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Research Article

A New Framework for Reactive Power Dispatch in Electricity Markets

[1]Javad Saebi, [2]Hossein Hakimollai, [2]Hassan Soleimani Amiri and [1]H. Ghasemi
[1]School of Electrical and Computer Engineering (ECE), University of Tehran, Tehran, Iran
[2]West of Tehran Province Power Distribution Company (WTPPDC), Tehran, Iran

Abstract: This study proposes a reactive power dispatch model within the context of electricity markets considering both technical and economical issues. The model utilizes a new metric introduced here for reactive power reserve management in voltage control areas. Besides minimizing total reactive power payments, the objective function manages for an optimum reserve in each voltage control area. The proposed reactive power dispatch model is decoupled from active power dispatch and the generators' active power is assumed fixed during the procedure. The relation between active power and reactive power of a synchronous generator is also included in the model by considering the generators' capability curves. The CIGRE 32-bus test system is used to demonstrate the feasibility and aspects of the proposed model.

Keywords: Ancillary services, electricity market, reactive power markets, reactive power reserve

INTRODUCTION

Reactive power dispatch is a short-term planning activity carried out by system operators in order to ensure secure power system operation. Reactive power has a significant effect on system security as it is directly associated with power system voltage stability. For instance, voltage collapse usually occurs in heavily loaded systems and in areas that do not have sufficient reactive power reserve. As indicated by the Western Electric Coordinating Council (WECC), reactive power reserve in the system can be used as an indicator for voltage stability assessment (Abed, 1999). Therefore, in order to avoid voltage problems across the system, special case must be taken in obtaining sufficient reactive power reserve in all areas of the power system.

Due to the nature of reactive power, reactive power cannot be transmitted over long distances. So, a power system is usually divided into several Voltage Control Areas (VCA) that are independent from the viewpoint of trading reactive power within them (Zhong and Bhattacharya, 2002).

In Dong *et al*. (2005), reactive power reserve has been used to improve voltage stability for the whole system; however, the local nature of reactive power has not been considered. In this study, a new metric for reactive power reserve is introduced that considers voltage control areas in reactive power management.

Federal Energy Regulatory Commission (FERC) has recognized reactive power and voltage control services from synchronous generators as one of six ancillary services and the providers are eligible for financial compensation. So, in a deregulated environment, the cost of providing reactive power must be considered in reactive power dispatch.

Reactive power ancillary services can be provided based on two different time horizons: A long-term stage that is named as reactive power procurement and a short-term stage that is reactive power dispatch (El-Samahy *et al*., 2008). Reactive power procurement is done on a seasonal basis; contracted generators and price components of reactive power are determined. In reactive power dispatch, a rescheduling of reactive power must be done based on real-time loading conditions. Different objective functions is used in previous studies that just consider technical issues associated with reactive power dispatch, such as transmission losses minimization (Lamont and Fu, 1999; Rahiel *et al*., 2010), or maximization of system loadability to minimize the risk of voltage collapse (Milano *et al*., 2004). In El-Samahy *et al*. (2007), a cost based reactive power dispatch is proposed that only minimizes total payments to find optimal dispatch of reactive power; however, it does not consider technical issues to provide a secure operation condition.

In this study, a new framework for reactive power dispatch in electricity markets is proposed. In order to consider both technical and economical issues associated with reactive power dispatch, the proposed framework considers reactive power reserve management as well as reactive power payments.

