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Analysis of A Load Damping Coefficient On System Frequency Regulation in Wind Farm Integrated Power System

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Abstract: The presence of frequency sensitive loads such as motors has sustainable impact on power system frequency response (SFR). With increasing wind power penetration into the power system, guidelines for frequency regulation need to be revised to ensure system stability and reliability. Frequency regulation becomes more critical with the presence of frequency sensitive loads in wind integrated power system. This paper presents the impact of frequency sensitive loads on system frequency when wind farm is integrated with the conventional power system. A small-signal linearized model of variable speed wind turbine generator is derived. The typical SFR model is developed for wind farm integrated power (WFIP) system. Sensitivity and stability analysis is carried out for linearized model of WFIP system. The observations drawn from the analysis can be useful for the system operators for decision making of appropriate schemes for primary frequency control, demand response, and setting of relays, etc. for secure and stable power system operation. The proposed analysis is validated by system using MATLAB simulation studies.

Keywords: Frequency Response, Load Damping Co-Efficient, Sensitivity And Stability Analysis, Variable Speed Wind Turbine.

I. INTRODUCTION

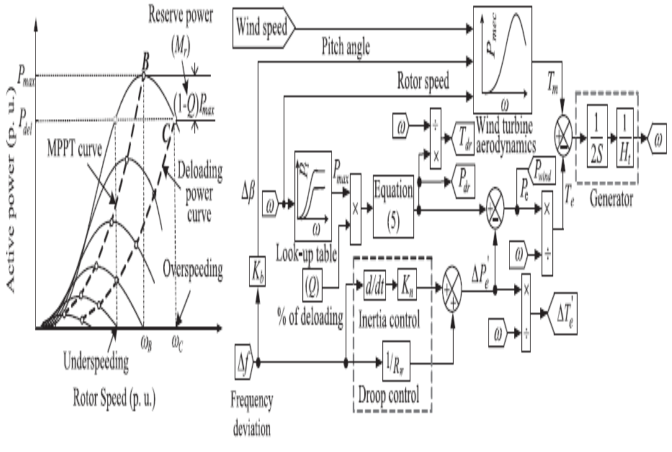
Wind power is highly variable and unpredictable in nature which may contribute to the power imbalance. After a disturbance occurs in the system, the prediction of the post-disturbance frequency behaviour should contain sufficient information to inform operators, or a closed loop controller, if the post-disturbance frequency deviation will be a threat to system security and to allow adaptive control actions to be designed to counter any threat posed by a frequency deviation. The prediction method would generate a prediction online, based on wide area measurements of frequency and active power that are recorded within the period of approximately one second after a disturbance to the active power balance of the system. The intent of this research is to contribute to the development of real time adaptive corrective control for future power systems as prediction of the post-disturbance frequency behaviour would be a valuable resource for improving frequency control and situational awareness during a disturbance. Traditionally power systems have been planned and operated based on offline security assessments. However, as power systems become increasingly complex the potential risk of blackouts increases and the creation of methods for the online security assessment of a power system has become an area of great interest in an attempt to combat this threat. The introduction of wide area measurement technologies means that the data necessary to perform these online assessments has become increasingly available to system operators.

Methods have been proposed that assess the voltage stability and rotor angle stability using tools such as pattern classification, decision trees and the calculation of security indices. Methods have also been proposed for assessing frequency stability. Much of this research has focused upon the prediction of the post-disturbance frequency behaviour. This thesis seeks to offer a contribution to this body of research with a focus on the prediction of the transient frequency response of a power system after a large disturbance. Moreover, under smart grid environment, there will be high penetration of controllable loads which consists of lots of motor loads. Hence, it is necessary to investigate the impact of load damping coefficient (D) on SFR in wind farm integrated power (WFIP) system. The frequency stability issue without considering D becomes intractable. The contributions of the proposed research work are as follows: 1) This paper is aimed to study the impact of load damping coefficient (D) on SFR for a wind farm integrated with conventional sources. A small signal linearized model of deloaded WTG is established in Section III to analyze the SFR for load frequency control (LFC) model. 2) The mathematical derivations for sensitivity analysis of frequency deviation (Δf) with respect to D and stability performance of WFIP. 3) System are derived in Sections IV and V respectively. 4) This analysis can be helpful for the system operators to plan the activities appropriately such as: selection of different POR, setting of load shedding relays, emergency demand response (EDR), etc.

