Combinational Pricing Method for Active and Reactive Power in Power System

J. Aghaei A. Kazemi H. A. Shayanfar M. Yari

Iran University of Science and Technology (IUST)

Abstract: This paper proposes a price mechanism with one price assigned for each level of bundled real and reactive power. The better allocation under this pricing method raises system efficiency via better allocation of the reactive power reserves, neglected in the traditional pricing approach. Pricing reactive power separately is not very practical since its cost is highly dependent on real power output. Equilibrium allocation of the bundled pricing is simulated on the simple 3-bus system power auction and compared with free reactive power optimal power flow solution. The efficiency of this approach is shown in the general case, and tested on the 30-bus IEEE network with piecewise linear cost functions of the generators.

Keywords: Optimal Power Flow (OPF), Power Factor, Reactive Power Pricing, Combinational Pricing Method

I. Introduction

An efficient transmission network plays a crucial role in growing power markets around the world. In the last five years generating capacity grew enormously; however, transmission investment has been declining for many years. Many countries have already adopted competitive market programs where an Independent System Operator (ISO) or Regional Transmission Organization (RTO) is responsible for scheduling and dispatching generators on regional networks, implementing a market-based mechanism for allocating scarce transmission capacity [1].

The direct current (DC) system model is a common approximation for estimating spot market prices under a constrained network. The DC load model is insufficient since it ignores reactive power effects on the production of real power, line congestion and voltage constraints.

Hogan in Reference [2] created a separate price mechanism for reactive power in order to stimulate its production with a purpose of satisfying voltage constraints. Later, Kahn and Baldick in [3] demonstrated that although Hogan's pricing example for reactive power yielded a Pareto improving (more efficient) dispatch, it was not a solution of the formal optimal power flow problem. After 1994, the theoretical discussion of reactive power pricing shifted into the engineering literature, where it focused on how marginal reactive power should be determined and priced. Hao [4], [5] explored the technical and economical issues of determining reactive power structures, and designed a practical solution for managing reactive power services. Reference [6] discussed auction design for ancillary services.

A great deal of engineering researches centered on the technical side of the solution algorithm. Weber in [7] modified standard optimal power flow (OPF) analysis to simulate real and reactive power prices. Gil [8] proposed a theoretical approach of marginal cost pricing for reactive services. Alvarado [9] suggested marginal cost pricing for dynamic reactive power. These studies emphasize the important role of reactive power in the efficient production and distribution of electricity. They conclude first, that a DC approximation is not sufficient to mimic power flows in a congested network; and second, that reactive power output itself is costly and creates network congestion.

This paper represents a first step in filling this gap. An alternative pricing mechanism will be presented where the prices of real and reactive power are merged into one bid, without distinct separation of value for each power component. While formulating their bids generators evaluate the overall profit they expect to obtain from production. In addition, separating real and reactive power bids is not very practical, since the optimal reactive power bid is extremely volatile, depending on real power output.

In the next chapter a simple three bus network OPF solution is presented as a starting point. It is shown that when reactive power costs are neglected, the OPF solution tends to allocate too much of reactive power requirement to generators located closer to the load. This paper explains how reactive power cost is related to the cost of real power, and demonstrates gain when reactive power cost are taken into consideration for the standard 30-bus IEEE network model with piecewise linear costs of the generators.

II. Power Network Model

First, the bundled pricing on a small 3-bus triangular AC network example will be demonstrated, in which there are two generators and a load connected by transmission lines (see Fig.1). Load flow in Fig.1 represents economic dispatch of the generators, neglecting reactive power costs. That is, in order to satisfy the load (1500 MW; 300 MVAr in this example) in the cheapest possible way, the first generator (G1) has to produce 847.1 MW real and 8.1 MVAr reactive power, while the second generator (G2) has to produce the remaining 721.6 MW and 371.1MVAr . The solution is found by solving a formal non-linear cost minimization subject to transmission, voltage and generation constraints. No prices are used to calculate the efficient allocation (Table 1).

