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Australasian Universities Power Engineering Conference

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9 -12 December 2007

"Innovation in Power Engineering"

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16-06	A. K. De Bhowmick	Power System Expansion Planning of Oman New Restructured Environment (A. K. De Bhowmick & T. M. S. Al-Khusaibi, Oman Electricity Transmission Company, Sultanate of Oman)

Session 4C: Transmission and Distribution

Chair: Mr. Eric Goddard

20-16	Keerati Chayakulkheeree	Application of Distributed Slack Bus Power Flow to Competitive Environments (K. Chayakulkheeree, Sripatum University, Bangkok, Thailand)
20-17	Warunee Srisongkram	Analysis and Control of Shunt-Compensator for Mitigating Unbalanced Voltages (W. Srisongkram, Rajamangala University of Technology (RMUT) Suvannabhumi, N. Phanthuna, RMUT Phra Nakorn, P. Boonchiam, W. Subsingha, RMUT Thanyaburi & N. Mithulananthan, Asian Institute of Technology, Thailand)
20-18	Hio Nam O	The Effect of Insulation Loss and Semi- Conducting Layers on Pulse Propagation Behavior of Power Cables(H. N. O, T. R. Blackburn & B. T. Phung, The University of New South Wales, New South Wales, Australia)
20-06	M. Rahman	Transmission Line Performance Against Lightning Investigated Using Flash 1.81 (M. Rahman, J. A. Gillespie, Powerlink Queensland, Queensland, Australia, M. Darveniza & T. K. Saha, University of Queensland, Queensland, Australia)
20-21	M. Oloomi-Buygi	Toward Fairness in Transmission Loss Allocation (M. Oloomi-Buygi, Shahrood University of Technology & M. R. Salehizadeh, Islamic Azad University, Tehran, Iran)
20-08	Farid Karbalaei	A Novel Method for Emergency Voltage Control (F.Karbalaei, M. Kalantar & A. Kazemi, Iran University of Science and Technology, Tehran, Iran)
20-10	Sahar Aslanzadeh	Study of Distributed Generation Islanding Impact on Power Quality in IEEE 34-bus Radial Distribution System (S. Aslanzadeh, V. Salehi & S. Jamali, Iran University of Science and Technology, Tehran, Iran)

20-07	Mohammad F. El-Naggar	A Novel Image-Based Approach for Discrimination between Internal Faults and Magnetizing Inrush Currents in Power Transformers (M. F. El-Naggar, A. M. Hamdy, S. M. Moussa & N. K. Ibrahim, Helwan University, Cairo, Egypt)
20-12	Remy Tiako	Investigation of Power System Stabilizer (PSS) Parameters Optimization Using Multi-Power Flow Conditions (R. Tiako & K. A. Folly, University of Cape Town, Rondebosch, South Africa)
20-02	Sadegh Jamali	A New Approach to Adaptive Single Pole Auto Reclosing of Power Transmission Lines (S. Jamali & A. Parham, Iran Uninersity of Science and Technology, Tehran, Iran)
20-11	Vahid Salehi	Maintaining of Islanding Condition of Distributed Generation for Redial Distribution System by D-STATCOM (V. Salehi, S. Aslanzadeh & S. Jamali, Iran University of Technology, Tehran, Iran)

Session 3D: Modelling and Simulation & AI Applications in Power Systems

12-12	Carson Care	Predicting Magnetic Field Emission from HV Substations through Computer Modelling and Verifying the Accuracy of Simulated Results (C. Care, M. S. Eliott, P. N. Le, S. J. McGuinness, Ergon Energy Corporation Ltd., Queensland, Australia)
12-01	Mark Glickman	The Use of Digital Phase Locked Loops for Estimation of Instantaneous Frequency Rate in Distributed Power Networks (M. Glickman, S. Kam, Queensland University of Techology, Queensland, Australia & Z. Hussain, RMIT University, Victoria, Australia)
12-04	Syed Aqeel Ashraf	Analytical and Simulation Study of Partial Discharge Acoustic Signals (S. A. Ashraf, Salalah College of Technology, Salalah, Oman, B. G. Stewart, D. Hepburn & C. Zhou, School of Engineering, Science and Design, Glasgow, UK)
01-01	Umakanta Choudhury	Polar Fuzzy Logic Based Power System Stabilizer (U. Choudhury, Galgotia's College of Engineering & Technology, Utterpradesh, India, D. K. Chaturvedi, Dayalbag Educational Institute, Utterpradesh, India & Ibraheem, Jamia Millia Islamia, New Delhi, India)
01-03	G.Mokryani	Identification of Ferroresonance Based On Wavelet Transform and Artificial Neural Network (G. Mokryani, Islamic Azad University of Ilkhchi, Iran, M. R. Haghifam, Islamic Azad University of tehran South, Tahran, Iran & J. Esmaeilpoor, Islamic Azad University of Bukan, Iran)

