Fair Clearing of Reactive Power Market

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ABSTRACT
In this paper, new reactive power market structure is studied and presented. In this paper, after separating active and reactive losses from each other, the reactive losses which are generated from active power flow is considered in the reactive power market. As this reactive power loss are generated by the implementation of the energy market and not related to reactive power market, they must be generated mandatory by each unit. So, the main purpose of this paper is to consider reactive losses of the active power flow without any payment to it. Hence, this study tries to improve reactive power market and create fair competition in reactive power generation through modifying the market structure. The advantage of this method is determining the mandatory region of units based on both active power output and its distance from the load. In order to stimulate the proposed method, IEEE 24 is used, and this method is compared with each the conventional reactive power market. As it will be shown, the total payment by ISO will be reduced by using this method.

KEYWORDS: Restructured power system, Power market, Ancillary services, Reactive power, Power losses.

1. INTRODUCTION

In recent decades, electrical grids have been restructured around the world and changed from the previous exclusively vertical state to the competitive one. Such restructuring has led to the separation of different services, which had been previously supplied by electricity companies. Although energy exchange is the main purpose of electricity markets, in order to have a secure and reliable power system, ancillary services are vital and should be appropriately supplied.

In a competitive electricity market, the appropriate components of this market are formed by the proper selection of the following factors:

1) Market structure, 2) Payment mechanism, 3) Pricing model

Reactive power market structure is chosen according to environmental and political circumstances. This ancillary service is usually separated from real power, and an independent market is implemented for it. Nevertheless, in some references, by simultaneously executing active and reactive power markets, integrated optimization has been performed on the costs [1]. In [2, 3], by considering a combined objective function, a framework has been presented for optimization on all the active and reactive power costs. In [4] the economic effect of double auction bilateral power transaction on reactive power market is considered. Reactive power may be implemented as real time, day-ahead, seasonal, or a combination of the mentioned time frames. [5, 6] uses day- ahead reactive power market. These markets use HFMOEA approach for optimization the reactive power market. The optimization is done over three components: payment function, voltage stability, network losses.

An appropriate payment structure should be considered for ancillary service providers of reactive power while giving attention to technical (for example, local nature of reactive power, generators' capacity curve, etc.) and economical (generation cost of reactive power for generators, including opportunity cost, sale type, market power, etc.) issues. A pay as bid market is proposed [7] and compared with the market clearing price market. In this paper, after modifying the optimal power flow model, the Expected Payment Function of generators is used to develop a bidding framework while Total Payment Function based optimal power flow is used to clear the pay as bid market.

The pricing model is another important issue in managing the ancillary services of reactive power and should reflect the generation cost of this power of different suppliers in a non-discriminative way. Pricing model refers to the allocation of reactive power costs for different participants. In [8], the pricing model based on the capacity curve of power plants have been employed.

Besides the mentioned three factors, other parameters could be considered in the reactive power market. In [9] the influence of the high penetration of wind energy on reactive power planning using benders decomposition is investigated. This paper investigates the uncertainties of reactive power and a multi – scenario framework is proposed for it. [10] Propose new DC power flow method which is used in the process of the clearing of the reactive power market. Based on the results, this method has very satisfied results in the different systems. The [11] for improving system stability proposes a new combined reactive power and reactive power reserve market. This method encourages market providers to participate in both of the markets and also improve network stability.

It is usually mandatory to generate some reactive power by generators in reactive power markets. There are different methods for determining this amount in different markets all over the world. In conventional reactive power market, the generators must produce or absorb some reactive power mandatorily in the specified region. This region is defined by using power coefficients for both reactive power absorption and generation regions. Since this region, without considering generators active power flow output and its contract are mandatory, it seems unfair. On the other word, in the conventional methods, the generators effect on power system losses is not considered and two generators with different reactive power losses may force to generate same reactive power for free. In the proposed structure, firstly the reactive power losses caused by active power flow with respect to its contract is calculated. In the next step, the reactive power market runs by ISO and scheduled generation of each producer is defined. Considering such losses in the reactive power market and creating proper structure is the main purpose and advantage of this paper. In this paper, a new method is proposed for considering mandatory generation range of units, which is based on the active power transaction amount between units and loads.