For a secure and stable power system operation. Frequency stability is defined as: "the ability of a power system to maintain steady frequency following a severe system upset resulting in a significant imbalance between generation and load" by a joint IEEE/CIGRE working group. It is the role of frequency control to guarantee the frequency stability of a power system and the measures employed by frequency control. Guaranteeing frequency stability is a necessity because the frequency of a power system is a key measure of the health of that power system, as it reflects the active power balance in the system; that is, the instantaneous imbalance between the generation of, and demand for active power in the system. Therefore, any event that disturbs this active power balance will cause the frequency to deviate from nominal. Examples of such disturbances include the loss, or deloading, of a generator and sudden increases or decreases in the load demand. The performance of many power system elements is dependent on the frequency of the power with which they are supplied. For example, turbine blades experience cumulative damage when forced to operate during frequency deviations of more than 2.5 Hz from the nominal frequency and any auxiliaries driven by motors, e.g. the coolant pumps of a nuclear power plant, will slow down as the frequency falls, potentially compromising their operation. Therefore, a large deviation from nominal can cause the behaviour of many system elements to vary dramatically from their normal modelled behaviour and can lead to cascading failures that will further stress the power system, aggravate the frequency deviation and eventually lead to a blackout. In future power systems adaptive corrective control will be a necessity as the increasing levels of uncertainty that will be encountered in the future may severely compromise the traditional deterministic control.

II. SYSTEM MODELING

The power-rotor speed (P − ω) characteristics equation of wind turbine is non-linear in nature as given. So at a particular rotor speed, wind turbines exhibit maximum power. This point is called MPP. To operate on the MPP, WTGs are employed with different MPP tracking (MPPT) devices. VSWTGs can be operated at a reduced power level [point ‘C’ in Fig. 1(a)] instead of MPP [point ‘B’ in Fig. 1(a)] and it is called as deloading operation of WTG. Due to deloading operation, the remaining power is saved as reserve, which can be utilized for long term frequency regulation. In this paper, overspeeding based deloading operation is considered. The reduced order dynamic model of deloaded WTG is shown in Fig. 1(b).



(a) (b)

Fig.1.(a) MPP and deloaded curve. (b) Modeling of variable speed WTS.

In order to participate in short term frequency regulation, the frequency sensitive controllers (e.g., droop and inertia controls) are also implemented in the modeling of VSWTGs as shown in Fig.1(b).

A. Linearized Model of WTG

The sensitivity and stability analysis of power system for frequency regulation can be analyzed by using small signal analysis. Hence, in this paper, the complete derivation of deloaded WTG with small signal linearized transfer function is derived by considering POR i.e., droop control and inertia control. The linearized model of WTG is expressed as a small change or disturbance in wind speed and/or frequency. The frequency excursions may be controlled by changing the electrical power and/or the mechanical power with respect to (w. r. t.) change in frequency of the power system. In practice, it is known that the dynamics of the frequency response improves with low value of Rw and vice-versa. However, the dynamics of the frequency response is better at high value of Kn as compared to low value.

B. Sensitivity Function Derivation

LFC plays an important role in the power system. A well designed and operated power system must cope with disturbances in system parameters, changes in load, etc. and it should maintain the system frequency within its limits as per the grid code. The LFC analysis can be done by using small signal transfer function of linearized model of a power system. In this paper, linearized model of wind farm is integrated with linearized model of multi-source conventional power plants in a simple network model as shown in Fig.2. The linearized model of WTG is represented as multi input– single output (MISO) transfer functions, where the input parameters are taken as change in load (ΔPL), change in wind velocity (Δvj) and output parameter is the frequency deviation (Δf). The wind farm consists of three WTSs. Similarly, the conventional power system consists of two thermal power plants, two hydro-power power plants and two gas-turbine power plants. The conventional power system is modeled as single input– single output system and it is implemented with automatic gain control (AGC) control as shown in Fig. 2. The change in load (ΔPL) is taken as input and output is the frequency deviation (Δf) for conventional power plants. The data and the linearized model transfer functions of the conventional power plants are taken. The linearized transfer functions of thermal, hydro and gas-turbine power plants are denoted by ZT i(s), ZW i(s) and ZGi(s)(s) respectively in Fig2. In Fig. 2, Heq represents the inertial constant of the conventional power system.

