2015 23rd Iranian Conference on Electrical Engineering (ICEE)

Impacts of Wind and Conventional Power Coordination on the Short-Term Frequency Performance

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Abstract— **According to the environmental concerns, the utility of renewable energies is rapidly growing up. As wind power penetration increases, power industry tends to replace conventional generation units with the wind power resources. Modern wind energy conversion machines are not able to participate in frequency response since the machines are decoupled from the grid by back-to-back voltage based converters. In this paper, the coordinated control approach takes advantage of the fast response capability associated with electronically-controlled wind energy conversion, allowing the stored kinetic energy in rotational mass to release in order to provide temporarily inertia and primary frequency response (PFR) support. This paper investigates the impact of coordination of inertia, the PFR and combined inertia-PFR support between wind farms and conventional generators on the frequency response of updated IEEE-39 bus power system. The simulation results show the significant improvement in the frequency performance with coordination between wind farms and conventional generators. The simulation is performed by Matlab's SimPowerSystems block set.**

Keywords* — *Inertia control; primary frequency control; primary frequency response; coordination control; wind power penetration; conventional power plant.

I. INTRODUCTION

THE ability of a power system to maintain its electrical frequency within a safe range is crucial for power system stability and reliability. An interconnected power system must have sufficient resources to support and return the frequency of power system to the acceptable range to a variety of contingency events [1]-[2]. Due to the environmental concerns, utilizing of renewable energy is growing up rapidly. Recently, Wind energy has had a significant contribution in modern power systems, although its stochastic nature result in several challenges in power system operation and control [3]. As the wind penetration increases, power industry tends to displace conventional generation units to the wind power resources. The constant increase of wind power penetration, leads to derail more and more conventional generation units. The modern wind power resources such as Doubly-Fed Induction Generators (DFIG) wind turbines are fundamentally different from conventional generators [4]. The DFIG wind turbines are not capable to participate in frequency response since the machines are decoupled from the grid by back-to-back voltage based converters. So the absence of inertia and primary frequency response -like conventional generators- of these wind resources at high penetration of wind power, can result in a larger Rate of Change of Frequency (ROCOF) and steady-state deviation from nominal or scheduled frequency. On the other hand, the combination of inertia and PFR of wind power resources is crucial at high wind power penetration in power systems to arrest electrical frequency changes before triggering under-frequency load-shedding relays [3]. So, in two recent decades system operators have become worry about the performance of primary frequency regulation of power system with high penetration of WECS, and many researchers and experts focused on enhancement of primary frequency control of power systems. It is possible for variable speed wind turbines to participate in the inertial response and PFR of power system and emulate the role of conventional generators to improving the frequency response characteristic to the desirable value [2].

As mentioned, in recent years, many researchers have placed their focus on the frequency regulation capability of the wind turbines generation. In [5], authors pointed that for a 2 MW DFIG, the amount of inertia of rotor is approximately six times that of its electrical generator. So the stored kinetic energy of the rotors of the large scale wind farms is sufficient to support the reduced inertia of power system , which caused by high penetration of variable-speed wind turbines, through adding the extra control loops, sensitive to the network frequency [6]. For example, the stored kinetic energy in rotating mass of DFIG could be utilized to provide temporary frequency support like the droop response and inertia response of conventional generators by adding extra proportional loops that are sensitive to ROCOF and frequency changes. The impact of utilizing both additional control loops on primary frequency response is investigated [7]. These additional controllers can be installed in the power electronic converter of the variable-speed wind turbines and can provide the participation of wind turbines in short term primary frequency control for few seconds due to the limitation in stored kinetic energy. So an additional control mechanism like Automatic Generation Control (AGC) is needed to bring the frequency of power system back to the reference value [6]-[8].

As pointed in [6], the power system level control of wind farms (supervisory control level) can support the secondary frequency control by coordination between wind farms and conventional generators to recover the frequency to the desire value faster than the no coordination control case. By implementing of this control mechanism, the conventional generators can accelerate their support to the grid frequency with better performances of the frequency security indices such as ROFC, nadir and steady-state deviation, in comparison with wind farms-only support [4].

This study focuses on investigating the sensitivity of various performance metrics for primary frequency control with considering high penetration levels of wind power. In [8], the impact of coordination control between provided PFR-only support from wind farms and other conventional generators is investigated. So the major motivation of this work is investigating the impact of inertia coordination and combination of coordinated inertia and PFR support between wind farms and selected set of AGC-controlled generators, on frequency response behavior in the short term frequency framework.