In the second section, modeling of reactive power losses in the reactive power market is studied. Reactive power market clearing according to the mentioned cases in the two previous sections is studied in the third section. In the fourth section, the simulation results are presented and, finally; in the fifth section, the conclusion is made.

2. CONSIDERING REACTIVE POWER LOSSES IN COST FUNCTION

Since the generators with high power exchange with far loads have a more contribution in losses, the existing markets are not appropriate for market settlement. In other words, a power plant with high active power generation must have more contribution in reactive power losses, and payment for the reactive power generation should not consist this amount, i.e. two units with different active power output, which are contracted with the same loads, should generate different reactive power output mandatorily. On the other hand, a power plant close to the consumer does not need to generate reactive power to contribute to the reactive power losses. So it can generate more reactive power. For considering this two proposes, first, allocation of reactive power losses as a result of active power flow must be done. This reactive loss consideration is the advantage of proposed structures in comparison of existing methods. In accordance with the described method in [12], reactive power losses can be obtained as follows:

$$Q_{loss}^{Ti}=\sum_{k=1}^{NB}\left[\begin{array}{l}\left(I_{kx,adj}^{Ti}\right)^2+\left(I_{ky,adj}^{Ti}\right)^2\\+C_k^{\mathrm{Re}}\times\frac{\left(I_{kx,adj}^{Ti}\right)^2}{I_k^{\mathrm{Re},sum}}+C_k^{\mathrm{Im}}\times\frac{\left(I_{ky,adj}^{Ti}\right)^2}{I_k^{\mathrm{Im}e,sum}}\end{array}\right]\times XL_k \tag{1}$$

where:

$$I_k^{\mathrm{Re},sum}=\sum_{i=1}^{NT}\left(I_{kx,adj}^{Ti}\right)^2,\ I_k^{\mathrm{Im},sum}=\sum_{i=1}^{NT}\left(I_{ky,adj}^{Ti}\right)^2 \tag{2}$$

$$C_k^{\mathrm{Re}}=\sum_{i=1}^{NT}\sum_{\substack{j=1\\i\neq j}}^{NT}\left(I_{kx,adj}^{Ti}\times I_{kx,adj}^{Tj}\right), C_k^{\mathrm{Im}}=\sum_{i=1}^{NT}\sum_{\substack{j=1\\i\neq j}}^{NT}\left(I_{ky,adj}^{Ti}\times I_{ky,adj}^{Tj}\right) \tag{3}$$

The equation (1) could be rewritten as follow:

$$\begin{aligned}Q_{loss}^{Ti}&=XL_K\times I^2=XL_K\times\frac{P_{i,j}^2+Q_{i,j}^2}{V_i^2}\\&=\frac{XL_K\times P_{i,j}^2}{V_i^2}+\frac{XL_K\times Q_{i,j}^2}{V_i^2}=K\times(P_{i,j}^2+Q_{i,j}^2)\\&=Q_{loss,p}^{Ti}+Q_{loss,Q}^{Ti}\end{aligned} \tag{4}$$

As shown in statement (4), reactive losses can be divided into two parts: 1) Reactive power loss caused by active power flow, and 2) Reactive power losses caused by reactive power flow. Considering that the objective of the proposed reactive power market is to eliminate the losses caused by active power flow and create an independent market, therefore allocated reactive losses for transaction Ti will be:

$$Q_{loss,p}^{Ti}=\sum_{k=1}^{NB}\left[\left(I_{kx,adj}^{Ti}\right)^2+C_k^{\mathrm{Re}}\times\frac{\left(I_{kx,adj}^{Ti}\right)^2}{I_k^{\mathrm{Re},sum}}\right]\times XL_k \tag{5}$$

So, the allocated reactive losses for unit u in bus i is:

$$Q_{loss}^{i,u}=\sum_{j=1}Q_{loss,p}^{Tj} \tag{6}$$

In (6), the summation is done on all transaction associated with unit u in bus i.

