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The ancillary reactive power service pricing in a Deregulated electricity market

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Abstract*— The amount of real power that can be transferred in a power system depends on the reactive power/voltage support. Appropriate management of reactive power is indispensable for supporting power system reliability and security. Most researches have been focused on active power as the main good transacted in electricity markets. On the other hand, the reactive power production is highly dependent on real power output and it is mainly confined to local consumption. To avoid market power and secure operation of the system, a feasible and fair method for pricing of reactive power is important in the deregulated electricity market. Appropriate pricing for reactive power as an ancillary service is a challenging problem. In this paper, a method for the pricing of reactive power support using optimal power flow is proposed. This model is simulated by using MATLAB with power system simulation package MATPOWER. The validation of the proposed method is tested on IEEE 9 bus test system.
***Keywords*— Reactive power, Ancillary Service, Deregulated electricity market.**

I. INTRODUCTION

Deregulation in general involves unbundling of electric power systems into the three basic parts of generation, transmission and distribution under the ownership, responsibility and control of three companies 1.Generation companies (Gencos), 2.Transmission companies (Transcos) and 3.Distribution companies (Discos), with a central coordinator, called an independent system operator (ISO)[1]. In Deregulated power system, the fundamental responsibility of the Independent System Operator (ISO) is to maintain system reliability and security by arranging ancillary services such as spinning reserve, reactive power support, energy balancing, frequency regulation and black start etc[2]. In conventional vertically integrated power system, the cost of reactive power support is in general recovered by two means, one is to include the cost of reactive power support into energy price and the other is to use load power factor penalty. In the deregulated environment, the cost of reactive power support should be considered separately. The conventional pricing methods of reactive power support do not fit into the market environment any more, a practical and reasonable pricing scheme for reactive power support is needed[3].

The reactive power management and pricing mechanisms are different for each deregulated electricity market and depend on frame work of contracts and market operation. Usually the ISO enters into contracts with reactive power suppliers for their service provisions. As per the NERC's Operating Policy in the US market , only that reactive power supplied by synchronous generators are considered as an ancillary service and can receive payment(financial compensation) for their services. The same is applied in UK and Australian markets. The Australian market additionally considers reactive power from synchronous condensers as ancillary service. On the other hand, restructured markets in the Nordic countries have not any provision for payments towards reactive power services .In Sweden the accountability for managing reactive power lies with network companies, with certain policies from the ISO, stipulating that there should be no exchange of reactive power over different network voltage levels and transformers. To meet these requirements, individual entities, such as local and regional networks, have to make arrangement for their own reactive power. In a similar manner in Netherlands, the network companies have to take care of their reactive power requirement on their own. These companies However these companies purchase reactive power locally through bilateral contracts with generators or through exchange with other network companies. The generators which have contract for the reactive power service are paid for their reactive power capacity and no payment for reactive energy support.

The technical and economic issues of determining reactive power service in an open-access environment is discussed in [5].A summary of the modifications in optimal power flow algorithms for reactive power pricing is proposed in [6].In [7] the economic costs of reactive support are analyzed and a cost-based reactive power dispatch methodology is presented, by minimizing the total cost of reactive support which keeps all bus voltages within acceptable limits. Ref. [5] proposes two kinds of reactive pricing structures with compensation of generators' capability for reactive power support taken into account. Ref. [9] integrates the production cost of reactive power and the voltage stability margin requirement of pre and Post contingencies into the OPF problem formulation .The design of a localized reactive power competitive market for ancillary services at the level of individual voltage-control areas proposed in [10].Ref [11] discusses various complex issues of reactive power management and pricing in deregulated power systems in the context of the new operating paradigms, proposing some policy solutions. Ref[12] propose an algorithm for tuning reactive power resources with the objectives of Optimizing active power losses and optimizing system voltage profile and stability. An approach to design reactive power capacity markets by conducting annual auctions for the procurement reactive power capacity by the system operator is proposed in[13].Ref [1] proposes an algorithm using floating point genetic algorithm (FPGA) was developed to solve the optimum reactive power allocation problem in power systems under open market environment. Two optimization algorithms, particle swarm optimization (PSO) and Genetic algorithm (GA) method are used to solve the problem of optimum allocation of reactive power in deregulated environment and the results are compared in[14]. In [15] the Production cost of reactive power and investment cost of capacitor Banks are included into the objective function of the OPF problem, sequential linear programming method used to solve the optimal problem.

