real power losses in field windings will increase. The cost of increased real power losses is the *operating cost component* of reactive power provision. Unlike the fuel costs that represent the operating cost of active power production, operating cost for reactive power support is small.

The capability of a synchronous generator to supply or absorb reactive power is restricted by its capacity constraints, which are armature current limit, field current limit and underexcitation limit [6]. If the generator operates on the limiting curve, any increase in Q will require a decrease in P to satisfy the winding heating limits. This means that the unit has to reduce its real power output when higher reactive power output is required. The loss of revenue due to the reduction of real power is termed as *opportunity cost* for providing reactive power [7]. Opportunity cost is a significant issue in reactive power cost analysis. In the electricity markets of New York and Australia, opportunity costs of reactive power are financially compensated to generators in case of revenue lost due to the requests of increasing reactive power.

B. Costs of reactive power support from transmission devices

Transmission network devices, such as capacitor banks and SVCs, are usually required to control voltages through the network. Different devices act in different ways for voltage control and reactive power support. In transmission or distribution networks, when reactive power compensation is required, shunt capacitors and reactors are connected or switched to the system. These devices provide reactive power by modifying the network characteristics. On the other hand, SVCs supply or absorb reactive power automatically to maintain voltage levels when it is needed.

The reactive power costs from capacitor banks are mainly due to the capital costs and operating costs of the devices. The operating costs are often with small values. Since capacitor banks are switchable devices and have limited numbers of switching operations, each switching operation corresponds to a depreciated capital cost [5]. We can see that capital cost is the main portion of the total cost of providing reactive power from a capacitor bank.

Compare to capacitor banks, SVCs have better regulating characteristics and faster response speeds following a disturbance. Because of their fast response speed, SVCs are more effective than capacitors for preventing transient voltage instability. In steady-state conditions, SVCs are used to maintain the desired output, say, Q_{set}, which is often set to be close to floating output so that rapid capacitive boost is available for disturbances [8]. On the other hand, SVCs are more expensive than capacitor banks. A good way of voltage control for a network company is to have a mixture of reactive power facilities with both capacitor banks and SVCs. Shunt capacitors can be used first to satisfy unity power factor operation of nearby generators, then, some SVC capabilities are reserved for system disturbances.

In [8], some cost data is provided for reactive power compensation equipment in an existing substation. It shows that, the installation costs of shunt capacitors depend on voltage levels, and there is not much difference in operating costs for capacitors with different voltage levels. The operating costs of SVCs are around 10 times bigger than that of shunt capacitors. The installation costs of SVCs relate to many factors, such as configuration and complexity of the SVC system.

III. REACTIVE POWER MARKET MODEL

In our previous work [7, 9, 10], some market issues about reactive power provided by generators have been studied. A reactive power procurement method is proposed in [7] to maximize the societal advantages considering generators' reactive power bids and sensitive factors. In [9], a market model for reactive power provided by generators has been proposed. In the model, only generators are paid for their reactive power support services. Reactive power cost of a generator is composed of three components: availability cost, operating cost, and the opportunity cost. Corresponding to the three cost components, generators bid for availability payment, operation payment and opportunity payment. In the localized reactive power market for generators that we proposed in [10], we noticed that there are a few strategic buses in a control area where a reactive power provider will have immense market power.

In this section, we will propose a reactive power market, in which network devices are also included as market participants and are paid for their reactive power support services. Furthermore, we will discuss the issues of mitigating and eliminating market power in a local reactive power market by extending market participants.

A. Reactive power bidding for network devices

In deregulated electricity markets, the ISO might not know the cost information of all reactive power equipment. To establish a reactive power payment mechanism, an option is to call for bids from all market participants willing to provide reactive power.

As discussed in Section II, the reactive power costs for network devices comprise capital cost components and operating cost components. The operating costs for network devices are small compare to capital costs. The capital costs for static var compensation systems and capacitor banks are different. Normally, it is more expensive to build static VAr systems than install capacitor banks.

We propose a two-part bidding structure for network devices. Corresponding to the capital cost components and operating cost components, network devices bid for availability payment b_i and operating prices v_i for the quantities of reactive power supplied or absorbed from the system. The bidding structure is shown as in Fig. 1.

