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Voltage security constrained active and reactive power pricing considering reactive market power

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Abstract Reactive power support and voltage stability are considered to be very essential for preserving system security. This paper proposes a new market-based approach for voltage security constrained active and reactive power pricing. The problem is modeled as a multi-objective OPF in which the social welfare and the distance to voltage collapse point are maximized at same time. An important feature of the proposed approach is using the reactive market power index, Herfindahl–Hirschman Index (HHI), to assign optimal weighting factors of the multi-objective function. In addition, in this method not only the reactive power is considered but typical price is also provided based on real costs. The results show that the proposed method allows market operators and participants to preserve the level of security and social welfare within acceptable range by controlling the weighting factors and monitoring the HHI with regard to reactive market power. Using the proposed method and considering reactive power market, a suitable range of weighting factor can be determined ensuring the optimal bidding as well as satisfying the voltage security of the system.

Keywords Electricity market · Multi objective optimal power flow · Reactive market power · HHI index · Voltage security

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1 Introduction

Power industry has experienced restructuring during the past two decades. While this restructuring process has resulted in establishment of a competitive environment for energy trade, preserving the system security has remained as administrative role taken care by system operator. To support system security, services other than energy, specified as ancillary services, are required. Among these services, reactive power management is very essential to support power system security and preserve voltage stability. Reactive power has dominant effects on real energy transfer and it can support the secure operation of the system as an ancillary service. However, most researches have focused on active power market as the main good transacted in electricity markets.

In stressed power systems, in which the transmission lines are heavily loaded, voltage stability margin becomes very small. As a result the system may become vulnerable to voltage collapse when the reactive power is not supported properly. Hence, maintaining the system security can be one of the main concerns for market operators and participants. On the other hand, to ensure the availability of ancillary services, the providers of such services should be paid properly. Furthermore, reactive power can dominantly affect the energy market clearing price. The supply and demand of system should be balanced in real time by dispatching generation in the most economic way taking into account all physical constraints.

Various investigations have been carried out to find the most economic solution for the problem. The spot pricing theory has been developed by Schweppe et al. [1] based on the principle of marginal cost in a perfectly competitive market in 1988. Strbac et al. [2] have proposed a new method for evaluating the optimal balance between preventive and corrective security actions. In [3,4] Rosehart et al.

have applied Multi-objective Optimal Power Flow (MOPF) to compute the cost of voltage security. Milano et al. [5] have presented the effect of voltage security on available transfer capability and nodal congestion prices. Cost-based reactive power pricing considering voltage security has been proposed by Chung et al. [6]. Milano et al. [7] have presented the sensitivity-based technique to estimate power directions in market clearing model of security constrained OPF. In [8,9] the authors have investigated the design and operation of reactive power market at voltage control area. A competitive reactive power scheme in electricity markets considering voltage security has been presented by EI-Araby and Yorino [10]. In [11], to evaluate the system security price, the authors have applied the MOPF problem for maximization of social benefit as well as the voltage stability margin. In [12], El-Samahy et al. have proposed a reactive power market model, in which the reactive power social advantage is maximized considering system security and bids from service providers. Kuo et al. [13] have proposed a multi objective formulation, named normalized weighting method, for the reactive power and voltage control in a distribution system. Khajjayam and Feliachi [14] have presented a nonlinear multi-objective optimization problem for using the reactive support Static VAr Compensator (SVC).

In some of the aforementioned references, an optimization procedure is employed to tackle the voltage security constrained (VSC) problem. As we know, in multi-objective function, the value of weighting factors plays an important role in the process of optimization and the obtained solution. However, the effect of these factors is not discussed properly so far, especially regarding the reactive market power. So, determining the suitable range for these factors so that the social welfare and security margin to be maximized and reactive market power is avoided is our main concern in this paper. Accordingly, this paper proposes a new method for voltage-stability-constrained market-based study with consideration of reactive market power (HHI). In our method, for determining the appropriate values of weighting factors a new approach has been developed. Thereby the reactive market power index has been utilized in assigning suitable margins to these weighting factors. Therefore, while the objective function is satisfied, the competitiveness of the market is also preserved.

