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Comparison of Control Schemes for Frequency Support in DFIG based WECS

D. Nagaria*, G.N. Pillai*[1] and H.O. Gupta*

Abstract – *In most parts of the world, the wind power generation, along with other renewable technologies, offers the sustainable, non-polluting and secure option for generating electricity over the long term. The increasing share of wind energy conversion systems (WECS), such as doubly fed induction generators (DFIGs), in electricity power generation would result in a reduction of conventional generator power plants. The variable speed wind turbine (VS-WT) units equipped with DFIGs contribute negligible inertial response to frequency variations. This paper compares different control schemes to provide frequency support in variable speed WECS equipped with DFIG during the system frequency changes. Addition of a supplementary control loop connects the turbine inertia directly to the grid and power can be exchanged with the grid during the frequency variations. Simulation results on a 9 MW wind turbine system equipped with DFIGs illustrate the contributions to frequency support with the proposed control strategies. Comparison of different control strategies have been carried out, when the system is subjected to the grid frequency excursion and load variation. Amongst the three control schemes considered in the present study, it has been found that inertial response of the proportional controller is the best. The particle swarm optimization (PSO) technique is used to tune the controller parameter for minimizing the frequency deviation and maximizing the release of energy. It has been found that inertial response of the system with the PSO optimised proportional controller gives improved results.*

Keywords – Doubly fed induction generator, frequency variations, inertial response, particle swarm optimization, supplementary control loop, wind energy conversion system.

1. INTRODUCTION

As a result of increasing environmental concern, more and more electricity is generated from renewable energy sources in many parts of the world. Presently the wind power generation is the most widely emerging renewable energy technologies in electricity systems and its capacity is increasing globally [1]. Modern wind turbines use complex technologies including power electronic converters and sophisticated control systems. The use of DFIG is becoming increasingly important in wind power applications. Compared with the conventional generators they enable variable speed operation which reduces the mechanical stresses on the wind turbines, noise, requirements for the pitch angle controllers, rating of power electronic converters and thus improves the overall efficiency. In addition, the power electronic converters may provide a significant degree of control of reactive power flow between DFIG and grid [2].

The increasing share of variable speed WECS, such as DFIG, in electricity power generation would result in a reduction of the number of connected conventional generator power plants. It is anticipated that these WECS perform some of the duties that conventional power plants presently deliver but possibly, they impose a number of operational constraints on the electricity system. One of the important aspects excluding these duties is the system inertia, which has an extremely important role as it determines the sensitivity of the system during the frequency variations and the same has been considered here [3]. It has been observed that standard fixed speed WECS with directly connected generators contribute to power system inertia, with the inertias of generator and wind turbine rotor, due to strong coupling between the generator and the power system frequency. On the other hand, standard variable speed WECS, such as DFIG, control power independently and thus decouple the generator torque from grid frequency. Due to decoupling of mechanical and electrical system, the variable speed WECS contributes negligible to the power system inertia [4], [5]. Operating a large number of variable speed WECS in place of conventional generator power plants would reduce the effective inertia of the power system. Lower system inertia results in larger and faster frequency deviations after the occurrence of a variation in generation or load.

The high impact of intermittent wind energy generation has already been reported for certain control areas where there is a direct correlation between larger frequency deviations and larger amount of wind in the system [6]. The frequency deviations are smaller when less wind is on the system and deviations increase as more wind is placed on the system. Thus, from the dynamic stability point of view, the penetration of wind energy is characterized by smaller damping and inertia

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constants of the grid. With high penetration of wind power, the system would be unable to absorb unbalances due to the intermittent nature of wind without risking the stability, power quality, or frequency control.

One way to address the problem with inertia is to combine WECS with high inertia energy storage systems. Improvements in the flywheel energy storage technology have demonstrated that it is especially appropriate to combine other technologies with wind energy to manage power system inertia [7].The other possible solutions for increasing the inertial response include wind penetration reduction during low system load [5] and inclusion of supplementary control to the DFIG [8].

This paper considers the inclusion of supplementary control to provide the inertial response in variable speed WECS equipped with DFIG. It is possible to configure the DFIG to change the referenced torque with frequency variations. The supplementary torque signal connects the turbine inertia directly to the power system and wind turbine will release the energy during a frequency drop and draw the energy on increasing the frequency. Three different control schemes are proposed for supplementary control loops. The simulations are carried out using power system block set in Matlab/Simulink. Simulations on a 9 MW WECS equipped with DFIG show that these controllers are able to improve the system frequency response. The performance of the controllers is compared when the system is subjected to grid frequency drop and load variation. The PSO technique is implemented to tune the controller parameter for minimizing the frequency deviation and maximizing the release of energy. Comparison of control strategy with PSO optimize controller have been carried out.

2. WIND ENERGY CONVERSION SYSTEM

A WECS has three energy stages: wind energy stage, mechanical energy stage and electrical energy stage. The general scheme of a WECS includes wind turbine and electrical generator with power electronic converters and sophisticated control systems. The core of wind turbine consists a rotor that extracts energy from wind and converts into mechanical power and a generator converts this mechanical power into electrical power. The various subsystems of WECS are explained below.

Wind Turbine

In this study, a simplified model of wind turbine is used for aerodynamics with averaged wind speed as an input. The mechanical power P_{mech}, captured by a wind turbine depends on its performance coefficient C_p for a wind velocity v and can be represented by [1]:

$$P_{mech} = \frac{1}{2} C_p(\lambda,\theta)\rho\pi R^2 v^3 \quad (1)$$

where ρ and R correspond to the air density and the radius of the turbine propeller, respectively.