REACTIVE POWER MARKET

In a competitive electricity market, the Independent System Operator (ISO) should provide reactive power

Corresponding Author: Javad Saebi, School of Electrical and Computer Engineering (ECE), University of Tehran, Tehran, Iran

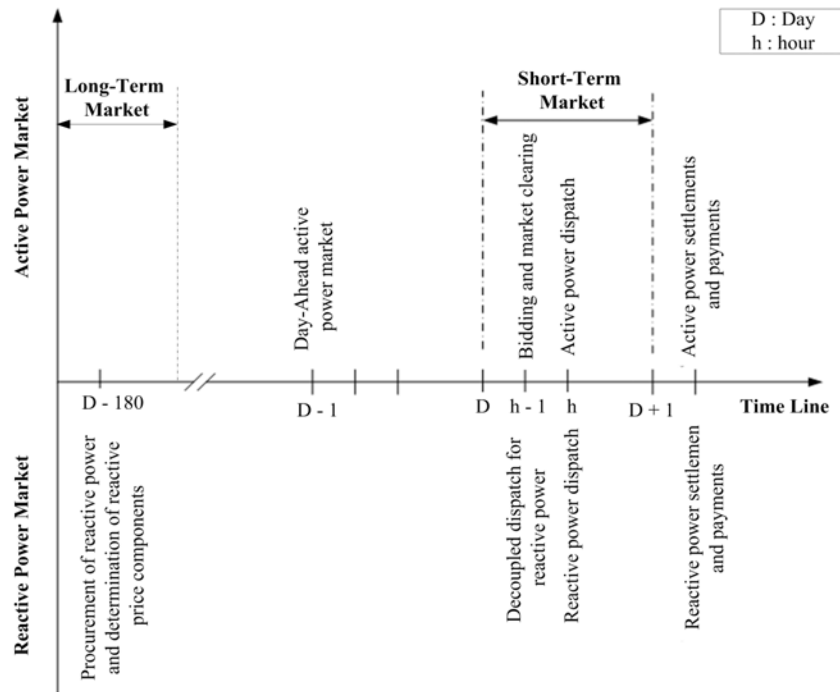

Fig. 1: Time scale of reactive power ancillary service market

support from service providers at minimum cost while ensuring a secure operation of the power system. If reactive power market is run in real time, issues such as exercising reactive market power and system security problems may arise (El-Samahy *et al*., 2008). Thus, a reactive power procurement market is run which works on a seasonal time horizon; contracted generators and reactive power price components are determined. Then, in real time, according to pre-determined reactive power prices, reactive power dispatch is run to determine optimal VAr dispatch and payments. In this study, VAr dispatch is decoupled from MW dispatch, i.e., after running active power dispatch and determining the real power generation of each generator, reactive power dispatch is run and the active power generation of generators is fixed during the procedure. The decoupling of real and reactive power is suggested in Papalexopoulos *et al.* (1989), El-Keib and Ma (1997) and Paucar and Rider (2001). Figure 1 illustrates the time scale of reactive power market.

It is important to note that a coupled dispatch, simultaneously dispatching active power and reactive power, gets the solution closer to the optimal; however, computational burden becomes an issue for real power systems. Decoupled reactive and active OPF provides the required flexibility for spot market applications; and reduce the problem associated with model complexity (El-Samahy *et al*., 2007).

PROPOSED REACTIVE POWER DISPATCH

In this study, reactive power reserve management is used to meet system security requirements. For this purpose, a new metric is introduced that considers VCAs in reactive power reserve management. Reactive power cost minimization is also included in the objective function of reactive power dispatch problem.

Reactive power reserve management: The reactive power reserve is the ability of the generators to support bus voltages under high loading conditions or contingencies (Dong *et al*., 2005). Reactive power cannot be transmitted over long distances thus defining and calculating reactive power reserve is more complicated compared to active power reserve.

Due to the nature of reactive power, reactive power and voltage control services are required to be provided locally. Also, to restrict the effects of reactive market power, power systems must be divided into VCAs and for each VCA, a uniform price is determined. A VCA is independent of trading reactive power in other VCAs and the reactive power transfers between VCAs are normally low. So, reactive power reserve in each VCA must be managed separately; thus, this matter must be seen in reactive reserve management problem as well.

Various definitions of reactive power reserve can be founded in Leonardi and Ajjarapu (2008). The effective reactive power reserve is interesting because it considers the reactive power dispatch at the point of voltage collapse and hence gives the actual amount of reactive reserve. It is good to mention that all definitions of reactive power reserve reported in Leonardi and Ajjarapu (2008) can be used here.

