

University of Kurdistan

Dept. of Electrical and Computer Engineering

Smart/Micro Grid Research Center

smgrc.uok.ac.ir

Intelligent Coordination of Demand Response and Secondary Frequency Control in Multi-area Power Systems

P. Babahajiani, H. Bevrani, and Q. Shafiee

Published in: Proceedings of the 1st IEEE conference on new research achievements in electrical and computer engineering, CBCONF 2016

(Expected) publication date: 2016

Citation format for published version:

Babahajiani P., Bevrani H., Shafiee Q., (2016). Intelligent Coordination of Demand Response and Secondary Frequency Control in Multi-area Power Systems. In proceedings of the 1st IEEE conference on new research achievements in electrical and computer engineering (CBCONF 2016), Tehran, Iran, pp. xx-xx.

Copyright policies:

- Download and print one copy of this material for the purpose of private study or research is permitted.
- Permission to further distributing the material for advertising or promotional purposes or use it for any profit-making activity or commercial gain, must be obtained from the main publisher.
- If you believe that this document breaches copyright please contact us at smgrc@uok.ac.ir providing details, and we will remove access to the work immediately and investigate your claim.

Intelligent Coordination of Demand Response and Secondary Frequency Control in Multi-area Power Systems

Pouya Babahajiani^{1,2}, Hassan Bevrani², Qobad Shafiee²

¹Department of Research and Development

Kurdistan Barez Tire Corporation

Sanandaj, Kurdistan, Iran

Email: p.babahajyani@ec.iut.ac.ir

²Department of Electrical and Computer Engineering

University of Kurdistan

Sanandaj, Kurdistan, Iran

Emails: bevrani@uok.ac.ir; q.shafiee@uok.ac.ir

Abstract—Frequency control is among most important issues in a power system due to increasing size, changing structure and the complexity of interconnected power systems. Increasing economic constraints for power system quality and reliability and high operational costs of generation side controllers have inclined researchers to consider demand response as an alternative for preserving system frequency during off-normal conditions. However, the main obstacle is calculating the accurate amount of load related to the value of disturbances to be manipulated, specifically in a multi-area power system. Dealing with this challenge, this paper makes an attempt to find a solution via monitoring the deviations of tie-line flows. The proposed solution calculates the magnitude of disturbances and simultaneously determines the area where disturbances occurred, to apply demand response exactly to the involved area. To address communication limitations, the impact of demand response delay on the frequency stability is investigated. Furthermore, this paper introduces a fuzzy-PI-based supervisory controller as a coordinator between the demand response and secondary frequency control avoiding large frequency overshoots/undershoots caused by the communication delays. To evaluate the proposed control scheme, simulation studies are carried out on the 10-machine New England test power system.

Index Terms—Frequency control, fuzzy-PI coordinator, multi-area power system, regional demand response, time delay.

I. INTRODUCTION

Following a severe system stress, say a large generation loss or noticeable step load disturbances, the power imbalance between generation and demand may lead system to under frequency situations. In such cases, the system needs to be controlled in a short time (within tens of seconds), yet the combined response of traditional methodologies such as governors and automatic generation controllers (primary and secondary controllers) may not be sufficient, reliable and secure [1]. In addition, due to the slow dynamic of generators mechanical parts, frequency cannot be restored in the first few

seconds. Although energy storage devices (e.g. batteries, flywheels and ultra capacitors) have been introduced to improve the performance and stability in the power systems [2], due to the low efficiency, high operational cost of the devices [3], and also high operational cost of generation side controllers [4], demand response has been taken into account as a solution to enhance power system reliability and security [5]-[7].

Demand response is the ability to control and manipulate demand side loads to turn them off/on or change their consumption based on situation and in response to power quality, system security, voltage and frequency, technical and economic constraints, applied by grid operators. This concept first was introduced by Shweppe et al. [8], in 1980, responding to the need for seeking a faster and more reliable method than the traditional ones, to maintain balance between generation side and demand side.

Typically, power system frequency control has been divided into two main categories: 1) normal controls applied in the normal situations to stay in or return into normal condition, 2) emergency controls, for instance, under frequency load shedding (UFLS), which are applied in emergency conditions, as the last option to prevent the risk of cascade faults and additional generation events [1]. Recent studies have shown that demand response could play more important and effective role, and as the first option not the last, in order to control the system frequency. Furthermore, demand response has the potential to decrease the generation side contribution in frequency control that consequently reduces CO₂ emission [9], energy consumption and the required amount of reserves and hence the system operational costs [10]. Appliances which are capable of performing their duty, in spite of compulsory blackouts during the day without causing any harm to the customers, are most suitable for demand response. Electric water heaters, refrigerators,

freezers, air conditioners, ovens, heating systems and plug-in electric vehicles are examples of these appliances [11], [12].

Demand response because of its fast dynamic could be an appealing alternative to damp the system frequency deviations. In the literature, the impact of demand response on system frequency control has been studied. A technical review on some practical challenges of contributing demand response in power systems frequency control, such as synchronization of electrical loads, advantages/drawbacks of centralized and decentralized structures have been provided in [13]. In [4], a distributed frequency control algorithm through randomizing frequency response of smart appliances is proposed, which monitor the grid frequency and respond independently based on frequency thresholds. In this approach it is assumed that generation side controllers are deactivated and demand response is completely responsive.

The contribution of demand response in frequency control of power systems and isolated microgrids [14], [15], has been studied in the literature using frequency-sensitive load controllers with different frequency-time characteristics [11], [16], saturable reactors [17], and selective load control scheme, with the contribution of electric vehicles charging interfaces [18]. Moreover, coordination of demand response and local frequency control, considering the impact of communication delay on frequency stability is investigated in [9], [19].