The reactive power price cannot be obtained accurately by conventional optimal power flow models which usually ignore the production cost of reactive power. In this paper, the authors include the production cost of reactive power into the objective function of the optimal power flow problem, and use MATLAB interior point solver to solve the optimization problem and obtain reactive power marginal price accordingly.

II. REACTIVE POWER ISSUES

A. *Cost of reactive power*

Although reactive power costs constitute very small percentage of total power industry costs, it is very important to make clear analysis on reactive power market. In economics, the total cost of any commodity consists of i. fixed cost component and ii. Variable cost component [16].The fixed cost is mainly the capital investment of equipment. The main purpose of Generators is producing real power, they play a vital role in the management of reactive power ancillary service. Some markets roughly assume that the investment cost is all real power cost. Several research works propose to allocate this cost to different function One simple way is to divide it according to the power factor. Variable costs are the costs in economics that are connected to the output quantity. Since the fuel cost is independent of reactive power output , the variable cost of generators include operation, maintenance and opportunity costs.

Opportunity cost is the most important part of reactive power cost. The generators capacity is limited by the synchronous generator's armature current limit, field current limit, and the under-excitation limits. Because of these limits, the generation of reactive power may require a reduction of real power generation. Opportunity cost is the lost benefit of this reduction of real power generation.

B. *Value of Reactive Power*

The value of reactive power support is interconnected to security and reliability. A reasonable valuation method can support and encourage investigation of reactive power equipment. The value of reactive power support is not depend on the cost, but related to several factors. Reactive power is location dependent, and long distance transmission is not suggested. A reactive power source nearer to the load center can satisfy the requirement efficiently, so it has a higher value. The resources which can provide reactive power dynamically and can respond quickly are better in maintaining the stability of the system. Thus dynamic resources such as synchronous condensers are more valuable than shunt capacitors.

C. *Pricing of reactive power support*

In vertically integrated power utilities, the reactive power support cost is normally recovered by including reactive power cost in the energy price or using load power factor penalty. These methods overlook the value contribution of reactive power for the system control. Pricing of reactive power support is an important issue. An accurate pricing structure of reactive power is not only profitable to recover the costs of reactive power providers, but also provide useful economic information for real-time operations.

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There are two kinds of pricing mechanisms in electricity markets

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1) *Real time pricing:* The spot price for electric energy buying and selling is determined by the supply and demand conditions at that instant. Real-time pricing approach can provide economic information for system operation. However, it has many disadvantages in practical applications. In some cases, the real-time price is quite sensitive to operation conditions and the system constraints, which could lead to considerable price fluctuations. The real-time price is usually obtained from optimal power flow based algorithms, which have convergence problems because of several nonlinear constraints. The revenue gained by the real-time pricing may not be sufficient to recover the total cost. Furthermore, it doesn't consider the higher value of dynamic resources. Several modified OPF approaches are proposed to solve reactive power pricing problems. In this paper A decoupled optimal power flow formulation is used to carry out active and reactive power pricing simultaneously and independently. The active power sub problem minimizes total operating costs of providing active power, while the reactive power sub problem minimizes the total operating costs of providing reactive power plus a specified amount of active power at the balance generator.
2) *Cost allocation:* The principle of cost allocation methods is allocating the total cost of reactive power supply to each load. Traditional allocation method can also used in a reactive power cost allocation, such as postage stamp, contract path, and MW mile method. However, these methods are too rough and are not suitable in electrical market.

III. REACTIVE POWER PRICING

Active and reactive marginal prices are normally obtained by solving the optimal power flow in which objective function subject to a set of equality and inequality constraints.