In order to implement the voltage-stability-constrained market-based pricing method of this paper, the bid prices have to be provided. As the market participant' offers are based on marginal costs, at first the cost-based pricing approach is examined and a reasonable bid price for active and reactive power is provided. Then according to these bid prices, the VSC problem is solved. So this paper mainly focuses on the effects of electricity pricing on reactive market power using a multi objective OPF in which both active and reactive power markets are considered simultaneously. It is worth mentioning that, in most studies in which the reactive power price is required, a percentage of bid prices of active power is used as an estimate for reactive power price [13], thus leading to approximate pricing. In contrast in this study, the cost-based pricing approach is used for both active and reactive power.

The presented paper is organized in five sections. The procedure of the voltage-stability-constrained market-based pricing is discussed in details in Sect. 2. In Sect. 3, the proposed model is fully described with the aid of solution algorithm. The simulation results are demonstrated in Sect. 4. The conclusions that can be drawn from this paper are presented in Sect. 5.

2 Voltage-stability-constrained market-based pricing

The voltage-stability-constrained optimal power flow (VSC-OPF) is a nonlinear multi objective optimization problem. In this multi-objective optimal power flow (MOPF), the social welfare and the distance to voltage collapse point are simultaneously maximized as shown below:

$$\text{Min} - w_1 \times \text{social welfare} - w_2 \times \lambda_c \tag{1}$$

The objective function consists of both social welfare and maximum loading margin weighted by factors w_1 and w_2, respectively ($w_1 + w_2 = 1,\ w_1 > 0\ ,\ w_2 > 0$). To simplify the optimization problem without losing its generality, it is assumed that $w_1 = (1 - w)$ and $w_2 = w$. Then, for each studied system, w is properly scaled ($0 < w < 1$).

To help the market participants in establishment of reactive power market, this model is modified such that it includes the reactive power costs:

$$\text{Min} - w_1 \left(C_{\mathrm{D_P}}^T P_\mathrm{D} + C_{\mathrm{D_Q}}^T Q_\mathrm{D} - C_{\mathrm{S_P}}^T P_\mathrm{S} - C_{\mathrm{S_Q}}^T Q_\mathrm{G} \right) - w_2 \lambda_c \tag{2}$$

where P_S and P_D represent bounded supply and demand active power bids in MW; $C_{\mathrm{S_P}}$ and $C_{\mathrm{D_P}}$ are bid prices for active power supply and demand in \$/MWh; $C_{\mathrm{S_Q}}$ and $C_{\mathrm{D_Q}}$ represent vectors of supply and demand bids for reactive power in \$/MVArh, and Q_G stands for generated reactive power in MVAr. The subscript c in this objective function represents the system at limit or "critical" conditions associated with the maximum loading margin λ_c.

The constraints for the problem are the standard set of equality and inequality constraints, as given below:

$$f(\delta, |V|, Q_\mathrm{G}, P_\mathrm{S}, P_\mathrm{D}) = 0$$
$$f_c(\delta_c, |V|_c, Q_{\mathrm{G_c}}, P_\mathrm{S}, P_\mathrm{D}) = 0$$
$$\lambda_{c_{\min}} \le \lambda_c \le \lambda_{c_{\max}}$$
$$P_{S_{\min}} \le P_\mathrm{S} \le P_{S_{\max}}$$
$$P_{D_{\min}} \le P_\mathrm{D} \le P_{D_{\max}}$$

$$
\begin{aligned}
&Q_{\mathrm{G}_{\min}} \le Q_{\mathrm{G}} \le Q_{\mathrm{G}_{\max}}\\
&Q_{\mathrm{G}_{\min}} \le Q_{\mathrm{G}_{\mathrm{c}}} \le Q_{\mathrm{G}_{\max}}\\
&I_{ij}(\delta, |V|) \le I_{ij_{\max}}\\
&I_{ji}(\delta, |V|) \le I_{ji_{\max}}\\
&V_{\min} \le V \le V_{\max}\\
&V_{\min} \le V_{\mathrm{c}} \le V_{\max}
\end{aligned}
\tag{3}
$$

where the equality constraints represent active and reactive power flow equations. The inequality constraints are loading margin limit, supply and demand bid blocks, limits of reactive power support, and thermal limits and security limits, respectively. V and δ represent the magnitude and angle of the bus voltage; Q_{G_i} stands for the generator reactive power; P_{ij} and P_{ji} represent the power flowing through the lines in both directions; I_{ij} and I_{ji} are line currents in both directions.