In terms of considering demand response as a kind of spinning reserve, some works have been done in [20]. H. Hao et al. in [21] tried to evaluate the effect of controllable loads on system frequency response, and more specifically on the load damping coefficient. In [22], the exploitation of demand response as frequency controlled reserve, using simple frequency threshold based controllers is suggested. In [23], the impact of utilizing appliances with programmable thermostats, relay-controlled loads and industrial pump loads, on frequency regulation of an island in the Baltic Sea, with high penetration of wind energy has been tested. Authors in [24] addressed a decentralized optimal load control methodology via estimating the amount of generation and demand imbalance, in a single area power system, using an unbiased and minimum variance estimation method.

Despite high contribution of demand response in frequency regulation, several operating concerns still exist. On the one hand, over-shedding can cause unnecessarily shedding of load and frequency stays above its nominal level and consequently lead system to excessive over-frequency. On the other hand, light utilization of demand response during system faults may degrade its positive impacts, for instance, on primary frequency control, CO₂ emission, energy consumption and system operational costs. Hence, knowing the accurate magnitude of disturbances and the location of shed load specifically in a multi-area power system or a cluster of microgrids is vital [25]. Despite significant works in the literature, there is still no single work to estimate the accurate amount of load change in a multi-area power system.

In response to this challenge, the present paper proposes a

method to find the value of step load changes as the most severe disturbances using the tie-line power changes and simultaneously determine the area where disturbances occurred, to implement demand response regionally (regional demand response). Since time delay, e.g. communication delay and measurement delay may degrade the system performance and causes instability, a fuzzy-PI-based supervisory coordinator is exploited to avoid this physical constraint.

In traditional power systems, the secondary frequency control is mostly done by the conventional PI controllers that are usually tuned based on prespecified operating points. In case of any change in the operating condition, the PI controllers cannot provide the assigned desirable performance. Recent work of the authors in [2] demonstrates that fuzzy logic can be used as a suitable intelligent method for online tuning of PI controller parameters. In the present work, a fuzzy-based demand response and secondary frequency loop coordinator is proposed.

The rest of this paper is organized as follows: Section II presents regional demand response (RDR) and the methodology to calculate the magnitude of disturbances based on the second derivative of tie-line power changes. The fuzzy-PI based scheme is addressed in Section III. Section IV gives the test system details and parameters. In Section V simulation studies are provided to demonstrate the effectiveness of the proposed methodology. Finally, Section VI concludes the paper.

II. REGIONAL DEMAND RESPONSE

A. Estimation of System Load Change

Power systems have a highly nonlinear and time varying nature. However, for the purpose of frequency control synthesis and analysis in the presence of load disturbances, a simple linearized low order model is used. In comparison with other system dynamics (voltage and rotor angle), the dynamics that affecting frequency response are relatively slow, in the range of seconds to minutes [1].

In a power system with N -control areas, the total tie-line power change between area i and other areas is [1]:

$$\begin{aligned} \Delta P_{tie,i} &= \sum_{\substack{j=1 \\ j \neq i}}^N \Delta P_{tie,ij} \\ &= \frac{2\pi}{s} \left[\sum_{\substack{j=1 \\ j \neq i}}^N T_{ij} \Delta f_i - \sum_{\substack{j=1 \\ j \neq i}}^N T_{ij} \Delta f_j \right] \end{aligned} \quad (1)$$

where, Δf and T_{ij} are the frequency deviation and synchronizing torque coefficient, respectively. Suppose that in a two area power system, a disturbance is applied just to area one:

$$\Delta P_{tie,1} = \frac{2\pi}{s} (T_{12} \Delta f_1 - T_{12} \Delta f_2) \quad (2)$$

According to Fig. 1, where elements of a control area, i.e., control area i , are represented with a simple first order model

and R , T_{gij} and T_{ji} are speed droop characteristic, governor time constant and turbine time constant, respectively, one can write:

$$\Delta f_2 = (-\Delta P_{tie,2} - \Delta P_{L,2} + \sum_{i=1}^n \Delta P_{m2i}) \frac{1}{D_2 + 2H_2s} \quad (3)$$

With no speed governing at $t = 0^+s$, $\sum \Delta P_m = 0$ [1]. In addition, $\Delta P_{L,2} = 0$; then (3) can be simplified as

$$\Delta f_2 = \frac{-\Delta P_{tie,2}}{D_2 + 2H_2s} \quad (4)$$

where

$$\Delta P_{tie,2} = \frac{2\pi}{s} (T_{21}\Delta f_2 - T_{21}\Delta f_1) \quad (5)$$

At $t = 0^+s$

$$\Delta f_2 = \frac{-\Delta P_{tie,2}}{D_2 + 2H_2s} \quad (6)$$

Considering (5), one can write

$$(D_2 + 2H_2s)\Delta f_2 = \frac{-2\pi}{s} T_{21}(\Delta f_2 - \Delta f_1) \quad (7)$$

$$\Delta f_1 = \left(\frac{2H_2s^2 + D_2s}{2\pi T_{21}} + 1 \right) \Delta f_2 \quad (8)$$

Taking the inverse Laplace transform, the time domain equation is obtained

$$\Delta f_1 = \Delta f_2 + \frac{D_2}{2\pi T_{21}} \frac{d}{dt} \Delta f_2 + \frac{2H_2}{2\pi T_{21}} \frac{d^2}{dt^2} \Delta f_2 \gg \Delta f_2 \quad (9)$$

Since Δf_1 is proportional to the second derivative of Δf_2 which is considerably greater than Δf_2 , at $t = 0^+s$, Δf_2 in (2) could be ignored and

$$\Delta P_{tie,1} = \frac{2\pi}{s} T_{12} \Delta f_1 \quad (10)$$

Hence, for a multi-area power system (1), at $t = 0^+s$ the term $\sum_{j=1, j \neq i}^N T_{ij} \Delta f_j$ can be ignored.