Tueday, 11 December (10:30-12:10)

Parallel Technical Sessions (4A, 4B, 4C, 4D, 4E)

Session 4A: Electrical Machines

05-10	Yi Wang	A Survey of Direct Torque Control Schemes for Permanent Magnet Synchronous Motor Drives (Y. Wang, J. Zhu & Y. Guo, Sydney University of Technology, New South Wales, Australia)
05-11	Tania Parveen	Induction Motor Parameter Identification from Operational Data (T. Parveen, G. Ledwich & E. Palmer, Queensland University of Technology, Queensland, Australia)
05-12	Lester Chong	Application of Concentrated Windings in Interior Permanent Magnet Machine (L. Chong, R. Dutta & M. F. Rahman, University of New South Wales, New South Wales, Australia)
05-13	Sayyed Mohammad Mehdi Mirtalaei	A Novel Sensorless Control Strategy for Brushless DC Motor Drive Based on Fuzzy Logic Observer (S. M. M. Mirtalaei, J. S. Moghani & M. Shahbazi, Amirkabir University of Technology, Tehran, Iran)
05-19	Syaiful Bakhri	Investigation and Development of a Real-Time On-Site Condition Monitoring System for Induction Motors (S. Bakhri, M. Ertugrul, W. L. Soong & S. Al-Sarawi, University of Adelaide, South Australia, Australia)

Session 4B: Power System Operation and Planning

16-23	David Spackman	Long Term Demand Forecast for an Electricity Distribution Network (D. Spackman, G. Sivakumar, N. C. Nair, The University of Auckland, Auckland, New Zealand & P. Yeung, Vector Limited, Auckland, New Zealand)
16-07	Farzad Kavehnia	Long Term Demand Forecasting in Distribution Systems Using Fuzzy Interface System (F. Kavehnia, H. Keivani & A. Mohammadi, Islamic Azad University)
16-08	M. Gilvanejad	A Novel Algorithm for Distribution Network Planning Using Loss Reduction Approach (M. Gilvanejad, H. Ghadiri, M. R. Shariati, S. Farzalizadeh, Niroo Research Institute, Iran & A. Arefi, Tavanir Co.)
16-26	Kazuto Yukita	A Study of Load Frequency Control for MicroGrid (K. Yukita, K. Mizuno, T. Ota, S. Washiru, K. Taniguchi, Y. Goto & K.Ichiyanagi, Aichi Institute of Technology, Toyota, Japan)
16-12	Steve Ling	Economic Load Dispatch: A New Hybrid Particle Swarm Optimization Approach (S. H. Ling, H. H. C. Iu, The University of Western Australia, Western Australia, Australia, K. Y. Chan & S. K. Ki, The Hong Kong Polytechnic University, Hong Kong)
16-09	A.Badri	Investigation of GenCos' Optimal Bidding Strategies in Oligopolistic Power Markets (A. Badri, S. Jadid, Iran University of Science and Technology, Tehran, Iran & M. P. Moghaddam, Tarbiat Modarres University, Tehran, Iran)

Session 4C: Transmission and Distribution

20-16	Keerati Chayakulkheeree	Application of Distributed Slack Bus Power Flow to Competitive Environments (K. Chayakulkheeree, Sripatum University, Bangkok, Thailand)

Presented in AUPEC 2007, Perth, Western Australia, 9-12 December, 2007

APPLICATION OF DISTRIBUTED SLACK BUS POWER FLOW TO COMPETITIVE ENVIRONMENTS

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Abstract

This paper presents the mathematical model of distributed slack bus power flow (DSPF) program and its application to competitive electricity supply industry (ESI). The advantage of DSPF is its ability to compute the frequency deviation when the ACE is treated as fixed value. It can represent the automatic generation controls (AGC) for maintaining nominal frequency. More specifically, the proposed method can diversify the power imbalance to voltage controlled buses in the system via participation factor. Therefore, the AGC of the generators can be incorporated in the analysis. The participation factors of the generators are obtained by the weighted average of AGC accepted quantities in ancillary services market. The results shows that the proposed method can satisfactory represent the system behaviour that all generators are response to power imbalance. In addition, the proposed method results in the better justified AGC setting in competitive electricity market than that of using single slack bus power flow. The DSPF is tested with the IEEE 30 bus system and compared to single slack bus power flow solution. Numerical results shown that the method can effectively represent the generation control characteristics to the power flow model and potentially be applied to simulate the competitive electricity markets.