The generator and load power directions in the current and maximum loading conditions are defined as follows:

$$
\begin{aligned}
&P_{\mathrm{G}} = P_{\mathrm{G}_0} + P_{\mathrm{S}}\\
&P_{\mathrm{L}} = P_{\mathrm{L}_0} + P_{\mathrm{D}}\\
&P_{\mathrm{G}_{\mathrm{c}}} = \left(1 + \lambda_{\mathrm{c}} + k_{\mathrm{G}_{\mathrm{c}}}\right) P_{\mathrm{G}}\\
&P_{\mathrm{L}_{\mathrm{c}}} = (1 + \lambda_{\mathrm{c}})\, P_{\mathrm{L}}
\end{aligned}
\tag{4}
$$

where P_{G_0} and P_{L_0} represent those parts of generator and load powers not offered to the market, $k_{\mathrm{G}_{\mathrm{c}}}$ is a scalar variable used to distribute the system losses associated only with the solution of the critical power flow equations in proportion to the power injections obtained in the solution process.

Then, the spot prices of active and reactive power can be obtained by applying Karush–Kuhn–Tucker (KKT) conditions.

2.1 Cost-based pricing

Although, in the power market, reactive power plays a very important role in assuring successful transaction of electric energy, in all methods presented so far [14], the bid prices for reactive power have been taken as a percentage of active power bids. In contrast, in our proposed method, the typical values for both supply and demand bid prices of active and reactive power are provided using cost-based approach. Therefore, as compared with previous works, now all market participants will take part in competitive market with reasonable bid prices.

The cost-based active and reactive power pricing is performed using an OPF formulation to minimize active and reactive power production cost. Active and reactive marginal prices are obtained through solving optimal power flow in which a scalar objective function is minimized and equality and inequality constraints are simultaneously observed.

This is a non-linear optimization problem consisting of an objective function and a set of equality and inequality constraints. The objective function corresponds to the cost of active and reactive power production. The 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, active and reactive generation limits, power transfer limits, thermal limits, and security limits, respectively. Theses are defined as follows:

$$
\begin{aligned}
&\text{Min } C_{\text{total}} = \sum_{i=1}^{N_g} [\mathrm{Cost}(P_{\mathrm{G}_i}) + \mathrm{Cost}(Q_{\mathrm{G}_i})]\\
&\text{s.t. } \ f(\delta, |V|, Q_{\mathrm{G}}) = 0\\
&P_{\mathrm{G}_{\min}} \le P_{\mathrm{G}_i} \le P_{\mathrm{G}_{\max}}\\
&Q_{\mathrm{G}_{\min}} \le Q_{\mathrm{G}_i} \le Q_{\mathrm{G}_{\max}}\\
&I_{ij}(\delta, |V|) \le I_{ij_{\max}}\\
&I_{ji}(\delta, |V|) \le I_{ji_{\max}}\\
&|V_i|_{\min} \le |V_i| \le |V_i|_{\max}
\end{aligned}
\tag{5}
$$

where $\mathrm{Cost}(P_{\mathrm{G}_i})$ and $\mathrm{Cost}(Q_{\mathrm{G}_i})$ are active and reactive power cost function, respectively. According to the type of reactive power supply sources, other constraints may be added to the aforementioned formulation. Based on the above optimization problem, the typical values for bid prices of all participants in electricity market are provided.

The cost of reactive power produced by a generator is composed of two components: fixed costs (investment costs) and variable costs. Variable costs consist of operating costs and the opportunity cost. The opportunity cost is imposed on generator because of compulsory reduction of the active power generation due to reactive power production. In most of research in this field, the cost of reactive power is considered as a percentage of active power, which is an approximate method, while in this paper a more accurate method is used to calculate the cost of reactive power. This method is based on our proposed method described in [15] in which the accurate relation between active and reactive power is used to assign a quadratic function for cost function of reactive power support. All various components of reactive power cost including investment cost, operation cost, and opportunity cost have been included in this approach.