The value of Heq is defined by the mass of all the generating units and motors connected to the power system. It is well know that the wind farms affect the net inertial constant (Heq, Lp) of the power system when integrated with conventional power system. The value of Heq, Lp varies with change in wind penetration level in the power system. In this paper, the wind penetration level (Lp) is taken as 25%. The linearized LFC-model of WFIP system is represented as a MISO-transfer functions as shown in Fig. 2. The SFR is affected by variations in load as well as wind speed. Hence, here, changes in both load (ΔPL) and wind velocity (Δvj) are taken as the two input disturbances and frequency deviation is considered as the output response. Considering one disturbance at a time, the change in system frequency (Δfp) w. r. t. ΔPL by keeping $\Delta vj = 0$, is expressed as shown at the bottom of the page, where, M is the number of generating units from each conventional power source and N is the number of WTGs in the wind farm. In this paper, M is taken as 2 and N = 3. Similarly, the output system frequency deviation (Δfk) w. r. t. input disturbance Δvj by keeping $\Delta PL = 0$, is written as shown at the bottom of the page. When both inputs are activated simultaneously (i.e., ΔPL and Δvj), the net output frequency deviation is obtained by combining. The net frequency deviation (Δf) is evaluated as shown at the bottom of the page. For continuously varying frequency sensitive loads, D affects the frequency response of the power system. To calculate the sensitivity analysis of Δf w. r. t. D, the partial derivative of w. r. t. D is derived and expressed. According to control theory, the unit-less sensitivity function (SD) of Δf w. r. t. D is derived from which are given at the bottom of the next page. As load damping coefficient (D) represents the load characteristic in the power system, this does not depend on wind power generation.

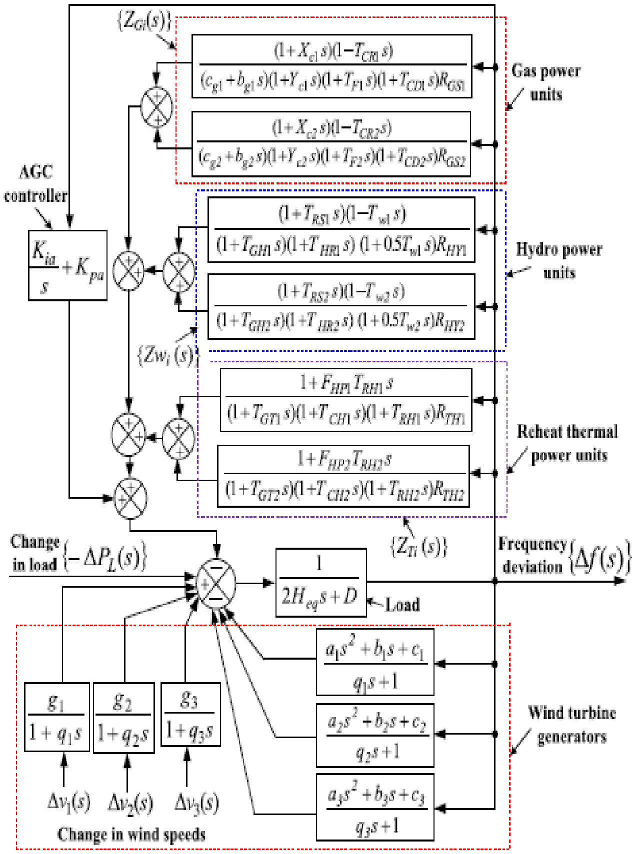


Fig2. LFC model for multi sources WFIP system.

