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A stochastic framework for reactive power procurement market, based on nodal price model

Hamed Ahmadi, Asghar Akbari Foroud *

Electrical Engineering Department, Semnan University, Semnan, Iran

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ABSTRACT

A new modified nodal pricing method is presented in this paper to calculate reactive power price. This article tries to solve the problems of traditional nodal pricing methods to be able to consider opportunity and availability costs for the generators. A modified model of generators reactive power production cost has been used in OPF objective function considering normal and contingency conditions. Availability cost would be estimated considering the volume of network demand from the generators in contingency states through probability calculations. This cost would be paid to all the units that possibly will needed to produce reactive power in contingency states. Purvey of required availability of generation units to deal with emergency conditions, encouraging providers to invest in critical areas in the network and fair distribution of reactive power production costs over several producers are some advantages of the proposed method. The proposed method is tested on IEEE 24 bus RTS and is compared with the uniform pricing method.

1. Introduction

Regarding the restructured power systems, one of the most important tasks of the independent system operator is to maintain the power system in a safe and reliable condition using ancillary services. There must be sufficient amount of reactive power in the system in order to keep the voltage of nodes in allowed ranges and also to increase lines' loading capacity in designated levels [1,2].

Considering the importance of reactive power issue, it is essential to adapt an appropriate model for the formation of reactive power market, in which, the reactive power cost has to be correctly calculated and the fair price payment to producers should be determined properly. Different methods for calculating the price of reactive power has been presented in papers [3–9] among which, the following can be mentioned:

- Reactive power pricing based on load power factor (coefficient) rate which the generators are always forced to produce power at a specify range of power factor and network reactive power demand is provided in this way [1].
- Reactive power pricing, in the framework of cost allocation, tracking reactive power using postage stamps methods, graph theory [10,11] and using the modified admittance matrix [12,13] are some parts of this pricing method.
- Uniform reactive power pricing, a uniform price for all network consumers has been proposed in these articles [3,14–16].
- Nodal reactive power pricing, Martin et al. [17] determined nodal reactive and active power prices at each favorite node system for the first time using Lagrange factor. This method was then developed in other resources [18–25]. Each of these studies has been trying to calculate the reactive power nodal price through modifying OPF objective function and combining it with subjects like reserve capacity and voltage stability.

The importance of the reactive power, unlike the active power, is highly related to its production location in the network. In an event, it is possible that the reactive power production of an expensive unit is necessary due to stability limits. While, the reactive power produced far from the necessitated location is not desirable even if the price is low. As a result, adopting uniform price for total produced reactive power with no consideration of its production location is not favorable while, Nodal pricing can be more efficient.

Reactive power producers would not have much tendency to take part in reactive power production under some methods such as the ones based on power ratio; and they often do not declare their real production capacities. Also, while the announced objective for cost allocation based methods offer a fair price, but they do not achieve this important goal due to solving complications problem and reactive power non-linear and localized conditions. Furthermore, the production units could not accurately analyze the market conditions with those methods in order to propose

* Corresponding author. Tel.: +98 912 4618433; fax: +98 231 3354091.
E-mail address: aakbari@semnan.ac.ir (A. Akbari Foroud).

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the right price in contracts accordingly. While, since nodal pricing can be proportional to unit's real production cost (that is considered in this paper), it can offer fair price for reactive power. Nodal pricing of reactive power can be an efficient signal to investment on reactive power resources in necessary locations in the network. It also will adequately help the network operator to improve the application conditions and recognize the network demand better signal to maintain voltage stability.

However, there are also some critics for traditional nodal reactive power pricing which point out a number of disadvantages for it. Traditional nodal reactive power pricing, does not provide a correct economic signal, due to special form of the reactive power production cost function. On the other hand, in traditional nodal pricing method, only generators that have won in the market for reactive power production can receive money. But the system needs some units to deal with haphazard incidents and keep its safety which may not be selected to generate reactive power in normal conditions. These units are needed to generate reactive power at any time the ISO determines, and the network needs this power to keep the voltage under control in an adequate zone. Therefore, it is necessary to pay these units for maintaining availability. Also perhaps some generators are forced to reduce some portion of their active power production capacities to produce reactive power; these units expect to receive some opportunity compensation for these lost opportunities, but the opportunity and availability compensations are not considered in traditional nodal pricing methods of reactive power.

