A New Framework for Reactive Power Market Considering Power System Security

A. Rabiee*, H. A. Shayanfar* and N. Amjady**

Abstract: This paper presents a new framework for the day-ahead reactive power market based on the uniform auction price. Voltage stability and security have been considered in the proposed framework. Total Payment Function (TPF) is suggested as the objective function of the Optimal Power Flow (OPF) used to clear the reactive power market. Overload, voltage drop and voltage stability margin (VSM) are included in the constraints of the OPF. Another advantage of the proposed method is the exclusion of Lost Opportunity Cost (LOC) concerns from the reactive power market. The effectiveness of the proposed reactive power market is studied based on the CIGRÉ-32 bus test system.

Keywords: Reactive power market, Expected Payment Function (EPF), Total Payment Function (TPF), Lost Opportunity Cost (LOC).

1 Introduction

One of the main reasons for some of the recently major blackouts in the power systems around the world such as those occurred in September 23, 2003 in Sweden and Denmark, September 28, 2003 and etc. was reported as insufficient reactive power of system resulting in the voltage collapse. So, reactive power is essential for the integrity of the power system and maintaining the system with acceptable margin of the security and reliability [1]-[3].

In recent years, some papers are published in the area of optimal pricing of the reactive power [4]-[9]. All of them assume that the consumer of the reactive power should pay for the reactive power support service and the producers of the reactive power are remunerated. The other works consider technical issues of the power system in addition to economical aspects [10]-[13]. In [14], the authors determine the minimum reactive power (Q_{min}) that each generator needs to transfer its own active power through the power system. The Q_{min} is determined only for the heavily loaded condition.

Kankar Bhattacharya *et al* have designed a competitive reactive power market [15]-[18]. The generator Expected Payment Function (EPF) is defined so that the ISO can easily call for reactive bids from all parties [15]. In [16], a competitive reactive power market is designed for the reactive power ancillary service. Mitigating market power, a localized reactive power market is proposed in [17]. J. Zhong proposed a pricing mechanism for the other components of the reactive power compensator in a competitive market [18].

A few works included voltage security in the reactive power pricing [19]-[20]. In [19], a cost-based reactive power pricing is proposed, which integrates the production cost of reactive power and voltage stability margin requirement of pre- and post-contingencies into the OPF problem. In [20], a two-level framework is proposed for the operation of a competitive reactive power market taking into account system security aspects. The first level, i.e. procurement, is on a seasonal basis while the second level, i.e. dispatch, is close to the real-time operation. In that work, the reactive power procurement is considered as an essentially long-term issue, i.e. a problem in which the Independent System Operator or ISO seeks optimal reactive power “allocation” from possible suppliers that would be best suited to its needs and constraints in a given season [20]. This optimal set should ideally be determined based on the demand forecast and system conditions expected over the season [20]. However, seasonal market for the reactive power encounters problems. First, the reactive power consumption of system is so volatile that its forecasting over a season

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* The Authors are with the Center of Excellence for Power Systems Automation and Operation, Department of Electrical Engineering, Iran University of Science and Technology (IUST)
E-mails: rabiee@iust.ac.ir, hashayanfar@yahoo.com
** The Author is with the Department of Electrical Engineering, Semnan University, Semnan, Iran.
E-mail: amjady@tavanir.org.ir

becomes very hard. Second, the reactive power requirement of the system strongly depends on the loading condition of network which further complicates the prediction of the reactive power requirement of the power system over a long horizon. Third, the occurrence of different planned/unplanned outages and effects of maintenance scheduling (such as generators and transmission lines entering to circuit after their maintenance period) in a season can change the configuration of the power system, leading to more complexity of designing a seasonal reactive power market. Fourth, over the long time of a season, the ISO can handle the reactive power requirements of the system only with the selected generators of the network that have contract with them to become available for reactive power compensation which is to some extent in contradiction with the local nature of the reactive power. Accordingly, as one of the paper contributions, this paper presents a day-ahead reactive power market model which considers power system security.

Another contribution of the paper is the elimination of LOC from the EPF of synchronous generator in the reactive power market. The maximum reactive power output of a synchronous generator is limited by its capability curve and if a generator in the reactive power market is required, by the ISO, to generate reactive power more than the respective limit, it must decrease its active power to adhere the capability curve. Thereby, the generator will be compensated for the lost of revenue termed as the LOC. This active power reduction of generator however, is associated with the re-scheduling of generating units to balance the load demand of the system. In this paper, a new framework for reactive power market is proposed in such a way that the generators no longer be required to reduce their active power during the settlement of reactive power market.