3 Description of proposed model

This paper presents a new market-based algorithm for accurate pricing of active and reactive power considering both voltage security and reactive market power. In this algorithm, as previously mentioned, at first the typical bid prices for each market participant are provided using the cost-based pricing approach. Then, assuming these typical values as market bids, the voltage-security-constrained market-based pricing is examined for different values of weighting factors in the multi-objective function of the optimization problem.

As we know, the weighting factors are crucial and play very important role in solution and process of the optimization problem. On the other hand, there is a strong relation between voltage security and reactive market power as a result of its location based nature [16]. Hence, selecting unsuitable value for weighting factors may lead to reactive market power. Therefore, assigning appropriate values to these weighting factors considering reactive market power is highly desirable. However, little attention has been paid to this problem so far. In fact, no significant investigation has been carried out to establish a systematic approach for assigning proper values for weighting factors. Most researches have been focused on trial and error based approach. This paper also proposes a new approach, utilizing reactive market power index, for determining the appropriate margin for these weighting factor.

In this method, the effect of voltage-security-constrained market-based study on reactive market power is examined through the use of a multi objective OPF-based approach in active and reactive power market. To measure reactive market power, HHI is applied. HHI is one of the most common indexes utilized for measuring market power. Based on the values of this index, regions of the system where additional sources of reactive power injection may be required can be determined. In fact, if such a region exists, then, reactive market power is presumed to exist.

The degree of market power increases as system stress increases. This paper also investigates the impact of voltage security and system loading on reactive market power.

3.1 Computing the HHI

Herfindahl–Hirschman Index (HHI) is one of the most common indexes for measuring market power. This index is determined as below [16]:

$$\mathrm{HHI} = \sum_{i=1}^{N} s_i^2 \tag{6}$$

where s_i represents the percentage of market share of each participant and N is the number of market participants. The summation is made over all N participants in a given market, so the degree of local reactive market power for each load bus in the system is determined by this index. Theoretically, the maximum value of HHI equals 10,000 corresponding to the case where there is only one supplier in the market. In such a case, we have a pure monopoly. According to merger guidelines of US department of Justice, the values of HHI less than 3,800 correspond to the unconcentrated market [17].

If HHI is defined based on the entire range of reactive power available to each generator, then the voltage changes due to injections at generator m are obtained from the following equation:

$$\begin{bmatrix} \Delta\theta \\ \Delta V \end{bmatrix} = \left(J^{-1} e_i^{Q}\right) Q_i^{m\arg in} \tag{7}$$

where J is the Jacobian matrix; e_i^Q is a vector of all zeros except for a nonzero in the position corresponding to bus i where reactive power is injected. $Q_i^{m\arg in}$ stands for the reactive power margin at generator m and is defined as the difference between its maximum reactive power capability and its current reactive power output ($Q_i^{m\arg in} = Q_i^{\max} - Q_i^{\mathrm{actual}}$). Computing ΔV_i due to generator m for participant i, s_i can be calculated as follows:

$$s_i = 100 \frac{\Delta V_i}{\sum_{k=1}^{n_g} \Delta V_i} \tag{8}$$

Now, the value of HHI can be computed using equation (6). The value of HHI is increased as $Q_i^{m\arg in}$ decreases. On the other hand, the value of HHI decreases when the number of generators increases.