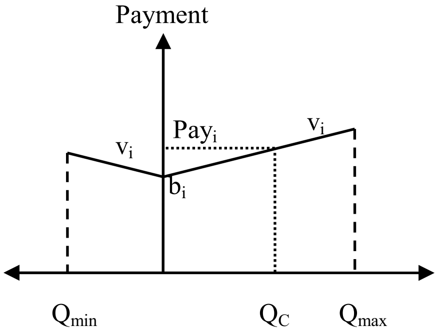

Fig. 1. Reactive power bidding structure for transmission network devices.

As shown in Fig. 1, device owners bid for both supplying and absorbing reactive power. If a device *'i'* is selected for reactive power support, it will be paid for the availability payment b_i plus the operating payment $v_i*Q_{C,i}$, where $Q_{C,i}$ is the quantity of reactive power supplied. Thus, by providing $Q_{C,i}$, device *'i'* ask for a payment Pay_i as following:

$$Pay_i = b_i + v_i * Q_{C,i}$$

We should note that the availability payment represents the capital costs of devices. Capital cost is an annualized number and it is further divided into a day's or an hour's scale.

B. Market settlement model

In a competitive reactive power market, the owners of transmission network devices and generators are the participants of the market. In the market, both generators and network companies submit their price offers to the ISO for reactive power provisions. Generators submit their three-part offer prices base on availability payment, operating payment and opportunity payment [9]. Network companies submit price offers for their devices base on availability payment and operating payment, which has been discussed in Section III-A. The ISO will calculate uniform market prices for generators and network devices base on all offer prices and reactive power requirement. The market uniform prices are obtained for generators and network devices, separately. The market participants are paid with the uniform prices.

We propose an OPF based optimization approach for market settlement. The objective of the approach is to minimize the total payment to generators and network companies. The reactive power market settlement is subject to network constraints.

1) Objective function

The objective is to obtain the uniform market prices to minimize the total payment to generators and network companies.

$$\text{Minimize } \sum_{i\in cap} CapPay_i + \sum_{j\in gen} GenPay_j \qquad (1)$$

Where,

i, j	index for buses
cap	index for network VAr device at a bus
gen	index for generator at a bus
CapPay	payment for network device
GanPay	payment for generator

The payment for network devices *i*, $CapPay_i$, includes two components, availability payment and operating payment, as shown in (2).

$$\sum_{i\in cap} CapPay_i = \sum_{i\in cap} (\rho_{c0} + \rho_{c1} QC_i) \qquad (2)$$

In (2), ρ_{c0} and ρ_{c1} are the uniform availability price and uniform operating price, respectively, obtained for the capacitors and SVCs in the network. The uniform prices are decided by the offer prices of the last device being selected to satisfy reactive power requirement. If a device is selected to provide reactive power, it will be paid for uniform availability payment. In addition, operating payment will be paid for the supplied quantity of reactive power at the uniform operating price.

The second term in (1) is the payment for generators for their reactive power provision. It is described as (3). The payment to generators shall depend on the market price of the three components of reactive power, being offered by the providers. Reactive power output from a generator is classified into three components: Q_1, Q_2 or Q_3, in corresponding to availability payment, operating payment and opportunity payment respectively. Accordingly, only one of the binary variables W_2 and W_3 can be selected. In (3), ρ_{g1} is the *uniform availability price*, ρ_{g2} is the *uniform operating* *cost* while ρ_{g3} is the *uniform opportunity price*. If a provider is selected, W_1 will be 1 and it will receive the availability price irrespective of its reactive power output.

$$\sum_{j\in gen} GenPay_j = \sum_{j\in gen}(\rho_{g1}\cdot W_{1,j} + \rho_{g2}\cdot W_{2,j}\cdot Q_{2,j} + \rho_{g2}\cdot W_{3,j}\cdot Q_{A,j} + \frac{1}{2}\rho_{g3}\cdot W_{3,j}\cdot Q_{3,j}^2) \qquad (3)$$

The principle of highest-priced offer selected determining the market price, is applied with additional system constraints. The system constraints are as follows:

2) Constraints

- Load flow constraints

$$PG_i - PD_i = \sum_j V_i V_j Y_{ij}\cos(\theta_{ij} + \delta_j - \delta_i) \qquad (4)$$

$$QG_i + QC_i - QD_i = -\sum_j V_i V_j Y_{ij}\sin(\theta_{ij} + \delta_j - \delta_i) \qquad (5)$$