Effective reactive power reserve of a generator is defined as the difference between reactive power output of the generator at the point of voltage collapse and current reactive power generation (QV^{col}_g-Q_g). The QV^{col}_g can be calculated by an OPF with the objective being, for instance, maximizing voltage stability margin assuming uniform increase in loads (El-Samahy *et al*., 2008; Lamont and Fu, 1999).

In Dong *et al*. (2005), reactive power reserve has been used to improve voltage stability for the whole system without using VCAs. Here, a Normalized Effective Reactive Power Reserve (NERPR) is introduced, which can be used to take into account VCAs in the optimization process. For this purpose, the reactive reserve of each VCA is divided by its maximum reactive reserve without considering other areas. The maximum reactive power reserve Q^*_{Rk} at area *k* is calculated using an OPF as follows:

$$Max\, Q^*_{R_k} = \sum_{g\in k}(Q^{Vcol}_{Gg} - Q_{Gg}) \quad (1)$$

$$P^0_{Gi} - P_{Di} = V_i \sum_j V_j Y_{ij} \cos(\theta_{ij} + \delta_j - \delta_i) \;\; , \forall i \quad (2)$$

$$Q_{Gi} - Q_{Di} = -V_i \sum_j V_j Y_{ij} \sin(\theta_{ij} + \delta_j - \delta_i) \;\; , \forall i \quad (3)$$

$$Q^{\min}_{Gg} \le Q_{Gg} \le Q^{\max}_{Gg} \;\; , \;\forall g \quad (4)$$

$$V_i^{\min} \le V_i \le V_i^{\max} \;\; , \;\forall i \quad (5)$$

$$\left|S_{ij}\right| \le S^{\max}_{ij} \;\; , \;\forall i, j \quad (6)$$

By solving this optimization problem for each area *k*, we can define NERPR area *k* as follows:

$$NERPR_k = \frac{(1+\beta_k)}{Q^*_{R_k}} \sum_{g\in k} \alpha_g .(Q^{Vcol}_{Gg} - Q_{Gg}) \quad (7)$$

where,

α_g : Coefficient to show the importance of generator *g* ($0\le\alpha_g\le1$)

β_k : Coefficient to show the importance of area *k* ($0\le\beta_k\le1$) from the ISO's perspective

Normally, α_g = 1 and β_k = 0; however, the ISO may change these coefficients based on its understanding from the characteristic of the power system under study.

Then, total NERPR of system can be calculated:

$$NERPR = \sum_k NERPR_k \quad (8)$$

Although calculating NERPR are decoupled from MW dispatch and are less complex compared to solving coupled MW and MVA dispatch, but an OPF is required to be solved to find $Q^*_{R_k}$ for each area and hence computational time maybe an issue in real-time. To address this issue, we suggest that for normalizing reactive power reserve of each VCA, its reactive power reserve can be divided by its total reactive power capacity, i.e., $\sum_{g\in k}(Q^{\max}_{Gg} - Q^{\min}_{Gg})$, instead of $Q^*_{R_k}$.

By using normalized value NERPR in each VCA, we can get a better distribution of reactive reserve in each VCA when total NERPR of the system is maximized. This is due to the fact that in the objective function, reserves in all VCA are treated equally. Note that if instead of NERPR the values of reactive reserve are used, some areas will get higher while others not having enough reserve.

Reactive power payments: In a deregulated environment, the cost of providing reactive power services must be also considered in reactive power dispatch problem.

Figure 2 illustrates capability curve of a synchronous generator. If real power and terminal voltage are fixed, the armature and field winding heating limit curves determine the capability of the generator to generate reactive power (Fitzgerald *et al*., 1992). These limits are determined in Fig. 2, where, V_t is the terminal voltage of the generator, I_a is the armature current, E_f is the excitation voltage and X_5 is the synchronous reactance. The P_{GR} is determined by interception of the two curves. Assume that real power output at the operating point A is P_{GA}; if $P_{GA}\le P_{GR}$, the generator's field heating limit determines the maximum reactive power capability of the generator (Q_{GA}); whereas, when $P_{GA}\ge P_{GR}$, this limit is imposed by the generator's armature winding heating limit.