The rest of paper is organized as follows: in section II, the frequency performance metrics that used in this paper is described. The details of IEEE-39 bus test system for performing the simulations are introduced in section III. Section IV, Provides description of proposed control method for coordination between wind farms and conventional generators. Section V gives the different scenarios and wind penetration levels for investigating the impact of control strategies on frequency response. The results of different active power control strategies for coordination between wind powers and conventional generators are provided in section VI. In section VII, conclusion is given.

II. FREQUENCY RESPONSE METRICS

In this work, the similar frequency response metric that described in [9], is used. In Fig. 1 a typical frequency response following unit trip is shown [10].In normal operation, the system frequency will be kept close to 60 Hz, which is the nominal frequency of the interconnected power system. In power systems, major requirements are total system inertia, amount of PFR that can be supported by power resources of the system following a contingencies, and the response speed of this PFR [11]-[12]. As shown in Fig. 1, Point A represents the frequency before the disturbance, Point C represents the maximum drop of frequency (Nadir frequency) due to loss of kinetic energy of rotating mass of system following the disturbance and Point B represents the network frequency after governor response (primary frequency control) and before starting of the corrective secondary frequency control. Also Point D represents the steady state frequency after 60 seconds of occurrence of disturbance. The value of C is determined by the inertial response and capability of PFR of resources following disturbance in power system. Continued PFR after domination of Point C, stabilized the frequency to Point B that referred to the steady-state frequency.

The study presented in this paper, focused on analysis the impacts of different levels of wind power penetration, considering wind farms as usual without capability of PFR support, as well as by allowing wind power to support inertia, PFR and combination of them to the system frequency regulation and these power supports will be coordinate with conventional generators.

The metrics that used in this study to analysis the frequency performances are:

1- Value of nadir frequency (Point C)
2- Value of settling frequency (Point B)
3- Transition time from Point A and B.
4- Transition time from Point C to B.
5- The ratio of Point C to Point B as known as CB_R metric.

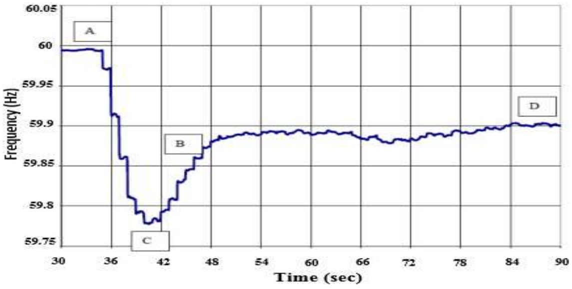

Fig. 1. Description of frequency response metrics [10].

III. NEW ENGLAND TEST SYSTEM

New England system is a well-known test system that widely used as a standard system for testing of the new power system analysis and control methodologies. The test system that used in this study, represent a greatly reduced model of the power system in New England with a same topology. The system has 10 generators, 12 transformers, 19 loads and 34 transmission lines. The system parameters are given in [13].

The 39-bus system consists of 3 interconnected areas. The total system capacity is 886.54 MW of conventional generation. In Area 1 there are 221.63 MW of conventional generation and 265.25 MW of load. There are 232.83 MW of

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This work is financially supported by research Office at the University of Kurdistan. S. Ataee, R. Khezri, M. R. Feizi and H. Bevrani are with Department of Electrical and Computer Eng, University of Kurdistan, Sanandaj, PO Box 416, Kurdistan, Iran. Corresponding author's e-mail: sirwan.ataee@gmail.com

conventional generation and 232.83 MW of load in Area 2. Also there are 183.17 MW of conventional generation and 124.78 MW of load in Area 3.

All of the conventional generators are equipped with power system stabilizer and speed governors. For simulations that presented in this work, similar to real power system, the important inherent requirement and basic constraints such as governor dead-band and generation response rate that imposed by system dynamic and characteristic, are considered.

IV. CONTROL METHODOLOGY

The main objective of this study is to investigate the impacts of provided coordination support from wind turbines and conventional generators at high penetration levels of wind power on the short-term frequency response, by several performance metrics. For this purpose, in any penetration level, the DFIG-based wind turbines are equipped with fast primary control support. The Fixed Speed Induction Generator (FSIG) based wind turbines considered without supportive control to the primary frequency regulation.

A. Coordination Control between Wind farms and Conventional Power Plants

The secondary frequency control provided by the AGC unit acts after primary frequency regulation of the power resources that considered to overcome the undesirable transient part of frequency response and restore the frequency to the reference value [14].