Now, assume that load disturbances are applied to area i :

$$\Delta P_{tie,i} = \frac{2\pi}{s} \left(\sum_{j=1, j \neq i}^N T_{ij} \Delta f_j \right) = \frac{K}{s} \Delta f_i, \quad \text{at } t = 0^+s \quad (11)$$

where

$$K = 2\pi \sum_{\substack{j=1 \\ j \neq i}}^N T_{ij} \quad (12)$$

According to Fig. 1

$$\Delta f_i = \frac{-1}{D_i + 2H_i s} (\Delta P_{tie,i} + \Delta P_{L,i}) \quad (13)$$

Considering (11) and (13), one can write

$$\left(\frac{s}{K} + \frac{1}{D_i + 2H_i s} \right) \Delta P_{tie,i} = \frac{-\Delta P_{L,i}}{D_i + 2H_i s} \quad (14)$$

For a step change in load by $\Delta P_{L,i}$, Laplace transform of the

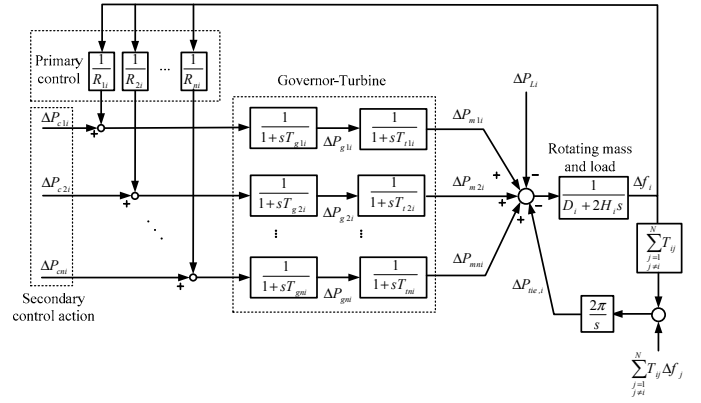


Fig. 1. Block diagram representation of control area i

load change is:

$$\Delta P_{L,i}(s) = \frac{\Delta P_{L,i}}{s} \quad (15)$$

Substituting (15) in (14) yields

$$\begin{aligned} \Delta P_{tie,i} &= \frac{-K \Delta P_{L,i}}{s(2H_i s^2 + D_i s + K)} \\ &= -\Delta P_{L,i} \frac{K/2H_i}{s(s^2 + D_i/2H_i + K/2H_i)} \end{aligned} \quad (16)$$

$$\begin{aligned} s^2 \Delta P_{tie,i} &= -\Delta P_{L,i} \frac{(K/2H_i)s}{s^2 + (D_i/2H_i)s + K/2H_i} \\ &= -\frac{\Delta P_{L,i} K}{2H_i} \times \frac{s}{s^2 + 2\zeta\omega_n + \omega_n^2} \end{aligned} \quad (17)$$

where

$$\omega_n^2 = \frac{K}{2H_i}, \quad \zeta = \frac{D_i}{4H_i \sqrt{K/2H_i}} \quad (18)$$

Taking the inverse Laplace transform, the time domain equation is obtained

$$\frac{d^2 \Delta P_{tie,i}(t)}{dt^2} = \frac{\Delta P_{L,i} \omega_n^2}{\sqrt{1-\zeta^2}} e^{-\zeta\omega_n t} \sin(\omega_n \sqrt{1-\zeta^2} t - \phi) \quad (19)$$

where

$$\phi = tg^{-1} \frac{\sqrt{1-\zeta^2}}{\zeta} \quad (20)$$

Hence, the second derivative of tie-line power at $t = 0^+s$ is proportional to the $-\Delta P_{L,i} K/2H_i$

$$\begin{aligned} \frac{d^2 \Delta P_{tie,i}}{dt^2} &= -\Delta P_{L,i} \frac{\omega_n^2}{\sqrt{1-\zeta^2}} \sin(tg^{-1} \frac{\sqrt{1-\zeta^2}}{\zeta}) \\ &= -\Delta P_{L,i} \frac{K}{2H_i} \end{aligned} \quad (21)$$

Therefore, (21) allows us to calculate the magnitude of the disturbance applied to area i :

$$\Delta P_{L,i} = -\frac{H_i \frac{d^2 \Delta P_{tie,i}(t)}{dt^2}}{\pi \sum_{\substack{j=1 \\ j \neq i}}^N T_{ij}} pu. \quad (22)$$

As can be seen, the step load is negatively proportional to the second derivative of the disturbed area tie-line power. Furthermore, the signs of other areas tie-line powers are different from the tie-line power of area i as the disturbed area at $t = 0^+s$. Thus, based on these results the disturbed area could be easily distinguished.

Now, similarly the tie-line power of the other areas at $t = 0^+s$ can be calculated. According to the analysis provided in (6)

$$\Delta P_{tie,j} = -\frac{2\pi}{s} T_{ij} \Delta f_i, \quad j \neq i \quad (23)$$

Considering (8) and (20), $\Delta P_{tie,j}$ can be obtained as follows

$$\Delta P_{tie,j} = -\frac{2\pi T_{ij}}{K} \Delta P_{tie,i}, \quad j \neq i \quad (24)$$

Therefore, the signs of other areas tie-line powers are different from the tie-line power of area i as the disturbed area at $t = 0^+s$.

B. Contribution Mechanism

Considering above analytic approach, an algorithm is proposed for implementing the RDR in frequency control. At the first step of the algorithm the second derivative of tie-line flows of all areas are calculated. Since the second derivative may be sensitive to noise, a high pass filter is utilized. It should be noted that, this filter does not add such accountable delay to the algorithm.

Afterward, based on the sign of tie-line flows, the disturbed area, i.e., area i , is identified under the following conditions:

$$\text{If } \frac{d^2}{dt^2} \Delta P_{tie,j} > 0 \quad \text{and} \quad \frac{d^2}{dt^2} \Delta P_{tie,i} < 0$$

or

$$\text{If } \frac{d^2}{dt^2} \Delta P_{tie,j} < 0 \quad \text{and} \quad \frac{d^2}{dt^2} \Delta P_{tie,i} > 0$$

for $j=1, \dots, n, \quad j \neq i$

The value of load to be disconnected or reconnected in each area (RDR_j) during the demand response process is obtained:

$$RDR_j = 0 \quad \text{for } j=1, \dots, n, \quad j \neq i \quad (25)$$

and

$$RDR_i = \frac{-H_i \frac{d^2}{dt^2} \Delta P_{tie,i}(t)}{\pi \sum_{\substack{j=1 \\ j \neq i}}^n T_{ij}} \times \gamma \quad (26)$$

$0 < \gamma < 1$ is the participation factor which could be determined by the system operator. $\gamma=0$ means that all the required regulation would be provided by the generation side and the RDR has no participation, and $\gamma=1$ means that the total available active loads for the RDR are involved in the system frequency control. The impact of the different values of γ is investigated in the simulation studies.