1. Introduction

Power system are steadily growing and have become large and more complex with interconnections to neighboring system for reliable and economic operation under dynamic as well as steady state operating condition [1-4]. Deregulation and restructuring of electricity supply industry (ESI) have been taking place in several countries to improve efficiency, lower electricity price, and tackle financial debts. Different structures were adopted in different countries.

To obtain optimal power dispatch under price based environment, electricity and ancillary services could be dispatched successively by the series of linear programming (LP) [5] or simultaneously by the mixed integer linear programming (MILP) [6]. The line flow limits were neglected to simplify the problem. To incorporate line flow limit constraints, an optimal dispatch problem can be formulated as an extended problem in the optimal power flow (OPF) [7-9].

The theoretical analysis presented above is dependent upon the concept of a single slack bus. Recall that the slack bus issue arises primarily because of lack of prior knowledge of system losses. Because of this, to maintain the real power balance on the system one cannot specify the real power generated at all generators. Mathematically, the need for slack bus is seen in the singularity of the load flow real power Jacobian. Therefore, the computed losses on the transmission system are a function of the choice of a slack bus.

In the actual operation of electric power systems there is no single slack bus, instead there are many generators distributed geographically throughout the system which take on the function of a slack bus. To account for this, a distributed slack bus power flow analysis is needed. Moreover, the pricing for losses or imbalances on the system should correspond to actual operation for the pricing scheme.

Many researchers recognized the inadequacy of a single slack bus and its diverse effects on the steady state calculations in power systems. For example, [10] used a linear transformation to distribute the real power imbalance reflected at the slack bus by self balancing pairs, assuming a lossless system. In [11-

14], the approach is based on participation factors, which resembles actual operation of power systems.

In this paper, an application of distributed slack bus power flow to competitive electricity supply industry (ESI) is introduced. The participation factors of the generators are obtained by the weighted average of AGC accepted quantities in the ancillary services market. The results shows that the proposed method can satisfactory represent the system behavior that all generators are response to power imbalance. In addition, the proposed method results in the better justified AGC setting in competitive electricity market than that of using single slack bus power flow.

The organization of this paper is as follows. Section II addresses the mathematical model of DSPF. The concept of AGC operation as ancillary services under competitive environment is discussed in Section III. Optimal power dispatch based on offered price and quantities including DSPF application to competitive ESI are illustrated in Section IV. Numerical results on the IEEE 30 bus test system are demonstrated in Section V. Lastly, the conclusion is given.

2. Mathematical Model

The generator's prime mover responses and AGC action are included as primary and secondary controls. Active power generation at bus can be considered as,

$$P_{Gi} = P_{Gset\,i} + P_{Gei}, \qquad (1)$$

$$P_{Gi}^{\max} \geq P_{Gi} \geq P_{Gi}^{\min}, \qquad (2)$$

where

- P_{Gi} is the real power generation of the generator connected to bus *i* (MW),
- $P_{Gset\,i}$ is real power schedule at bus *i* (MW),
- P_{Gei} is real power generation due to primary and secondary control at bus *i* (MW),

$$P_{Gei} = -\frac{1}{r_1}\Delta F + \alpha_i \Delta G, \qquad (3)$$

$$\sum_{i=1}^{NG} \alpha_i = 1.00, \qquad (4)$$

$$\Delta F = F - F_0, \qquad (5)$$

where

- r_i is the speed-droop setting on turbine governor in generating plant connected to bus *i* (Hz/MW),
- ΔF is steady-state frequency deviation (Hz),
- F is actual system frequency (Hz),
- F_0 is schedule system frequency (Hz),
- α_i is participation factor of generator connected to bus *i*,
- NG is total number of buses connected to the generators, and
- ΔG is static area control error (MW).