2 The Proposed Method

In this section, inspiring with the generator Expected Payment Function (EPF) proposed in [16], a new EPF for is proposed. The reactive power capability curve of a generator is shown in Fig. 1. The explanation to Q_{base}, Q_A, Q_B can be found in [16].

The offer structure of the i^{th} synchronous generator in the reactive power market is formulated as the following equation [16]:

$$EPF_i = a_{0,i} + \int_{Q_{Min}}^{0} m_{1i}\,.dQ_i + \int_{Q_{base}}^{Q_A} m_{2i}\,.dQ_i + \int_{Q_A}^{Q_B} m_{3i}\,.Q.dQ_i \tag{1}$$

The coefficients in Eq. (1) represents the various components of the reactive power cost incurred by the i^{th} unit where a_0 is availability price offer in dollars, m_1 is cost of loss price offer for operating in under excited mode ($Q_{min} < Q \leq 0$) in \$/MVAr-h, m_2 is cost of loss price offer for operating in region ($Q_{base} \leq Q \leq Q_A$) in \$/MVAr-h and m_3 is opportunity price offer for operating in region ($Q_A \leq Q \leq Q_B$) in \$/MVAr-h/MVAr-h (Fig. 2). $a_{0,i}$, $m_{1,i}$, $m_{2,i}$, and $m_{3,i}$ are the bid values of the i^{th} provider for the reactive power market. The opportunity cost is a quadratic function of Q (Fig. 2).

The reactive power is cleared based on the minimization of the total payment to the participants of the reactive power market as [16]:

$$TPF = \sum_{i \in gen} \begin{pmatrix} \rho_0\,.W_{0,i} - \rho_1\,.W_{1,i}\,.Q_{1,i} + \rho_2\,.W_{2,i}\,.Q_{2,i} \\ + \rho_2\,.W_{3,i}\,.Q_{A,i} + \dfrac{1}{2}\rho_3\,.W_{3,i}\,.Q_{3,i}^2 \end{pmatrix} \tag{2}$$

According to Eqs. (1) and (2), the generator receives the opportunity cost by entering to region III where, the generator will be required to reduce its active power in order to meet the system reactive power requirement. Accordingly, a re-schedule of active power dispatch will be required to compensate for the corresponding real power deviation from the dispatched values which are fixed and determined earlier in the energy market [20], [21]. The lost opportunity is a challenging issue in the reactive power markets. Our proposed solution for this problem is the elimination of LOC from the reactive power market design while considering the capability curve limits of the generators. The active power of each generator is determined in the energy market and is used as the input data in the reactive power market.

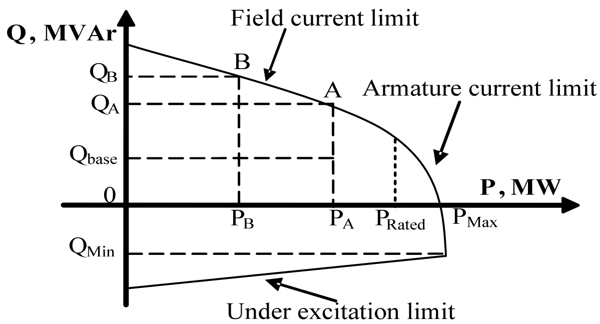

Fig. 1. Synchronous generator capability curve

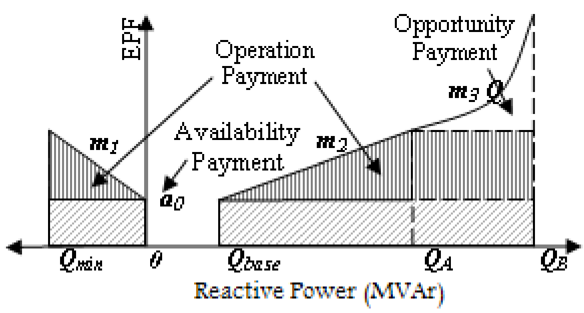

Fig. 2. Reactive power offer structure of provider

Suppose that the active power of a unit be P_{g0} as shown in Fig. 3. If this unit produces reactive power more than Q_{g0} then it enters into region III. The value of Q_{g0} is determined by the field current limit if P_{g0} is lower than P_{GR}, and by the armature current limit if P_{g0} is greater than P_{GR}. P_{GR} is the intersection of field current and armature current limit curves (MVA rating of the generator [16]). In the reactive power market, if the maximum reactive power production of the unit is limited to Q_{g0}, then the unit never enters into region III. Hence, deviation from the active power dispatch of the energy market and consequent rescheduling of the generating units no longer is required. As another result, the LOC payment will be eliminated form the TPF of the reactive power market. In this work, avoiding from entering to region III and dealing with its associated problem, the maximum reactive power production of each unit is limited to its Q_{g0}, i.e. $Q \le Q_{g0}$ where, Q is the reactive power output of the generator.