PG	real power generation at a bus.
QG	Reactive power support by generator at a bus.
QC	Reactive support from network devices at a bus.
PD	real power demand at a bus.
QD	Reactive power demand at a bus.
V	Voltage at a bus
Y	Element of network admittance matrix
θ	Angle associated with Y

- Reactive power limits for network devices:

$$QC_{Min,i} \le QC_i \le QC_{\max,i} \qquad (6)$$

- Reactive power constraints for generators

$$QG_i = Q_{2i} + Q_{3i} \qquad (7)$$

- Determining the uniform market prices for network devices:

  The following constraints ensure that the market prices ρ_{c0} and ρ_{c1} equal to the highest offer price that has been accepted.

$$U_i \cdot b_i \le \rho_{c0} \qquad (8)$$

$$U_i \cdot v_i \le \rho_{c1} \qquad (9)$$

  Where, U_i is an integer variable. If the device at bus i is selected to provide reactive power, U_i=1. Otherwise, U_i=0.

- Market price limits for generators

$$W_{1,i} \cdot a_{1,i} \le \rho_1 \qquad (10)$$

$$\left(W_{2,i} + W_{3,i}\right)\cdot m_{2,i} \le \rho_2 \qquad (11)$$

$$W_{3,i} \cdot m_{3,i} \le \rho_3 \qquad (12)$$

$$W_{1,i} = W_{2,i} + W_{3,i} \qquad \forall\, i \in gen \qquad (13)$$

  Where, a_1 is the availability price offer of generator, m_1 is the operating price offer, and m_3Q is the opportunity price offer [9].

- Reactive power limits for generators
- Bus voltage limits

IV. CASE STUDY

The Cigre 32-bus test system is used to examine the proposed market settlement. As reactive power market is a local market, the system is separated into three local control areas according to electrical distance, as shown in Fig. 2 [10]. We have found in [10] that there are some strategic buses in Zone A. The generators located on the strategic buses held market power to raise the uniform market prices of Zone A.

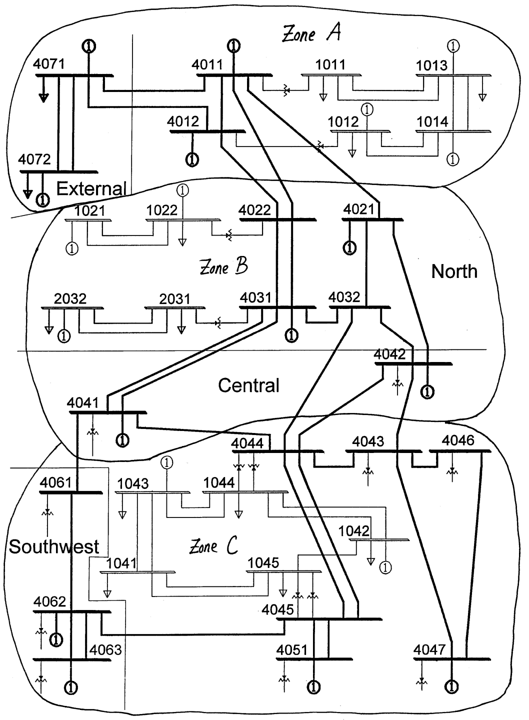

Fig. 2. CIGRE 32-bus test system network configuration.

In this section, we will first test the proposed reactive power market settlement for network devices and generators. Then, we will examine the effect of market power mitigations by introducing more network devices to reactive power market. Four study cases are simulated to examine the proposed reactive power market.

A. Base case

In the base case, only generators are paid for their reactive power support services. With the system shown in Fig. 2, uniform market prices are obtained for generators in Zone A, Zone B and Zone C, respectively. The brief simulation results are shown as in Table I. The second row of the table gives the payment to Zone A, B and C respectively. The third and forth rows show whether market power exist in a zone and which generator held market power. It is found in the base case that generator on bus "4072" held market power in Zone A. That means, Zone A has to buy reactive power from generator "4072" even if the generator offer a high price, thus the uniform prices of Zone A are raised by generator "4072".

TABLE I
BASE CASE

Zone	A	B	C
Payment for each zone	19.78	4.29	2.07
Market power exists?	Yes	No	No
The generator that hold market power	Bus 4072	—	—

B. Case-1:add more network devices to eliminate market power

In this case, we add more reactive power providers to examine the possibility of eliminating market power. Assume that additional network VAr devices are installed on bus "4071", "4012", "4021" and "4042". In this study case, the network VAr devices are assumed providing free reactive power, and there is no payment for network devices. The followings are found in the simulation. The generator on bus "4072" no longer has market power. In the simulation, if the offer price of generator "4072" increases, generator "1013" will replace "4072" and become new price setter. If the offer price of "1013" increase, generator "4011" will be price setter. We can find that no generator held market power after introducing more VAr devices to provide reactive power.