In case of power demand deviation,

$$\Delta G = \Delta P_D + B\Delta F, \qquad (6)$$

$$\Delta P_D = \Delta P_D - P_{D0} + B\Delta F, \qquad (7)$$

$$P_D = \sum_{i=1}^{NB} P_{Li} + P_{loss} \qquad (8)$$

where,

- B is bias factor setting of AGC control regulator, constant for area load frequency characteristic (MW/ Hz),
- P_D is total real power demand (MW),
- ΔP_D is total real power demand deviation (MW),
- P_{Li} is the real power load at bus *i* (MW),
- P_{Loss} is the real power loss of system (MW),
- NB is total number of buses, and
- P_{D0} is initial total real power demand (MW).

Considering the complex power balance equations at *NB* buses and separating the real and imaginary parts, *2NB* number of non-linear equations is obtained [14]. These can then be solved by Newton-Raphson iterative technique. The complex power is,

$$\begin{aligned} S_i &= P_i + jQ_i \\ &= (P_{Gi} - P_{Li}) + j(Q_{Gi} - Q_{Li}) \\ &= (P_{Gseti} + P_{Gei} - P_{Li}) + j(Q_{Gi} - Q_{Li}). \end{aligned} \qquad (9)$$

The power balance equations can be expressed as,

$$P_i = \sum_{j=1}^{NB} |V_i||V_j||y_{ij}|\cos(\theta_{ij} - \delta_{ij}),\ i = 1,...,NB, \qquad (10)$$

$$Q_i = -\sum_{j=1}^{NB} |V_i||V_j||y_{ij}|\sin(\theta_{ij} - \delta_{ij}),\ i = 1,...,NB, \qquad (11)$$

where,

- S_i is the injected appearance power at bus i (MVA),
- P_i is the injected real power at bus i (MW),
- Q_i is the injected reactive power at bus i (MVAr),
- Q_{Gi} is the reactive power generation at bus i (MVA), and
- Q_{Li} is the reactive power load at bus i (MVA),
- $|V_i|$ is the voltage magnitude of bus *i* (V),
- $|y_{ij}|$ is the magnitude of the y_{ij} element of Y_{bus} (mho),
- θ_{ij} is the angle of the y_{ij} element of Y_{bus} (radian), and
- δ_{ij} is the voltage angle difference between bus *i* and *j* (radian).

In the steady state power flow analysis, considering a system of *NB* buses and assuming *NG* numbers of voltage controlled buses, the unknowns are,

- (*NB-1*) number of voltage phase angle at (*NB-1*) buses. More specifically, the generator buses voltage phase angle ($\delta_{i,reference}$, *i* is not reference bus) are unknown variables, and
- (*NB-NG*) number of voltage magnitudes at (*NB-NG*) buses. More specifically, the load buses

voltage magnitude ($|V_i|$, $i \in$ load bus) are unknown variables.

Considering that the active power injected at a bus does not change significantly for a small change in the magnitude of bus voltage. Similarly, the reactive power injected at a bus does not change for a small change in the phase angle of bus voltage. Therefore, the corresponding sensitivity coefficients are neglected.

In this paper, ΔG is selected as the unknown. Therefore, the total number of unknowns is *2NB-NG*. Assuming bus 1 as a voltage phase angle reference for other buses, the linearized equations for decoupled Newton-Raphson iterative solution can be written as,

$$\begin{bmatrix} \Delta P_1 \\ \Delta P_2 \\ \vdots \\ \Delta P_{NB} \end{bmatrix} = \begin{bmatrix} \frac{\partial P_1}{\partial G} & \frac{\partial P_1}{\partial \delta_2} & \cdots & \frac{\partial P_1}{\partial \delta_N} \\ \frac{\partial P_2}{\partial G} & \frac{\partial P_2}{\partial \delta_2} & \cdots & \frac{\partial P_2}{\partial \delta_{NB}} \\ \vdots & \vdots & \cdots & \vdots \\ \frac{\partial P_{NB}}{\partial G} & \frac{\partial P_{NB}}{\partial \delta_2} & \cdots & \frac{\partial P_{NB}}{\partial \delta_{NB}} \end{bmatrix} \begin{bmatrix} \Delta G \\ \Delta \delta_2 \\ \vdots \\ \Delta \delta_{NB} \end{bmatrix}, \tag{12}$$