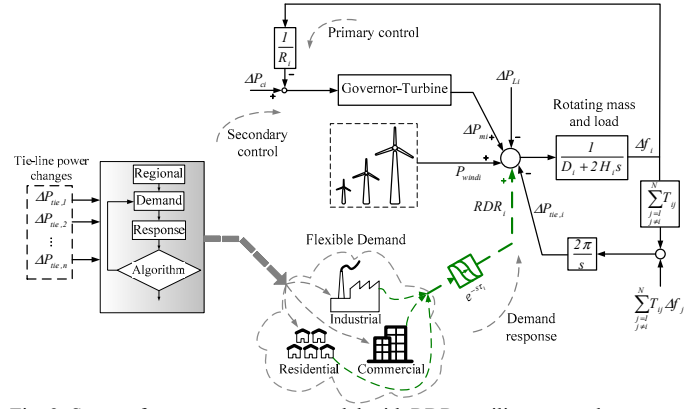


Fig. 2. System frequency response model with RDR auxiliary control.

It should be noted that, once the tie-line flows is employed to calculate the value of the load disturbance, they would not be used for about 2 or 3 seconds, as disconnecting or reconnecting loads for demand response task causes changes in tie-line flows again which may be interpreted as disturbance itself.

In this algorithm the RDR is utilized under the circumstance of sudden load changes. Other types of disturbances, such as wind power fluctuations, are handled by the generation side. Thus, a deadband is used to meet this purpose.

Fig. 2 shows how the RDR algorithm contributes in the system frequency control, where τ_i is the RDR delay of area i . In this algorithm it is assumed that at any time, step load is applied only to one of the areas. This assumption is quit close to the reality. Provided that the step load is applied to two areas, for instance, in such a case, those two areas could be considered as one area and the tie-line flow of this new area with other areas could be monitored and considered for calculations. The mentioned assumption is just for simplicity and it is not a limitation for the proposed method.

III. FUZZY-PI-BASED SUPERVISORY COORDINATOR DESIGN

Time delay is an intrinsic feature of each physical system and demand response is not an exception. As mentioned, following a step change in load, demand response could have contribution in restoration of the system frequency. But, in case the demand response action is associated with time delay, during the time delay generators try to compensate the occurred power imbalance, for instance via increasing their generations. Afterward, when demand response interferes as a supplementary control and compensates all or a part of the load/generation imbalance, the additional generation, produced during the time delay, may cause considerable frequency overshoots and impose instability to the system performance.

In this paper, fuzzy logic is used to cope with this phenomenon and to adjust the responsive generators according to the amount of regulation provided by the RDR. Furthermore, the fuzzy logic is able to compensate the inability of the classic control theory for covering complex power systems with uncertainties and inaccuracies. In this

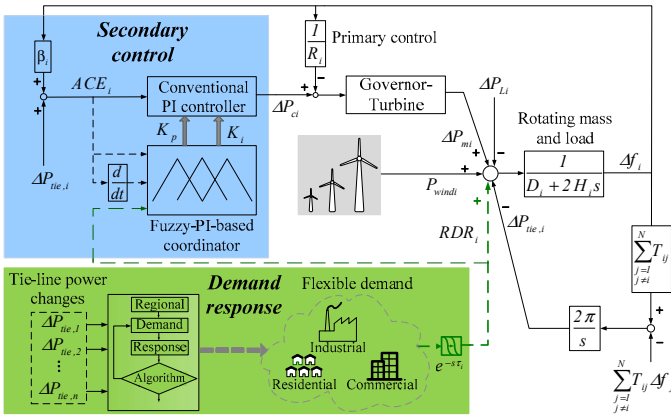


Fig. 3. System frequency response model with both RDR and supervisory fuzzy-PI-based coordinator.

case, fuzzy logic is used as a supervisor for fine tuning of conventional PI controllers [2].

In the present work, the PI controller is remained, and the fuzzy logic is used for on-line tuning of its parameters. Therefore, this control configuration provides a smooth performance in startup and transient circumstances and it could be more acceptable for real-time LFC application.

In the present paper, in each control area, to cover both time delay side effects and system uncertainties, the RDR signal, the updated area control error (ACE) and its derivative are used as the inputs of the fuzzy block. ACE is defined as a linear combination of frequency and tie-line power changes [26]:

$$ACE = \beta \Delta f + \Delta P_{tie} \quad (27)$$

where β is the frequency bias.

Minimizing the frequency deviations due to fast changes in output power of wind turbines, limiting the tie-line power interchanges in an acceptable range and protecting the system against excessive frequency overshoots/undershoots due to existing communication delay in applying demand response, are the main goals of this effort. Fig. 3 shows how supervisory fuzzy-PI-based coordinator contributes in frequency regulating.

In order to apply the fuzzy logic to each area, a set of fuzzy rules consisting of 60 rules is used to map input variables, i.e., ACE, its derivative and RDR_i , to output variable. The membership functions corresponding to the input and output variables have been arranged based on triangular membership function which is most popular one. The antecedent parts of each rule are composed by using AND function (with interpretation of minimum). Here, Mamdani fuzzy inference system is also used.

IV. CASE STUDY

The New England test system is widely used as a standard system for testing of the power system analysis and control synthesis methodologies. This system has 10 generators, 19 loads, 34 transmission lines, and 12 transformers. Here, the test system is updated by adding three wind farms in buses 5, 26, and 21. A single-line diagram of the updated system is shown in Fig. 4.