A. *Non linear problem formulation*

The optimal power flow problem is a nonlinear optimization problem. A typical objective is to minimize a performance function subject to system equality and inequality constraints. The general constrained optimization problem can be defined mathematically as

Minimize

$$f(u,x) \quad (1)$$

subject to the following equality and inequality constraints

$$g(u,x) = 0 \quad (2)$$

$$h(u,x) \geq 0 \quad (3)$$

where *u* defines system controllable quantities and *x* defines system dependent variables

B. *Objective function*

The objective function of the OPF problem for minimization of active and reactive power costs can be expressed as follows Summation of active and reactive power production costs,

$$C_{Total} = \sum_{i=1}^{N_g} Cost(P_{Gi}) + Cost(Q_{Gi}) \quad (4)$$

where,

Cost(P_{Gi}) : Active power cost function of generator *i* ,

Cost(Q_{Gi}) : Reactive power cost function of generator *i* ,

Ng : Number of generators

C. Constraints

The constraints, considered in this problem, are the standard set of equality and inequality constraints which are normally considered in OPF. In fact, the set of equality constraints represent the standard power flow equations for active and reactive power and the set of inequality constraints represent the physical and security limits of the system as below

$$\sum_{i=1}^{N} P_{Gi} - \sum_{i=1}^{N} P_{Di} - P_{Loss} = 0$$

$$\sum_{i=1}^{N} Q_{Gi} - \sum_{i=1}^{N} Q_{Di} - Q_{Loss} = 0$$

Where

$$P_{Loss} = \sum_{i=1}^{N} |Vi||Vj||Yij|cos(\theta ij + \delta j - \delta i)$$

$$Q_{Loss} = \sum_{i=1}^{N} |Vi||Vj||Yij|sin(\theta ij + \delta j - \delta i)$$

and,

$P_{G\,min} \leq P_{Gi} \leq P_{G\,max}$

$Q_{G\,min} \leq Q_{Gi} \leq Q_{G\,max}$

$P_{Gi}^2 + Q_{Gi}^2 \leq S_{Gi\,max}$

i=1,2,….N_g

$|Vi|min \leq |Vi| \leq |Vi|max$ i=1,2,….N (5)

In the above equations different variables are defined as below

N: Number of buses of the network

P_{Gi},Q_{Gi} : Supply of active and reactive power at *i* th bus

P_{Di},Q_{Di} : Active and reactive demand at *i* th bus

$S_{Gi\,max}$: Maximum apparent power at bus *i*

$Vi = |Vi| \angle \delta_i$: Voltage phasor at bus i

$Yij \angle \theta ij$: The *j*th element of admittance matrix.

IV. SIMULATION RESULTS

To validating the method proposed it has been applied to IEEE 9-bus system(Fig.1).Tables1 and 2 shows the generator and load characteristics of the system. To be able to make comparison between the proposed method and previous algorithms, we have simulated two different cases as below

a)Case1: Only the cost for real power produced by generators is considered in the objective function

b)Case2: The costs for both reactive and active power have considered in the objective function. In this case, the cost function has been modeled based on the conventional reactive cost formulation with reactive power coefficients.

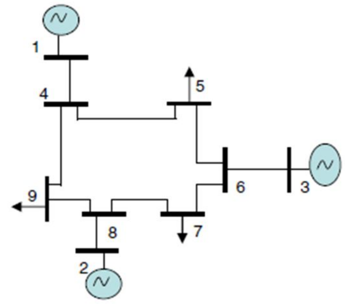

Fig1. I EEE 9 bus test sytem

TABLE 1 Generators characteristics

Bus No	a	b	c	P_{max} MW	P_{min} MW	Q_{max} Mvar	Q_{min} Mvar
1	0.11	5	150	250	10	300	-300
2	0.085	1.2	600	300	10	300	-300
3	0.11225	1	335	270	10	300	-300

Table 2 Load characteristics

Bus No	Active Power (MW)	Reactive power (Mvar)
5	150	50
7	200	60
9	170	55

Table 3 and Table 4 shows the simulation results for the above two mentioned cases.

Table 3 Simulation results for case 1

Bus No	P_G (MW)	Q_G (MVAR)	λp ($/MW)	λq ($/MVAR)	Total cost ($/hr)
1	157.44	47.57	39.637	---	11893.98
2	217.69	38.91	38.207		
3	152.62	19.8	38.392		

Table 4 Simulation results for case 2

Bus No	P_G (MW)	Q_G (MVAR)	λp ($/MW)	λq ($/MVAR)	Total cost ($/hr)
1	161.50	37.52	40.529	15.009	12492.37
2	215.12	54.12	37.771	5.412	
3	151.33	22.70	38.015	13.618	

V. CONCLUSION

The study on a competitive market for reactive power services in deregulated electricity systems have attempted in this paper. The market is based on offers from generators and in this paper the reactive power price is allocated only to synchronous generators. This paper makes a survey on the significant issues about reactive power in deregulated environment and a pricing mechanism based on active and reactive power generator coefficients is presented. The proposed reactive pricing method is simple and flexible, it is simple compared with conventional methods. Therefore, it is more compatible with non-discriminatory philosophy of open access deregulated systems.