The main advantage of the proposed solution is the elimination of active power re-dispatch in addition to the elimination of the lost opportunity cost from the reactive power market. Another advantage of the proposed method is that the EPF of the generator just includes the availability and cost of losses component and the quadratic part of EPF related to the LOC is removed, changing the EPF from nonlinear to linear which is easier to solve. So, the EPF of generator in the new framework can be written as follows.

$$EPF_i = a_{0,i} + \int_{Q_i}^{0} m_{1i}\,.dQ_i + \int_{Q_{base,i}}^{Q_i} m_{2i}\,.dQ_i \tag{3}$$

Fig. 4 shows the EPF of the proposed framework for reactive power market. Form this figure it can be observed that the EPF is a linear function. Furthermore, it can be seen that the generator can produce reactive power ultimately up to its Q_{g0}. The modified TPF can be mathematically formulated as follows:

$$TPF = \sum_{i\in gen} \begin{pmatrix} \rho_{0,i}\,.W_{0,i} - \rho_1\,.W_{1,i}\,.Q_i + \\ \rho_2\,.W_{2,i}\,.\left(Q_i - Q_{base,i}\right) \end{pmatrix} \tag{4}$$

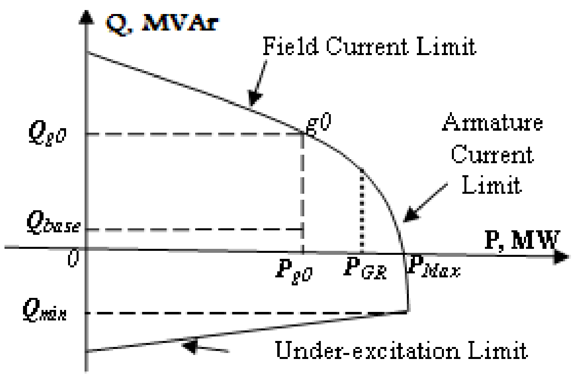

Fig. 3. Synchronous generator capability curve

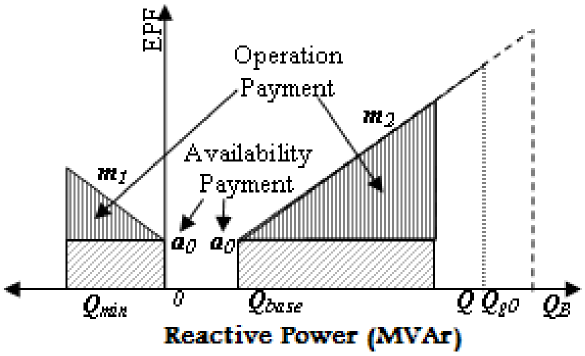

Fig. 4. EFP of new reactive power market framework

The binary variables $W_{0,i}$ $W_{1,i}$, $W_{2,i}$, in Eq. (4) have similar description to Eq. (2). If the i^{th} provider is selected in the reactive market and operated in one of the regions I, II then $W_{1,i}+W_{2,i}=1$, otherwise $W_{1,i}+W_{2,i}=0$. ρ_0, ρ_1, ρ_2 in Eq. (4) are also similar to Eq. (2). The new TPF shown in Eq. (4) is the objective function of the OPF problem, which should be solved for clearing of the reactive power market.

3 Market Settlement

Clearing of the reactive market in the form of the OPF is formulated as follows:

$$\text{Min} \sum_{i\in gen} \left(\rho_{0,i}\ W_{0,i} - \rho_1 W_{1,i}\, Q_i + \rho_2 W_{2,i}\,(Q_i - Q_{base})\right) \tag{5}$$

Subject to the following constraints:

1) Load flow constrains:

$$P_{gk} - P_{dk} = \sum_j V_k V_j Y_{kj} \cos\left(\delta_k - \delta_j - \theta_{kj}\right) \tag{6}$$

$$Q_{gk} - Q_{dk} = \sum_j V_k V_j Y_{kj} \sin\left(\delta_k - \delta_j - \theta_{kj}\right) \tag{7}$$

$$\hat{P}_{gk} - \hat{P}_{dk} = \sum_j \hat{V}_k \hat{V}_j Y_{kj} \cos\left(\hat{\delta}_k - \hat{\delta}_j - \theta_{kj}\right) \tag{8}$$

$$\hat{Q}_{gk} - \hat{Q}_{dk} = \sum_j \hat{V}_k \hat{V}_j Y_{kj} \sin\left(\hat{\delta}_k - \hat{\delta}_j - \theta_{kj}\right) \tag{9}$$

where

k, j	The buses indices
P_{gk}	Active power generation at bus k in per unit at current operating point
P_{dk}	Active power demand at bus k in per unit at current operating point
Q_{gk}	Reactive power generation at bus k in per unit at current operating point
Q_{dk}	Reactive power demand at bus k in per unit at current operating point
V	Voltage magnitude at current operating point
δ	The angle of voltage at current operating point
^	A symbol indicating security loading point
Y_{kj}	Magnitude of element k and j of admittance matrix
θ_{kj}	The angle of element k and j of network admittance matrix