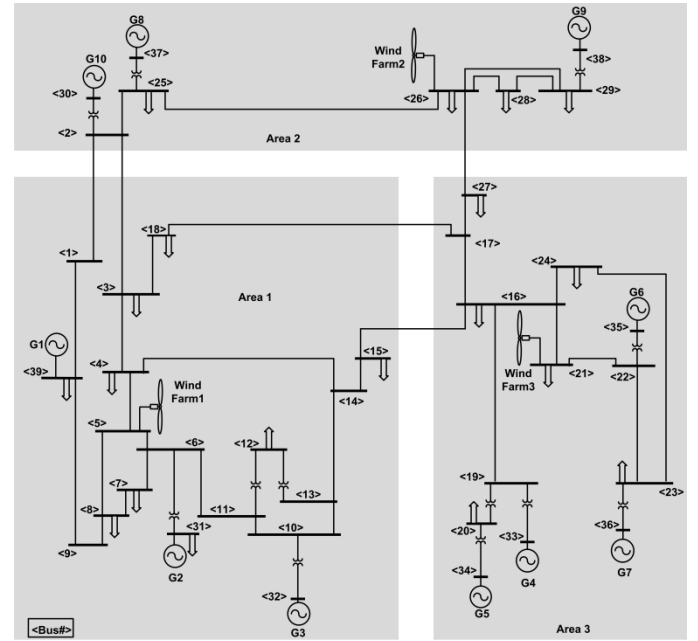


Fig. 4. Modified single-line diagram of 39-bus test system with three wind farms [28].

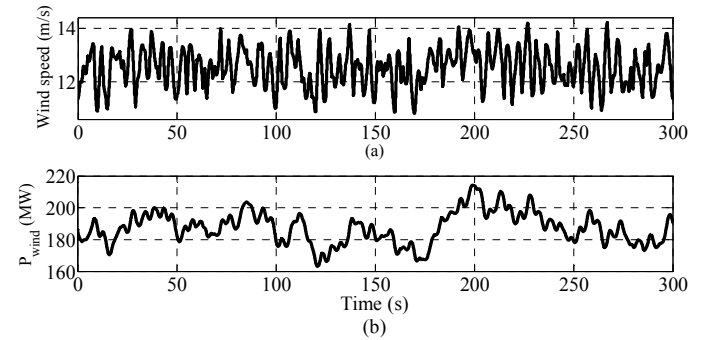


Fig. 5. Wind velocity and power: (a) wind velocity pattern and (b) total wind power generation.

The total system installed capacity is 404.85 MW of conventional generation and 185.9 MW of average wind power generation. There are 134.57 MW of conventional power generation, 61 MW of average wind power generation, and 329.25 MW load in Area 1. In Area 2, there are 106.381 MW of conventional power generation, 54 MW of average wind power generation, and 74.051 MW load. In Area 3, there are 163.9 MW of conventional power generation, 72 MW of average wind power generation, and 182.01 MW load. All power plants in the power system are equipped with speed governor and power system stabilizer. In addition, the important inherent requirement and basic constraints such as governor dead band and generation rate constraint imposed by physical system dynamics are considered. Other system parameters are given in [27].

In the present work, similar to the real-world power systems, the conventional generation units are responsible to provide spinning reserve for the sake of load tracking and the load-frequency control (LFC) task. Here, it is assumed that only one generator in each area is responsible for the LFC task; G1 in Area 1, G9 in Area 2, and G4 in Area 3. All LFC

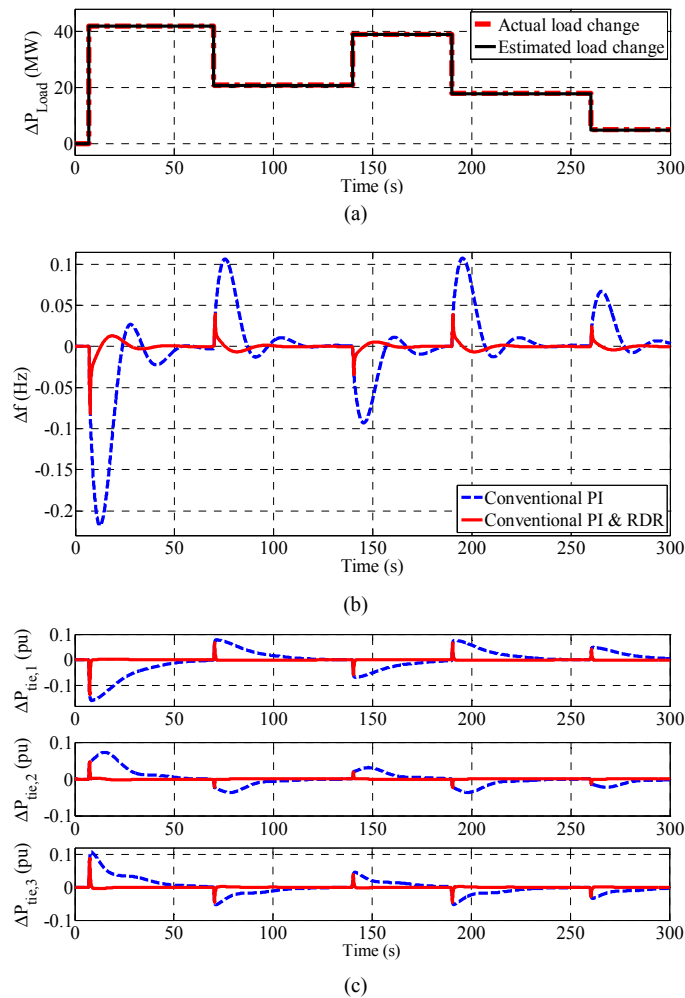


Fig. 6. System response following a sequence of step load changes in area 1: (a) load change pattern and estimated load change, (b) system frequency response; comparison of conventional PI controller versus the RDR contribution, (c) tie-line power interchanges; conventional PI (dashed), contribution of the RDR (solid).

loops use conventional proportional-integral (PI) controllers. In order to evaluate the proposed method properly, high-penetration of wind power (about 30%) along with random variations of wind velocity have been considered. Fig. 5 demonstrates the wind velocity pattern and total wind power generation.