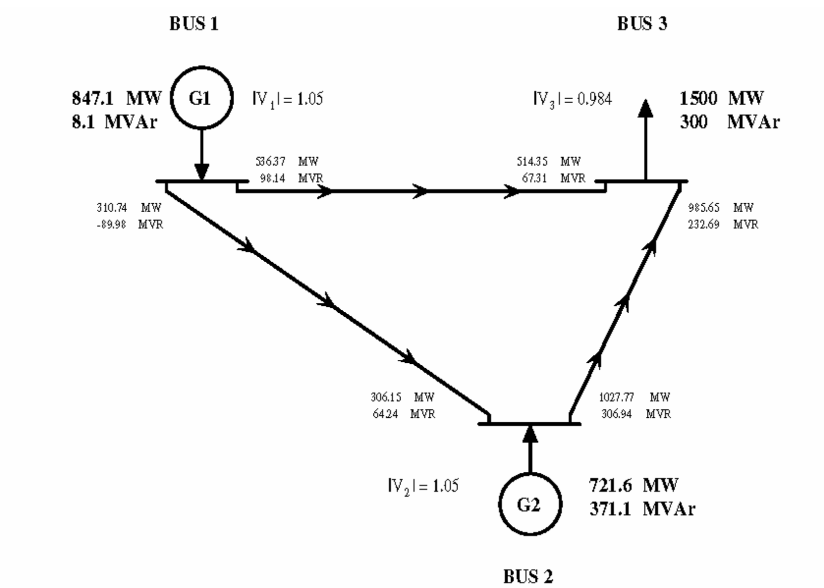


Fig.1: Triangular Network OPF example

A competitive market is another way to obtain the same efficient allocation. Efficiency is obtained by dispatching generators via a price mechanism. Competition in the power market is organized in the form of an auction, where cheaper generators presumably underbid more expensive generators. When competition eliminates expensive (inefficient) producers, power is produced efficiently (i.e. at the lowest possible cost). Ref. [2] designed a nodal price mechanism allowing the system to reach efficiency via market competition. When reactive power can be produced at no cost, nodal prices set equal to marginal cost in the competitive market will result in an efficient allocation, as shown in Fig.1.

Locational marginal cost prices (LMPs) provide fair competition among generators and ultimately yield efficient dispatch. Under this approach, reactive power is supposed to be a free good when production is adjusted in such a way as to minimize real power losses such that voltage constraints and line congestion are not violated.

Table 1 demonstrates changes in OPF when costs of reactive power are taken into consid-eration. Distortions increase substantially when the reactive power demand is higher. If demand for reactive power jumps to 700MVAr, the OPF solution ignoring the cost of reactive power requires the second generator to produce 730 MW, and 707 MVAr. When generator 2 produces 730 MW, only 240 MVAr can be produced at no cost. Therefore, when the cost of reactive power is taken into consideration, a larger share of the reactive power is produced by the first generator.

Table 1: OPF results when costs of reactive power are neglected

Demand		Free Reactive Power				Costly Reactive Power			
		Generator 1		Generator 2		Generator 1		Generator 2	
MW	MVAr	MW	MVAr	MW	MVAr	MW	MVAr	MW	MVAr
1500	**200**	**846.03**	**-18.48**	**720.38**	**290.87**	**847.55**	**69.69**	**719.59**	**206.65**
1500	**300**	**847.11**	**8.15**	**721.62**	**371.18**	**845.8**	**97.08**	**723.61**	**286.06**
1500	**500**	**850.33**	**62.77**	**725.10**	**536.11**	**851.72**	**330.78**	**727.63**	**287.4**
1500	**700**	**855.10**	**119.39**	**730.03**	**707.37**	**858.58**	**417.60**	**731.31**	**437.55**

III. Pricing Method

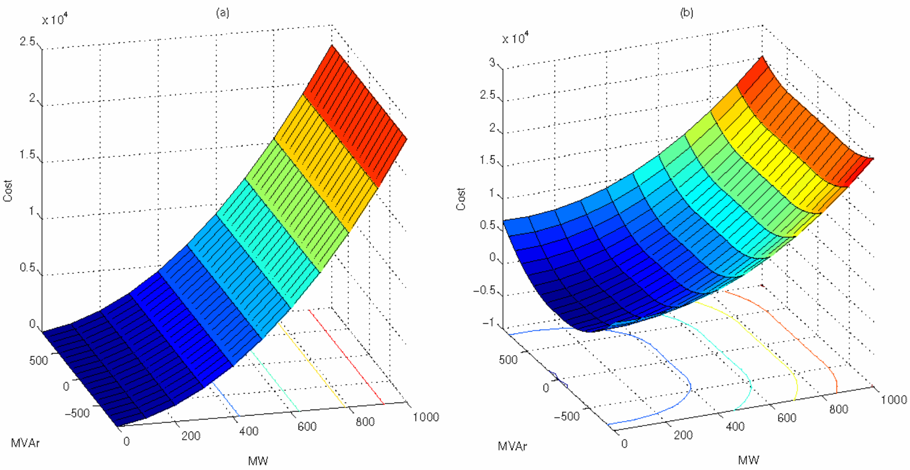
Since it is necessary to consider cost of reactive power, OPF solution results in more efficient distribution of reactive reserves and therefore we have more efficient system. A price mechanism that is self enforce will help to improve efficiency, also excites competition and more investment in reactive reserves.At present, no market is expanded for reactive power because generators don't have incentive for producing reactive power unless system operator needs them. Opportunity cost of reactive power depends highly on real power output. In the example (Fig 1), 240 MVAr can be produced without any cost when generator produces 730 MW real power.This amount of reactive power can be produced by synchronous condenser that absorbs 7.2 MW real power. Since total generation costs depend on both active and reactive powers, generators should be paid for the combination of active and reactive power.