2) The operation constraints of generators:

$W_{0,i}, W_{1,i}, W_{2,i} \in \{0,1\}$ i: The unit index (10)

$$Q_{min,i} \le W_{1,i} \cdot Q_i \le 0 \quad (11)$$

$$W_{2,i} \cdot Q_{base,i} \le W_{2,i} \cdot Q_i \le Q_{g0,i} \quad (12)$$

$$W_{1,i} + W_{2,i} \le W_{0,i} \quad (13)$$

$$Q_{\min,i} \le Q_i \le Q_{g0,i} \quad (14)$$

$$Q_{g0,i} = \begin{cases} \sqrt{(V_{t,i} I_{a,i})^2 - P_{g0,i}^2} & if \;\; P_{g0,i} > P_{GR,i} \\ \sqrt{\left(\dfrac{V_{t,i} E_{af,i}}{X_{s,i}}\right)^2 - P_{g0,i}{}^2} - \dfrac{V_{t,i}^2}{X_{s,i}} & \\ & if \; P_{g0,i} < P_{GR,i} \end{cases} \quad (15)$$

where $P_{g0,i}$ is the i^{th} unit active power generation determined earlier in the active power market and $P_{GR,i}$ is the intersection of the field current and armature current limit curves (MVA rating of the generator).

3) Constraints related to market price determination:

$$W_{0,i} \cdot a_{0,i} \le \rho_0 \quad (16)$$

$$W_{1,i} \cdot m_{1,i} \le \rho_1 \quad (17)$$

$$W_{2,i} \cdot m_{2,i} \le \rho_2 \quad (18)$$

4) Security constrains:

$S_{b,i} \le S_{b,i}^{\max}$ (Overload constraint, $S_{b,i}$ is the apparent power of branch i at current operating point) (19)

$V_k^{min} \le V_k \le V_k^{max}$ (Voltage drop constraint at current operating point) (20)

$VSM \ge VSM^{spec}$ (VSM constraint) (21)

($\lambda \ge \lambda_{min}$) (Voltage security margin constraint) (22)

$$\hat{P}_{gk} = (1 + \lambda + k_G) P_{gk} \quad (23)$$

where, the variable K_G represents the unknown losses for the security power flow Eqs. (8) and (9) [22].

$$\hat{P}_{dk} = (1 + \lambda) P_{dk} \quad (24)$$

$$\hat{Q}_{dk} = (1 + \lambda) Q_{dk} \quad (25)$$

$\hat{S}_{b,i} \le S_{b,i}^{max}$ ($\hat{S}_{b,i}$ indicates apparent power of the i^{th} branch at security loading point) (26)

$V_k^{min} \le \hat{V}_k \le V_k^{max}$ (Voltage drop constraint at security loading point) (27)

When the i^{th} reactive power provider is not selected or is selected and operated in one of regions I, II then the constraint (13) will be satisfied in the equality form (*0=0* and *1=1*, respectively). However, when the i^{th} provider is selected for the reactive reserve then this constraint will be satisfied in the inequality form (*0 < 1*). Equation (14) indicates that the reactive power generation of each unit should not be more than $Q_{g0,i}$ which is determined by (15), reflecting the capability curve limit of each unit and avoiding from entering to region III. Under certain loading condition, some generators may be asked to supply reactive power in region III, in which case, the generators will be required to reduce their active power in order to meet the system requirement. Consequently, a re-scheduling of their active power dispatch will be required to compensate for this real power deviation from the already dispatched values. Equation (14) however, solves this problem with another method. In this method the generators are allowed to produce reactive power no more than the Q_{g0} of units determined by Eq. (15). The lack of the reactive power of the system is compensated by the increase of reactive power output of other nearby units not reaching the capability curve limit. In other words, instead of entering a unit into the nonlinear region III, reactive output of a number of units is increased in the linear region II to meet the reactive power requirement of the system. Therefore, by the proposed method, reactive power settlement no longer requires active power re-dispatch.