V. SIMULATION RESULTS AND DISCUSSION

For the sake of simulation, four scenarios are examined and the effectiveness of the proposed method is investigated in MATLAB/SIMPOWER environment. It is assumed that in each control area 30% of loads are available for demand response actions, i.e., 98.77 MW in Area 1, 22.21 MW in Area 2 and 54.6 MW in Area 3.

At the first scenario, to demonstrate a comparison of conventional PI controller versus the RDR contribution clearly, random variations of wind velocity is eliminated and the system is examined in the face of a sequence of step load changes which is plotted in Fig. 6 (a), and a communication delay of 0.5 s. Furthermore, to show the efficiency of the

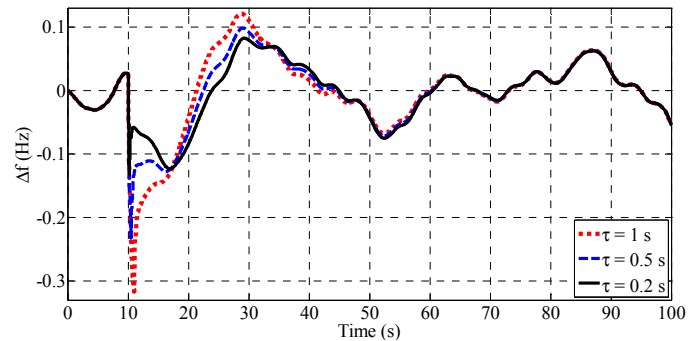


Fig. 7. Impact of communication delay (τ) on the performance of the proposed RDR scheme in response to a 115 MW step load at $t=10$ s.

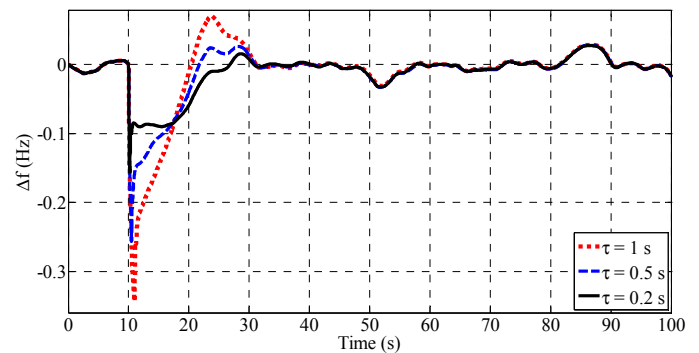


Fig. 8. Performance of the supervisory fuzzy-PI-based coordinator for different RDR delays.

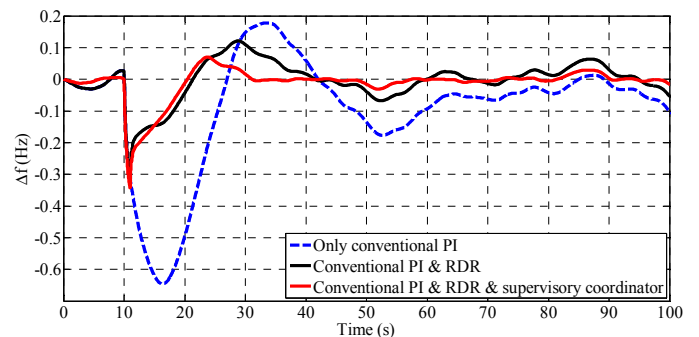


Fig. 9. Performance evaluation of the RDR and supervisory fuzzy-PI-based coordinator in comparison with the conventional PI controller for 1 s communication latency.

calculations provided in Section II, the estimated load changes are also depicted in Fig. 6 (a). As can be seen, there is a significant resemblance between the estimated and actual load changes. Fig. 6 (b) and Fig. 6 (c) show that the proposed RDR can effectively reduce the amount of the frequency excursion and variations, and also demonstrate that the tie-line power changes are maintained within a narrow band.

At the next scenario, a severe step load disturbance of 115 MW applied to the area 1 at $t=10$ s, while considering high-penetration of wind power along with random variations of wind velocity in the system. First to evaluate the impact of communication delay of the RDR, the system is tested for different values of communication latency, without the contribution of supervisory coordinator. The results are depicted in Fig. 7. It can be seen that, the value of the