The C_p can be described as the portion of mechanical power produced from the total power available from the wind, and it is unique for each turbine. This C_p is generally defined as a function of the tip-speed-ratio λ and pitch angle θ [9]:

$$C_p(\lambda,\theta) = c1*\left(\frac{c2}{\lambda_i} - c3*\theta - c4\right)e^{\frac{-c5}{\lambda_i}} + c6*\lambda \quad (2)$$

with,

$$\frac{1}{\lambda_i} = \frac{1}{\lambda+0.08\theta} - \frac{0.035}{\theta^3+1} \quad (3)$$

and,

$$\lambda = \frac{\omega R}{v} \quad (4)$$

where ω represents the rotational speed of the wind turbine and coefficients *c1* to *c6* are given in Appendix.

The C_p-λ characteristics, for the different values of pitch angle θ, are illustrated below in Figure 1. The maximum value of C_p (C_{p_max}=0.48) is achieved for θ=0 degree and for λ=8.1. This particular value of λ is defined as nominal value, λ_nom.

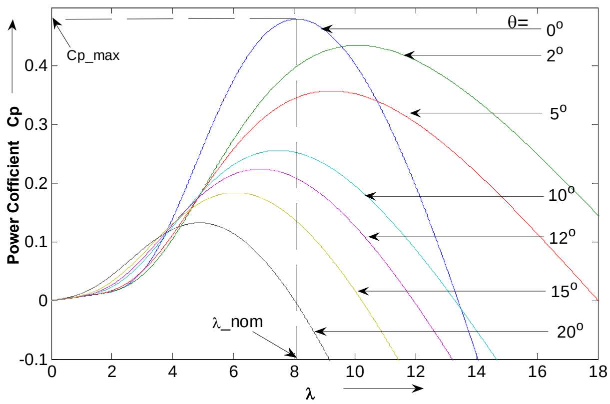

Fig. 1. C_p-λ characteristics.

DFIG Model

The basic configuration of a grid connected DFIG with wind turbine is shown in Figure 2. In order to cover a wide operation range, from sub-synchronous to super-synchronous speeds, a back-to-back converter is connected to the rotor. This converter connects the rotor to the power system while the stator is connected directly to the power system. This enables the capabilities of DFIG to deliver the power to grid through stator as well as rotor, whereas the rotor can also absorb power depending on the rotational speed of the rotor. The basic equations of DFIG are considered here. The equations describing a doubly fed induction generator can be found in literature [10].

Mechanical System

For a simple mechanical system of moment of inertia J and damping F, the rotor swing equation is:

$$T_e = J\dot{\omega} + F\omega + T_m \quad (5)$$

where mechanical torque, T_m, is due to wind and electromagnetic torque, T_e, for a machine with p pole pairs is given by:

$$T_e = \frac{3}{2} pL_m (I_{qs} I_{dr} - I_{ds} I_{qr}) = \frac{3p}{2} \frac{L_m}{L_{ss}} (\psi_{qs} I_{dr} - \psi_{ds} I_{qr}) \quad (6)$$

In Equation 6, the stator current and flux linkage components are, respectively, (I_{ds}, I_{qs}) and (ψ_{ds}, ψ_{qs}) and those of the rotor are (I_{dr}, I_{qr}) and (ψ_{dr}, ψ_{qr}). The DFIG's magnetizing inductance is L_m and stator self inductance is L_{ss}

Control Systems

The fifth-order induction machine model with mechanical system is employed in the case of the DFIG wind turbine. In this WECS model the IGBT based Voltage-sourced converters (VSC) are represented by equivalent voltage sources generating the AC voltage averaged over one cycle of the switching frequency. The effect of harmonics is not modeled, but the dynamics resulting from control system and power system interaction is preserved.

This paper considers that DFIG extracts the maximum amount of wind power within the limit of the machine. The maximum power tracking characteristics is shown (solid bold curve) on the turbine output power versus rotor speed characteristic in Figure 3 [9]. The rotor speed is proportional to the wind speed and varies with the cubic root of the power and square root of the corresponding torque. The torque-speed characteristic used as dynamic reference for generator torque, T_{set_point}, demand as a function of measured generator speed and this generates the reference current for rotor current controller. A proportional-integral (PI) controller is used to obtain the rotor-injected voltage, V_{dr}. The details description about the controller can be found in [10], [11].

The pitch angle controller is used in conjunction with rotor speed controller to control the rotor speed (at-rated). However, this controller is only active only to limit maximum output power at high wind speed. In these circumstances, the rotor speed can not be controlled by increasing the electromechanical torque anymore, as this would lead to overloading the generator and the converter.

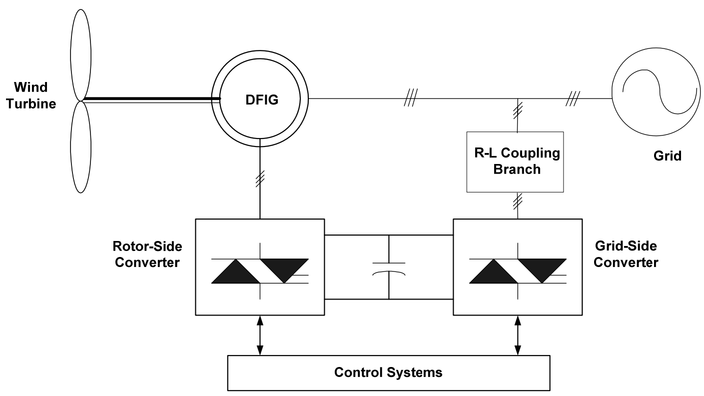

Fig. 2. The basic configuration of DFIG.