Equations (19) to (27) include security constraints at the current operating point, i.e. Eq. (19) and Eq. (20), VSM constraint, i.e. Eq. (21), voltage security constraints, i.e. Eq. (22) to Eq. (25), and constraints of the security loading point, i.e. Eq. (26) and Eq. (27). From Eq. (22) it can be observed that voltage security margin should be greater than the specified value [22]. For this purpose, there should be enough distance between the current operating point and the voltage collapse point. In the steady state voltage stability studies, the P-V curve, as shown in Fig. 5, has been generally used and its nose point considered as the system voltage collapse point. However, in the literature it has been shown that in the systems with inconstant-power loads, the real voltage collapse point is the SNB of the bifurcation curve (or point B'' on P-V curve in Fig. 5) instead of the nose point (NP) of P-V curve (point B') [23]. Nevertheless, when all the loads are constant-power type, nose point just coincides with the saddle point node [24]. It should be mentioned that in this work the loads are assumed to be constant-power type.

Referring to Fig. 5 as a typical P-V curve of a power system, the Voltage Stability Margin (VSM) value is the horizontal distance between the current operating point (B) and the voltage collapse point (B'). The VSM in the load domain (λ) indicates the power system maximum load-ability in terms of voltage stability. In other words, the constraint of the voltage stability restricts the increment of loading level of the power system and the VSM demonstrates its related upper limit in the load domain [25]. Accordingly, the VSM index which is used in this work will be as the following equation:

$$VSM = \frac{MVA^L - MVA^N}{MVA^N} = \frac{MVA_{(B')} - MVA_{(B)}}{MVA_{(B)}} \quad (28)$$

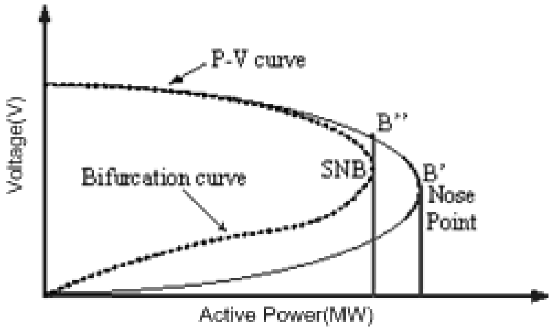

Fig. 5. Bifurcation and P-V curves of an inconstant-power load.

In Eq. (21), VSM^{spec} indicates specified value of the VSM. Considering a broader viewpoint, in Fig. 6 both voltage security margin and VSM are shown. The security loading point refers to the maximum allowable load increment at which overload and voltage drop constraints, indicated in Eq. (26) and Eq. (27), are satisfied. The voltage security margin is the distance between the current operating point and security loading point (Fig. 6).

The conventional voltage stability indices, like Eq. (28), indicate the stability border at which the power system has stable solution without considering the quality of the operating point. Besides, the operator usually determines a proper voltage range, as shown in Fig. 6, in order to keep high quality voltages and to prevent the electric power devices from damages in addition to active power losses reduction [26]. In other words, the security constraint should be satisfied not only at the current operating point but also at the system security loading point (Fig. 6).

The inequality constraints Eqs. (21) and (22) show the VSM constraint and voltage security constraint, respectively. Both VSM and λ have been implemented by using the continuation curve. The continuation curve in this paper is obtained by the well-known predictor/corrector mechanism. Details of this mechanism can be found in [27]. According to Fig. 6 of the paper, security loading point (λ) is the intersection of horizontal line V_{min} with the continuation curve. It is noted that the load increase scenario of loads and generation increase scenario of the generating units in continuation curve, is based on the equations Eq. (23) to Eq. (25) of the paper.

The above formulation from Eq. (5) up to Eq. (27) shows a mixed integer nonlinear programming (MINLP) optimization problem. It should be noted that in this work, the variation of active power losses of transmission lines due to the reactive power adjustments is ignored and so the outputs of the active power dispatch (obtained from the energy market) can be assumed constant during the clearing of reactive power market.

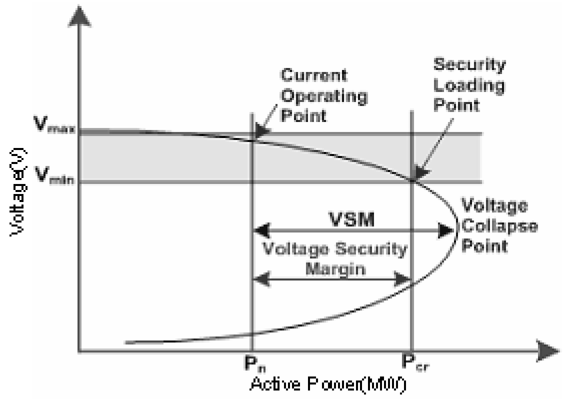

Fig. 6. Representation of current and security loading points

4 Results

The proposed reactive power market framework is examined on the well-known CIGRÉ-32 bus test system [28], shown in Fig. 7, and compared with the framework presented in [16]. The test system is separated to three voltage-control areas using the concept of electrical distance [17], resulting in the localized reactive power market. In the previous method, the participants of reactive power market are supposed to submit their four components of offer prices (a_0, m_1, m_2, m_3).