and

$$\begin{bmatrix} \Delta Q_{NG+1} \\ \Delta Q_{NG+2} \\ \vdots \\ \Delta Q_{NB} \end{bmatrix} = \begin{bmatrix} \frac{\partial Q_{NG+1}}{\partial V_{NG+1}} & \frac{\partial Q_{NG+1}}{\partial V_{NG+1}} & \cdots & \frac{\partial Q_{NG+1}}{\partial V_{NB1}} \\ \frac{\partial Q_{NG+2}}{\partial V_{NG+1}} & \frac{\partial Q_{NG+2}}{\partial V_{NG+2}} & \cdots & \frac{\partial Q_{NG+2}}{\partial V_{NB}} \\ \vdots & \vdots & \cdots & \vdots \\ \frac{\partial Q_{NB}}{\partial V_{NG+1}} & \frac{\partial Q_{NB}}{\partial V_{NG+2}} & \cdots & \frac{\partial Q_{NB}}{\partial V_{NB}} \end{bmatrix} \begin{bmatrix} \Delta V_{NG+1} \\ \Delta V_{NG+2} \\ \vdots \\ \Delta V_{NB} \end{bmatrix}. \tag{13}$$

The above relation can be written as,

$$[\Delta P] = [J_1]\begin{bmatrix} \Delta G \\ \Delta \delta \end{bmatrix}, \tag{14}$$

$$[\Delta Q] = [J_2][\Delta V], \tag{15}$$

where,

$[J_1]$ is $(NB \times NB)$ matrix, and

$[J2]$ is $(NB\text{-}NG) \times (NB\text{-}NG)$ matrix.

The power mismatch can be computed as,

$$[\Delta P^k] = [P_{specified}] - [P_{calculated}], \tag{16}$$

$$[\Delta Q^k] = [Q_{specified}] - [Q_{calculated}], \tag{17}$$

where,

k is the iterative count,

$[P_{specified}]$ is the column matrix represents the specified real power injection at bus i (MW), i = 1,…, *NB*,

$[P_{calculated}]$ is the column matrix represents the calculated real power injection at bus i (MW) using Eq.(10) , i = 1,…, *NB*,

$[Q_{specified}]$ is the column matrix represents the specified reactive power injection at bus i (MW), i = *NG*+1,…,*NB*, and

$[Q_{calculated}]$ is the column matrix represents the calculated reactive power injection at bus i (MW) using Eq.(11), i = *NG*+1,…,*NB*.

The estimated bus voltage, X, and calculated power are used to evaluate the element of the Jacobian matrices $[J_1]$ and $[J_2]$. ΔX, $\Delta\delta$ and ΔV can be obtained from,

$$\begin{bmatrix} \Delta X \\ \Delta \delta \end{bmatrix} = [J_1]^{-1}[\Delta P], \tag{18}$$

$$[\Delta V] = [J_2]^{-1}[\Delta Q]. \tag{19}$$

Then the variables are updated as,

$$X^{k+1} = X^k + \Delta X^k, \tag{20}$$

$$\delta^{k+1} = \delta^k + \Delta\delta^k, \tag{21}$$

$$V^{k+1} = V^k + \Delta V^k. \tag{22}$$

The iterative process is repeated until ΔP^k and ΔQ^k for all buses are within a specified tolerance.

3. AGC as Ancillary Services

In competitive electricity and ancillary services markets, the independent system operator (ISO) must match supply and demand in an optimal and secure manner under the generator operational and transmission system constraints in real time. For reliability and security reasons, ISO purchases ancillary services such as automatic generation control (AGC), spinning and non-spinning reserves from the ancillary services providers or generation companies either on mandatory or competitive basis [6-9].

The AGC is the ability of (capacity provided by) the generating unit to respond to signals from the ISO to provide control area balancing, frequency bias and time error correction. Therefore, it is a secondary frequency regulation. Generally, the operating practice requires the AGC to drive the area control error (ACE) to “cross zero” every specified time interval [6]. More specifically, AGC is the regulating capability that responds in an effort to continuously balance in minute to minute load variations [6-7]. Regulating capacity is converted to an AGC commodity which is a weighted average of the MW response available in ten minutes [7]. However, each generator can choose to offer any quantities and associated prices for electricity, AGC, Ten-minute spinning reserve (TMSR) and Thirty-minute operating reserve (TMOR), given generator capability [7].