Consequently, cost proposal on power market should be provided as combination of every single price assigned for each level of both real and reactive powers. Graphically, both costs and bid functions are demonstrated as three dimension surfaces. Each of bid or cost levels are characterized by two coordinates: MW and MVAr (Fig. 2).

When reactive power has no cost as Fig. 2(a), the surface of cost is flat. If we need to supply reactive power outside of the range 0.95 lading to 0.9 lagging power factor, it should be generated through synchronous condenser that it is at expense of real power as Fig. (2b). In the figures we can observe reactive capability curves or the same cost curves. These curves are flat when reactive power is free. We can reach to the result that the cost of reactive power can be calculated if it is modeled as the cost of additional real power, so we need to generate it. This method is very practical for reactive power cost instead of costing of reactive power separately from active power. When power is sold, generators propose their marginal cost. In case of combinational pricing, each generator proposal will equal sum of the changes in costs due to incremental changes both in real and reactive powers (Fig. 3).

$$\mathrm{Cost}\ (G_i) = \mathrm{Cost}\ (MW_i) + \mathrm{Cost}\ (MVAr_i(MW_i))$$
$$= \mathrm{Cost}(MVAr_i, MW_i)$$

$$MC_i = \mathrm{Cost}\ (MW_i(0)) + \mathrm{Cost}(MVAr_i(0)).\ VAr'(MW_i)$$



(a) (b)

Fig 2: Cost example for: (a) free reactive power; (b) costly reactive power

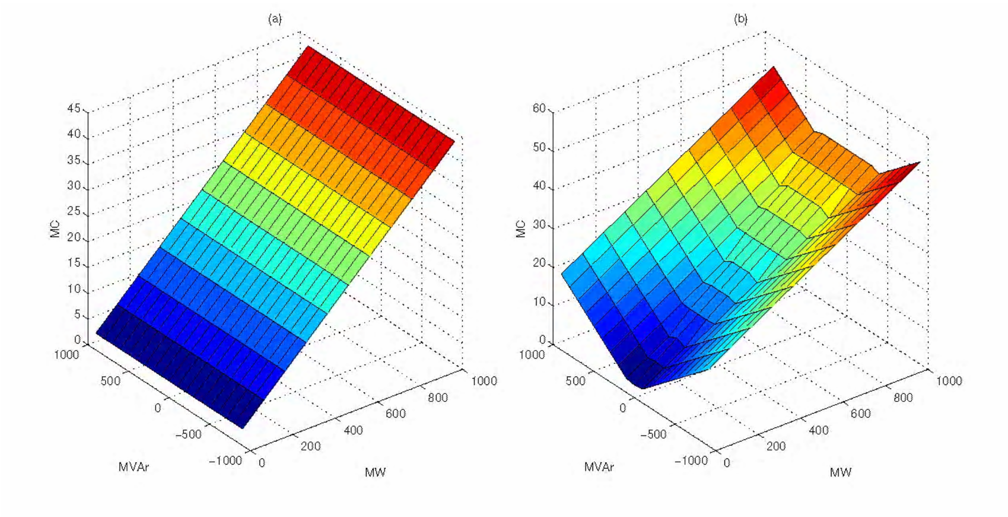


Fig. 3: MC_i=LMP_i surface for: (a) free reactive power; (b) costly reactive power

IV. Costs of Reactive Power

Unlike real power, reactive power is usually cheap to produce within a certain range. The three major sources of reactive power production are capacitor banks, synchronous condensers, and generators. This paper focuses on the reactive power share coming from moving machines such as generators and synchronous condensers for which reactive power capacity is proportional to active power output. That is, a certain amount of reactive power can be produced by generators at no cost; otherwise reactive power is produced by synchronous machines at the expense of real power.