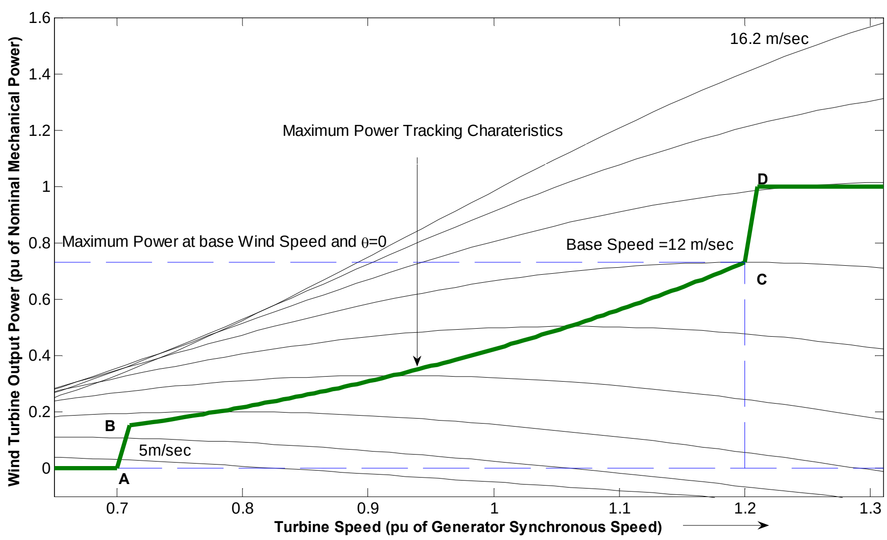

Fig. 3. The turbine power characteristics.

3. FREQUENCY DUTIES IN DFIG VS-WT

Kinetic Energy

A rotating mass of inertia J kg/m^2, with a rotating speed ω rad/sec, possess a kinetic energy E_k that can be written as follows [12]:

$$E_k = \frac{1}{2}J\omega^2 \ , \ E_k = E_{k\_base}\left(\frac{\omega}{\omega_{s\_base}}\right)^2 = E_{k\_base}\left(\frac{f}{f_{s\_base}}\right)^2 \quad (7)$$

where ω_{s_base} = base speed, rad/sec
f_{s_base} = base frequency, Hz
E_{k_base} = Kinetic Energy at base frequency, J (or Ws)

From Equation 7, it is clear that the kinetic energy stored in the rotating mass of wind turbine is proportional to inertia and the square of rotational speed, while this rotational speed is dependent on the wind speed in WECS. Hence, the kinetic energy stored in the rotating mass of wind turbine depends on the wind speed.

The stored kinetic energy of the entire turbine rotor is high as the inertia of turbine blades is much higher than that of the electrical generator. Therefore, turbine kinetic energy can be used to support the power system. Whereas, compared to the turbine rotor, the generator has a much higher rotational speed that results in a large amount of kinetic energy.

Frequency Response Phenomenon of DFIG

According to the system grid codes, frequency support can be provided by each generator on the power system [5]. In the power system with synchronous or induction machines, when the frequency reduces from its operating value, kinetic energy is released from the rotating mass due to strong coupling between mechanical and electrical system. This reduces the rate of change of frequency drop. With the proper implementation of the control system in the rotor circuit, variable speed WECS extracts maximum power from the wind and is largely unaffected by any change in frequency of the power system. This behavior differs the effect of variable speed WECS with the fixed-speed WECS.

Therefore, variable speed WECS do not have a primary control reserve and are not able to contribute to primary frequency control in the classical way. The kinetic energy stored in their inertia gives the turbines the possibility to support primary frequency control for a short period [13]. The magnitude of the inertial response of a DFIG depends on the extent by which the rotational speed changes in response to system frequency variations. As the result of accurate control, the coupling of rotational speed to system frequency is poor and the resulting inertial response is largely removed. Thus, if WECS equipped with DFIG displaces conventional generators, the frequency support inertial response is detrimentally affected [14], [15].

The response of WECS equipped with DFIG for a frequency change can be explained using the torque–speed characteristics [3], [8]. The following phenomena take place:

- Due to reduction in frequency, the generator speed starts dropping. This phenomenon can be considered as retardation in the set point torque, T_{set_point}, acting on the rotating mass.
- The power that can be extracted from a rotating mass, is obtained by taking the derivative of the kinetic energy expressed in Equation 7, available at any speed, as shown below:

$$P = \frac{dE_k}{dt} = J\omega\frac{d\omega}{dt} \quad (8)$$

Substituting the inertia constant H, the power in Equation 8 can be represented as:

$$P(pu) = 2H\omega(pu)\frac{d\omega(pu)}{dt} \quad (9)$$

Therefore, the per-unit retardation in torque is proportional to $d\omega/dt$ and thus to df/dt is given by:

$$T(pu) = 2H\frac{d\omega(pu)}{dt} \quad (10)$$

- As the rotor speed starts reducing, the DFIG electromagnetic torque, T_e, is brought down by the control system along the maximum power tracking curve (from operating point C towards B). At the same time, the aerodynamic mechanical torque, T_m, starts increasing from operating point (this is a very slow action compared to the change in T_e). The reduction in T_e and enhancement in T_m result in an accelerating torque, which acts as a restoring torque for the speed change.

In order to restore the inertial response, torque set point referenced value, T_{sp_ref}, should be increased and cancelled out the accelerating torque. This phenomenon allows the machine to operate at a reduced speed. In this work, the torque set point referenced value T_{sp_ref} is increased by adding a supplementary signal taken from an additional controller, which will respond corresponding to frequency variation.

Supplementary Control for Inertial Support

As discussed earlier that WECS equipped with DFIG contribute negligible inertial response to frequency variation, it is desirable to configure the DFIG to change the referenced torque with frequency variations [3], [8], [15].

The supplementary control loop, as shown in Figure 4, configures the DFIG to change the torque set point referenced value, T_{sp_ref}, during frequency variations. The supplementary control loop torque, ΔT, is added to the set point torque, T_{set_point}, of the DFIG variable speed wind turbine to provide the torque set point referenced value, T_{sp_ref},. This signal, in the same way as a natural inertial response, will impart energy to the system as frequency drops and absorb energy from the system as frequency increases. In this way, a supplementary control loop connects the turbine inertia directly to the grid, and power can be exchanged with the grid during the frequency variations.