The TMSR is a resource capacity synchronized to the system which is capable to immediately supply energy or reduce demand and fully available within ten minute [6-7]. TMSR is required to respond to contingencies including generator or transmission line outages, not minute to minute load variations like AGC.

The TMOR is the capability of the generator to respond in 30 minutes. TMOR can be referred to the resource from non-synchronizing generator only as suggested [7]. But TMOR could be extended to include either off-line generating unit that can start and ramp up to the specified level of output or synchronized generating unit which can increase the output between 10 and 30 minutes [6].

4. Optimal Power Dispatch Based on Offered Prices and Quantities

The objective functions for optimal power dispatch in electricity market can be expressed as [6, 8-9],

Minimize

$$S = \sum_{i=1}^{NG} \begin{bmatrix} \sum_{j=1}^{NS_i} S_{ij} P_{Gij} + OAGC_i \cdot AGC_i + \\ OTMSR_i \cdot TMSR_i + OTMOR_i \cdot TMOR_i \end{bmatrix}, \quad (23)$$

subject to the power balance constraints in Eqs.(9) and (10),

where,

$$P_{Gi} = \sum_{j=1}^{NS_i} P_{Gij} \text{, for } i = 1, \ldots, NG, \quad (24)$$

$$0 \le P_{Gij} \le P_{Gij}^{\max} \text{, for } j = 1, \ldots, NS_i, \quad (25)$$

and the line flow limit constraints,

$$|f_l| \le f_l^{\max} \text{, for } l=1, \ldots, NC, \quad (26)$$

and the security constraints,

$$AGCR = \%AGC \cdot (\sum_{i=1}^{NTD} P_{Di} + P_{loss}) \le \sum_{i=1}^{NG} AGC_i, \quad (27)$$

$$TMSRR = \%TMSR \cdot (\sum_{i=1}^{NTD} P_{Di} + P_{loss}) \le \sum_{i=1}^{NG} TMSR_i, \quad (28)$$

$$TMORR = \%TMOR \cdot (\sum_{i=1}^{NTD} P_{Di} + P_{loss}) \le \sum_{i=1}^{NG} TMOR_i, \quad (29)$$

and the generator maximum operating limit constraints,

$$\begin{bmatrix} P_{Gi} + AGC_i + \\ TMSR_i + TMOR_i \end{bmatrix} \le P_{Gi}^{\max} \text{, for } i = 1, \ldots, NG, \quad (30)$$

and the generator minimum operating limit and AGC low regulating limit constraints,

$$\left(A_i \cdot (P_{AGC,i}^{low} - P_{Gi}^{\min}) + Z_i \cdot P_{Gi}^{\min} - P_{Gi}\right) \le 0 \text{, for } i=1,\ldots,NG, \quad (31)$$

where, $P_{AGC,i}^{low} \ge P_{Gi}^{\min}$, for $i = 1, \ldots, NG$,

and the AGC limit and high regulating limit constraints,

$$0 \le AGC_i \le AGC_i^{\max} \cdot A_i \text{, for } i = 1, \ldots, NG, \quad (32)$$

$$P_{Gi} + AGC_i \le P_{AGC,i}^{high} \text{, for } i=1, \ldots, NG, \quad (33)$$

where, $P_{AGC,i}^{high} \le P_{Gi}^{\max}$, for $i = 1, \ldots, NG$,

and the AGC supply constraints,

$$A_i - Z_i \le 0 \text{, for } i = 1, \ldots, NG, \quad (34)$$

where, $A_i \in \{0,1\}$ and $Z_i \in \{0,1\}$, for $i = 1, \ldots, NG$,

and the TMSR limit constraints,

$$0 \le TMSR_i \le TMSR_i^{\max} \cdot Z_i \text{, for } i=1,\ldots,NG, \quad (35)$$

and the TMOR limit constraints,

$$0 \le TMOR_i \le TMOR_i^{\max} \text{, for } i = 1, \ldots, NG, \quad (36)$$

where,

AGC_i is accepted AGC quantity supplied by generator at bus i (MW),

$AGCR$ is total system AGC requirement (MW),

$AGC_i^{\max}$ is offer AGC quantity of generator at bus i (MW),

A_i is on or off AGC status of the generator at bus i,

f_l is MVA flow of line or transformer l (MVA),

$f_l^{\max}$ is MVA flow limit of line or transformer l (MVA),

NC is total number of line flow and transformer loading terminal constraints,

NS_i is number of segments of generator supply cost function at bus i,

$OAGC_i$ is AGC offer price of generator at bus i (\$/MWh),

$OTMSR_i$ is TMSR offer price of generator at bus i (\$/MWh),

$OTMOR_i$ is TMOR offer price of generator at bus i (\$/MWh),

$P_{AGC,i}^{high}$ is high regulating limit of generator at bus i (MW),

$P_{AGC,i}^{low}$ is low regulating limit of generator at bus i (MW),

$P_{Gij}^{\max}$ is generator offer block j at bus i (MW)