However, sensitivity of frequency deviation (Δf) w. r. t. D affects due to intermittent nature of wind power. Highly fluctuating and unpredictable nature of wind speed affects wind power generation. Due to mismatch between generation and load demand, system frequency deviates from its nominal value. Hence, initial slope of frequency gradient and dynamics of frequency response (i.e., settling time, dips/peaks, etc.) are different in case of WFIP system for different wind speeds with the same value of D. The comparative simulation results of frequency deviation sensitivity w. r.t. D for conventional power system and WFIP system is given. It can be seen that for stable power system, the frequency deviation is bounded by a different boundary for WFIP system and conventional power system. If the time-domain output frequency deviation (Δf) response is un-bounded with bounded time domain inputs of ΔPL and Δvj , the system is unstable i.e., the output response is infinite with finite value of input. It means that as per power system prospective for unstable system, the frequency deviation will not remain within their specific limit as per the grid codes. According to control system theory, when at least one pole of the Laplace characteristic function is located on the right of the s-plane, system becomes unstable. In case of WFIP system, i.e., it is observed that the net frequency deviation depends on the change in wind speed, system operating points, configuration of the power system, etc. for a particular value of D.

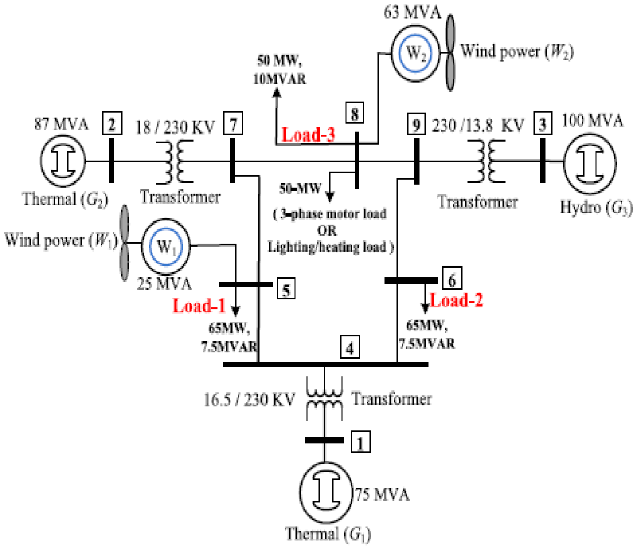


Fig3. IEEE-9 bus standard test system model.

To verify the given analysis, for illustration purpose, IEEE- 9 bus test system (Fig. 3) is chosen as case study. The modeling and data of the conventional power sources (i.e., thermal and hydro) and synchronous generators are taken. In IEEE-9 bus system, the generating capacities of three conventional generators are G1-100 MVA, G2-150 MVA and G3-100 MVA. Hence, total generation capacity of conventional power system is 350 MVA. In case of WFIP system, two DFIG based wind farms are connected at Bus-5 (W1) and Bus-8 (W2) with ratings 25 MVA and 63 MVA respectively is shown in Fig. 3. After integrating wind power to the system, the MVA capacity of the conventional sources reduces accordingly so that wind penetration level becomes 25% and total generation capacity of WFIP system becomes 350 MVA. Therefore, after integrating wind system, the capacities of G1,G2 and G3 are taken as 75 MVA, 87 MVA and 100 MVA respectively. The modeling and data of WTGs are taken. In this project, the heating/lighting loads are taken as the three phase resistive load. For resistive loads, the electrical power is independent of frequency. In order to represent the motor load, we have taken three-phase induction motor. The frequency control services that are available to a transmission system operator are separated into different levels of control. These levels of control include: fast actions that only have a local influence on frequency, slower actions that allow the frequency across the entire system to be managed and emergency actions that can be called upon as a last resort to limit the size and duration of any large frequency excursions that develop.

C. Primary Control

Primary control is provided by the governor of a generator and is expected to be available within a few seconds. It is based upon the relationship that causes a change in the electrical loading, and therefore electrical torque, of a generator to translate into a change in the rotor speed of that generator. This change in rotor speed will change the electrical frequency of the power produced by the generator. Control of this change in electrical frequency can be achieved by comparing the measured rotor speed to a reference speed to identify any deviation. This change in speed signal can then be used to calculate the adjustment to the primary energy input of the generator that will be necessary to correct the power imbalance at the generator terminals and limit the speed deviation this imbalance has caused. A block diagram of this process can be seen in Figure 4.