The objective of this study is to evaluate and compare the different possible control schemes for supplementary control loops, to get the best possible inertial response and the smallest frequency deviation. Furthermore, optimization is also carried out to tune the controller parameters for getting the desired performance.

Derivative Controller: In this scheme the controller action, supplies an additional amount of power, proportional to the rate of change of frequency. Noise on the measurement may cause large variations in the torque set point, *ΔT*. The impact on mechanical drive train loads due to this derivative supplementary control action is minimized by adding a first order low pass filter after the derivative output to modify the rate of change of power injection. Delay on this filter reduces the rate of increase of the electromagnetic torque and the magnitude of the peak torque [8]. The structure of the supplementary control loop for inertia control is shown in Figure 5.

Proportional plus Derivative Controller: The second type of controller is a proportional plus derivative controller. The additional torque set point, *ΔT*, is based on the absolute deviation and rate of change of the frequency from the nominal value. Schematic implementation of the controller is shown in Figure 6. In this scheme also, to minimize the impact of supplementary control on mechanical drive train loads, a first order low pass filter is used after the derivative output.

Proportional Controller: The third control scheme considered for inertia response is proportional controller. The additional torque set point, *ΔT,* is proportional to the absolute deviation of the frequency from the nominal value. The structure of the controller is shown in Figure 7.

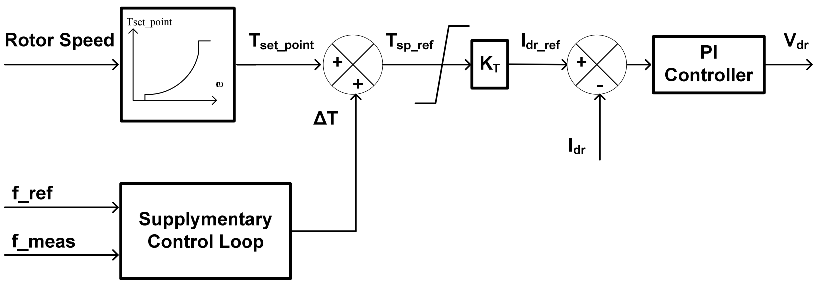

Fig. 4. Supplementary controller for inertia response.

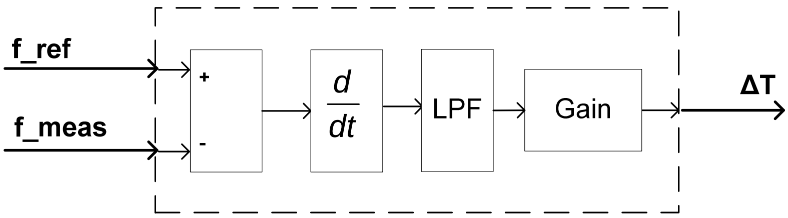

Fig. 5. Derivative controller in supplementary control loop.

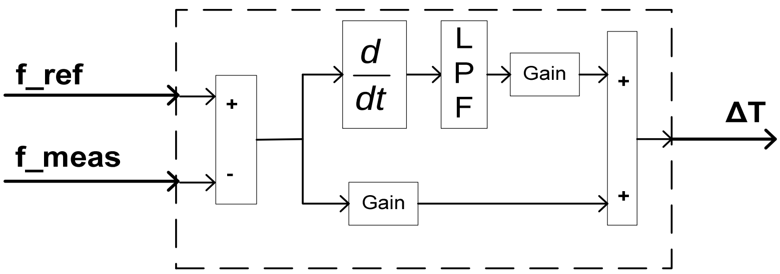

Fig. 6. Proportional plus derivative controller in supplementary control loop.

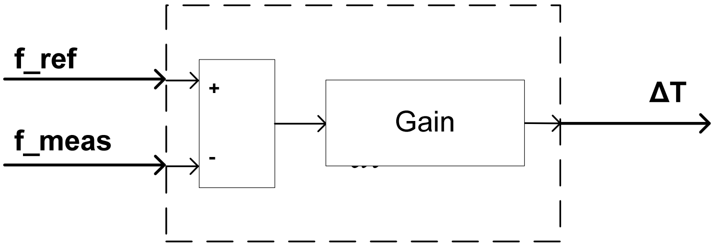

Fig. 7. Proportional controller in supplementary control loop.

4. CASE STUDIES

The performance of the controllers has been evaluated on the system shown in Figure 8. The test system used for the evaluation of different control scheme is a 9 MW variable speed WECS equipped with DFIG connected to a grid of 60 Hz frequency. The WECS is connected to a 25 kV distribution system exports power to a 120 kV grid through a 30 km, 25 kV feeder. A purely resistive load of 8 MW is connected at 575 V bus through a switch, Switch 1. The WECS parameters and supplementary controller parameters for the said system are as given in Appendix. The controller parameters are obtained after repeated trials to optimize the response. The influence of the supplementary controller on the performance of the system is investigated, when the system is subjected to (i) Grid frequency excursion (ii) Load variation in the network. For both the evaluation cases initial value of wind turbine is corresponding to a wind speed of 10.2 m/sec. The initial value of DFIG output power is 0.48 pu, T_{sp_ref} is 0.44 pu and rotor speed is 1.09 pu. As the rotor speed is below the maximum permissible speed 1.2 pu, the pitch controller is not activated. Therefore, the DFIG performance is not regulated by the pitch controller.

Grid Frequency Excursion

Initially, the system is considered in steady state with generation and load balanced. The Switch 1 is closed and frequency is constant at its reference level. In this case electricity grid frequency drops by 0.25 Hz at time t=2.5 sec due to generation imbalance. Figure 9 shows the performance of WECS equipped with DFIG for the event of frequency drop with the different control schemes in the supplementary control loop. Figure 9(i) is showing frequency variation with the implementation of different controller structures. The minimum frequency is approximately 59.62 Hz when there is no supplementary controller. Inclusion of supplementary control loop results in improving the minimum frequency as depicted in Figure 9(i).