The obtained reactive power scheme for network device on each bus is given in the fifth column of Table III.

C. Case-2 and Case-3

In Case-2, some numbers within a given range are used to represent the offer prices of availability price b_i and operating price v_i. The offer prices are shown in the third and fourth column of Table III. The information about payment and market power of Case-2 is given in Table II. Compare Table II with Table I, we can see that the market power in Zone A is eliminated by introducing network devices into reactive power market. The payment to Zone A is reduced significantly, and the payments to zone B and Zone C keep the similar level.

TABLE II
CASE-2

Zone	A	B	C
Total payment	4.25	4.84	2.92
Market power exists?	No	No	No

In Case-3, we reduce the value of b_i to 1/5 of that in Case-2 to test the situations with different availability offer prices. The reactive power schemes of network devices obtained from Case-1, Case-2 and Case-3 are listed in the 5th, 6th and 7th column of Table III, respectively.

From Table III, we can find the following:

- In Zone A, Zone B and Zone C, those devices with lower offer prices have the priorities to be selected. The amount of reactive power scheduled for a device will decrease when its offer price increase.
- In Zone B and Zone C, the reactive power schemes and selections for network devices don't change much with offer prices change, because these two zones have sufficient balanced reactive power sources.
- In Zone A, reactive power supplied by network devices can help to eliminate market power. If a network device offer higher price, it may not be selected by the market.

TABLE III
OFFER PRICES AND REACTIVE POWER SCHEMES FOR CASE-1, CASE-2 AND CASE-3

	Device on bus i	Offer bids		Reactive power		
		bi	vi	Case-1	Case-2	Case-3
Zone A	4071	0.49	0.11	0.25	0	0.26*
	4012	0.75	0.18	1.00	0	0
	1013	0.51	0.07	1.01	1.01*	1.01
Zone B	4021	0.59	0.22	0	0	0
	4042	0.53	0.19	0.58	1.00	1.00
	1022	0.56	0.11	0.50	0.50	0.50
	1021	0.84	0.30	0	0	0
Zone C	4051	0.66	0.16	1.00	1.00	1.00
	1043	0.82	0.20	0.27	0.18	0.18
	4043	0.86	0.33	2.00	1.14	1.11
	4046	0.50	0.10	1.00	1.00	1.00
	1041	0.84	0.17	1.13	0.52	0.51
	1044	0.55	0.21	2.00	2.00	2.00
	1045	0.61	0.22	1.21	1.23	1.23

V. DISCUSSIONS

From the results of above case studies, we consider to classify control areas according to their VAr sufficiency into two types: *VAr balanced areas* and *VAr unbalanced areas*. The two types of areas can be defined as following: a) For a *VAr balanced area*, sufficient reactive power sources are located reasonably within the area. The reactive power exchanges with other areas are small, and the reactive power flows within the area are small. b) For a *VAr unbalanced area*, the reactive power flows within the area and the exchanges with other areas are big. There exists market power within the VAr unbalanced area.

In our study cases, Zone A can be classified as VAr unbalanced area. Zone B and Zone C can be classified as VAr balanced areas. We can get the following conclusions about reactive power market in VAr balanced area and VAr unbalanced area.

- In a VAr balanced area, the offer price change of a network device mostly will not change the market selection of VAr devices. Only the quantities of reactive power schemes may be changed for those devices with high offer prices.
- In a VAr unbalance area, whether a device can be selected for reactive power provision is very sensitive to the prices offered by the device owners.

VI. CONCLUSIONS

This paper develops an auction based pricing mechanism for the reactive power provided by network devices. The price offered by network reactive power devices are based on availability cost component and operating cost component. Reactive power market uniform prices are obtained for network devices. From the analysis of the results, we found the following conclusions. In an area with balanced reactive power sources, an auction mechanism has less effect on the reactive power schemes of network devices. In an area that reactive power sources are not balance located, a VAr auction mechanism will help the ISO to decide the most economic reactive power schemes, and to minimize the payment.

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VIII. BIOGRAPHIES

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