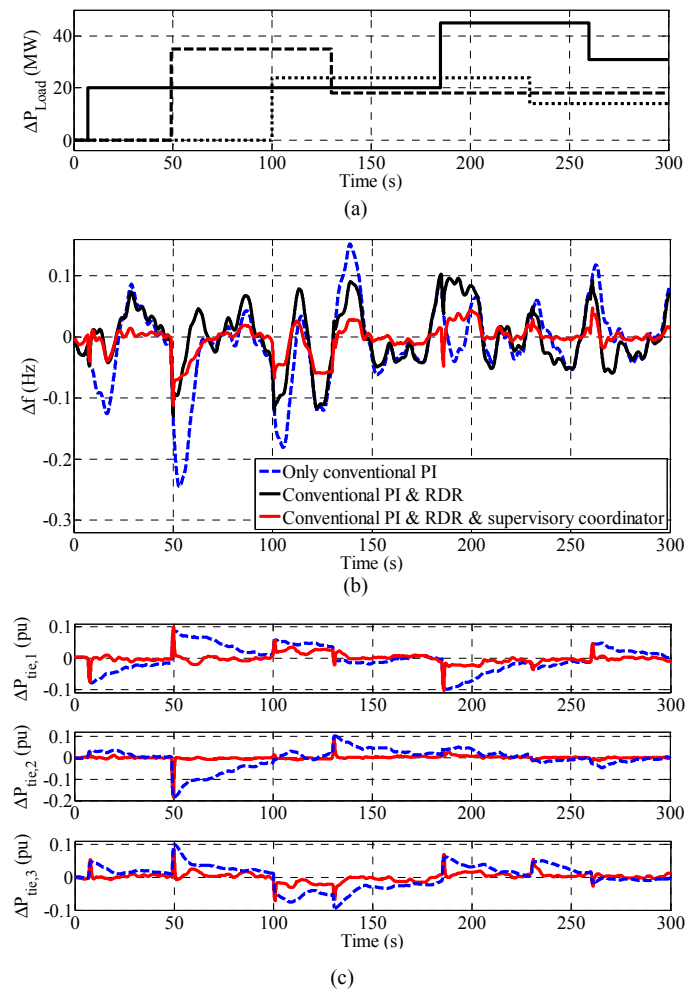


Fig. 10. System response following a sequence of step load changes in all areas: (a) load change pattern; Area 1 (solid), Area 2 (dashed), Area 3 (dotted), (b) system frequency response, (c) tie-line power interchanges; conventional PI (dashed), coordination of the RDR and supervisory fuzzy-PI-based coordinator (solid).

frequency overshoot, following the interference of the RDR, is increased as the value of the communication delay get increased. Next, to cope with these overshoots and also system disturbances, the supervisory fuzzy-PI-based coordinator is added to the closed loop system and results are plotted in Fig. 8.

Finally, to show a comparison of conventional power plant frequency response versus the RDR and supervisory fuzzy-PI-based coordinator contribution, the test is repeated with the communication delay of 1 s, as shown in Fig. 9. For the rest of the simulations, τ is assumed to be 1 s.

At the third scenario, random step loads are applied to all three areas according to Fig. 10(a). System frequency response and tie-line power changes, in the case of comparing the performance of conventional controllers versus participation of the RDR and supervisory fuzzy-PI-based coordinator are given in Fig. 10(b) and 10(c), respectively. The obtained results show that the designed method can ensure a good performance in a multi-area power system in the existence of random step load changes and wind power

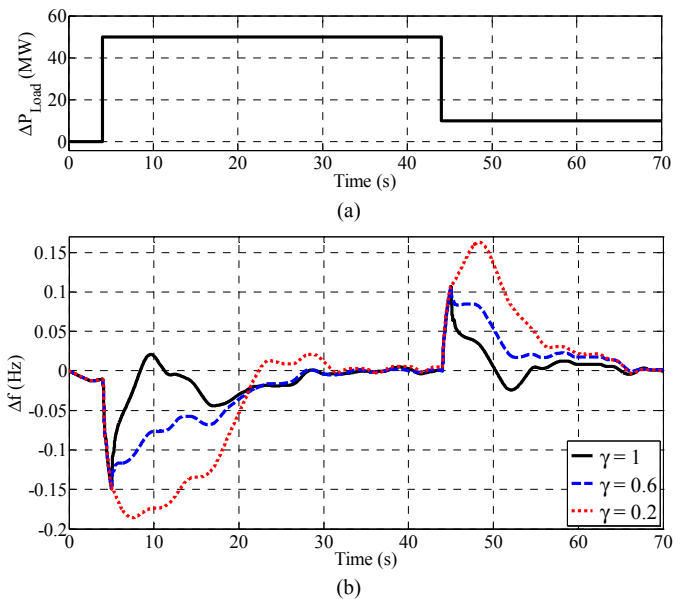


Fig. 11. Impact of changing the contribution of the RDR (participation factor γ) in the required regulation: (a) load change pattern, (b) system frequency response.

fluctuations. As the last scenario, a comparison between the contribution of the generators and the RDR in frequency regulation is made, by studying the impact of participation factor γ . To do so, the the system is examined at the presence of step load changes as depicted in Fig. 11(a) and the results are demonstrated in Fig. 11(b). As expected, lower participation of the RDR results in more frequency variations and less system performance.

VI. CONCLUSION

This paper proposes a regional demand response to cooperate in system frequency control of multi-area power systems. The striking feature of the proposed RDR scheme is the use of second derivative of tie-line power changes to extract the size and location of the experienced disturbances during contingent events, which is proved by mathematical calculations. A fuzzy-PI-based supervisory controller is introduced as a coordinator between the demand response and secondary frequency control to adjust the responsive generators according to the amount of regulation provided by the RDR. This coordinator will cover not only the system uncertainties but also time delay side effects of the RDR scheme.

The provided simulation studies on the 10-machine New England test power system illustrate the effectiveness of incorporating regional demand response and supervisory fuzzy-PI-based coordinator, at the presence of high wind power fluctuations, random load changes and communication delays, in multi-area power systems.

REFERENCES

- [1] H. Bevrani, *Robust Power System Frequency Control*. 2nd Ed., New York: Springer, 2014.