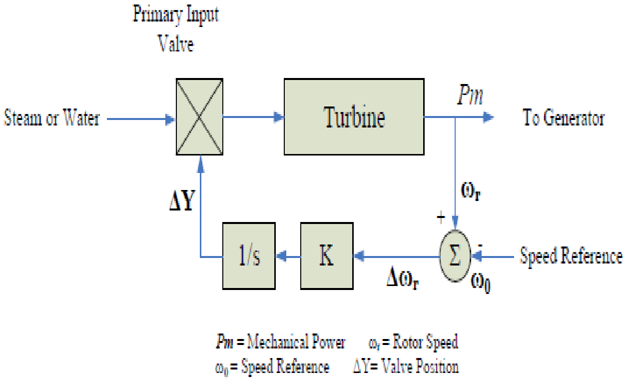


Fig4. A block diagram of a simple governor controller that implements primary control.

D. Secondary Control

The purpose of secondary control actions is to restore the system frequency to the nominal set point and ensure that any tie-line flows in the system are at their contracted level. This action is necessary because the primary control achieved through the introduction of a speed droop can only act to limit the deviation and not to correct it. This secondary control is achieved by moving the load reference set point of some, or all, of the system generators to allow an increase, or decrease, in the power generated thus allowing the frequency to be returned to the nominal value. Moving the set point in this way is achieved by subtracting a load reference set point variable from the speed change feedback loop to give the new controller block diagram depicted in Figure 5.

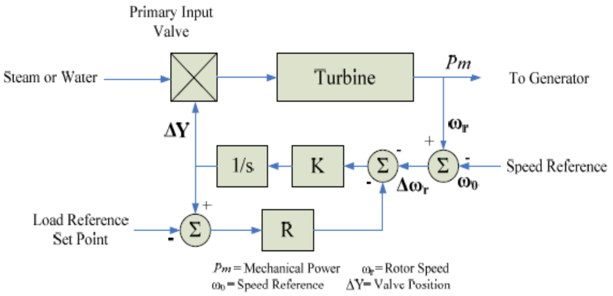


Fig5. Block diagram of a simple governor controller for a generator with the addition of a feedback loop that allows the load set point to be moved. This controller can therefore supply secondary control.

E. Tertiary Control

Tertiary control acts after the system frequency has been returned to, or very near to, the nominal value. Tertiary control is different to primary and secondary control because it does not deal directly with controlling the frequency. Instead the main task of tertiary control is to ensure that the resources tasked with providing primary and secondary control are sufficient to deliver the necessary control actions, as defined in the relevant regulations, when they are called upon. Ensuring that these control actions are available may require generators to be redispatched if the control actions taken previously have exhausted the capability of those units, or others, to provide the necessary control actions. This change in the dispatch of generators is also used to ensure that both the load and the necessary frequency control services are provided in the most economic way possible; whilst maintaining the desired level of system security. The actions available to tertiary control include: adjusting the set point of a generator and turning on, or off, fast starting generation units. Fast starting is usually defined as a generator capable of generating rated power within fifteen minutes of being turned. These actions can be taken either manually or automatically depending on the system operator practices. When planning control actions it is important to consider the availability of plant capacity in the form of de-loaded units as well as spinning and standing reserve that will be able to provide the necessary capacity for any desired control action. It can sometimes be cost effective to partially de-load a medium sized unit, to provide reserve, rather than starting an additional generator. It is also important to bear in mind during tertiary control that due to the local nature of most control actions it is not just the MVA capacity of reserve that is important. Rather, the physical location of reserve on the network is also a parameter in determining its value, as a small amount of reserve in a key strategic location may offer more benefit than a larger reserve elsewhere.

F. Modelling of the System Frequency Response

Models of frequency response are usually tailored for a specific generation technology such as a steam turbine, combined cycle unit, hydro power or wind generation and they are included as part of complete models of the technology and not just its frequency response. Therefore, the complexity of these models meant that it was inconceivable to estimate the parameter values of any of these models or a composite model based on them using only the limited data available to the prediction methods that are considered in this research. This complexity meant that the simplified frequency response model, was considered as the basis for any frequency prediction based on approximate models. This model represents the system frequency as a single equivalent frequency and assumes that the system is dominated by reheat steam turbines. The model for the response to disturbance, Pd, which is modelled as step change in the active power demand is depicted in Figure 6.

