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# A novel cost reducing reactive power market structure for modifying mandatory generation regions of producers

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ABSTRACT

In this paper, a new reactive power market structure is studied and presented. Active power flow by itself causes active and reactive losses. Considering such losses in the reactive power market is the main purpose of this paper. Therefore, this study attempts to improve the reactive power market and create fair competition between producers. To that end, first, a new allocation method for reactive power losses is presented and the contribution of each producer in reactive losses is calculated. In the next step, this share of losses is used to modify the mandatory generation region of units. Then, a new structure is proposed for the reactive power market. This novel structure leads to reduction of system costs in the deregulated power system, which is one of the main policy implications of this paper. Finally, simulations show that the total payment by Independent System Operator will be reduced via application of the proposed methods leading to reduction in system costs. This cost reduction will be significant enough to encourage Independent System Operators to utilize such a structure. In addition, by implementing the new proposed methods, assignment of costs related to reactive power loss will be more justifiable for each generator.

## 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. This change has been achieved by the complete separation of generation and transmission activities and development of competition in the generation sector. Such restructuring has led to the separation of different services, which were 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 most electricity markets, system operators supply these services via commercial contracts with the market participants.

Among the six ancillary services defined in Order No. 888 of the Federal Energy Regulatory Commission (FERC), supplying reactive power is one of the most important services in system security. This service plays a very effective role in the secure operation of power systems. Nowadays, reactive power markets are implemented in different countries including Canada, India, Australian, Japan, Argentina, Netherlands, Belgium, Sweden, Britain, Iran, etc. In the restructured power system, economic signals besides network constraints are the basic factors of ISO in making operational decisions (Acharya and Mithulananthan, 2007; Balamurugan et al., 2015; Bradbury et al., 2014; Ghazvini et al., 2015; Govardhan and Roy, 2014; Ikeda et al., 2012; Jiang et al., 2015; Zheng et al., 2015). In a competitive electricity market, the appropriate components of the market are formed by proper selection of the following factors:

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

The reactive power market structure is chosen according to environmental and political circumstances. This ancillary service is usually separated from real power for which an independent market is implemented. Nevertheless, in some references, integrated optimization has been performed on the costs by simultaneously executing active and reactive power markets (Ahmadi and Foroud, 2016). In order to prevent interference of the reactive power market and the energy market, independent markets are used for both powers (El-Samahy et al., 2008; Kargarian et al., 2012; Rabiee et al., 2009b). In this model, the output of the active power market is used as the input for this market. Because of different constraints in a reactive power market, the amount of active power cannot be constant in all generators and has to change in order to maintain the stability of the grid. As a result, one of the important issues in the separated active and