3. REACTIVE POWER MARKET BY CONSIDERING REACTIVE LOSSES

In order to model the losses in the payment structure, a new method is proposed. In this method, reactive losses are considered before market closing. This market is shown in Fig. **1**. The blue region is mandatory and all of the active units must generate it for free. So in this market, simultaneous with declaring the amount of active power won by every unit in the energy market, the amount of reactive power, which should be mandatory generated by the unit, is declared. So, all the generators must generate its share of reactive power losses. Market modeling will be as follows:

$$TPF = \sum_{i=1}^{NG}\sum_{u=1}^{NU_i} J^{i,u}_{payment} \tag{7}$$

$$J^{i,u}_{payment} = \begin{pmatrix} \rho_0 \times W_0^{i,u}\left(Q_{\max}^{i,u} - Q_{\min}^{i,u}\right) \\ -\rho_1 \times W_1^{i,u} \times Q_1^{i,u} + \rho_2 \times W_2^{i,u} \times \left(Q_2^{i,u}\right) \\ +\rho_2 \times W_3^{i,u} \times \left(Q_3^{i,u}\right) + \frac{1}{2}\rho_3 \times W_3^{i,u} \times \left(Q_3^{i,u} - Q_{A,new}^{i,u}\right)^2 \end{pmatrix} \tag{8}$$

$$\begin{aligned} & W_1^{i,u} \times Q_{\min}^{i,u} \le Q_1^{i,u} \le 0 \\ & 0 \le Q_2^{i,u} \le W_2^{i,u} \times Q_{A,new}^{i,u} \\ & W_3^{i,u} \times Q_{A,new}^{i,u} \le Q_3^{i,u} \le W_3^{i,u} \times Q_{B,new}^{i,u} \\ & W_1^{i,u} + W_2^{i,u} + W_3^{i,u} \le 1 \end{aligned} \tag{9}$$

$$Q_g^{i,u} = Q_1^{i,u} + Q_2^{i,u} + Q_3^{i,u} + Q_{loss}^{i,u} \tag{10}$$

As shown in equation (10), $Q_{loss}^{i,u}$ is the mandatory reactive power which must be generated by each unit; either it won in reactive power market or not.

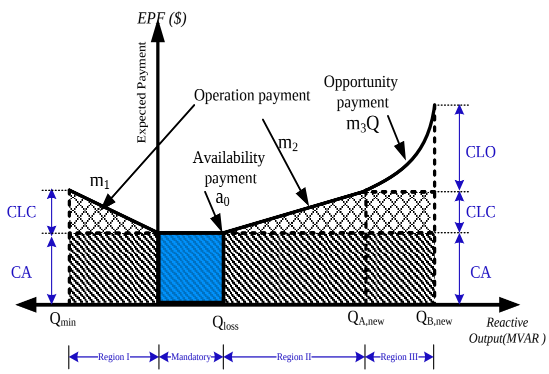

Fig. 1. proposed reactive power structure.

4. CONSTRAINTS IN THE REACTIVE POWER MARKET

The aim of implementing reactive power market is to optimize the total payment function (7), while $J^{i,u}_{payment}$ is equal to (8), while different system constraints are satisfied. These constraints explained in the following subsections:

4.1. Power flow equations:

$$\sum_{u=1}^{NU_i} P_{g,con}^{i,u} - P_d^i = \sum_j V_i V_j Y_{ij} \cos(\theta_{ij} + \delta_j - \delta_i) \tag{11}$$

$$\sum_{u=1}^{NU_i} Q_g^{i,u} + Q_C^i - Q_d^i = -\sum_j V_i V_j Y_{ij} \sin(\theta_{ij} + \delta_j - \delta_i) \tag{12}$$

4.2. Operational constraints of generators

$$\begin{cases} Q_A^{i,u} = \sqrt{\left(\frac{V_t^{i,u} E_{af}^{i,u}}{X_s^{i,u}}\right)^2 - (P_g^{i,u})^2} - \frac{\left(V_t^{i,u}\right)^2}{X_s^{i,u}} & if\ P_g^{i,u} < P_{g,rated}^{i,u} \\ Q_A^{i,u} = \sqrt{S_{rated}^{i,u} - (P_g^{i,u})^2} & if\ P_g^{i,u} > P_{g,rated}^{i,u} \end{cases} \tag{13}$$

The output power of the generator is limited by capability curve limits of the unit. When active power output and terminal voltage are fixed, the field current and armature current limits determine the reactive power output of the unit. So, if $P_g^{i,u} < P_{g,rated}^{i,u}$ then the unit operates on field current limit region and the first constraint is correct. On the contrary, if $P_g^{i,u} > P_{g,rated}^{i,u}$ the unit operates on armature current limit region and second constraints are correct.