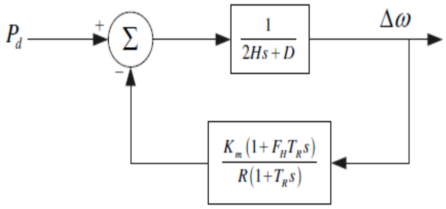


Fig6. The Simplified Frequency response model for the system frequency response to a disturbance of magnitude Pd.

III. SIMULATION RESULTS

CASE-1: FREQUENCY DEVIATION RESPONSE AT D = 0 WITHOUT POR SUPPORT BY WTGS

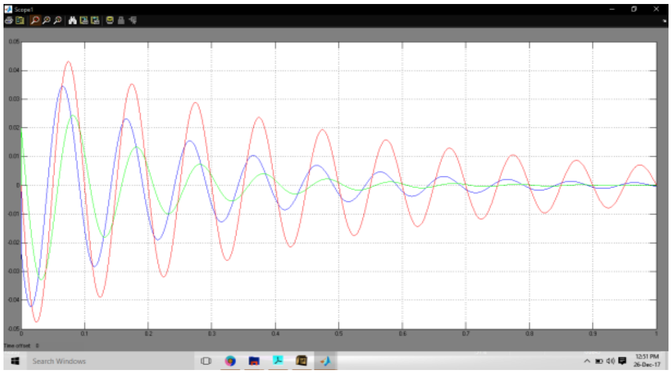


Fig7. Frequency deviation response at D=0 without POR support by WTGs.

A step load change (ΔPL) of value 1.0 p.u. at t = 0sec is incorporated in the simulation. In general, dips/peaks in SFR are more, when the value of D is lowest (i.e., without motor load). Therefore, in order to show the most crucial scenario, the lowest value of D (i.e., D = 0) is considered to analyze the SFR. First, the responses of frequency deviation for D = 0 without POR by WTGs are shown in Fig. 7. From Fig. 7, it can be seen that the dips/peaks in frequency deviation (Δf) are less in conventional power system as compared to WFIP system without POR support by WTGs. This happens because according the net inertia of the system reduces due to integration of WTGs without frequency support. As per power contribution by WTG is less at low wind speed as compared to high wind speed. This means that availability of reserve power is more in case of 12 m/sec wind speed as compared to 6 m/sec wind speed. Therefore, dips/peaks in frequency deviations are relatively less in case of WTG having wind speed of 12 m/sec as compared to WTG having wind speed of 6 m/sec.

CASE-2: FREQUENCY DEVIATION RESPONSE AT D = 0 WITH POR SUPPORT BY WTGS

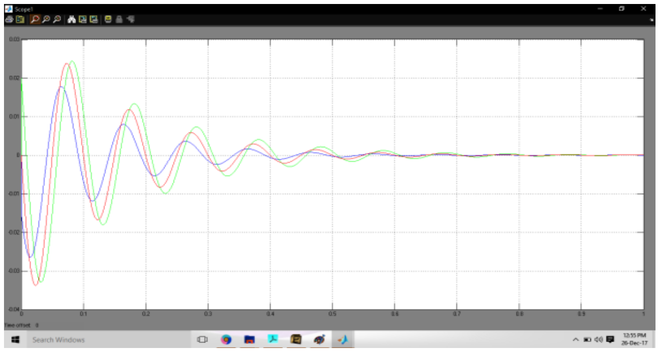


Fig8. Frequency deviation response at D=0 with POR support by WTGs.