3.2 Solution algorithm

The flowchart of Fig. 1 shows that how the proposed method can be implemented for determining the value of weighting factors of objective function (Eq. 2) so that the social welfare and voltage stability margin are maximized and market power will not appear. This algorithm is described as follows:

Step 1 The reactive power cost function for all generators is calculated.
Step 2 The optimization problem based on cost-based pricing (Eq. 5) is solved using the active and reactive power cost functions. Based on the obtained results, the typical values for bid prices of all participants in electricity market are provided. Then, both supply and demand will take part in the competitive market based on these prices.
Step 3 The weighing factor is initialized to $\mathrm{w}_2 = 0$, which is the market-based pricing without considering voltage security.
Step 4 The market-based multi-objective optimization problem (Eqs. 2, 4) is solved and acceptable power bids and local marginal prices for all participants are determined for each value of w_2. Also the reactive market power index (Eq. 6) is computed for this case.
Step 5 If $\mathrm{w}_2 = 1$, then the algorithm stops; otherwise, $w_2 = w_2 + \Delta w$ and the procedure returns to Step 4. When the procedure is terminated, the HHI values for all cases are obtained. By using theses values the appropriate range for weighting factor is determined.

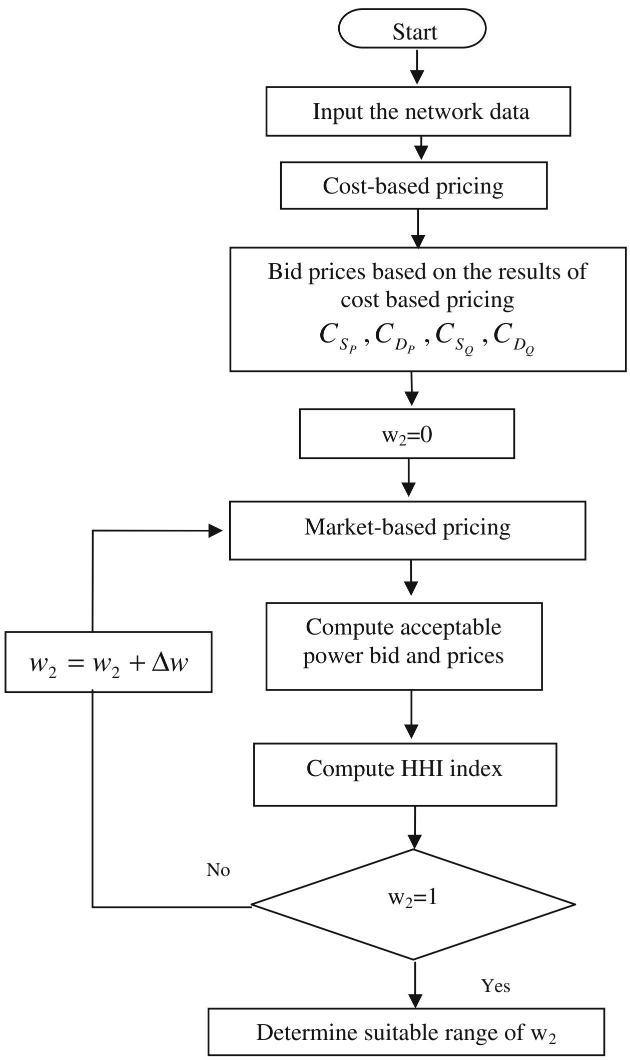

Fig. 1 Flowchart of proposed method

4 Case study

To investigate the validity of the proposed algorithm, the method is applied to IEEE 14-bus test system. The parameters for the test system are given in Table 1. The required data are found in [18].

1. Cost-based pricing The cost-based optimization problem for active and reactive power is solved using Eq. 5. The results are shown in Table 2. According to the obtained results a reasonable base for market participants is provided, so upon this base they (i.e. supply and demand) can participate in market. Therefore, using the cost-based pricing, typical values of bids are presented in Table 3.

2. Market-based pricing In this stage, voltage-stability-constrained optimal power flow is analyzed using typical bid prices obtained in the previous stage (Table 3). Figure 2 shows the effect of weighting factor w on maximum loading margin λ_c for 14 bus system. As expected, it can be observed that higher values of λ_c imply higher security levels.