Load Variation in the Network

In this case, initially the system model is in steady state, with generation and load balanced, Switch 1 is open, and frequency is constant at its reference level. The system frequency variation is introduced by the sudden change in the load at steady state. A load of 8 MW is connected by closing the Switch 1 at time 2.0 sec and this load variation results in a frequency drop. Figure 9 shows the performance of the DFIG for a load variation in terms of frequency drop. Figure 9(i) is showing the frequency variation with different control structures in the supplementary control loop, same as in previous case. The minimum and maximum frequencies are approximately 59.52 Hz and 60.19 Hz respectively, when there is no supplementary controller. Similarly, in this case the inclusion of supplementary control loop is improving the minimum and maximum frequencies as depicted in Figure 9(i).

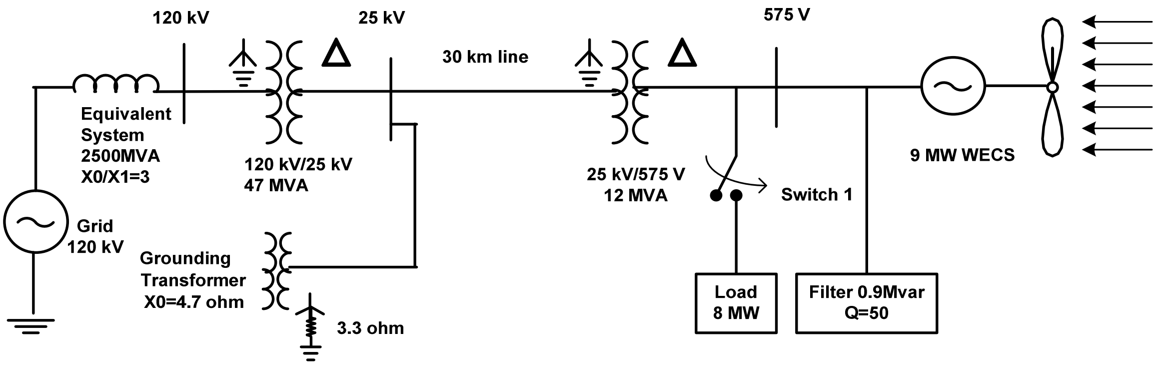

Fig. 8. Single line diagram of 9 MW VS-WT equipped with DFIG.

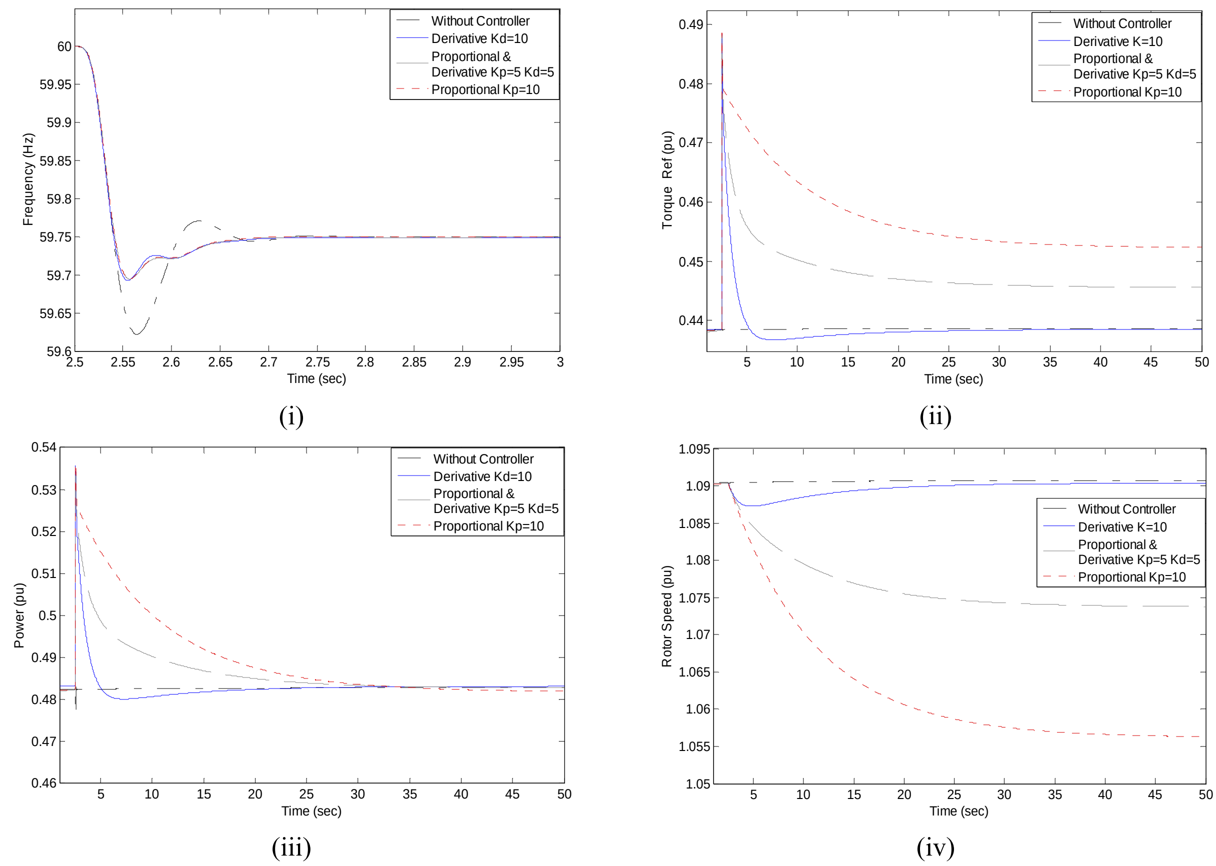

Fig. 9. WECS performance during grid frequency drop of 0.25 Hz at time t=2.5 sec due to generation imbalance (i) frequency response (ii) generator power output (iii) reference value of torque (iv) generator rotor speed.