Now considering POR support by WTGs, the frequency deviation response is plotted in Fig. 8. From Fig. 8, it can be observed that peaks/dips in frequency deviation are relatively low in case of WFIP system as compared to conventional power system. In Fig. 8, the lowest frequency dip is reduced by 15.528% in case of 6 m/sec and 27.011% in case of 12 m/sec as compared to conventional power system. Moreover, it can be seen that the settling time for frequency response is faster in case of WFIP system with POR support by WTGs as compared to the conventional power system. The above observation can be justified through, where it can be seen that the net inertial constant (Heq, Lp) of the system increases by participating in frequency regulation by WTG. The value of the net inertial constant (Heq, Lp) directly affects the initial slope and ROCOF response of the power system. However, the steady state frequency is mainly affected by D and droop setting (RLP).

CASE-3: FREQUENCY DEVIATION DERIVATIVE RESPONSE AT D= 0 WITH POR SUPPORT BY WTGS.

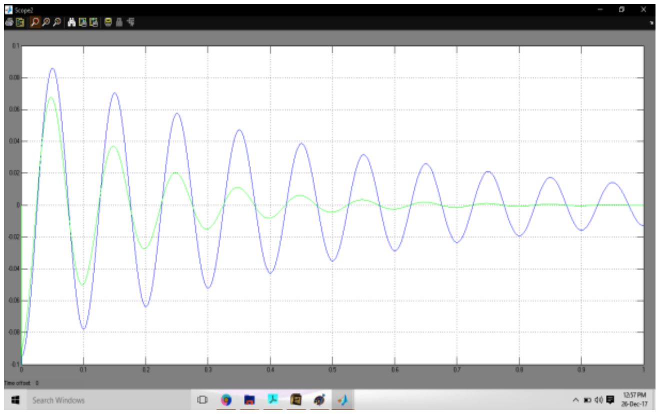


Fig9. Frequency deviation derivative response at D = 0 with POR support by WTGs.

For D = 0, the ROCOF deviation and frequency deviation sensitivity w. r.t. D for WFIP system with POR support are shown respectively. From Fig. 9, it can be seen that the response of the frequency deviation derivative is relatively sluggish for conventional power system as compared to WFIP system. The largest frequency dip occurs when ∂Δf (t)

∂t = 0 (i.e., tc1 and tc2 in Fig. 9), where tc1 corresponds to conventional power system and tc2 corresponds to WFIP system with POR support by WTGs. The time at which the lowest frequency deviation dip occurs is called as critical time (tc). The corresponding critical time for conventional power system and WFIP system for 6 m/sec are found to be tc1 = 0.764 sec and tc2 = 0.987 sec respectively.

CASE-4: FREQUENCY DEVIATION RESPONSE FOR DIFFERENT VALUES OF D WITH POR SUPPORT BY WTGS FOR 6 M/SEC WIND SPEED.

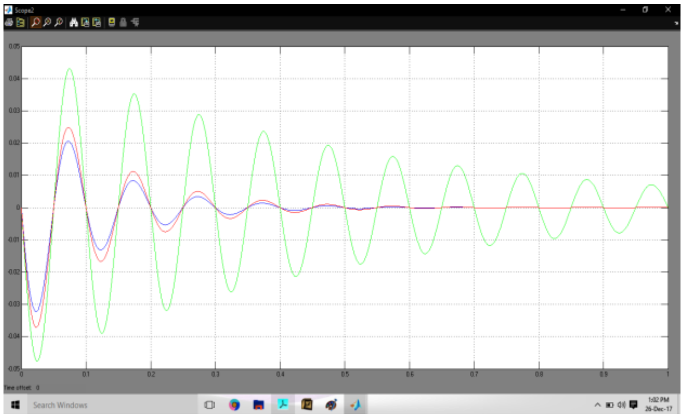


Fig10. Frequency deviation response for different values of D with POR support by WTGs for 6 m/sec wind speed.

In order to evaluate the impact of D on SFR, three different values of D (i.e., 0, 0.4 and 0.8) are considered in Fig. 10. The simulation results are plotted with POR support by WTGs at 6 m/sec wind speed. It is observed that the sensitivity of the frequency deviation (Δf) with respect to D is visible in Fig.10. Fig. 10 indicates that the dips/rises in frequency deviations are comparatively less at higher value of D. In Fig.10, the value of lowest frequency dip is reduced by 10.16% for D = 0.4 and 22.46% for D = 0.8 as compared to the value for D = 0. This demonstrates that motor load has their own inertial response and they contribute to the frequency stabilization. Such kind of plots which are shown above can be drawn for different values of wind speeds and D for the analysis purpose.