Table 1 Generators characteristics

No. bus	P_D, MW	Q_D, MVAr	P_G, MW	$Q_{G_{\lim it}}$, MVAr
1	–	–	–	[+50, −40]
2	21.7	12.7	55	[+50, −40]
3	94.2	19	55	[+50, −40]
4	47.8	3.9	–	–
5	7.6	1.6	–	–
6	11.2	7.5	35	[+50, −40]
7	–	–	–	–
8	–	–	35	[+50, −40]
9	29.5	16.6	–	–
10	9	5.8	–	–
11	3.5	1.8	–	–
12	6.1	1.6	–	–
13	13.5	15.8	–	–
14	14.9	5	–	–

Table 2 The results of cost-based pricing

No. bus	ρ_P, \$/MWh	ρ_Q, \$/MVArh
1	12.231	1.313
2	12.232	1.313
3	12.231	1.315
4	12.230	1.32
5	12.230	1.295
6	12.231	1.312
7	12.232	1.311
8	12.232	1.313
9	12.230	1.32
10	12.231	1.315
11	12.233	1.32
12	12.236	1.307
13	12.228	1.323
14	12.238	1.325

Figure 3 shows the accepted supply side bids for active power as functions of weighting factor. The accepted demand side bids are shown in Fig. 4. Referring to these figures, it can be observed that the behavior of active power producers with regards to voltage security level is not similar to each other. When the level of voltage security is increased, some producers reduce their production, while some others increase. On the other hand, in such a situation all buyers do the same behavior. It means that if the level of voltage security is increases, they will reduce their demands.

The accepted bids for reactive power are shown in Fig. 5 as functions of the weighting factor. It is obvious from this

Table 3 Typical values of bid prices

No. bus	$P_{D_{max}}^{bid}$, MW	$P_{G_{max}}^{bid}$, MW	C_{D_P}, \$/MWh	C_{S_P}, \$/MWh	C_{D_Q}, \$/MVArh	C_{S_Q}, \$/MVArh
1	–	20	–	13.5	–	1.33
2	12	15	14.2	12.5	1.44	1.2
3	20	12	13	11.8	1.28	1.21
4	14	–	16	–	1.63	–
5	2	–	11.8	–	1.24	–
6	5	10	13.7	15	1.36	1.48
7	–	–	–	–	–	–
8	–	12	–	12	–	1.11
9	10	–	10.5	–	1.01	–
10	3	–	11.2	–	1.16	–
11	1	–	14.4	–	1.49	–
12	1	–	12.2	–	1.21	–
13	4	–	15.1	–	1.48	–
14	6	–	13.3	–	1.35	–