$P_{Gi}^{\max}$ is maximum real power generation at bus i (MW),

$P_{Gi}^{\min}$ is minimum real power generation at bus i (MW),

P_{Gi} is real power generation at bus i (MW),

P_{Gij} is accepted generator offer block j at bus i (MW),

P_{loss} is total system real power loss (MW),

Q_{Gi} is reactive power voltage controlled generation at bus i (MVAR),

Q_{Di} is reactive power demand at bus i (MVAR),

S_{ij} is offer price block j of generator at bus i (\$/MWh),

$TMOR_i$ is accepted quantity of TMOR supplied by generator at bus i (MW),

$TMSR_i$ is accepted quantity of TMSR supplied by generator at bus i (MW),

$TMORR$ is total system TMOR requirement (MW),

$TMSRR$ is total system TMSR requirement (MW),

Z_i is committed or uncommitted status of generator at bus *i*,

$\%AGC$ is AGC requirement in percentage of total real power dispatch,

$\%TMOR$ is TMOR requirement in percentage of total real power dispatch, and

$\%TMSR$ is TMSR requirement in percentage of total real power dispatch,

By Eqs. (31), (32), and (34), the AGC offer of generator *i* can be selected ($A_i = 1$) only when the generator *i* is committed to the system ($Z_i = 1$) [6]. Under the AGC low and high regulating limits, the generator can perform AGC function. The AGC low regulating limit is higher than or equal to the minimum operating limit and AGC high regulating limit is less than or equal to the maximum operating limit.

The imbalances between contractual and physical electricity consumption in real time are handled by a balancing mechanism in balancing market (BM) [9]. Therefore, there is an opportunity for generators to sell their remaining available capability in BM. However, the ISO is required to simultaneously optimally dispatch the electricity and ancillary services markets. The DSPF is used for balancing electricity. The participation factors are obtained by,

$$\alpha_i = \frac{AGC_i}{\sum_{j=1}^{NG} AGC_i}, \quad (37)$$

where,

α_i is participation factor of generator connected to bus *i,*

$OEAGC_i$ is the offered energy price of AGC_i (\$/MWhr).

If the violated line sensitivity of the generator *i* is greater than zero ($\frac{df_l}{dP_{Gi}} > 0$), the AGC_i is set to zero. With this formulation, the AGC is distributed to all generators connected to the system in accordance with their offered price.

4. Simulation Results

The proposed method has been tested with modified IEEE 30 bus system. The network data was given in [15]. The offered price and quantities of electricity are given in [16]. The AGC, TMSR, and TMOR offered prices and quantities are shown in Table 1. The AGC, TMSR, and TMOR requirements are 3%, 5%, and 5%, of total demand, respectively.

The dispatch result is shown in Table 2. The line 9-11 flow is violate its limit and resulted in binding solution on the line 9-11 flow limit constraint.

Table 1 AGC, TMSR, and TMOR offered prices and quantities of IEEE 30 bus system

Gen	AGC		TMSR		TMOR	
Bus	MW	\$/MW	MW	\$/MW	MW	\$/MW
1	2	7	4	8	3	15
2	4	11	2	11	4	13
5	2	12	5	8	3	14
8	3	13	2	10	2	15
11	3	14	5	14	5	16
13	2	5	2	12	3	12

Table 2 Dispatch results of IEEE 30 bus system

Gen Bus	Electricity	AGC	TMSR	TMOR
1	70.65	2	4	3
2	20.00	4	2	4
5	82.50	0.5872	5	2.312
8	41.20	0	2	2
11	29.46	0	0	0
13	42.43	2	1.312	3