Based on a typical capability curve for a generator (Fig. 2), three regions of reactive power production in which the generator is eligible to receive payments can be defined. Note that the region ($Q_{Gblead}\le Q_G\le Q_{Gblag}$) in Fig. 2 is identified as mandatory region by the ISO and no payment is issued for producing/absorbing reactive power in this region (Zhong and Bhattacharya, 2002).

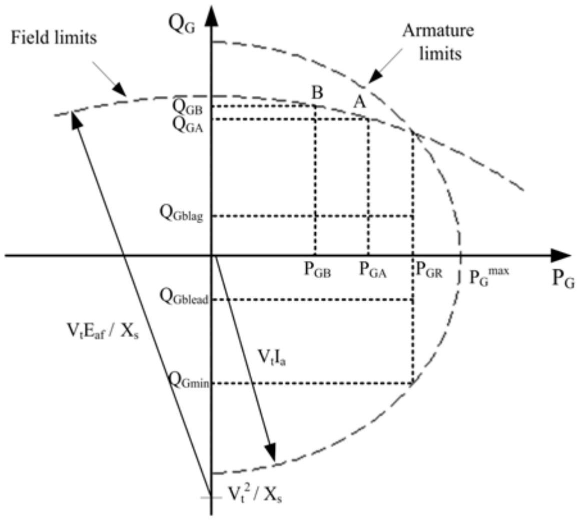

Fig. 2: Capability curve of a synchronous generator

- **Region I ($Q_{Gmin} \leq Q_G \leq Q_{Gblead}$):** In this region, generators expect availability payment (ρ_{0_g}[\$]) and payment for increase of loss in windings for absorbing reactive power more than the mandatory leading value $\left(\rho_{0_g}[\$/MVAr]\right)$. The payment to generators in this region can be defined as:

$$P_I = \rho_{0g} - \rho_{1g}.(Q_G - Q_{Gblead}) \tag{9}$$

- **Region II ($Q_{Gblag} \leq Q_G \leq Q_{GA}$):** It denotes the reactive power that a generator provides more than mandatory lagging value (Q_{Gblag}) without rescheduling its real power output. In this region, the generators expect an availability payment as well as a payment for the increased losses in windings $\left(\rho_{2_g}[\$/MVAr]\right)$ The payment to generators in this region can be defined as:

$$P_{II} = \rho_{0g} + \rho_{2g}.(Q_G - Q_{Gblag}) \tag{10}$$

- **Region III ($Q_{GA} \leq Q_G \leq Q_{GB}$):** It denotes the reactive power that a generator supplies at the expense of reducing its real power outputs. As mentioned before, the maximum reactive power capability of the generator at operating point A is Q_{GA}. At this point, if more reactive power is requested by the ISO, the generator must decrease its real power output to P_{GB} to be able to generate Q_{GB}. So, in this region, the generators expect an availability payment for providing reactive power support and an opportunity cost payment for reducing their real power output $\left(\rho_{0_g}[\$/MVAr^2]\right)$. The payment to generators in this region can be defined as:

$$P_{III} = \rho_{0g} + \rho_{2g}.(Q_G - Q_{Gblag}) + 0.5\,\rho_{3g}.(Q_G - Q_{GA})^2 \tag{11}$$

The price components of reactive power are determined in long-term procurement market. Determining reactive power prices in a timeframe different from that of active power reduces price volatility and thus helps reduce price spikes. To restrict the effects of reactive market power, uniform prices are determined for each VCA.

