Investigating the impacts of wind power contribution on the short-term frequency performance

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Investigating the Impacts of Wind Power Contribution on the Short-Term Frequency Performance

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***Abstract*— According to the environmental concerns, the utility of renewable energy is rapidly growing up. Recently, wind energy has had a significant proportion in renewable power resources. 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 spite of providing the ability for wind generation to contribute in frequency regulation, the effect of this contribution is not entirely perceived especially at different wind power penetration. This paper investigates the impact of the inertia, primary frequency response (PFR) and combination of those control procedures that provided based on fast primary control by wind turbines on performance of frequency response of updated IEEE-39 bus power system. The simulation results show the significant improvement in frequency performance with contribution of wind farms in primary frequency regulation.**

***Index Terms*— Inertia control, primary frequency control, primary frequency response, wind power penetration.**

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]. 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 [2]. 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 most popular generators used in wind energy conversion systems (WECS) are variable-speed machines, in particular Doubly-Fed Induction Generators (DFIG) and Permanent Magnet Synchronous Generators (PMSG) [3]. The modern wind power resources such as 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 this 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 [1]. 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]. One possible option to offset the effect of inertia reduction at high penetration of wind power in power systems, is to equip DFIG wind turbines with active power control loops at wind turbines control level [6].

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 masses 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]-[8]. Furthermore, deloading control can provide the wind power reserve to support frequency event in sub-optimal mode instead of Maximum Power Point Tracking (MPPT) operation mode [9]-[10]. All above 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 the few tens of seconds due to the limitation in stored kinetic energy.

In [11], the traditional pitch angle control that can be implemented for variable-speed and fixed-speed wind turbines, is used. The authors have pointed that this control method is valid when the rotor speed is above the maximum value for high wind speed conditions. The power support that provided by pitch angle control is slower than electronic converter based control because of the mechanical time constant of pitch controller. On the other hand, for low speed wind conditions the rotational speed controller can be used [5]. This control method is also based on electronic converter control that can provide the support faster than pitch angle control. In addition, applying this control in lower speed wind condition can protect the pitch blade from wear and tear rather than pitch angle control only [12].

This study focuses on investigating the sensitivity of various performance metrics for primary frequency control with considering high penetration levels of wind power and different control levels of wind turbines such as wind turbines, wind farms.

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 different active power control strategies for wind turbines based on fast primary control. Section V, gives the details of different scenarios and wind penetration levels. The results of impact of different active power control strategies for wind power resources on frequency performance, are provided in section VI. In section VII, conclusion is given. The simulation is performed by Matlab's SimPowerSystems block set.

II. Frequency Response Metrics

In this work, the similar frequency response metric that described in [13], is used. In Fig. 1 a typical frequency response following unit trip is shown [14].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 [15][16]. 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 represent 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 of impact 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.

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 (Pint 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.

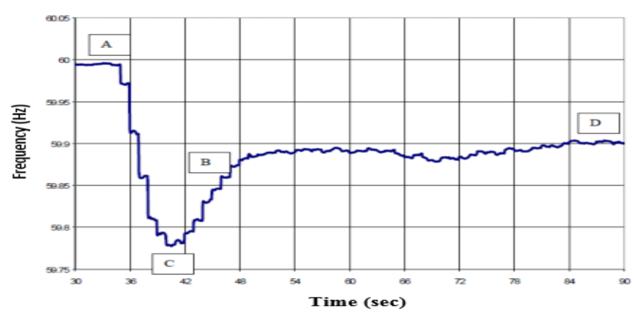

Fig. 1. Description of frequency response metrics.

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 [17].

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 conventional generation and 232.83 MW of load in Area 2.

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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 support from wind turbines 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. Wind Turbines Control

1) Inertia Control

Conventional generators and FSIG wind turbines can release their stored kinetic inertia in rotating masses to the power system for sudden mismatch of load and generation. While variable speed wind turbines cannot support inertial response due to the decoupling between rotor speed and grid frequency because of back-to-back converter that used in this type of wind turbines [3].