Table 3 Dispatch results of IEEE 30 bus system with single slack bus power flow

BUS	|V|	DEL	Pgen	Qgen	Pload	Qload
===	=====	=====	=====	=====	=====	=====
1	1.06	0	73.6	18.5	0	0
2	1.045	-1.4	20	29.2	21.9	12.8
3	1.029	-2	0	0	2.4	1.2
4	1.022	-2.3	0	0	7.7	1.6
5	1.01	-3	82.5	4.4	95.1	19.2
6	1.016	-2.6	0	0	0	0
7	1.006	-3.3	0	0	23	11
8	1.01	-2.3	41.2	8.1	30.3	30.3
9	1.054	-3	0	0	0	0
10	1.048	-4.9	0	0	5.9	2
11	1.082	0.1	29.5	15.4	0	0
12	1.063	-3.4	0	0	11.3	7.6
13	1.071	-0.4	42.4	7.1	0	0
14	1.048	-4.4	0	0	6.3	1.6
15	1.043	-4.6	0	0	8.3	2.5
16	1.049	-4.3	0	0	3.5	1.8
17	1.043	-4.9	0	0	9.1	5.9
18	1.032	-5.4	0	0	3.2	0.9
19	1.029	-5.7	0	0	9.6	3.4
20	1.033	-5.5	0	0	2.2	0.7
21	1.036	-5.4	0	0	17.7	11.3
22	1.036	-5.4	0	0	0	0
23	1.031	-5.3	0	0	3.2	1.6
24	1.025	-5.9	0	0	8.8	6.8
25	1.018	-6.2	0	0	0	0
26	1.001	-6.6	0	0	3.5	2.3
27	1.024	-6.1	0	0	0	0
28	1.012	-2.9	0	0	0	0
29	1.004	-7.3	0	0	2.4	0.9
30	0.992	-8.2	0	0	10.7	1.9

It is presumed that the load is increased by 1%, distributed to all bus proportionately to initial loads, during the time interval of AGC secondary control action. The total load is 286.23 MW. The power flow program with single and distributed slack bus are run to obtain final conditions after AGC take action. Table 3 shows the power flow result of single slack bus power flow. With single slack bus, the power imbalance is met by the generator at bus 1. The total real power generation is 289.18 MW and the total real power loss is 2.95 MW.

Table 4 shows the power flow result of DSPF. The DSPF results in the total real power generation of 289.15 MW with total real power loss of 2.92 MW. The results in Table 4 show that the proposed method can allocate the AGC dispatch to the generator corresponding to their accepted AGC in ancillary services market. The DSPF can be potentially applied to the competitive electricity market.

Table 4 Dispatch results of IEEE 30 bus system with DSPF

BUS	|V|	DEL	Pgen	Qgen	Pload	Qload
1	1.06	0	71.3	19.1	0	0
2	1.045	-1.3	21.4	28.6	21.9	12.8
3	1.029	-1.9	0	0	2.4	1.2
4	1.022	-2.2	0	0	7.7	1.6
5	1.01	-2.9	82.7	4.3	95.1	19.2
6	1.016	-2.5	0	0	0	0
7	1.006	-3.2	0	0	23	11
8	1.01	-2.3	41.2	8.1	30.3	30.3
9	1.054	-2.9	0	0	0	0
10	1.048	-4.8	0	0	5.9	2
11	1.082	0.2	29.5	15.4	0	0
12	1.063	-3.3	0	0	11.3	7.6
13	1.071	-0.2	43.1	7.1	0	0
14	1.048	-4.3	0	0	6.3	1.6
15	1.043	-4.5	0	0	8.3	2.5
16	1.049	-4.2	0	0	3.5	1.8
17	1.043	-4.8	0	0	9.1	5.9
18	1.032	-5.3	0	0	3.2	0.9
19	1.029	-5.6	0	0	9.6	3.4
20	1.033	-5.5	0	0	2.2	0.7
21	1.036	-5.3	0	0	17.7	11.3
22	1.036	-5.3	0	0	0	0
23	1.031	-5.2	0	0	3.2	1.6
24	1.024	-5.8	0	0	8.8	6.8
25	1.018	-6.1	0	0	0	0
26	1.001	-6.5	0	0	3.5	2.3
27	1.024	-6	0	0	0	0
28	1.012	-2.9	0	0	0	0
29	1.004	-7.3	0	0	2.4	0.9
30	0.992	-8.1	0	0	10.7	1.9

4. Conclusion

In this paper the DSPF is satisfactory represent the system behaviour that all generators are response to power imbalance. In addition, the proposed method results in the well justified for AGC in competitive electricity market.

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