The ISO seeks to find an optimal reactive dispatch that minimizes the following cost function:

$$Payment = \sum_g \rho_{0g} + \rho_{1g}.Q_{G1g} + \rho_{2g}.Q_{G2g} + 0.5\rho_{3g}.{Q_{G3g}}^2 \tag{12}$$

Proposed reactive power dispatch: The reactive power dispatch is formulated as an Optimal Power Flow (OPF) with primary objective of maximizing NERPR to ensure higher voltage stability margin. A second objective is to minimize total payments subject to various security constraints. Therefore, reactive power dispatch is formulated as:

$$z = Max\{w_1 \times NERPR + w_2 \times Payment\} \tag{13}$$

Note that in order to maximize NERPR and minimize payments, one should choose w1≥0 and $w_2 \geq 0$.
The constraints to the above OPF problem are:

$$P_{Gi}^0 - P_{Di} = V_i \sum_j V_j Y_{ij} \cos(\theta_{ij} + \delta_j - \delta_i) \quad , \forall i \tag{14}$$

$$Q_{Gi} - Q_{Di} = -V_i \sum_j V_j Y_{ij} \sin(\theta_{ij} + \delta_j - \delta_i) \quad , \forall i \tag{15}$$

$$Q_{Gg}^{\min} \leq Q_{Gg} \leq Q_{Gg}^{\max} \quad , \ \forall g \tag{16}$$

$$Q_{Gg}^{\max} = \begin{cases} \sqrt{\left(\frac{V_{tg}E_{fg}}{X_{sg}}\right)^2 - (P_{Gg}^0)^2} - \frac{V_{tg}^2}{X_{sg}} & , P_{Gg} < P_{GRg} \\ \sqrt{(V_{tg}I_{ag})^2 - (P_{Gg}^0)} & , P_{Gg} \geq P_{GRg} \end{cases}$$

$$V_i^{\min} \leq V_i \leq V_i^{\max} \quad , \ \forall i \tag{17}$$

$$\left|S_{ij}\right| \le S_{ij}^{\max}\ ,\ \forall i, j \tag{18}$$

$$\left|Q_{Gblead\ g}\right| \le Q_{G1g} \le \left|Q_{Gg}^{\min}\right|\ ,\ \forall g \tag{19}$$

$$Q_{Gblag\ g} \le Q_{G2g} \le Q_{GA_g}\ ,\ \forall g \tag{20}$$

$$Q_{GAg} \le Q_{G1g} \le Q_{GB_g}\ ,\ \forall g \tag{21}$$

$$Q_{G1g}.(Q_{G2g} + Q_{G3g}) \le 0 \tag{22}$$

$$(Q_{G2g} - Q_{GAg}).Q_{G3g} \ge 0 \tag{23}$$

$$Q_{Gg} = -Q_{G1g} + Q_{G2g} + Q_{G3g} \tag{24}$$

Note that constraints 19 to 24 are added to determine the region of reactive power generation of generator *g*.

IMPLEMENTATION AND TEST CASE RESULTS

The CIGRE 32-bus test system (Fig. 3) is used here to test the feasibility of using the proposed reactive power dispatch model (Walve, 1993). The test case has 20 generators that all are assumed to be eligible for financial compensation for providing/absorbing reactive power in all three regions of operation as discussed before; so Q_{Gblead} and Q_{blag} are assumed to be zero for all generators without any loss of generality. The system is split into three zones or voltage control areas as reported in Zhong *et al*. (2004). The optimization models, which are essentially a non-linear programming, are simulated in GAMS and solved using the MINOS solver.