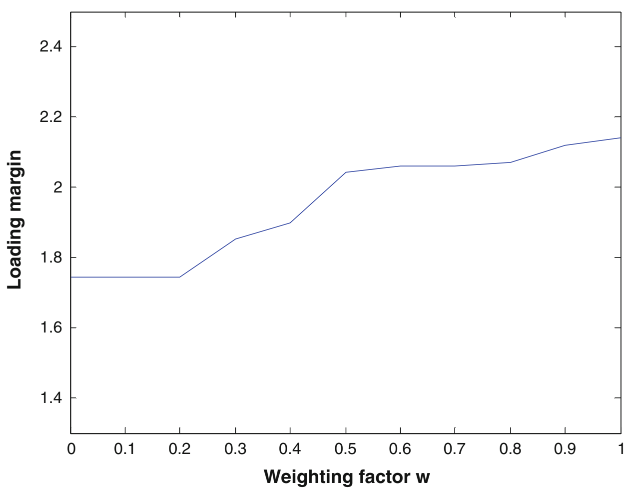

Fig. 2 Loading margin for 14-bus test system

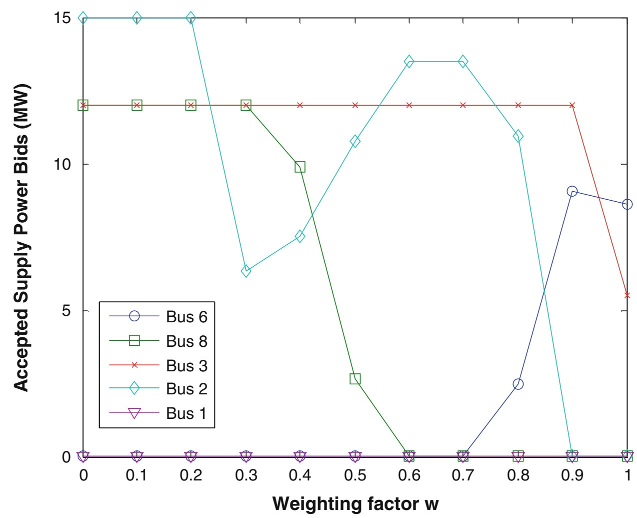

Fig. 3 Accepted supply power bid for 14-bus test system

figure that when the voltage security level reaches its maximum value, all generators will produce their maximum reactive power capacity. The effect of weighting factor on HHI for load buses is shown in Fig. 6. From this figure, it can be concluded that HHI rapidly increases when the security increases. In other words, considering a high-voltage security level (assigning high values for the weighting factor, e.g., 0.9), the system may experience reactive market power. To preserve competition, we should assign smaller values for the weighting factor which in turn implies that voltage security is not our primary concern. Therefore, determining a suitable range of the weighting factor is quite important so that the system requirements are satisfied.

In our example, the suitable range for the weighting factor is approximated to be within [0.4–0.8]. In fact for values smaller than 0.4, the system security is almost ignored and for values higher than 0.8, market power will happen. Since within this range, the HHI is below 3,800, the reactive market power dose not occur, competition is preserved. On the other hand, for weighting factor within this range the importance of at least 40 % and at most 80 % is given to the voltage security. It is also obvious from Eq. 1 in which $w_2\lambda_c$ or $w\lambda_c$ represents the distance to voltage collapse point. Therefore, it means that for lower values of w, less voltage security and for higher values, greater voltage security is provided. It should be mentioned that so far the role of this factor in voltage-security-constrained pricing method has not been investigated.

The proposed method is applied to the test system for $w_2 = w = 0.6$. Table 4 depicts the result for the VSC-market based pricing. It can be observed that, when the security level is increased (i.e. the system is less congested), the