By participation of variable-speed wind turbines in inertia response in power system, the inertia of entire system may mask the load change at the first few seconds of the load imbalance, because of the considerably released inertia from rotating mass of wind turbines. So this support may leads to delay in the response of conventional power plants to the following frequency events [15].

To resolve this issue, as shown is Fig. 2, the AGC-controlled conventional power plants must be aware of the amount of frequency control support of wind farms as soon as possible. The wind farms can be considered as an individual wind turbine with additional inertia and droop control loops.

The frequency support provided by two additional loops for the wind turbines, may be enough to enhance the frequency stability. However by wind and conventional power coordination control, a better frequency behavior can be achieved as shown later. The new control strategy proposed so that the output of individual (each or combination of them) wind farms control loops (not only droop control loop) is coordinated by system operator with a selected set of AGC-controlled conventional power plant through proper communication links. The supporting power ΔP from wind farms distributed by coordination control as follows:

$$P_{ci} = K_{ci}\Delta P \tag{6}$$

$$\sum_i K_{ci} = 1 \tag{7}$$

Where, P_{ci} is the coordination control signal, K_{ci} is the participation factor for each of selected conventional generators that considered for coordination control [8].

As shown in Table I, only one generator considered for the coordination control in each area; G1 in Area 1, G9 in Area 2 and G4 in Area 3. These generators are selected based on apparent power and effectiveness to support the frequency regulation. Also the communication delay is applied for the coordination control.

TABLE I
SELECTED CONVENTIONAL GENERATORS FOR COORDINATION CONTROL

Generator unit	Rated Power (MVA)	Participation Factor
G1	150	0.42
G9	120	0.34
G4	85	0.24

V. SCENARIO DEVELOPMENT

As mentioned previously, the main objective of this work is to investigate the sensitivity of performance metrics and the impacts of coordination between provided inertia and PFR from wind farms with selected set of conventional generators on the frequency response performance, with considering high wind power penetration in power system. For this purpose some of the conventional generators are replaced with DFIG (equipped with control support) and FSIG (without control support) wind farms to provide several simulation scenario cases as following:

Case1 (20% wind power penetration): For this scenario in Area 3, Gen 6 at bus 35, with 86 MW generation and in Area 1, Gen 3 at bus 32, with 90 MW power generation replaced with DFIG-based wind farms.

Case 2 (30% wind power penetration): This scenario is 1 and substituting the DFIG-based wind farms in Area 2, with Gen 10, at bus 30 and 66 MW generation.

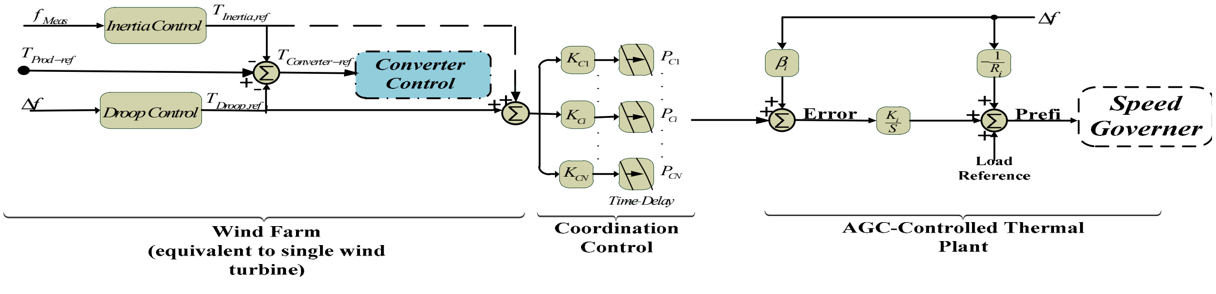

Fig. 2. Proposed control scheme for wind-conventional coordination control.

Case 3 (30% wind power penetration): This case is made by considering the wind power penetration in case 1 and replacing the FSIG-based wind farm in Area 2, with Gen 10, at bus 30 and 66 MW generation.

Case 4 (40% wind power penetration): This case is made by developing the Case 2 and replacing the DFIG-based wind farm in Area 1, with Gen 2 at bus 31 and 92 MW generation.