To illustrate the efficiency of using NERPR for reactive power reserve management instead of using absolute reactive reserve value that is used in Dong *et al*. (2005), two separate OPFs with mentioned objective functions are executed for CIGRE test system. Figure 4 shows the normalized amount of reactive reserve in each VCA. As shown in Fig. 4, using NERPR in the objective function of OPF leads to better dispatch of reserve in VCAs. Since reactive power must be provided locally, each VCA is independent of trading reactive power in other VCAs. So, providing a desirable margin for reactive reserve in each VCA is essential for increasing voltage stability and avoiding voltage collapse. According to Fig. 4, reactive reserve

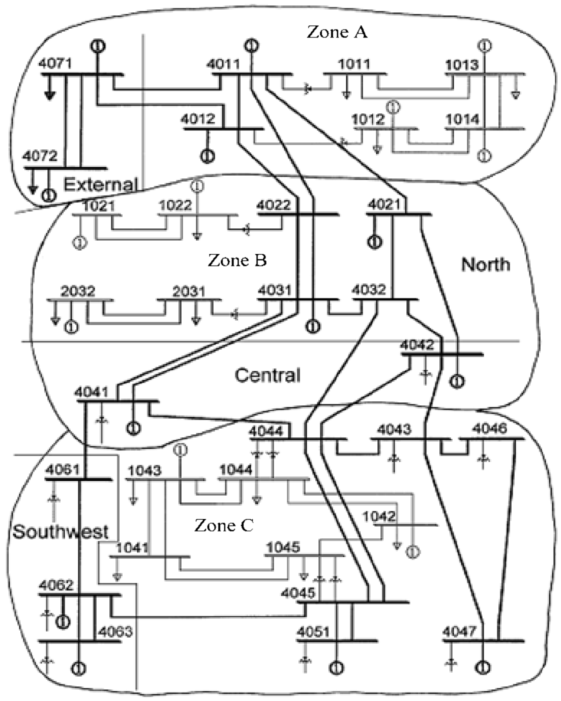

Fig. 3: CIGRE 32-bus system

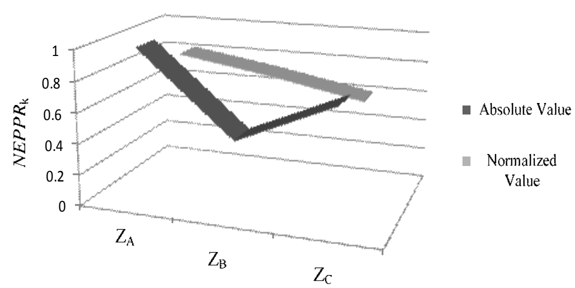

Fig. 4: Comparison of using normalized value of reserve and absolute value

in each VCA will be greater than 60% of maximum possible amount of reserve for that VCA (Q^*_{Rk}) by using the concept of NERPR; whereas, if the absolute reserve value is used, this value for Zone B will be less than 30% and it can create voltage security problem in Zone B.

The proposed reactive power dispatch model is applied on the CIGRE test system. Table 1 shows the input parameters for the dispatch model 13 to 24 that are the results of real power dispatch and long-term reactive power procurement (El-Samahy *et al*., 2008).

Assuming the objective function described by (13), w_1 and w_2 are selected as 1 and -0.01, respectively there

Table 1: Input parameters for the dispatch model

Zone	Bus	P^o_g	ρ_0	ρ_1	ρ_2	ρ_3
A	4072	1391.0	0.86	0.88	0.84	0.35
	4071	470.0				
	4011	461.0				
	4012	626.4				
	1013	492.0				
	1012	752.0				
	1014	400.0				
B	4021	282.0	0.92	0.91	0.90	0.36
	4031	329.0				
	4042	658.0				
	4041	282.0				
	2032	799.0				
	1022	235.0				
	1021	478.8				
C	4062	564.0	0.85	0.53	0.93	0.26
	4063	1128.0				
	4051	658.0				
	4047	800.0				
	1043	188.0				
	1042	376.0				