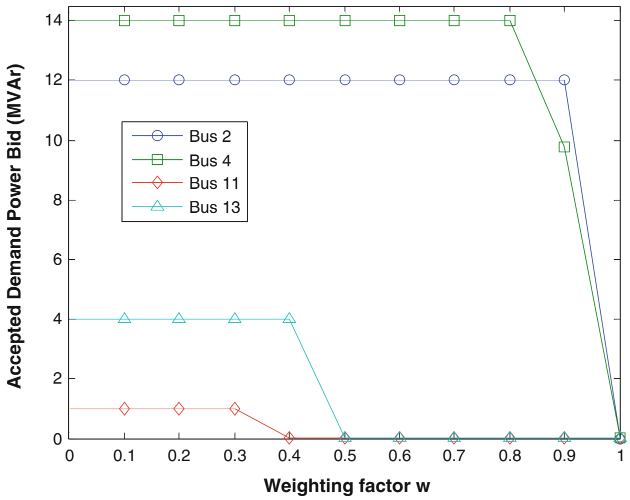

Fig. 4 Accepted demand power bid for 14-bus test system

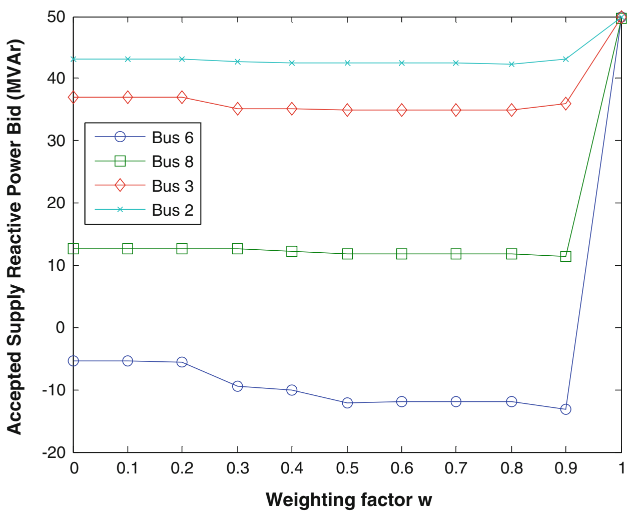

Fig. 5 Accepted supply reactive power bid for 14-bus test system

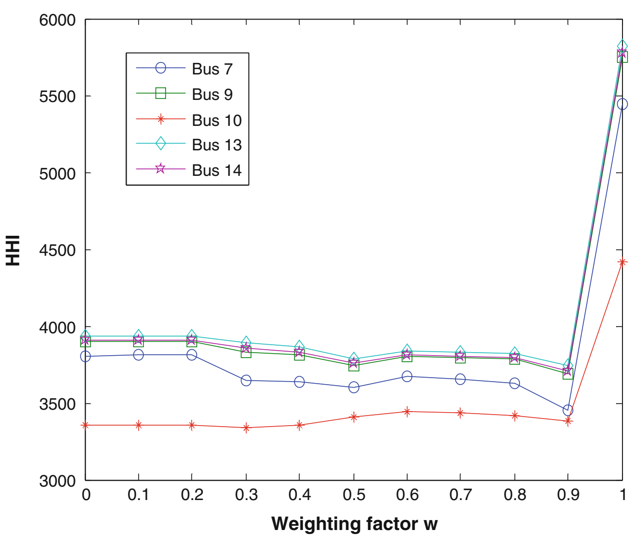

Fig. 6 HHI for load buses in 14-bus test system

Table 4 Simulation result for $w_2 = w = 0.6$

No. bus	P_S, MW	Q_S, MVAr	P_D, MW	ρ_P, \$	ρ_{Q_S}, \$
1	0.001	−13.14	–	4.93	0.52
2	13.47	42.57	12	5.01	0.5
3	12	35.06	0.001	5.16	0.47
4	–	–	14	5.17	0.55
5	–	–	0.001	5.12	0.56
6	0.001	−11.9	0.001	5.13	0.6
7	–	–	–	5.18	0.54
8	0.001	11.8	–	5.14	0.48
9	–	–	0.001	5.22	0.58
10	–	–	0.001	5.23	0.6
11	–	–	0.001	5.20	0.614
12	–	–	0.001	5.22	0.62
13	–	–	0.001	5.24	0.63
14	–	–	0.001	5.34	0.64

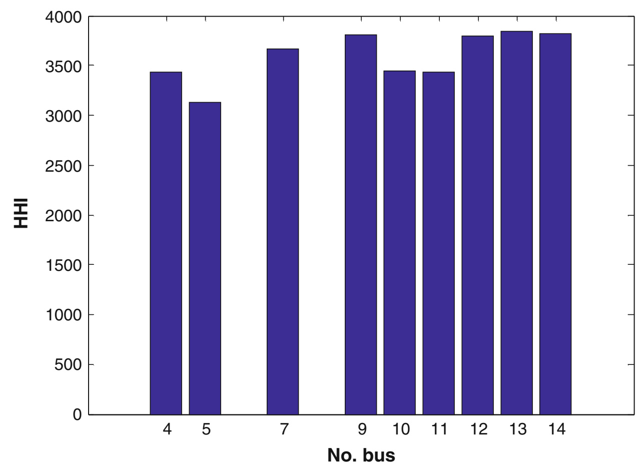

Fig. 7 HHI for each bus in the system in $w_2 = w = 0.6$

local marginal prices of active and reactive power decrease. Figure 7 shows HHI for all buses in the system. As expected, in this situation, there is no reactive market power, so HHI is less than 3,800 and the market is competitive.

5 Conclusion

This paper presents a new market-based algorithm for accurate pricing of active and reactive power considering both voltage security and reactive market power. In this algorithm, first of all, the typical values for bid prices for each market participant are provided using the cost-based pricing approach. Then, assuming these values as a base for market bids, the voltage-security-constrained market-based pricing is examined for different values of weighting factors in the multi-objective optimization problem.

The effect of weighting factor on HHI for load buses is investigated and it has been shown that HHI rapidly increases when the security level increases. Therefore, determining a suitable range for the weighting factor to satisfy system requirements seems to be very important.

This study shows that through the proposed method it is possible to find out a suitable range for weighting factor so that the desired security level is obtained and the competition is not sacrificed.

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