As shown in Fig. 2, by implementing the local control loop that is sensitive to the ROCOF to power reference of rotor-side converter of DFIG, the fast inertial response from DFIG can be provided. These additional loops, change actual torque set point ($T_{prod-ref}$) as an input for converter controller by controlling the generator current. This control method adopted the torque set point as a function of combination of ROCOF and grid frequency changes (Δf). The needed energy is taken from stored kinetic energy of rotating masses of WECS.

The amount of release kinetic energy for emulating inertial response depends on the properly tuned value of $K_{Inertia}$ that compared with utilizing of pitch angle control support [6]. Although the important issue that must be considered is the limitation of stored kinetic energy in rotating mass of wind turbines. So implementing of combination of two control loops would force the machine out of stable range due to undesirable reduction in rotor speed of machine. After restoring the grid frequency to a safe range, the rotor speed must be recovered by the additional control strategy. One possible way to restore the discharged kinetic energy and rotor speed to the desirable value, could be absorbing energy that is drown in turn from the grid [6].

As shown in Fig. 2, due to machine life time and technical issue [18], inertia control loop included ROCOF dead-band that is essential to avoid activating inertial response for wind turbine when it is not necessary. Different power systems may have different dead-bands [19].

In this study, the gain of $K_{Inertia}$ is tuned in a way that inject inertial response support about 10% of rated power of wind farms.

2) Droop Control

By implementing of this local control loop which is proportional to the frequency deviation, the droop active power support (PFR) characteristic of conventional generator can be emulated [20]-[21]-[22]. The frequency deviation is given by:

$$\Delta f = f_{Meas} - f_{ref} \qquad (1)$$

where f_{Meas} is the measured frequency of power system and f_{ref} is nominal or reference value of the frequency.

The important issue that must be noted is applying the boundary of dead-band that considered for this control loop. If it takes too long time to activate the droop support of wind turbine after the grid event, the obtained support may be little. On the other hand, if it activates the support too early, the support from prime mover and conventional governor response may not be started and then most of the required temporarily active power support to the grid will come from the wind turbine only. So according to the characteristic of the simulated power system and power imbalance, the boundary of the dead-band must be chosen carefully [19]. In this work, we have chosen the boundary of dead-band of droop control loops in a way the droop support from wind turbines will be started simultaneously with the response of conventional governors and prime movers.

It must be noted that, for the contribution of DFIG-based wind farms in primary frequency regulation that provided by fast primary control , the reference value for reactive power of DFIG wind turbines is set to zero.

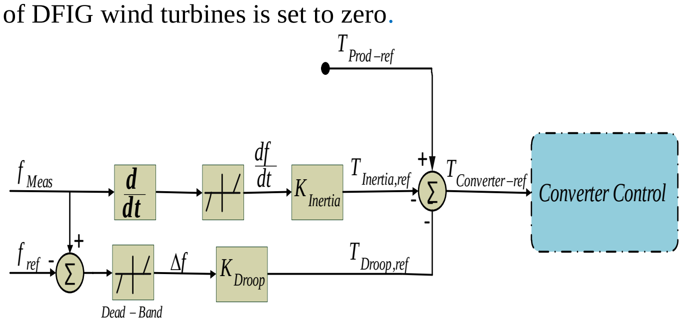

Fig .2. Proposed control strategy for DFIG wind turbines.

V. SCENARIO DEVELOPMENT

As mentioned previously, the main objective of this work is to investigate the sensitivity of performance metrics and the impact of capability of wind turbines to provide inertia and PFR on 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 with different wind power penetration levels 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 provided by considering the wind power penetration in Case 1 and substituting the DFIG-based wind farms in Area 2, with Gen 10, at bus 30 and 66 MW generation.

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 various active power control parameters on the frequency performance metrics is shown in Table. I.

TABLE I
THE SUMMARY OF PERFORMED SIMULATIONS

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

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) and different strategies for fast primary frequency control that applied on wind turbines such as: Inertia-only (red trace); PFR-only (blue trace) and combination of inertia and PFR (green trace) support.

In Figs. 3-6, declining of the nadir frequency and settling time with increment of wind generation level for no control support cases (black plots), caused by the lack of responsible conventional generators that replaced with farms.

By further investigating of the Figs. 3-6, the impact of strategy controls on different wind power penetration become more visible.