Table 2: Results of proposed reactive power dispatch model

Zone	Bus	Q_{G1}	Q_{G2}	Q_{G3}	Q_G	NERPR
A	4072	0.00	1.60	0	1.60	0.799
	4071	0.00	0.00	0	0.00	
	4011	1.00	0.00	0	-1.00	
	4012	0.17	0.00	0	-0.17	
	1013	0.00	0.00	0	0.00	
	1012	0.00	0.00	0	0.00	
	1014	0.00	0.00	0	0.00	
B	4021	0.30	0.00	0	-0.30	0.756
	4031	0.00	1.17	0	1.17	
	4042	0.00	0.00	0	0.00	
	4041	0.00	3.00	0	3.00	
	2032	0.00	2.83	0	2.83	
	1022	0.25	0.00	0	-0.25	
	1021	0.00	0.82	0	0.82	
C	4062	0.00	0.44	0	0.44	0.565
	4063	0.00	2.72	0	2.72	
	4051	0.00	2.33	0	2.33	
	4047	0.00	3.62	0	3.62	
	1043	0.00	0.67	0	0.67	
	1042	0.00	1.17	0	1.17	

Table 3: Comparison of the proposed model with El-samahy model

Parameter	Proposed model	Model in El-samahy *et al.* (2007)
$NERPR_A$	0.790	0.680
$NERPR_B$	0.760	0.790
$NERPR_C$	0.570	0.385
Reactive reserve (p.u.)	13.49	12.48
Payment ($)	37.65	36.09

by than total payments. The lower and upper bounds of bus voltages are selected as 0.95 and 1.05 in p.u, respectively. Table 2 shows the results of the proposed reactive power dispatch model. It can be seen from the results that there are no generators required to operate in Region III; hence, no MW rescheduling is required in reactive power dispatch. In high loading conditions, a real power rescheduling may be needed for providing more reactive power. The ISO would compensate the generators that are required to provide more reactive power than $Q_A$as shown in Fig. 2 at the Market Clearing Price (MCP) of real power market.

Table 3 shows the results of comparison of the proposed model with the model in El-Samahy *et al.* (2007). The model proposed in El-Samahy *et al.* (2007) uses reactive power payments as its objective function. We can see from the results that considering payments only in the objective function of reactive power dispatch cannot guarantee a desirable amount of reactive reserve in each VCA. For example, in this case, the proposed dispatch model secures NEPRP above 50% for all the zones; while the Model in El-Samahy *et al.* (2007) does not provide this for Zone C. However, it provides higher NERPR for Zone B (79% compared to 76%). The total reactive power reserve in the system is increased by 8.8% at the cost of a 4.3% increase in total payments to reactive power providers.

CONCLUSION

In this study, a reactive power dispatch model is proposed that considers both technical and economical issues. To ensure system voltage stability, reactive power reserve management is considered in the model. For this purpose, Normalized Effective Reactive Power Reserve (NERPR) is introduced as a new metric for reactive power reserve management that considers voltage control areas. The ISO's objective function in reactive power dispatch is defined using NERPR and total payment to generators for providing reactive power service.

The results show that using NERPR for management of reactive reserve is more efficient than absolute value of reserve. The proposed reactive power dispatch model is decoupled from active power dispatch and has not the complexity of coupled OPFs. The proposed model determines an optimal reactive power dispatch by providing a desirable reactive reserve margin for each VCA of the system thus making it useful for systems with several VCAs and local VAr requirements.

NOMENCLATURE

Q^{Vcol}_g Reactive power output of generator g at the point of voltage collapse

Q^*_{Rk} Maximum reactive power reserve in area *k* without considering other areas

Q_{Gi} Reactive power generation at Bus *i* in p

P^0_{Gi} Pre-determined active power generation of the generator *i* that is obtained from the results of the active power auction market