It must be noticed that the start-up and rated wind speed for DFIG turbines are specified as about 12.5 and 14 m/sec, respectively and assumed to be constant, while both of these values are specified as about 14 m/s for FSIG wind turbines. By considering the time framework for simulation (tens of seconds) in this work, this assumption seems to be reasonable. In all above Scenarios, three step load increment simultaneously are applied to the three area at 5s as follow: in Area 1, 6.6% of total area load; in Area 2, 5.48% of total area load and in Area 3, 6.6% of total area load.

VI. SIMULATION RESULTS

The summary of provided simulation scenarios that performed to investigate the impact of coordinated active power control strategies on the frequency performance metrics is shown in Table II.

TABLE II
THE SUMMARY OF PERFORMED SIMULATIONS

Cases and Penetration Levels (%)	**Simulation Scenarios**			
Case 1 (20%)	No Control Support	Inertia Only (10% of rated power) Coordination	PFR Only (2% Droop) Coordination	PRF (2% Droop)+Inertia (10% of rated power) Coordination
Case 2 (30%)				
Case 3 (30%)				
Case 4 (40%)				

Figs. 3-6 show the simulated frequency response that performed for four wind power penetration cases (Case 1, Case 2, Case 3 and Case 4) with considering coordination between wind farms and conventional generators at the supervisory control level of wind farms. Each control strategies at each wind penetration levels are based on the earlier mentioned control support from wind farms and the same support from selected set of AGC-controlled conventional generators.

As shown in Figs. 3-6, the frequency behavior had superior improvement as wind penetration increased. With inertia-only coordination control (red trace), the nadir value and transition time to frequency nadir increased more than the same support from wind farms (without coordination). The further improvement in frequency nadir is due to the additionally available inertia support from coordinated conventional generators to declining further ROCOF. For example by applying the coordinated-inertia support, the frequency nadir at 40% wind penetration level is increased from 59.48 (for no control support-black trace) to 59.63 Hz.

On the other hand, the impact of coordinated-PFR control on settling frequency had the same improvement result. For example greatest coordinated-PFR support, provided at 40% wind penetration level. So most improvement for settling frequency as expected is obtained for Case 4 that is increased from 59.73 (for no control support) to 59.75 Hz. The lesser improvement was seen in Case 3 due to no control support from replaced FSIG-wind farm that did not contribute in frequency regulation. By supporting the coordinated-PFR for Case 3, the settling frequency increased form 59.8 (for no coordinated support) to 59.81 Hz.

In Fig. 7, the frequency nadir with applying the various coordinated control strategies at different levels of DFIG-based wind power penetrations is shown. The improvement in nadir frequency for the combination of inertia and PFR coordinated control (green trace) is more than other coordinated strategy controls.

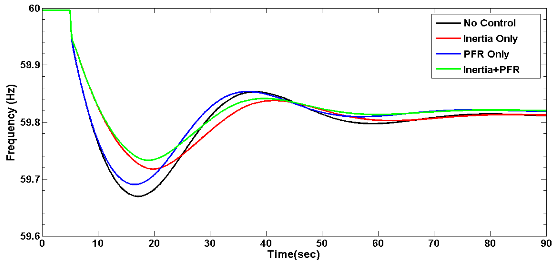

Fig. 3. Frequency response of Case 1 (20% wind power penetration) for coordinated control.

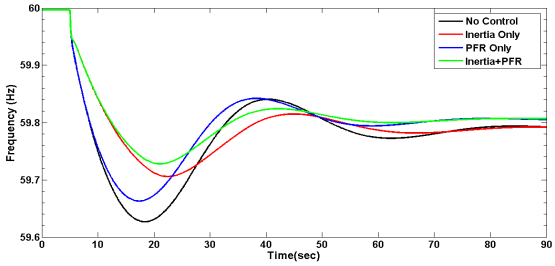

Fig. 4. Frequency response of Case 2 (30% wind power penetration) for coordinated control.

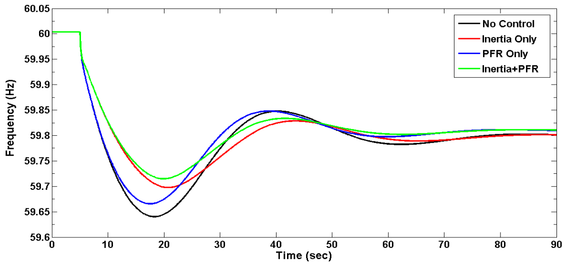

Fig. 5. Frequency response of Case 3 (30% wind power penetration) for coordinated control.