Frequency nadir is determined with the total stored kinetic inertia of rotating mass in machines, the number of generators that participate in PFR, type of grid disturbances and dynamic characteristic of power system [6]. As shown in Figs. 3-6, the inertial control (red trace) had significant improvement on frequency nadir in higher levels of wind penetration (See Fig. 6), compared with lower penetration (See Figs. 3-5) and no control support in each cases. This is because of supporting more inertial control support (about 10% of rated power of wind farms) from further installed wind farms compared with lower wind penetration levels. Also by providing inertia control support, the transition time to frequency nadir increased with increment in wind penetration levels. This is because, the inertia-only control support helps reduce the declining of the ROCOF.

On the other hand, the settling frequency determined by the droop support of the machines that participate in PFR [6]. As shown in Figs. 3-6 by providing droop support (about 2% of rated wind farms power) the settling value of frequency (Point B) and frequency nadir increased as well as wind penetration level increased. This is because of increment in available PFR support from further installed wind farms in higher wind penetration Levels. Because of the limitation in stored kinetic energy of rotating masses of wind farms, the improvement in settling frequency is less than improvement in frequency nadir. However, it was obviously higher than the no control support strategies for all wind penetration levels. By providing the PFR-only support, the greatest improvement was seen in 40% wind power penetration which settling value increased from 59.72 (for no control support) to 59.74 Hz. The lowest improvement was seen in Case 3 (See Fig. 6), because of absence of PFR support form uncontrolled FSIG-based wind farm that installed in the system.

As shown in Figs. 3-6, the combination of inertia and PFR control (green trace) support from wind farms, had most superior improvement on frequency performance. Implementing of this control strategy, gives significant improvement on the major frequency indices such as: rat of change, nadir and settling frequency.

In Fig. 7 the frequency nadir for all of the control strategies and for DFIG-based wind farm cases (Case 1, 2 and 4) is consulted. The combination of both inertia and PFR control for wind turbines had the best nadir improvement. As wind penetration increased the effectiveness of this combined control is more and more apparent. In 40% of wind penetration level, the biggest improvement obtained which increased the frequency nadir from 59.48 (for no control support) to 59.61 Hz.

The impact of combination of inertia and PFR control for wind farms on settling frequency is shown in Fig. 8. By providing the combined strategy control, the settling frequency is also increased. As mentioned earlier because of reduction in stored kinetic energy of rotating mass of wind turbines, due to realization of inertia response for the first few seconds, the ability of contribution of PFR form wind farm to system frequency is reduced. So in comparison with the improved frequency nadir by inertia control, the impact of droop control strategy does not show the same resolution on settling frequency.

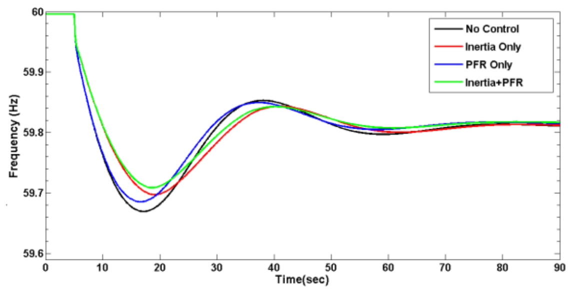

Fig. 3. Frequency response for Case 1 (20% Wind Power Penetration).

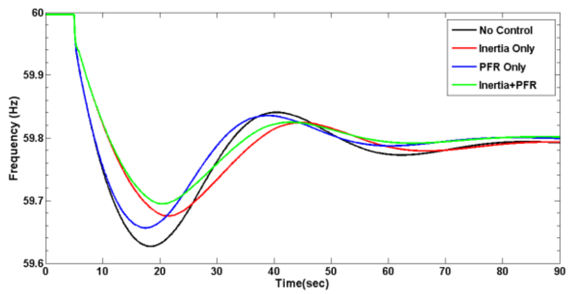

Fig. 4. Frequency response for Case 2 (30% Wind Power Penetration).