In relation (13), Eaf is the internal voltage of the synchronous generators, obtained from the following relation:

$$E_{af}^{i,u} = \frac{X_s^{i,u}}{V_t^{i,u}} \sqrt{P_{g,rated}^{i,u} + \left(Q_{g,rated}^{i,u} + \frac{\left(V_t^{i,u}\right)^2}{X_s^{i,u}}\right)^2} \tag{14}$$

4.3. Determining market prices:

Market prices are separately selected for every reactive power component. In this paper, the uniform auction is selected for market clearing. The following constraints assure that maximum offer prices are acceptable for a set of given offers:

$$W_0^{i,u} = W_1^{i,u} + W_2^{i,u} + W_3^{i,u} \tag{15}$$

$$W_0^{i,u} \times a_0^{i,u} \le \rho_0 \tag{16}$$

$$W_1^{i,u} \times m_1^{i,u} \le \rho_1 \tag{17}$$

$$\left(W_2^{i,u} + W_3^{i,u}\right) \times m_2^{i,u} \le \rho_2 \tag{18}$$

$$W_3^{i,u} \times m_3^{i,u} \le \rho_3 \tag{19}$$

4.4. Constraints of reactive power generation:

As mentioned in [13], the Var compensators are not considered in the reactive power market. So in this paper, just technical aspects of reactive compensators are considered [14], [15]. Reactive compensators such as capacitor and reactors [16] are defined by the following constraints:

$$Q_{\min}^{i,u} \le Q_g^{i,u} \le Q_{\max}^{i,u} \tag{20}$$

$$Q_{C,\min}^i \le Q_C^i \le Q_{C,\max}^i \tag{21}$$

4.5. Security constraints:

$$V_i^{\min} \le V_i \le V_i^{\max} \tag{22}$$

$$P_g^{slack} \leq P_{g,\max}^{slack} \quad (23)$$

$$\left|S^{i,j}\right| \leq S_{\max}^{i,j} \quad (24)$$

The voltage limits of each bus is explained by (22). Statement (23) is constraints of the active power generations of the slack bus. Statement (24) is the limits of line loading. These constraints assure the secure operations of the network.

5. SIMULATION RESULTS

The proposed method was tested in different case studies. This method was applied on IEEE 24 buses test system. Furthermore, the effects of the load condition are considered. For the simulation, as mentioned previously, first, reactive power losses caused by active power flow were obtained and, then, according to this data and other data of the network, the reactive power market was implemented. In these simulations, in order to get reactive power losses, MATLAB software was used. The optimization problem of reactive power market clearing is in the form of MINLP, which is modeled in GAMS software using DICOPT solver [17]. Different case studies are prepared as follows:

The proposed reactive power market was tested on IEEE 24-bus reliability network (Fig. **2**). This network has 32 synchronous generators, 1 synchronous condenser placed on bus 14, and 17 loads. Bus 1 is considered as the reference bus and the rests is PQ bus. The system total active and reactive loads are 2850MW and 580MVAr, respectively. The active power of the units determined in the energy markets is shown in Table 1. The information and specifications of the network, including line impedance, maximum and minimum active and reactive power generated by generators, were presented in [18].

In Fig. **3**, the amount of reactive power losses caused by this energy exchange is shown.

Every participant in the reactive power market presents four components to the market [18].Minimum and maximum voltage limits for all buses are considered as 0.95 and 1.05.

Reactive power market clearing is an MINLP problem. This model is solved using GAMS, which is strong software for solving these problems. Considering the offer prices and the proposed market model, the market prices and total prices by ISO will be as in Table 3. As shown the payment in the proposed method is 775.74 $ which is 12.41% less than the payment of conventional one (679.63 $).