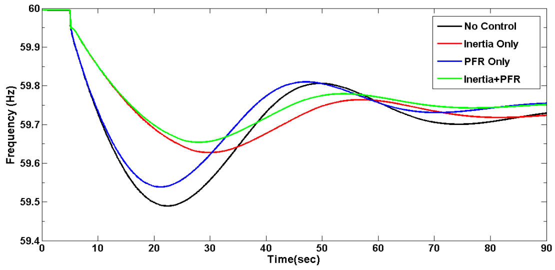

Fig. 6. Frequency response of Case 4 (40% wind power penetration) for coordinated control.

In Fig. 8, the frequency nadir in different cases for combination of inertia and PFR support from wind farms (Inertia$_W$+PFR$_W$-red trace) and combination of inertia and PFR for coordinated control (Inertia$_C$+PFR$_C$ -green trace), is compared. The impact of coordinated control on improvement of frequency nadir is more obvious in this figure. The great improvement is obtained at 40% wind penetration level which frequency nadir is increased from 59.48 (for no control support) to 59.65 Hz for combined coordinated control.

In Fig. 9 the comparison between settling frequency for combined-control support from wind farms (Inertia$_W$+PFR$_W$-red trace) and combined-coordinated control (Inertia$_C$+PFR$_C$ – green trace) is shown. The greatest improvement for settling frequency is seen at 40% wind penetration which is increased from 59.72 (for no control support) to 59.76 Hz with combined coordinated control. While the settling frequency for combined control support from wind farms was 59.74 Hz.

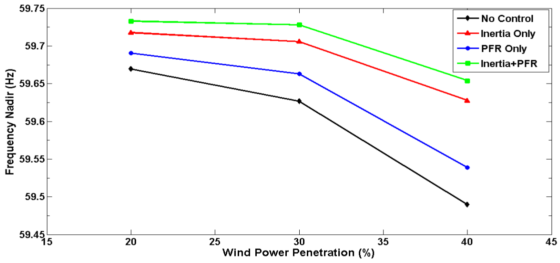

Fig. 7. Impact of coordinated control strategies on frequency nadir.

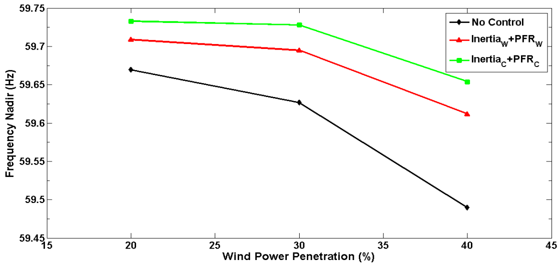

Fig. 8. Impact of control methods on frequency nadir.

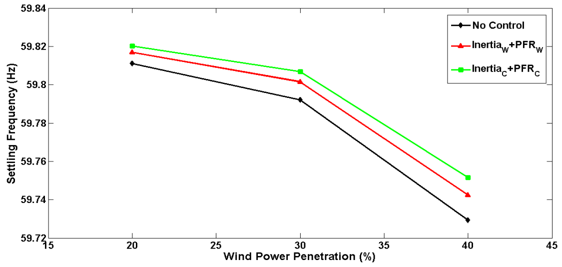

Fig. 9. Impact of control methods on settling frequency.

The response of output active power of the generator 1 in Area 1 as the most effective participated generator, is shown in Figs. 10-13. By further analysis of these figures, the impact of awareness of selected AGC-controlled generator is more apparent. The impact of combined (green trace) and inertia-only (red trace) coordinated control on generator response is more than the PFR-only one. This is due to smaller dead-band for inertia control compared with droop control loops that are entered as input to the selected generator power references. In addition of communication delay there is the time delay for generators to increase the output power to arrest the transient frequency changes in the first few seconds. As the DFIG-based wind penetration increased, the amplitude of the input power reference signals of conventional generators, increased. So the most power support provided by generators at 40% of wind penetration level (Fig. 13). It is noteworthy that the generator support for case 1 (Fig. 10) and case 3 (Fig. 12) are mostly similar because of equality in number of DFIG-based wind farms in these cases.

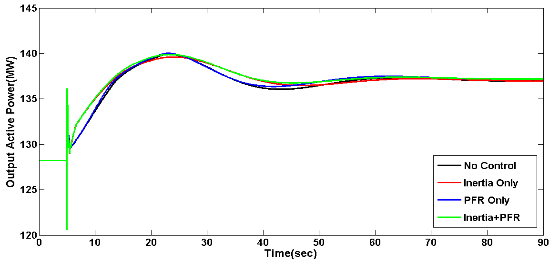

Fig. 10. Response of output active power of generator 1 for Case 1 (20% wind penetration).