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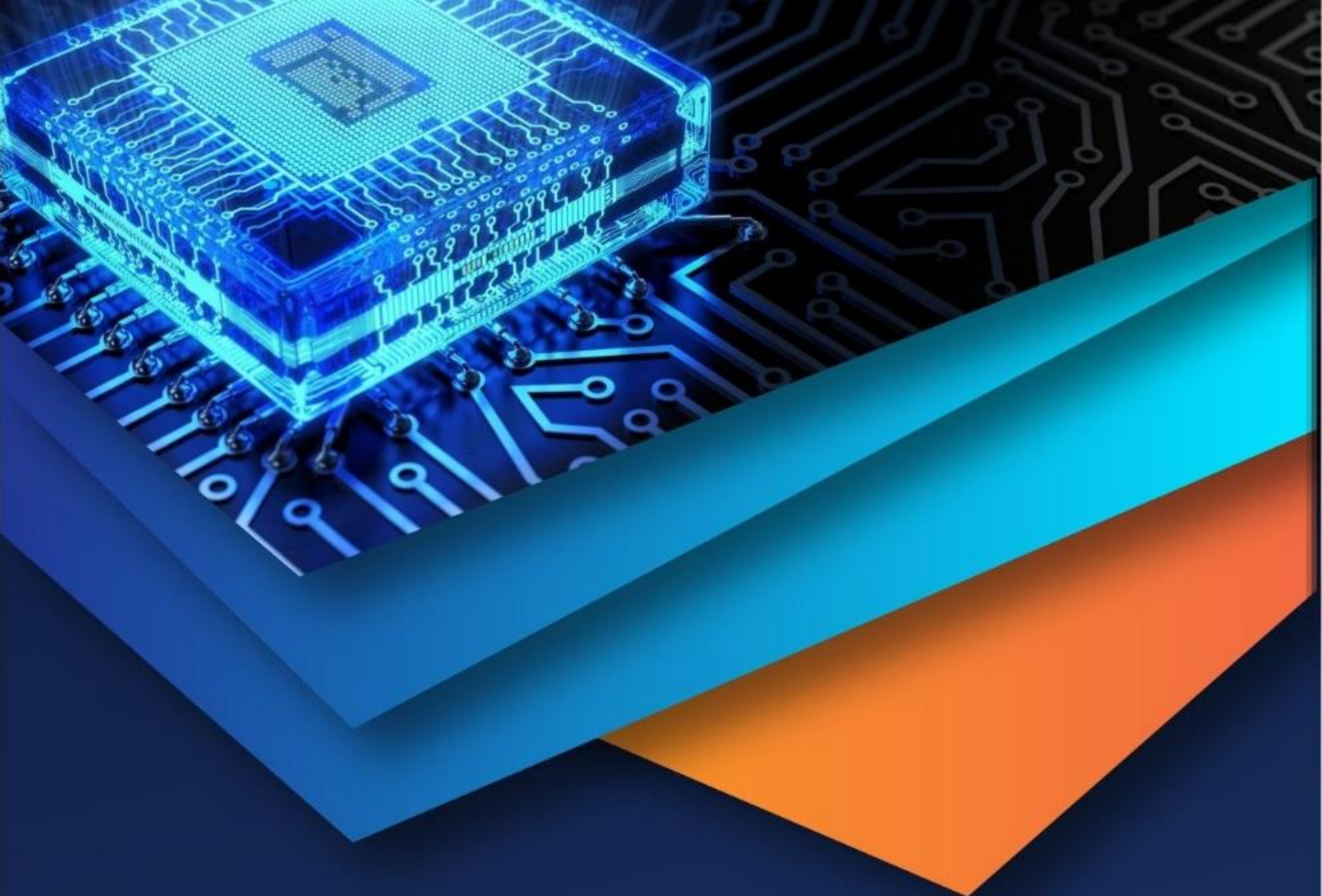

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