Reactive power is usually generated close to the load, since it can not be transmitted efficiently over a long distance. The example in Fig.1 illustrates this point, as most of the reactive power is produced by generator 2, which is located closer to the load.

A problem arises when a substantial amount of the reactive power is assigned to a single generator. Table 1 demonstrates OPF dispatch as reactive power demand increases. When load demands 1500 MW and 700 MVAr, the existing nodal pricing mechanism (as well as OPF) will require the second generator to produce 730.03 MW and 707.37 MVAr. However, under the normal requirements only about 240MVAr can be produced at no cost . The remaining share of the reactive power is going to be produced by a synchronous machine consuming approximately 19 MW real power, because the cost of reactive power is not accounted for by the LMP. Many papers in the engineering literature, such as [7] and [8] developed methodologies and solution simulation methods to account for the costs of reactive power. For purposes of this paper, the MatPower OPF solver was used. Reactive power is considered to be free within the normal reactive requirements set by NERC (0.95 leading and 0.9 lagging power factor). Otherwise, a synchronous machine will consume real power equal to about 3 % of the machines reactive-power rating. Mathematically, the cost of reactive power beyond normal rate can be approximated as an extra cost of real power.

$$\text{Cost}(P, Q) = \text{Cost}\,(P + 0.03(Q - Q^0))$$

where P is the demand of real power, Q is the demand of the reactive power and Q^0 is reactive power produced by generator at no cost.

Table 1 demonstrates the distortions that occur in the OPF solution if costs of reactive power are considered. The amount of real power allocation remains relatively constant; however, generator 1 increased its reactive power output, and freeing up excessive reactive power production of the second generator. Similar results are obtained by simulating the more realistic IEEE 30-bus, 6 generator system, with piecewise linear cost functions of the generators.

Table 2 demonstrates that if costs of reactive power are considered, more reactive power will be produced by generators 1 and 2 releasing excessive requirements from the expensive generator 3.

V. Conclusions

In this paper a pricing mechanism for real and reactive powers was proposed. One price is studied for different levels of real and reactive powers. As a result, the supply function of a generator becomes a surface in three-dimensional space. Efficiency gain of the combinational pricing over the traditional LMP is equivalent to the gain of OPF solution with reactive power cost, over the OPF with free reactive power. Combined pricing allows more efficient distribution of reactive power resources and creates autonomous competitive market mechanism for the reactive powers.

Table 2: OPF power output for 6 generators 30-bus IEEE test network

	OPF with free MVAR		OPF with costly MVAR	
Generator	**MW**	**MVAR**	**MW**	**MVAR**
1	36.00	-4.25	36.00	11.26
2	30.76	5.89	24.61	10.11
3	36.00	40.27	36.00	23.54
4	30.21	19.79	32.39	12.34
5	22.55	7.54	26.72	7.41
6	36.00	34.79	36.00	37.89

VI. Refrences

1. P. Joskow, "The Diffcult Transition to Competitive Electricity Markets in the U.S." Cambridge Working Papers in Economics, July 2003.

2. W. Hogan, "Markets in Real Electric Networks Require Reactive Prices" The Energy Journal, pp.211-242, 1993

3. E. Kirby, R. Baldick, "Reactive power is a cheap constraint", Energy Journal, Volume.15 (4), pp 191-201, 1994.

4. S. Hao, "A Reactive Power Management Proposal for Transmission Operators" IEEE Transactions on Power Systems, Vol. 18, NO. 4. November 2003.

5. S. Hao, A, Papalexopoulos, "Reactive Power pricing and management", IEEE Transactions on Power Systems, Vol. 12, Feb. 23-29, 1997

6. H. Singh, A. Papalexopoulos, "Competitive Procurement of Ancillary Services by an Independent System Operator" IEEE Transactions on Power Systems, Vol 14, No. 2, pp 498- 504May 1999.

7. J, Weber, "A Simulation Based Approach to Pricing Reactive Power" Hawai International Conference on System Sciences, 1998

8. J. Gil, "Reactive Power Pricing: A Conceptual Framework for Remuneration and Charging Procedures" IEEE Transactions on Power Systems, 1999, Vol. 15, pp.483-489

9. F. Alvarado, R. Brehm, L. Kirsch, A Panvini., "Retail pricing of reactive power service" EPRI Conference on Innovative Approaches to Electricity Pricing, La Jolla, CA, March 27-29, 1996.