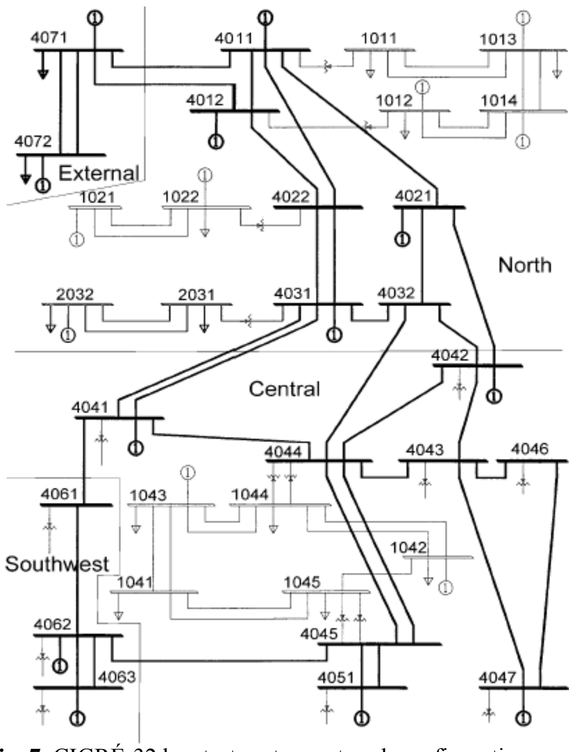

Fig. 7. CIGRÉ-32 bus test system network configuration.

Synchronous condensers are participated in the reactive power market with their opportunity cost (m_3) equal to zero as well. In the new framework however, the participants should submit (a_0, m_1, m_2) and the component of LOC offer price, i.e. m_3 is not needed. In this examination, a uniform random number generator is used to simulate the offer prices of generators shown in Table 1 [16]. It should be noted that the price components for the cost of losses (m_1, m_2) are assumed to be equal ($m_1 = m_2$). According to the pervious method, the participants are also required to send their Q_{base}, Q_A and Q_B (Fig. 1). Like [16], it is assumed that $Q_B = Q_{max}$, $Q_{base} = 0.10*Q_{max}$ and $Q_B = 1.5*Q_{g0}$ ($Q_B = 1.5*Q_A$). The lower and upper bounds of voltage are taken 0.95 pu and 1.05 pu, respectively. The power flow limits of all transmission lines are simply based on their voltage rating (2000 MVA for 400 kV lines, 350 MVA for 220 kV, and 250 MVA for 130 kV [21]).

Table 1. Reactive power offer Prices of participants and MCPs for the 3rd case of the new framework

Zone	Bus No	Unit No	a_0	m_1, m_2 m_1=m_2	m_3	MCPs of the 3rd Case
a	4071	1	0.4	0.41	0.20	ρ_0 = 0.96 ρ_1 = 0.59 ρ_2 = 0.86
	4011	1	0.77	0.75	0.25	
		2	0.82	0.85	0.29	
	1012	1	0.76	0.81	0.37	
		2	0.45	0.72	0.39	
	1013	1	0.65	0.59	0.21	
	1014	1	0.93	0.89	0.40	
	4072	1	0.96	0.86	0.46	
		2	0.84	0.86	0.45	
		3	0.73	0.69	0.39	
		4	0.76	0.65	0.41	
	4012	1	0.43	0.41	0.19	
		2	0.43	0.53	0.21	
b	1021	1	0.92	0.54	0.55	p0 = 0.92 p1 = 0.00 p2 = 0.99
	1022	1	0.50	0.58	0.25	
	4021	1	0.48	0.54	0.28	
	2032	1	0.88	0.80	0.39	
		2	0.65	0.68	0.22	
	4031	1	0.50	0.42	0.17	
	4042	1	0.69	0.68	0.39	
		2	0.43	0.54	0.28	
		3	0.47	0.62	0.28	
	4041	1	0.91	0.99	0.00	
c	1043	1	0.77	0.69	0.37	p0 = 0.92 p1 = 0.00 p2 =0.89
	1042	1	0.50	0.50	0.26	
		2	0.55	0.57	0.23	
	4062	1	0.85	0.85	0.45	
		2	0.49	0.68	0.31	
		3	0.53	0.68	0.31	
	4063	1	0.90	0.97	0.42	
		2	0.92	0.89	0.42	
	4051	1	0.73	0.79	0.44	
		2	0.78	0.78	0.44	
	4047	1	0.73	0.86	0.31	
		2	0.75	0.85	0.32	