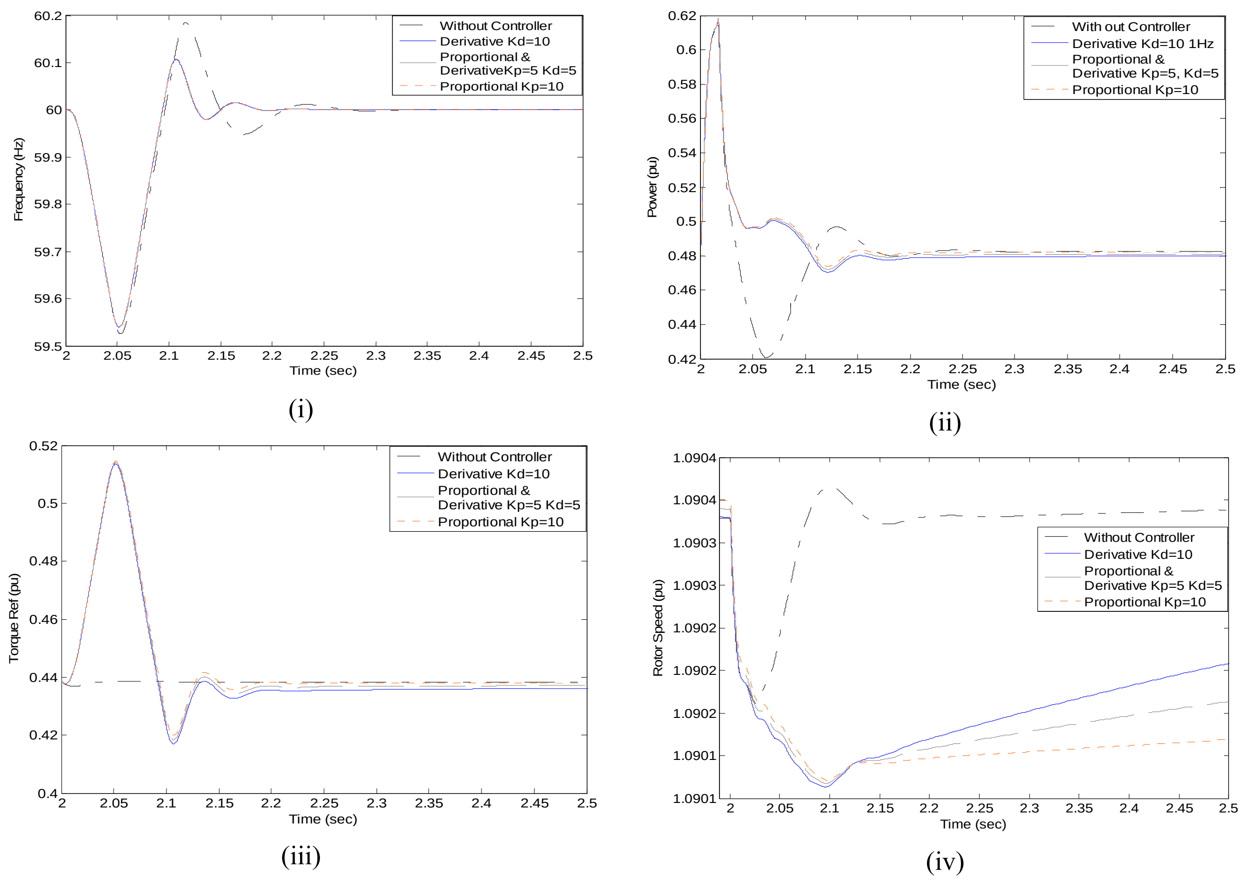

Fig. 10. WECS performance under load variation on power system at time t=2.0 sec (i) frequency response (ii) power output (iii) reference value of torque (iv) generator rotor speed.

5. RESULTS AND DISCUSSION

The inertial responses for both the evaluation cases corresponding to a wind speed of 10.2 m/sec are shown in Figures 9 and 10 respectively. Three different control schemes, which are tuned for the same peak value of power response, are compared. The network frequency signal is processed in the proposed control schemes to provide the inertial response and a speed reference set point for the torque set point. The Figures 9(iii) and 10(iii), show the torque set point referenced value corresponding to different control schemes in the supplementary control loop. As illustrated in Figures 9(iv) and 10(iv), supplementary control loop serves to slow down the rotor speed over the initial period following loss of generation, so that rotor stored kinetic energy is released corresponding to this speed change and output power temporarily increased. The output power plots of Figures 9(ii) and 10(ii), show the released power by WECS under different schemes. It is depicted clearly that the performance of third control scheme, i.e. proportional controller for inertia response is best amongst the three schemes. However, in proportional-derivative and proportional control schemes, wind turbine is forced to operate away from the maximum power extraction curve.

The quantitative analysis of control schemes is carried out for both the cases, i.e. the grid frequency excursion and load variation in the network, and shown in Tables 1 and 2, respectively.

Table 1. The numerical results for grid frequency excursion.

Control scheme	Energy released (kW-s)	Maximum change in rotor speed (pu)
Without controller	4.6116	-0.00004
Derivative controller	343.0232	-0.00328
Proportional and derivative controller	1808.5318	-0.01648
Proportional controller	3224.4978	-0.03422

Table 2. The numerical results for load variation in the network.

Control scheme	Energy released (kW-s)	Maximum change in rotor speed (pu)
Without controller	18.1426	-0.000211
Derivative controller	32.7468	-0.000318
Proportional and derivative controller	35.2675	-0.000324
Proportional controller	36.5452	-0.000331

The numerical values of energy released and maximum change in rotor speed, shown in the tables, clearly indicate that variable speed WECS equipped with DFIG provides a negligible frequency support without additional supplementary controller. The inclusion of supplementary control in WECS equipped with DFIG to provide the inertial response for frequency support, releases the energy during the frequency drop. It is quantified, that the use of proportional controller scheme in the supplementary control loop gives better inertial response than others during frequency variations.