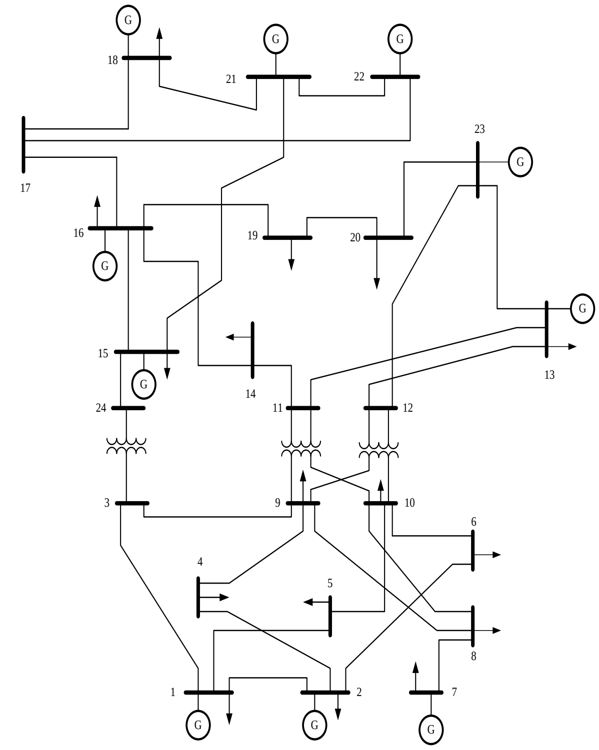

Fig. 2. IEEE 24 bus reliability test system.

Table 1. Reactive power market clearing prices.

	ρ_0 ($/MVarh)	ρ_1 ($/MVarh)	ρ_2 ($/MVarh)	ρ_3 ($/MVarh^2)	TPF ($)
Conventional	0.7	0	0.65	0.32	775.94
Proposed	0.7	0	0.65	0.32	679.63

The reactive power that each participant wins in all markets, and meanwhile the maximum produced reactive power by the generator, without any need to decrease the active power (QA), are shown in Table 4 (both according to the conventional method and the proposed method). The bolded value in this table represents entering the unit to the third region. Also, as can be seen from this table, some units are not elected in the reactive power market, but these units due to their participation in the reactive power losses must pay the cost of their share of the losses. In the conventional method, the share of reactive loss has not been taken into account by any units.

The payment of each generator in all markets is shown in Fig. **4**. This figure gives a good view to compare payments of different markets. As shown in this figure, in comparison to the conventional market, some units could not win in the proposed reactive power market or their payment reduces significantly. This is because of the high allocated reactive losses to these units.

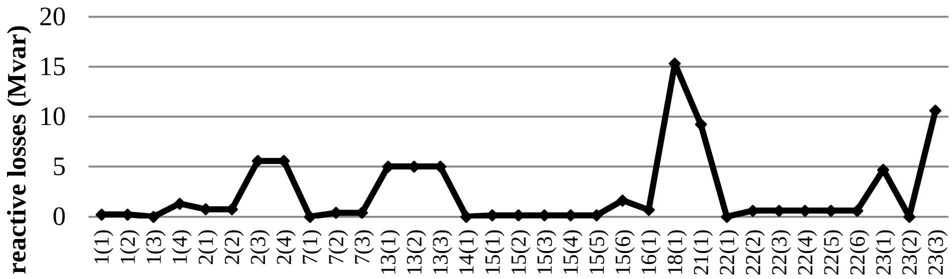

Fig. 3. Allocated reactive losses of each unit

Table 2. Reactive power output of each unit in different power market.