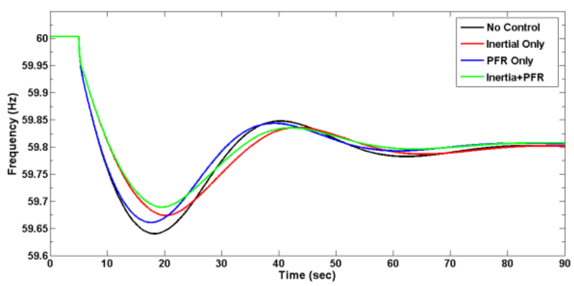

Fig. 5. Frequency response for Case 3 (30% Wind Power Penetration).

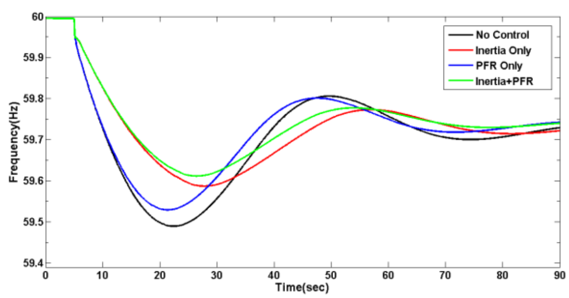

Fig. 6. Frequency response for Case 4 (40% Wind Power Penetration).

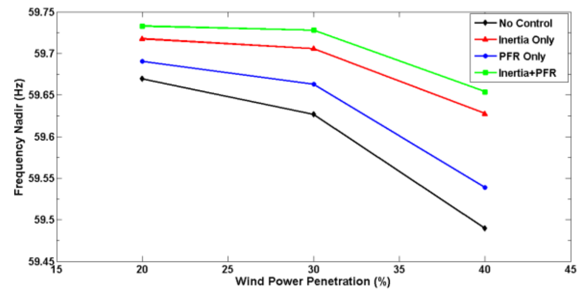

Fig. 7. Impact of wind power control on frequency nadir.

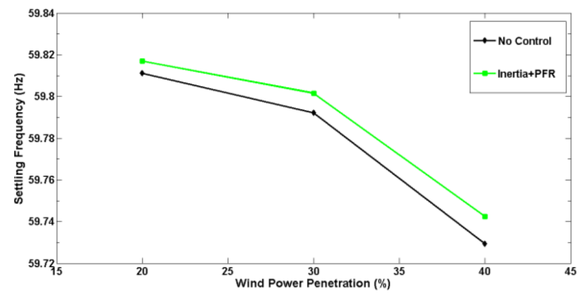

Fig. 8. Impact of wind power control on settling frequency.

In Table II, the CB_R performance metric for no control support (column 2) and combination of inertia and PFR control support (column 3), is calculated for all wind penetration levels. The value greater than 1 for CB_R means that the frequency nadir is at a lower frequency than the settling frequency [16].

In this work, the lower value for CB_R indicates more improvement in frequency performance, because of the significant improvement in nadir frequency compared with settling frequency improvement. As mentioned previously, this issue is due to reduction in amount of stored kinetic energy to support PFR after injecting the inertia support from wind farms to system frequency regulation.

The best CB_R metric is calculated for combination of inertia and PFR control support for Case 4. On the other hand, for no control support strategy, the biggest value for this metric also belongs to Case 4 because of the minimum number of conventional generators in this case.

TABLE II
IMPACT OF WIND FARMS CONTROL ON CB_R FREQUENCY PERFORMANCE METRIC

Cases and Penetration levels (%)	CB_R No Control	CB_R Inertia+PFR
Case 1 (20%)	1.749	1.590
Case 2 (30%)	1.796	1.538
Case 3 (30%)	1.805	1.618
Case 4 (40%)	1.885	1.494

VII. CONCLUSION

In this paper, several simulation scenarios are performed to investigate the frequency response of the IEEE-39 bus power system caused by increment of load in each area at different wind power penetration levels. The depth in frequency following the load disturbance can be improved by equipment the variable-speed wind turbines generators with inertia and PFR control support. 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, at high wind power penetration levels.

The impact of inertia-only, PFR-only and combination of inertia and PFR support from DFIG-based wind farms on frequency response are investigated. Simulation results shown that the amount of inertia and PFR supports can be tuned (especially at high wind penetrations) to improve frequency performance. For example, combining inertia and PFR support from wind powers lead to more improvement in nadir and settling frequency in any 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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