CASE-5: FREQUENCY DEVIATION RESPONSE

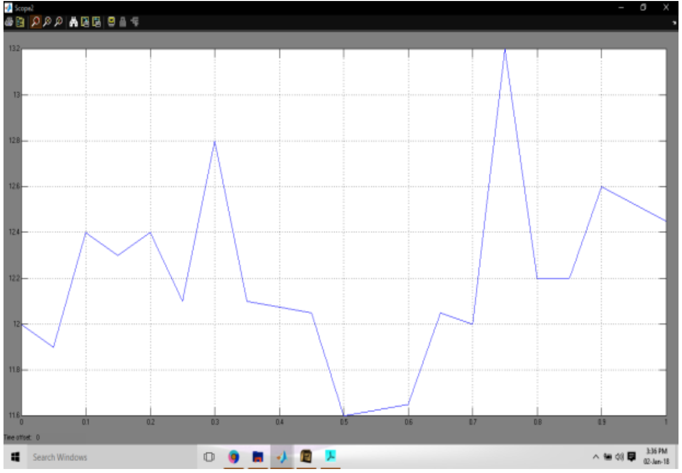


Fig11. Wind speed variations.

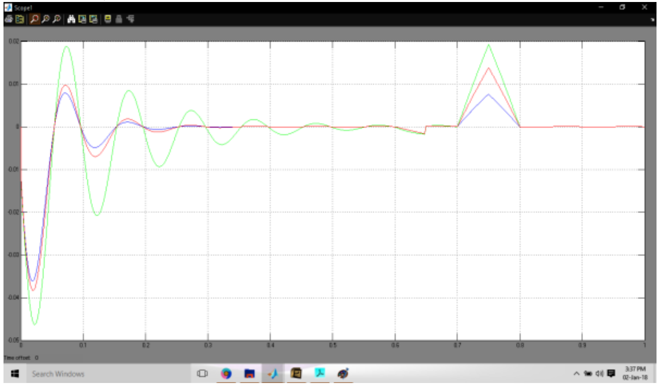


Fig12. Frequency deviation response.

In wind power system, the generated power of WTG depends on wind speed. Since wind is uncontrollable and random in nature, the output power of WTG varies with wind speed fluctuation, this fluctuation results into frequency variation. In this case, the SFR plots are plotted by considering the variations in wind speeds (Δvj) along with the step change in load (ΔPL). In order to represent the random and intermittent nature of wind speed, a mathematical modeling of wind speed is carried out. The wind speed is modeled as the combination of base wind speed, ramp wind speed, gust wind speed and noise wind speed as shown in Fig. 11. To represent the load, a step change in load (ΔPL) of value 1.0 p.u. at t = 0sec is taken in the simulation. For the above mentioned scenario, the response of frequency deviation is plotted in Fig. 12. From Fig. 12, it can be observed that the settling time of the frequency response is relatively faster and smoother (i.e., less dips/peaks) in case of WFIP system with POR support by WTGs as compared to without POR support. Also, it can be seen that the dynamics of the frequency deviation (Δf) is better in case of higher value of D as compared to lower value of D.

IV. CONCLUSION

This project investigates the effect of frequency-sensitive load on the frequency response of WFIP system. The mathematical derivations are formulated which are based on the transfer function of WFIP system to study the stability and sensitivity analysis with respect to load damping coefficient (D). The simulations are carried out for stable as well as unstable power system. Various SFR plots are drawn by applying the perturbations in load and wind speed in the WFIP system. From the simulation results, it is concluded that the dips/peaks in frequency response are less in case of WFIP system (with POR support by WTGs) as compared to the conventional power system. Due to smoothing of SFR with faster settling time, WFIP system improves the power quality of the power system. Effect of various values of D is analyzed for frequency deviation response. It can be concluded that WFIP system with POR gives better frequency response for higher values of D (i.e., motor loads). The proposed analysis can be helpful for the system operators for decision-making of appropriate POR control schemes, planning of EDR and setting of relays, etc. for secure and stable power system operation.

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