Bus number	Unit number	Q_{min} (MWar)	Q_{base} (MWar)	$Q_{A,new}$ (MWar)	Allocated losses (MWar)	Q_g(MWar) (conventional)	Proposed method Q_g(MWar)
1	1	0.00	1.55	12.18	0.056	0	0.22
	2	0.00	1.55	12.18	0.056	0	0.22
	3	-25	5.056	45.26	0.00	0	0
	4	-25	5.056	38.67	0.5357	0	1.3
2	1	0.00	1.55	12.18	0.1140	12.18	0.74
	2	0.00	1.55	12.18	0.1140	0	0.74
	3	-25	5.056	34.89	0.8548	0	5.58
	4	-25	5.056	34.89	0.8548	0	5.58
7	1	0.00	7.439	60.36	0.00	0	0
	2	0.00	7.439	47.49	1.0873	0	0.4
	3	0.00	7.439	47.49	1.0873	62.28	62.33
13	1	0.00	14.577	104.17	13.7512	131.19	5.02
	2	0.00	14.577	104.17	13.7512	0	109.19
	3	0.00	14.577	104.17	13.7512	0	5.02
14	1	-50	20.00	180	0.00	0	0
15	1	0.00	0.865	5.79	0.1509	7.79	7.79
	2	0.00	0.865	5.79	0.1509	5.79	0.14
	3	0.00	0.865	5.79	0.1509	0	0.14
	4	0.00	0.865	5.79	0.1509	5.79	5.93
	5	0.00	0.865	5.79	0.1509	7.79	0.14
	6	-50	11.31	80.33	1.7606	101.83	101.83
16	1	-50	11.31	84.5	1.817	101.83	101.83
18	1	-50	30.36	212.09	9.9984	0	15.33
21	1	-50	2.398	240.05	2.6242	0	9.23
22	1	-10	2.398	21.10	0.00	0	0
	2	-10	2.398	13.46	0.3255	20.81	0.6
	3	-10	2.398	13.46	0.3255	0	0.6
	4	-10	2.398	13.46	0.3255	0	0.6
	5	-10	2.398	13.46	0.3255	0	0.6
	6	-10	2.398	13.46	0.3255	20.81	21.58
23	1	-50	11.31	72.28	3.6636	0	4.7
	2	-50	11.31	139.06	0.00	0	0
	3	-25	25.72	164.97	8.2726	0	10.63

6. CONCLUSIONS

In this paper, a new method was presented for reactive power market structure, which the reactive power losses caused by energy market implementation were considered. In this method, ISO calculated the contribution of each unit in the reactive power losses and used it in the reactive power market clearing and settlement. Based on this concept, the mandatory region of units is determined based on active power output and its contracted loads. Since in this method, generators are not paid for their reactive losses caused by active power flow, then the payment costs by market were reduced. Consequently, the proposed method not only could improve justice among the market participants, but also could reduce the payment cost by ISO. It is shown in the simulation results that by using the proposed method, the TPF will be reduced. Also, the mentioned method, due to less allocation of losses to the producers with fewer transactions in the energy market or those who exchange power with their close consumers, could encourage producers to effectively participate in the reactive power market.

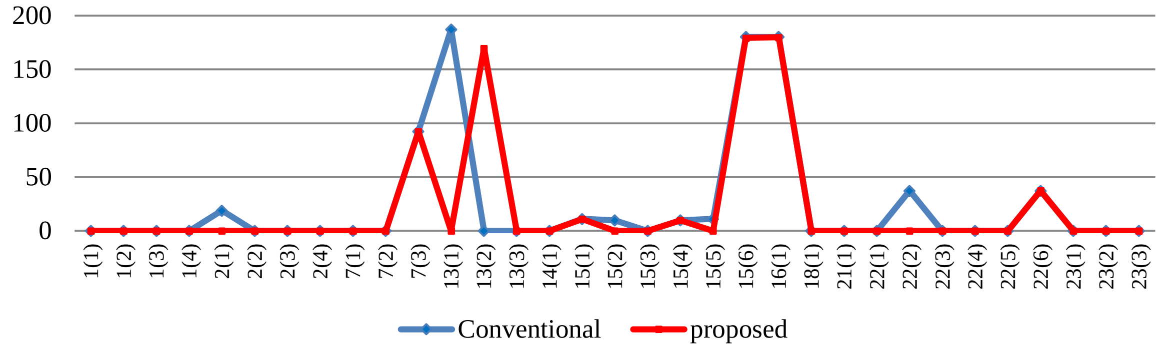

Fig. 4. Payments comparison of each power plant in two reactive power market.