An improved nodal pricing method is presented in this paper to calculate reactive power price. This article tries to solve the problems of traditional nodal pricing methods to be able to consider opportunity and availability costs for the generators. The reactive power service provision cost function which was previously used in Uniform Price markets is revised here and is used as the OPF objective function in proposed method. Also proposed method is capable to calculate the reactive power nodal price comprising availability cost in addition to reactive power production cost. Availability cost would be estimated considering the volume of network demand from the generators in contingency states through probability calculations. This cost has been considered to be paid to all the units which the network may demand those to produce reactive power in contingency conditions. So these payments are not necessarily exclusive to the units which have won the markets. Purvey of required availability of generation units to deal with emergency conditions, encouraging providers to invest in critical areas in the network and fair distribution of reactive power production costs over several producers are some advantages of the proposed method.

This article is presented in five sections. After the introduction, the method of calculating the reactive power production cost has been considered in Section 2. The reactive power market model based on nodal price is presented in Section 3. In fourth section, the proposed method is tested on IEEE 24 bus RTS [26] using GAMS software [27], and is compared with the uniform pricing method. Finally, conclusions are given in Section 5.

2. Total reactive power production cost

The importance of synchronous generators is a critical issue to provision of reactive power ancillary services. When reactive power and terminal voltage are constant in a synchronous generator, field coil and armature temperature range limits would determine the amount of reactive power produced by generator. Armature heating range limit is a circle with a radius of $R_1 = (V_t I_a)^{1/2}$ and the center of origin point which its equation is given by [28,29]

$$P^2 + Q^2 \leqslant (\sqrt{V_t I_a})^2 \quad (1)$$

And field thermal range limit is a circle with the radius of $R_2 = E_{af}V_t/X_s$ and the center of $C_2 = (0, -V_t^2/X_s)$ which is given by [28,29]

$$P^2 + (Q + V_t^2/X_s)^2 \leqslant (E_{af}V_t/X_s)^2 \quad (2)$$

which, in above relations, V_t is voltage on generator terminal, I_a is steady-state armature current, E_{af} is excitation voltage and X_s is synchronous reactance And P, Q are real and reactive power out of synchronous machine. Nominal value of the machine is intersection point of two circles (P_R). If $P < P_R$, then Q limit is imposed by heat flow range of generator excitation current, and if $P > P_R$, then the armature heating range will impose the constraints over production level Q [28,29].

Fig. 1 is considered to assist us with further evaluation. Q_{base} in this figure is the reactive power required by generator for its auxiliary equipment. If the operating point is set inside limiting curves (P_A, Q_{base}), then the generator can increase its produced reactive power from Q_{base} *to* Q_A without the need to adjust the P_A again. But this will cause losses to increase in coil and will result in increase costs. If the generator operates on the limiting curve, any increase in Q requires a reduction in P, as the coil heating range was intended. Also Fig. 1 shows that a smaller zone is designated for Q to implement the generator at under-excitation mood. This limitation is due to the heat concentrated in the end of terminal armature [1,3].

Under above mentioned considerations, reactive power production costs related to synchronous generator can be expressed by the following curve.

In Fig. 2, the reactive power production zones for the generator are as follows:

- Reactive power production zone $(0 - Q_{base})$

The produced reactive power in this zone is only sufficient for generator's auxiliary equipment which includes ancillary reactive applications such as injection pump motors. Therefore nothing would be paid to the generator for producing reactive power in this zone [3].

- Reactive power production zone $(Q_{base} - Q_A)$ and reactive power absorption zone $(0 - Q_{min})$

In this zone, the generator can produce or absorb the required reactive power without making any change in the amount of active power production. This can lead to an increase of real power loss in the excitation coil and the generator armature. Therefore, the generator expects an additional payment (perhaps according to real time market prices) from Independent System Operator (ISO) for being available to him [3].

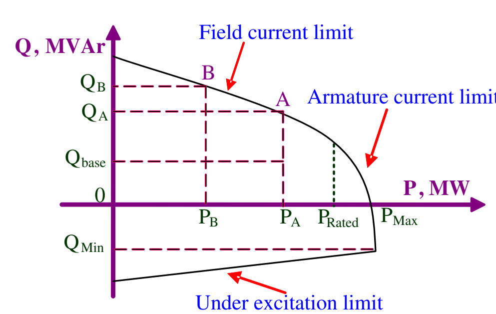

Fig. 1. Synchronous generator capability curve.