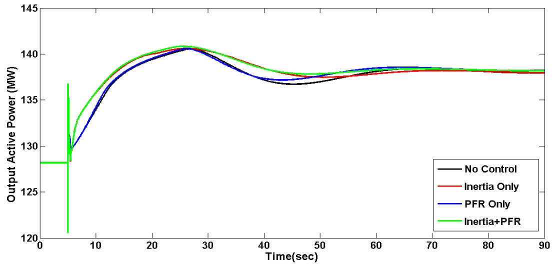

Fig. 11. Response of output active power of generator 1 for Case 2 (30% wind penetration).

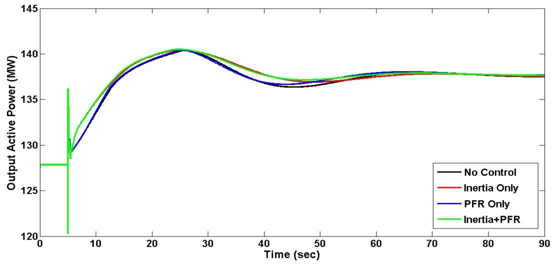

Fig. 12. Response of output active power of generator 1 for Case 3 (30% wind penetration).

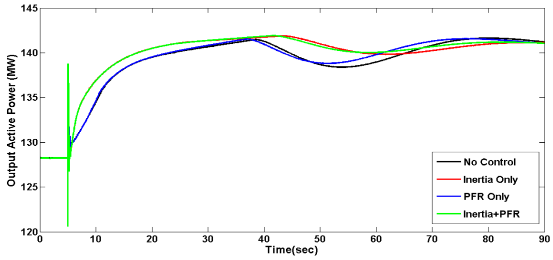

Fig. 13. Response of output active power of generator 1 for Case 4 (40% wind penetration).

In Table III, the CB$_R$ frequency performance metric for no control support (column 2), combination of inertia and PFR support from wind farms (column 3) and combination of coordinated inertia and PFR support (column 3), is calculated. The calculated CB$_R$ metric at column 2 and 3 show improvement as wind penetration levels increased. So, the greater improvement is obtained for Case 4 for combined coordinated support. The lowest improvement belongs to Case 3 due to lack of contribution of generation in frequency regulation in comparison with Case 1 and Case 2.

TABLE III
IMPACT OF COORDINATED CONTROL ON CB$_R$ FREQUENCY PERFORMANCE METRIC

Cases and penetration levels (%)	**CB$_R$ No Control**	**CB$_R$ Inertia$_w$+PFR$_w$**	**CB$_R$ Inertia$_C$+PFR$_C$**
Case 1 (20%)	1.749	1.590	1.485
Case 2 (30%)	1.796	1.538	1.408
Case 3 (30%)	1.805	1.618	1.507
Case 4 (40%)	1.885	1.494	1.393

VII. CONCLUSION

In this paper, several simulation scenarios are performed to investigate the effects of wind and conventional power plants coordination on the frequency response of the IEEE-39 bus power system caused by increment of load in each area at different wind power penetration levels. In recent years, steadily increasing of wind power penetration, leads to retirement of more and more conventional generation units. So with the new construction in power systems, the industry needs to research and develop the capability of new unconventional resources to provide the frequency support for power systems. The steadily increasing of wind power penetrations, affected the conventional power system frequency regulation in two ways: first the reduction in total system inertia, because of penetration of asynchronous power conversions and, second, the lack of contribution of this power conversions in frequency regulation. However, by equipment the new unconventional resources, especially variable-speed wind turbines generators with inertia and PFR control support, the transient frequency performance can be improved.

The main focus of the present work is to investigate the sensitivity of frequency performance metrics, following the load disturbance, by considering the inertia and PFR support from variable-speed wind turbines and coordinate these control supports with conventional generators, at high wind power penetration levels.

By implementing inertia and PFR coordination control strategies, the superior improvement in frequency performance in comparison with no control support, was seen. By inertia-only coordination the frequency nadir significantly increased. Also, the combination of inertia and PFR coordinated control shows the best improvement in frequency response for all of the wind power penetration levels so that the great improvement was seen at 40% wind penetration. The less improvement was seen in Case 3, because of presented FSIG-based wind farm in this Case, that provided no control support for frequency regulation in power system.

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