- [2] H. Bevrani, F. Habibi, P. Babahajyani, M. Watanabe, and Y. Mitani, "Intelligent Frequency Control in an AC Microgrid: Online PSO-Based Fuzzy Tuning Approach," *IEEE Trans. Smart Grid*, vol. 3, no. 4, pp. 1935-1944, Dec. 2012.
- [3] K. Pandiaraj, P. Taylor, N. Jenkins, and C. Robb, "Distributed load control of autonomous renewable energy systems," *IEEE Trans. Energy Convers.*, vol. 16, no. 1, pp. 14-19, Jan. 2001.
- [4] M. R. Vedady Moghadam, R. T. B. Ma, and Z. Rui, "Distributed Frequency Control in Smart Grids via Randomized Demand Response," *IEEE Trans. Smart Grid*, vol. 5, no. 6, pp. 2798-2809, Nov. 2014.
- [5] J. Medina, N. Muller, and I. Roytelman, "Demand Response and Distribution Grid Operations: Opportunities and Challenges," *IEEE Trans. Smart Grid*, vol. 1, no. 2, pp. 193-198, Sept. 2010.
- [6] N. Navid-Azarbaijani and M. H. Banakar, "Realizing load reduction functions by aperiodic switching of load groups," *IEEE Trans. Power Syst.*, vol. 11, no. 2, pp. 721-727, May 1996.
- [7] "Benefits of demand response in electricity markets and recommendations for achieving them: A report to U.S. Congress," U.S. Dept. Energy, 2006 [Online]. Available: <http://eetd.lbl.gov/ea/ems/reports/congress-1252d.pdf>.
- [8] F. C. Schweppe, R. D. Tabors, J. L. Kirtley, H. R. Outhred, F. H. Pickel, and A. J. Cox, "Homeostatic Utility Control," *IEEE Trans. Power App. Syst.*, vol. PAS-99, no. 3, pp. 1151-1163, May 1980.
- [9] K. Samarakoon, J. Ekanayake, and N. Jenkins, "Investigation of Domestic Load Control to Provide Primary Frequency Response Using Smart Meters," *IEEE Trans. Smart Grid*, vol. 3, no. 1, pp. 282-292, Mar. 2012.
- [10] M. Aunedi, P. A. Kountouriotis, J. E. O. Calderon, D. Angeli, and G. Strbac, "Economic and Environmental Benefits of Dynamic Demand in Providing Frequency Regulation," *IEEE Trans. Smart Grid*, vol. 4, no. 4, pp. 2036-2048, Dec. 2013.
- [11] G. Molina, x, A., F. Bouffard, and D. S. Kirschen, "Decentralized Demand-Side Contribution to Primary Frequency Control," *IEEE Trans. Power Syst.*, vol. 26, no.1, pp. 411-419, Feb. 2011.
- [12] A. Brooks, E. Lu, D. Reicher, C. Spirakis, and B. Wehl, "Demand Dispatch," *IEEE Power Energy Mag.*, vol. 8, no. 3, pp. 20-29, May-June 2010.
- [13] K. Dehghanpour and S. Afsharnia, "Electrical demand side contribution to frequency control in power systems: a review on technical aspects," *Renew. Sust. Energy Rev.*, vol. 41, pp. 1267-1276, Jan. 2015.
- [14] N. Rezaei and M. Kalantar, "Stochastic frequency-security constrained energy and reserve management of an inverter interfaced islanded microgrid considering demand response programs," *Int. J. Elect. Power Energy Syst.*, vol. 69, pp. 273-286, Jul. 2015.
- [15] N. Rezaei and M. Kalantar, "Smart microgrid hierarchical frequency control ancillary service provision based on virtual inertia concept: An integrated demand response and droop controlled distributed generation framework," *Energy Conv. Manag.*, vol. 92, pp. 287-301, Mar. 2015.
- [16] A. Molina-Garcia, I. Munoz-Benavente, A. D. Hansen, and E. Gomez-Lazaro, "Demand-Side Contribution to Primary Frequency Control With Wind Farm Auxiliary Control," *IEEE Trans. Power Syst.*, vol. 29, no. 5, pp. 2391-2399, Sept. 2014.
- [17] J. Hao, L. Jin, S. Yonghua, G. Wenzhong, X. Yu, S. Bin, L. Xiaomin, and D. Jianxun, "Demand Side Frequency Control Scheme in an Isolated Wind Power System for Industrial Aluminum Smelting Production," *IEEE Trans. Power Syst.*, vol. 29, no. 2, pp. 844-853, Mar. 2014.
- [18] C. Gouveia, J. Moreira, C. L. Moreira, and J. A. Pecas Lopes, "Coordinating Storage and Demand Response for Microgrid Emergency Operation," *IEEE Trans. Smart Grid*, vol. 4, no. 4, pp. 1898-1908, Dec. 2013.
- [19] S. A. Pourmousavi and M. H. Nehrir, "Introducing Dynamic Demand Response in the LFC Model," *IEEE Trans. Power Syst.*, vol. 29, no. 4, pp. 1562-1572, Jul. 2014.
- [20] J. A. Short, D. G. Infield, and L. L. Freris, "Stabilization of Grid Frequency Through Dynamic Demand Control," *IEEE Trans. Power Syst.*, vol. 22, no. 3, pp. 1284-1293, Aug. 2007.
- [21] H. Hao and L. Fangxing, "Sensitivity Analysis of Load-Damping Characteristic in Power System Frequency Regulation," *IEEE Trans. Power Syst.*, vol. 28, no. 2, pp. 1324-1335, May 2013.
- [22] X. Zhao, J. Ostergaard, and M. Togeby, "Demand as Frequency Controlled Reserve," *IEEE Trans. Power Syst.*, vol. 26, no. 3, pp. 1062-1071, Aug. 2011.
- [23] P. J. Douglass, R. Garcia-Valle, P. Nyeng, J. Ostergaard, and M. Togeby, "Smart Demand for Frequency Regulation: Experimental Results," *IEEE Trans. Smart Grid*, vol. 4, no. 3, pp. 1713-1720, Sept. 2013.
- [24] Z. Changhong, U. Topcu, and S. H. Low, "Optimal Load Control via Frequency Measurement and Neighborhood Area Communication," *IEEE Trans. Power Syst.*, vol. 28, no. 4, pp. 3576-3587, Nov. 2013.
- [25] J. J. Ford, H. Bevrani, and G. Ledwich, "Adaptive load shedding and regional protection," *Int. J. Elect. Power Energy Syst.*, vol. 31, no. 10, pp. 611-618, Dec. 2009.
- [26] P. Kundur, *Power System Stability and Control*: 1st Ed., Englewood Cliffs, NJ, U.S.A.: McGraw-Hill, Jan. 1994.
- [27] H. Bevrani, F. Daneshfar, and R. P. Daneshmand, "Intelligent Power System Frequency Regulations Concerning the Integration of Wind Power Units," in *Wind Power Systems*. vol. 0, ed: Springer Berlin Heidelberg, 2010, pp. 407-437.
- [28] H. Bevrani, P. R. Daneshmand, P. Babahajyani, Y. Mitani, and T. Hiyama, "Intelligent LFC Concerning High Penetration of Wind Power: Synthesis and Real-Time Application," *IEEE Trans. Sustain. Energy*, vol. 5, no. 2, pp. 655-662, Oct. 2013.