As the wind turbine operates at its rated power, the torque set point, T_{set_point}, hits its limit. Therefore the torque set point is not affected from the supplementary control loop and thus the turbine does not provide inertia support at this point. If the generator has the capability to produce the output power above the rated value the set point torque limit can be increased. In this way, the wind turbine can provide the inertial support.

During frequency dip and load variation occurs on a network, the network frequency falls rapidly, so it is important that the generators allocated for frequency regulation should remain connected to increase their power output as fast as possible to avoid the network frequency falling below the level that demands load disconnection.

6. OPTIMIZED TUNING OF CONTROL SCHEME

This section presents the optimal design of control scheme to provide frequency support in WECS equipped with DFIG during the system frequency changes. With the fact identified in the previous section that the use of proportional controller scheme in the supplementary control loop gives better inertial response during frequency variations, here the tuning of proportional controller parameter is considered for optimizing the desired performance.

The PSO technique is implemented to tune the controller parameter for minimizing the frequency deviation and maximizing the release of energy. The basic PSO algorithm is described literatures [16], [17].

Application of PSO

The traditional method of tuning doesn't guarantee optimal parameters of the controller. The system nonlinearity causes poor performances of the conventional controllers [16]. The PSO is implemented on a 9 MW WECS equipped with DFIG to tune the frequency support controller parameter for optimizing the desired performance. This method yield optimal parameters and free from the curse of local optimality. The parameter of the PSO, set for this work, is given in the Table 3.

The system is analyzed for frequency support during the load variation in the network. The criterion used to describe the system response includes the change in frequency with time and release of energy. The optimization problem is formulated in the form of objective function for minimizing the frequency deviation with time and maximizing the energy released.

The objective function is formulated in two parts, based on the relationship of the system performance with time. The first part of the objective function represents the frequency deviation with time in the form of integral time absolute error (ITAE). The second part of the objective function is formulated for maximizing the energy released. While the overall objective function has to minimize to attain the desired goal. The weighing factor β can vary from 0 to 1 as per the requirement in Equation 11.

$$\begin{aligned} &ObjectiveFunction = \\ &\beta * f_1 \text{(minimize frequency deviation with time)} \\ &+ (1-\beta)*f_2 \text{(maximize released energy)} \end{aligned} \tag{11}$$

Case Study:

The test system used in this study is same as shown in Figure 8. The performance of the system is analyzed with supplementary proportional controller and PSO tuned controller when the system is subjected to load variation in the network.

Here, the network system frequency variation is introduced by connecting a load of 8 MW through Switch 1 at time t=0.5 sec. This load variation results in frequency drop. The parameter of proportional controller is tuned corresponding to the objective function (Equation 11) for different value of weighting factor β, shown in Table 4.

For the performance evaluation, the initial value of wind turbine is taken corresponding to a wind speed of 10 m/sec. The initial value of DFIG output power is 0.48 pu, T_{sp_ref} is 0.44 pu and rotor speed is 1.09 pu. As the rotor speed is below the maximum permissible speed 1.2 pu, the pitch angle controller is not activated. Figure 11 shows the performance of WECS equipped with DFIG for load variation in terms of frequency drop. The frequency response, power output, reference value of torque and generator rotor speed plots are considered here for comparing the proportional controller in supplementary loop and PSO tuned proportional controller in supplementary loop for $\beta=1$.

Table 3. Swarm configurations of the PSO method.

Swarm parameters	Standard type PSO
Max. number of iterations	100
Number of particles	50
(w_{start}, w_{end})	(0.9, 0.4)
(c_1, c_2)	(2.0, 2.0)

Table 4. PSO tuned controller parameter.

Weighting factor β	1.0	0.9	0.8	0.7	0.6	0.5
PSO tuned controller parameter	11.440	12.342	13.029	14.012	15.143	16.057

7. RESULTS AND DISCUSSION

As illustrated in Figure 11(iv), supplementary control loop serves to drive down the rotor speed over the initial period following loss of generation so that rotor stored energy is released and output power temporarily increased. The network frequency signal is processed in the proposed control scheme to provide the inertial response and a speed reference set point for the torque set point. The torque set point referenced value corresponding to both the control schemes in the supplementary control loop is shown in Figure 11(iii).

For different values of β, the optimum value of the controller parameter is found using PSO. Figure 11 shows the improvement with the PSO tuned controller for $\beta=1$. The output power plots of Figure 11(ii) clearly show the performance of PSO tuned controller for inertia response is good as compared to proportional controller. However, in this scheme the wind turbine is forced to operate away from the maximum power extraction curve.

The quantified comparisons of the two responses corresponding to proportional controller and optimize control scheme with $\beta=1$ for the load variation in the network, are shown in Table 5.

The numerical results of energy released and maximum change in rotor speed, in the Table 5, clearly indicate that variable speed WECS equipped with DFIG provides best results for frequency support when the PSO tuned proportional controller is connected in the supplementary loop. The PSO tuned proportional controller provides better frequency response on the cost of operating away from the maximum power extraction curve.