REFERENCES

[1] H. Ahmadi and A. A. Foroud, **"Improvement of the simultaneous active and reactive power markets pricing and structure,"** *IET Generation, Transmission & Distribution,* Vol. 10, pp. 81-92, 2016.

[2] S. Hasanpour, R. Ghazi, and M. H. Javidi, **"A new approach for cost allocation and reactive power pricing in a deregulated environment,"** *Electrical Engineering,* Vol. 91, pp. 27-34, 2009.

[3] S. Soleymani, **"Nash equilibrium strategies of generating companies (Gencos) in the simultaneous operation of active and reactive power market, with considering voltage stability margin,"** *Energy conversion and management,* Vol. 65, pp. 292-298, 2013.

[4] S. Biswas, K. K. Mandal, and N. Chakraborty, **"Pareto-efficient double auction power transactions for economic reactive power dispatch,"** *Applied Energy,* Vol. 168, pp. 610-627, 2016.

[5] A. Saraswat, A. Saini, and A. K. Saxena, **"A novel multi-zone reactive power market settlement model: A pareto-optimization approach,"** *Energy,* Vol. 51, pp. 85-100, 2013.

[6] A. Saini and A. Saraswat, **"Multi-objective day-ahead localized reactive power market clearing model using HFMOEA,"** *International Journal of Electrical Power & Energy Systems,* Vol. 46, pp. 376-391, 2013.

[7] I. Maheshwari, G. Leena, and N. Saxena, **"Reactive Power Market Clearing based on Pay-as-Bid Method with System Security,"** *IJEM-International Journal of Engineering and Manufacturing (IJEM),* Vol. 6, p. 23, 2016.

[8] J. Zhong and K. Bhattacharya, **"Toward a competitive market for reactive power,"** *IEEE Transactions on Power Systems,* Vol. 17, pp. 1206-1215, 2002.

[9] X. Fang, F. Li, Y. Wei, R. Azim, and Y. Xu, **"Reactive power planning under high penetration of wind energy using Benders decomposition,"** *IET Generation, Transmission & Distribution,* Vol. 9, pp. 1835-1844, 2015.

[10] K. S. H. Beagam, R. Jayashree, and M. A. Khan, **"A New DC Power Flow Model for Q Flow Analysis for use in Reactive Power Market,"** *Engineering Science and Technology, an International Journal,* Vol. 20, pp. 721-729, 2017.

[11] A. Khandani and A. A. Foroud, **"Design of reactive power and reactive power reserve market,"** *IET Generation, Transmission & Distribution,* Vol. 11, pp. 1443-1452, 2017.

[12] K. Lo and Y. Alturki, **"Towards reactive power markets. Part 1: reactive power allocation,"** *IEE Proceedings-Generation, Transmission and Distribution,* Vol. 153, pp. 59-70, 2006.

[13] F. O. No, **"888,"** *Promotion of wholesale competition through open access non-discriminatory transmission services by public utilities and recovery of stranded costs by public utilities and transmitting utilities," Issued April,* 1996.

[14] W. Su and A. Q. Huang, **"A game theoretic framework for a next-generation retail electricity market with high penetration of distributed residential electricity suppliers,"** *Applied Energy,* Vol. 119, pp. 341-350, 2014.

[15] N. S. Pearre and L. G. Swan, **"Technoeconomic feasibility of grid storage: mapping electrical services and energy storage technologies,"** *Applied Energy,* Vol. 137, pp. 501-510, 2015.

[16] C. H. Antunes, D. F. Pires, C. Barrico, Á. Gomes, and A. G. Martins, **"A multi-objective evolutionary algorithm for reactive power compensation in distribution networks,"** *Applied Energy,* Vol. 86, pp. 977-984, 2009.

[17] M. U. s. Guide, **"The mathworks,"** *Inc., Natick, MA,* Vol. 5, pp. 333-333, 1998.

[18] C. Grigg, P. Wong, P. Albrecht, R. Allan, M. Bhavaraju, R. Billinton, *et al.*, **"The IEEE reliability test system-1996. A report prepared by the reliability test system task force of the application of probability methods subcommittee,"** *IEEE transactions on power systems,* Vol. 14, pp. 1010-1020, 1999.