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**Nomenclature**

| | |
|---|---|
| $a_0^{i,u}$ | Availability price, |
| I | Current flow from the branch |
| i, j | Indexes of buses |
| $J_{payment}^{i,u}$ | Payment of unit u in bus i |
| $m_1^{i,u}$ | Cost of loss price offer for operating in under-excited mode (absorb reactive power), |
| $m_2^{i,u}$ | Cost of loss price offer for operating in the armature current limit region, |
| $m_3^{i,u}$ | Opportunity price offer for operating in the field current limit region, |
| NG | Number of buses with synchronous generator or condenser, |
| $\mathrm{NU_i}$ | Number of units connected to the ith bus, |
| $\mathrm{N_L}$ | Number of buses with loads, |
| $P_d^i$ | Active power demand per bus, |
| $\mathrm{P}_{\mathrm{loss},i,j}$ | Active power loss in branch i, j, |
| $P_{g,con}^{i,u}$ | Real power generation by transaction, |
| $P_{loss,i,j}^{T_{n,m}}$ | Active power loss in branch i, j when contract Tn,m is deactivated, |
| $\mathrm{Q_{injected}}$ | Injected reactive power to the network, |
| $Q_{lead}^{i,u}$ | Leading reactive power of generator, |
| $Q_{lag}^{i,u}$ | Lagging reactive power of generator, |
| $Q_{\min}^{i,u}$ | Lower limit of reactive power generation, |
| $Q_{\max}^{i,u}$ | Upper limit of reactive power generation, |
| $Q_{base}^{i,u}$ | Reactive power required by generator for its auxiliary equipment, |
| $Q_A^{i,u}$ | Maximum allowable reactive power limit of generator g with reduction in real power generation, |
| $Q_B^{i,u}$ | Maximum allowable reactive power limit of generator g with reduction in real power generation, |
| $Q_{A,new}^{i,u}$ | Modified $Q_A^{i,u}$ by correcting cost function, |
| $Q_{B,new}^{i,u}$ | Modified $Q_B^{i,u}$ by correcting cost function, |
| $Q_{g,rated}^{i,u}$ | Rated reactive power of generator, |
| $Q_1^{i,u}$ | Under-excitation reactive power of generator, |
| $Q_2^{i,u}$ | Over-excitation reactive power of generator, |
| $Q_3^{i,u}$ | Reactive power of generator, operating in the opportunity region, |
| $Q_g^{i,u}$ | Reactive power generation per bus, |
| $Q_d^i$ | Reactive power demans per bus, |
| $Q_C^i$ | Reactive power support from shunt capacitor/reactor, |
| $Q_{C,\ \min}^i$ | Reactive power support from shunt reactor, |
| $Q_{C,\ \max}^i$ | Reactive power support from shunt capacitor, |
| $Q_{loss}^{i,u}$ | Allocated reactive losses for unit u in bus I, |
| $\mathrm{Q}_{\mathrm{loss},i,j}$ | Reactive power loss in branch i, j, |
| $Q_{loss,i,j}^{T_{n,m}}$ | Reactive power loss in branch i, j when contract Tn,m is deactivated, |
| $\mathrm{Q}_{\mathrm{loss}}^{P,T_{n,m}}$ | Allocated reactive loss for transaction Tn,m caused by active power flow, |
| $\mathrm{Q}_{\mathrm{loss}}^{Q,T_{n,m}}$ | Allocated reactive loss for transaction Tn,m caused by reactive power flow, |
| $\mathrm{Q'}_{\mathrm{loss},i,j}^{P,T_{n,m}}$ | Allocated reactive power loss in branch i, j caused by active power flow when contract Tn,m is deactivated, |
| $\mathrm{Q'}_{\mathrm{loss},i,j}^{n,m}$ | Allocated reactive power loss in branch i, j caused by reactive power flow when contract Tn,m is deactivated, |
| $\mathrm{Q}_{\mathrm{loss}}^{T_{n,m}}$ | Allocated reactive loss for transaction Tn,m, |
| $Q_{loss,p+}^{i,u}$ | Positive partition of allocated reactive power, |
| $Q_{loss,p-}^{i,u}$ | Negative partition of allocated reactive power, |
| $\mathrm{Q}_{\mathrm{loss},i,j}^{\mathrm{P}}$ | Reactive power loss in branch i, j caused by active power flow, |
| $\mathrm{Q}_{\mathrm{loss},i,j}^{\mathrm{Q}}$ | Reactive power loss in branch i, j caused by reactive power flow, |
| R | Branch resistance, |
| $S_{i,j}$ | Apparent power flows from bus i to bus j, |
| $S_{i,j}^{\max}$ | Maximum transmittable apparent power between nodes i and j, |
| $\mathrm{S}_{\mathrm{loss},i,j}$ | Actual loss in branch i, j, |
| $S_{loss,i,j}^{T_{n,m}}$ | Apparent power loss in branch i, j when contract Tn,m is deactivated, |
| $\mathrm{S}_{\mathrm{loss},i,j}^{\mathrm{T}}$ | Total apparent loss of $\Delta \mathrm{S}_{\mathrm{loss},i,j}^{T_{n,m}}$, |
| U | Indexes of units in the bus, |
| $V_i$ | Bus voltage, |
| $V_i^{\min}$ | Minimum allowable voltage at bus i, |
| $V_i^{\max}$ | Maximum allowable voltage at bus i, |
| $V_{ix}$ | Real parts of the bus voltage, |
| $V_{iy}$ | Imaginary parts of the bus voltage, |
| $W_0^{i,u}$ | Binary variables for discrete selection of a reactive power component selected from any region, |
| $W_1^{i,u}$ | Binary variables for discrete selection of a reactive power component from Region-I, |
| $W_2^{i,u}$ | Binary variables for discrete selection of a reactive power component from Region-II, |
| $W_3^{i,u}$ | Binary variables for discrete selection of a reactive power component from Region-III, |
| X | Branch reactance, |
| $Y_{i,j}$ | Element of admittance matrix of the grid, |
| $Yt_{i,j}$ | Reactance of the branches i and j, |
| $Ym_{i,j}$ | Susceptance of the branches i and j, |
| $\Delta \mathrm{S}_{\mathrm{loss},i,j}^{T_{n,m}}$ | Contribution of each transaction in the apparent power losses of branch i, j, |
| $\Delta \mathrm{S'}_{\mathrm{loss},i,j}^{T_{n,m}}$ | Allocated apparent power loss in branch i, j, |
| $\Delta \mathrm{P'}_{\mathrm{loss},i,j}^{T_{n,m}}$ | Allocated active power loss in branch i, j, |
| $\Delta \mathrm{Q'}_{\mathrm{loss},i,j}^{T_{n,m}}$ | Allocated reactive power loss in branch i, j, |
| $\theta_{i,j}$ | Appropriate angle for $Y_{i,j}$, |
| $\delta_i$ | Angle of voltage, |
| $\rho_0$ | Uniform availability price, |
| $\rho_1$ | Uniform operating price for absorbing reactive power, |
| $\rho_2$ | Uniform operating prices for producing reactive power, |
| $\rho_3$ | Uniform opportunity price for reactive power, |

reactive power markets is the method of approaching this issue, which is directly related to the lost opportunity cost. In (Ahmadi and Foroud, 2014; Hasanpour et al., 2009; Ketabi et al., 2010), by considering a combined objective function, a framework has been presented for optimization in all active and reactive power costs. In (Biswas et al., 2016) the economic effect of double auction bilateral power transaction on the reactive power market is considered. Reactive power may be implemented as real time, day-ahead (Ketabi et al., 2010; Malakar et al., 2016; Rabiee et al., 2009b; Saraswat et al., 2013; Zhong and Bhattacharya, 2002), seasonal (El-Samahy et al., 2006; Kargarian et al., 2011; Miguelez et al., 2007; Tamimi et al., 2010; Vyjayanthi and Thukaram, 2011), or a combination of the mentioned time frames (Aragon et al., 2015). Because of market sensitivity to load and grid circumstances, the day-ahead reactive power market can create market power and raise the total cost of reactive power. Being close to consumption time and, consequently, making more precise predictions about generation and consumption volumes and better allocation of reactive power are the advantages of the day-ahead market. (Aragon et al., 2015) proposes a three-stage time frame for the reactive power market. In the first stage, the ISO determines the technical requirements of the service considering different scenarios for the next annual period. In the next stage, in a day-ahead period, the ISO estimates the variable costs associated with the service. Once these have been incurred, and added to the fixed costs to conform to the total costs of