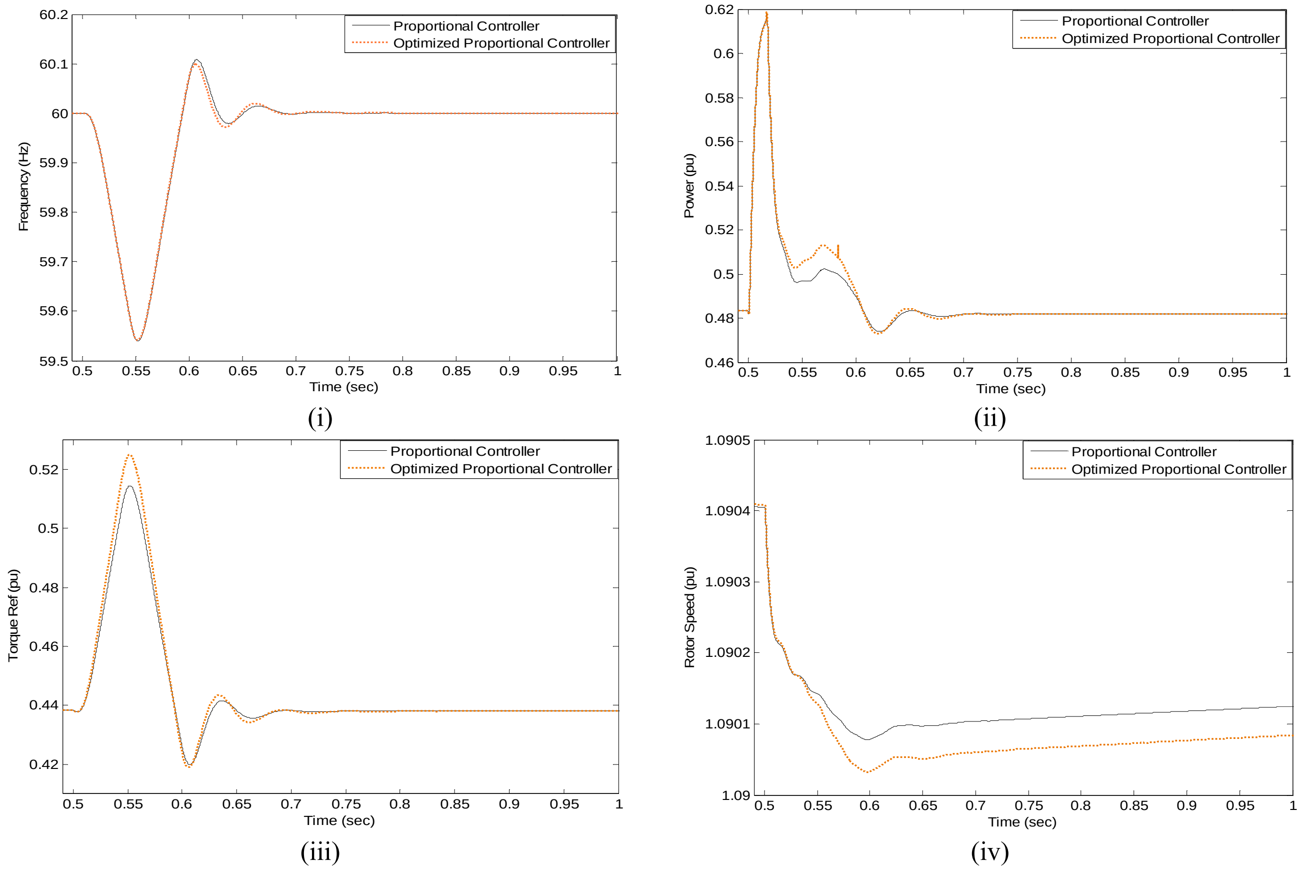

Fig. 11. WECS performance under load variation on power system at time t=0.5 sec (i) frequency response (ii) power output (iii) reference value of torque (iv) generator rotor speed.

Table 5. The numerical results for load variation in the network.

Control scheme	Energy released (kW-s)	Maximum change in rotor speed (pu)
Proportional controller (KP=10)	21.2171	-0.000328
PSO tuned controller (KP=11.44)	25.2879	-0.000376

8. CONCLUSION

With conventional generation, the kinetic energy is released from their rotating mass for change in the system frequency but this is not true in the case of variable speed WECS equipped with DFIG. Thus, if variable speed WECS equipped with DFIG displaces conventional generators, the frequency support inertial response is detrimentally affected. The simulation of 9 MW variable speed WECS equipped with DFIG, with and without additional supplementary control schemes for frequency variation, has been carried out when the system is subjected to the grid frequency excursion and load variation in the network. The addition of the supplementary control loop to the variable speed WECS equipped with DFIG, resulted in the improvement in system frequency response, in terms of the rate of change of the frequency and the maximum frequency variation that occurs, and also for the energy released by the system. Further, the achievable inertial response of the DFIG wind turbine generation is limited by operational constraints of the system. The graphical responses and numerical results demonstrated the capabilities of different control schemes. The responses show that the performance of the proportional control for frequency support is best amongst three control schemes considered here.

This improvement in inertial response depends upon the control scheme used to improve the frequency support and the parameters of the controllers. Hence, the optimization technique PSO is employed to tune the proportional controller parameter for minimizing the frequency deviation with time and maximizing the energy released. The simulation results and numerical results verified the efficacy of the PSO optimized controller.

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APPENDIX

WT-DFIG parameters

Turbine: Each-1.5 MW
base wind speed =12 m/s
base rotational speed (pu of nominal generator speed) =1.2
Coefficients: c1 =0.5176, c2 =116, c3 =0.4, c4 =5, c5 =21 and c6 =0.0068

Generator: Each- Rated Power P =1.67 MVA
Rated Voltage V =575 V
Rated Frequency f =60 Hz
Stator Resistance Rs(pu) =0.00706
Stator Reactance (pu) =0.171
Rotor Resistance (pu) =0.005
Rotor Reactance (pu) =0.156
Mutual Reactance (pu) =2.9
Inertia Constant H(s) =5.04
Friction Coefficient F(pu) =0.01
Pole pairs p =3

Supplementary controller parameters:
Derivative controller $K_D = 10$
Proportional-Derivative controller $K_P = 5$, $K_D = 5$
Proportional controller $K_P = 10$
Optimized Proportional controller $K_P = 11.44$ for $\beta = 1$