P_{Di} Active power demand at Bus *i* in p.u

Q_{Di} Reactive power demand at Bus *i* in p.u
V_i Bus *i* voltage magnitude in p.u
δ_i Bus *i* voltage angle in p.u
Y_{ij} Element of admittance matrix in p.u
θ_{ij} Angle of Y_{ij} in radians
$Q^{min}_{Gg}Q^{max}_{Gg}$ Minimum and maximum reactive power of generator *g* in p
V^{min}_{i},V^{max}_{i} Minimum and maximum allowable voltage levels at Bus *i* in p.u
S^{min}_{ij} Flow limit for the connecting Bus *i* to Bus *j* in p.u
$NERPR_k$ Normalized effective reactive power reserve of area *k*
P_{GR} Real power rating of synchronous generator
Q_{GA} Maximum reactive power limit of a generator without reduction in real power generation
Q_{GB} Maximum reactive power limit of a generator with reduction in real power generation
ρ_{0g} Availability price for generator g in \$
ρ_{1g} Price of losses in under-excitation region for generator gin \$/MVAr
ρ_{2g} Price of losses in over-excitation region for generator g in \$/MVAr
ρ_{3g} Lost opportunity price for generator g in $\$/MVAr^2$
Q_{G1g} Reactive power generation in region I in p.u
Q_{G2g} Reactive power generation in region II in p.u
Q_{G3g} Reactive power generation in region III in p.u

REFERENCES

Abed, A.M., 1999. WSCC voltage stability criteria, under-voltage, load shedding strategy and reactive power reserve monitoring methodology. IEEE Power Engineering Society Summer Meeting, Jul. 18-22, pp: 191-197.

Dong, F., B.H. Chowdhury, M. L. Crow and L. Acar, 2005. Improving voltage stability by reactive power reserve management. IEEE Trans. Power Syst., 20(1): 338-345.

El-Keib, A. and X. Ma, 1997. Calculating short-run marginal costs of active and reactive power production. IEEE Trans. Power Syst., 12(2): 559-565.

El-Samahy, I., C. Canizares, K. Bhattacharya and J. Pan, 2007. An optimal reactive power dispatch model for deregulated electricity markets. IEEE PES, Tampa, Jul. 24-28, pp: 1-7.

El-Samahy, I., K. Bhattacharya, C. Canizares, M.F. Anjos and J. Pan, 2008. A procurement market model for reactive power service considering system security. IEEE Trans. Power Syst., 23(1): 137-149.

Fitzgerald, E., C. Kingsley Jr and S.D. Umans, 1992. Electric Machinery. McGraw-Hill, New York.

Lamont, J.W. and J. Fu, 1999. Cost analysis of reactive power support. IEEE Trans. Power Syst., 14(3): 890-898.

Leonardi, B. and V. Ajjarapu, 2008. Investigation of various Generator Reactive Power Reserve (GRPR) definition for online voltage stability/security assessment. Power and Energy Society General Meeting-Conversion and Delivery of Electrical Energy in the 21st Century, Jul. 20-24, pp: 1-7.

Milano, F., C.A. Canizares and M. Invernizzi, 2004. Voltage stability constrained OPF market models considering N-1 contingency criteria. Electr. Power Syst. Res., 74(1): 27-36.

Papalexopoulos, A.D., C.F. Imparato and F.F. Wu, 1989. Large-scale optimal power flow: Effects of initialization, decoupling and discretization. IEEE Trans. Power Syst., 4: 748-759.

Paucar, V. L. and M.J. Rider, 2001. Reactive power pricing in deregulated electrical markets using a methodology based on the theory of marginal costs. Proceedings of the IEEE Large Engineering Systems Conference on Power Engineering, Jul. 11-13, pp: 7-11.

Rahiel, D., M. Khiat, A. Chaker and R. Haïmour, 2010. Reactive power optimization in transmission power system using interior point method. Int. Rev. Electr. Eng., 5(2): 614-618.

Walve, K., 1993. Nordic 32A- A CIGRE Test System for Simulation of Transient Stability and Long Term Dynamics. Svenska Kranftnat.

Zhong, J. and K. Bhattacharya, 2002. Toward a competitive market for reactive power. IEEE Trans. Power Syst., 17(4): 1206-1215.

Zhong, J., E. Nobile, A. Bose and K. Bhattacharya, 2004. Localized reactive power markets using the concept of voltage control areas. IEEE Trans. Power Syst., 19(3): 1555-1561.