4.1. Clearing of the Previous Method and the Proposed Method

The clearing of the proposed reactive power market framework is a MINLP problem. The model is solved in generalized algebraic modeling systems (GAMS), which is a high level programming platform, using the DIscrete COntinous OPTimization (DICOPT) solver on a Pentium IV, 512 MB RAM computer. The obtained results of the framework of [16] are shown in Table 2. The generator of bus 4021 in zone (b) enters to region III and is paid 695.88 ($) for LOC which is equal to 19.68% of TPF.

In addition to the LOC payment, a re-dispatch of energy market is also needed to compensate the decrease in the output of unit 4021 and balance the load of the system, which in turn imposes an additional payment to the system operator. In the proposed framework, both the voltage security margin and VSM (Fig. 6) are considered in the reactive power market. The lower limit of VSM (VSM^{spec}) is considered 10%. To represent the effect of VSM and voltage security margin on the TPF of reactive power market, three cases are considered. In the first case, the security constraints are exclusively considered at the current operating point. Neither voltage security margin nor VSM constraints are included in this case. In other words, only (19) and (20) from the security constraints are included in this case. In the second case, only the VSM constraint, i.e. (21), is added to the constraints of the first case. Finally, in the third case the security constraints at security loading point, i.e. (25) and (26) are also taken into account. The results of the three cases are shown in Table 3 and compared with the results of the framework given in [16].

Table 2. Results of the framework in [16]

Zone	ρ_0	ρ_1	ρ_2	ρ_3	LOC Payment	TPF
(a)	0.96	0.89	0.86	-	-	833.97
(b)	0.92	-	0.99	0.28	695.88($)	1479.72
(c)	0.92	-	0.97	-	-	1220.98
Total payment			3534.67($)			

Table 3. Results of the proposed framework in three cases and framework of [16]

		VSM^{spec}	Security Loading Point	Total Payment	VSM (%)	Execution Time (Sec)
Previous Method [16]		-	-	3534.7	7	15.7
Proposed Method	1st Case	-	-	2518.2	8	25
	2nd Case	10%	-	2539.2	12.38	26.5
	3rd Case	10%	6%	2751.89	16.79	32.8

According to this Table, the second case has more cost than the first one since in the second one, the *VSM* constraint should be also satisfied. The third case has more cost than the two previous cases due to additionally satisfying the constraints of the security loading point, i.e. the security margin constraint (Fig. 6). Therefore, it is concluded that, the ISO should charge more in the reactive power market for the purpose of having enough reactive support in the system and correspondingly maintaining the system security constraints at the specified levels. Table 4 shows the optimal solution of the new framework for the 3rd case, indicating status of each unit in the reactive power market, the amount of the reactive power output of each unit and also the payment of each unit.

Table 4. Optimal solution of the new framework for the 3rd Case

Zone	Bus No	Unit No	W_0	Qg (MVAr)	Payment ($)
a	4071	1	1	25.0	0.96
	4011	1	1	168.0	128.24
		2	1	221.3	165.46
	1012	1	1	15.0	0.96
		2	0	-	0.00
	1013	1	1	-15.0	9.81
	1014	1	0	-	0.00
	4072	1	1	135.7	91.86
		2	1	135.7	91.86
		3	1	119.7	86.67
		4	1	119.7	86.67
	4012	1	1	102.7	67.77
		2	1	78.3	55.36
b	1021	1	1	15.8	0.92
	1022	1	1	93.0	80.61
	4021	1	1	110.0	94.97
	2032	1	1	79.7	55.07
		2	1	66.1	49.03
	4031	1	1	125.4	107.74
	4042	1	1	259.3	222.98
		2	0	-	0.00
		3	0	-	0.00
	4041	1	1	244.7	213.47
c	1043	1	0	-	0.00
	1042	1	1	125.4	94.73
		2	0	-	0.00
	4062	1	1	233.8	182.30
		2	0	-	0.00
		3	0	-	0.00
	4063	1	0	-	0.00
		2	1	215.2	165.75
	4051	1	1	247.4	189.95
		2	1	247.4	182.95
	4047	1	1	212.0	162.90
		2	1	212.0	162.90
Total				**3593.3**	**2751.89**

From this Table it can be observed that some units (unit#1 of bus#1012 for example) are participated by the ISO in the reactive power market to have enough reactive reserve. These units are just paid for the availability payment and their reactive power output will be ultimately up to their Q_{base}. Also in the last column of Table 1, MCP of each component of the bid (ρ_0, ρ_1, ρ_2) for each zone of the network is taken.

4.2. Comparison of the Previous Method with the Proposed Method

In the proposed method, in addition to simply clearing of the reactive power market without any LOC payment, the ISO can clear the reactive power market based on the desired voltage stability and security margins by the proposed method. Comparing the results of the previous method with the proposed one, even in the case three, the ISO payment to the participants of the reactive power market is lower than the pervious method (as shown in Table 3). According to Table 3, the value of the TPF in the 3rd case of the proposed method is 2751.89 dollars which is $782.81 lower than the TPF of previous method ($3534.7). This is due to the fact that, the LOC payment, which is a quadratic function of Q and thereby includes high cost, is omitted from the TPF; leading to the lower payments in the reactive power market. These are the main advantages of the proposed method that can clear the reactive power market in a simpler and more transparent manner with lower total payment while considering the security of the power system. The LOC elimination from TPF makes the TPF to a simple linear objective function which totally could decrease the nonlinearity of the OPF problem (market clearing procedure). Besides that, the active power dispatches of generating units are not changed during the settlement of the reactive power market, which is another advantage of the proposed framework. It is observed that the voltages of all buses in both current and security loading points are in the given boundaries and the voltage drop and overvoltage concerns are relieved. Moreover, the lines flows of the network are less than their continuous MVA rating in the current and security loading points.

5 Conclusions

This paper proposes a new framework for the reactive power market. The TPF presented earlier in the literature are modified in such a way that it no longer includes the quadratic term related to the LOC payment, resulting in a linear objective function which is easier to optimize in comparison with the previous framework. Besides, the proposed method includes both voltage stability and security concerns of the power system. In other words, in the new framework, the ISO can clear the reactive power market at the specified levels of the VSM and voltage security margin. The other important advantages of the proposed method are the lower payment of the ISO to the participants of the reactive power market, and clearing the reactive power market without changing the active power output of the generating units determined in the energy market.

Instead of seasonal procurement model, in this paper a day-ahead reactive power market model is proposed. The long-terms (seasonal) contracts for reactive power procurement would likely reduce the possibility of exercising market power by generators, and could mitigate the problem of price volatility, which may arise when reactive power services are priced on a real-time (day-ahead) basis. On the other hand, in the long-term procurement of reactive power, the optimal set of generators should ideally be determined based on the reactive power demand forecast and system conditions expected over the season that encounter some serious problems mentioned in section I (introduction) of the paper. Considering the problems of seasonal procurement model for the reactive power, in a trade off between seasonal and day-ahead model, in this paper a day-ahead reactive power market model is proposed.

The proposed reactive power market framework deserves to more explanation in cases that system strongly requires to the reactive power of a special unit for any reason but it cannot be produced by that unit due to the capability curve limit. In this case, the reminder of the required reactive power should be produced by the other participants of the reactive power market not reaching to their capability curve limits. If no local participant can be found in this case, the required reactive power should be produced by remote units, which in heavy load conditions might lead to increase the losses of the system and overload lines. Nevertheless, this disadvantage can be alleviated by extending the participants of the reactive power market to the other sources of reactive power like FACTS devices and fast switching capacitor banks. This remedy will be assessed in the future work.

6 References

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Abdorreza Rabiee received his B. Sc. and M. Sc. degrees in Electrical Engineering in 2002 and 2004 from Shahid Chamran University of Ahwaz and Iran University of Science and Technology (IUST), respectively. Currently he is pursuing his PhD degree at IUST in electrical engineering. His research interests include distribution systems, power system economics and optimization.

Heidar Ali Shayanfar received his B.S. and M.S.E. degrees in Electrical Engineering in 1973 and 1979 and the PhD degree in Electrical Engineering from Michigan State University, U.S.A., in 1981. Currently, He is a Full Professor in Electrical Engineering Department of IUST, Tehran, Iran. His research interests are in the application of Artificial Intelligence to power system control design, dynamic load modeling, power system observability studies and voltage collapse. He is a member of Iranian Association of Electrical and Electronic Engineers (IAEEE) and IEEE.

Nima Amjady (M'97) was born in Tehran, Iran, on February 24, 1971. He received the B.Sc., M.Sc., and Ph.D. degrees in electrical engineering from Sharif University of Technology, Tehran, in 1992, 1994, and 1997, respectively. At present, he is a Professor with the Electrical Engineering Department, Semnan University, Semnan, Iran. He is also a Consultant with the National Dispatching Department of Iran. His research interests include security assessment of power systems, reliability of power networks, load forecasting, and artificial intelligence and its applications to the problems of power systems.