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Stability Enhancement of a Wind Turbine Based on Blades Pitch Angle Control using Fractional Order PID Controller

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ABSTRACT

This paper aims to control a fixed speed wind turbine driving three-phase synchronous generator. The generator is directly connected to the utility grid through RL filter and step-up transformer. At normal and abnormal conditions, the blades pitch angle of the turbine is controlled based on sensing the generator frequency to enhance the system stability using fractional order PIλDμ controller (FOPID). The performance of the proposed system is compared using classical Proportional-Integral-Derivative (PID) controller and fractional order PIλDμ controller. Different optimization techniques are used in this work for optimizing the two controllers. The three parameters of the classical PID controller are tuned by Ziegler-Nichols method, in addition to genetic algorithm optimization technique. The five parameters of the fractional order PIλDμ controller are tuned by multi-objective genetic algorithm optimization technique. The performance of the power system will be compared with the two controllers at four different operating conditions: a) at normal operation with constant wind speed b) at sudden changes in wind speed c) at three-phase short circuit for 300 ms at the generator terminals c) at a parameter change (increasing moment of inertia by 20%) . From the simulation results using MATLABTM software, the fractional order PID controller has better improvement in the wind turbine performance than traditional PID controller due to the increasing of two parameters in FOPID controller than classical PID controller. The main contribution of this paper is the controlling of the turbine blades pitch angle based on sensing the generator terminal frequency using well-tuned controller. The generator frequency has a direct relation with the generator speed, so over speed of the generator can be avoided using the proposed technique.

Key words: Wind turbine, synchronous generator, fractional order $PI^{\lambda}D^{\mu}$ controller, multi-objectives genetic algorithm. Blades pitch angle.

1. INTRODUCTION

Wind energy is one of the most promising and popular renewable sources in last years. Wind energy is a clean source of energy, able to replenish quickly, sustainable, and zero-carbon emission [1]. The only drawback of wind energy is the intermittent in nature based on season, site location and weather condition. There has been a continuous research and studies aim to enhance the power generation from renewable energy sources in recent years. For installing any wind farm, different studies and analysis must be done in order to integrate this power plant in the main utility grid [2]. Modeling and simulation of power systems using different software like MATLAB^{TM} and can insure the stability and the secure operation of the power system. Due to the increasing penetration of wind energy in the main grid, the control of the wind energy has become an important issue in development and research of wind power. Traditional power plants comprise synchronous generators driven by hydro, gas or steam turbines [3]. The voltage and frequency of traditional power plants can be controlled and held stable both in transient and steady state operation.

Nowadays, wind energy penetration in power systems increases and replaces more traditional power plants. The bad effect of this penetration of wind energy in power system in the power system stability and [4]. Therefore, the operators of power system with renewable sources must adjust their grid code requirements before connection to the main grid.

Recently, wind turbines were not to contribute to control the power system voltage and frequency, only the wind turbines are disconnect from the main grid when abnormal operating conditions occurred [5]. In this work, the wind turbine is not disconnected from the main grid at any operating conditions. The turbine blades pitch angle is controlled at different operating conditions to insure the system stability and security. In addition, the control system protects the system against over speed after recovering severe faults.

The PID controller is the famous form of feedback in use today in most power systems. Due to its simple function and performance robustness, the proportional-integral-derivative controller has been widely used in load frequency control of different areas and different power sources. Designing and tuning of PID controllers takes many researches and studies since Ziegler and Nichols presented their methods in 1942[6-8].

The non-integer or the so-called fractional-order proportional -integral- derivative (FOPID) controllers have been used in the last years both from academic research and industrial use. FOPID controller provides more flexibility in the controller design, comparing to the classic PID controllers, because they have five parameters to select (instead of three in case of classical PID controller). However, the five parameters of the FOPID also imply that the tuning of the controller can be more complex and take more time and effort. In order to overcome this problem, different methods for the tuning of a FOPID controller have been proposed [9-11]. In this paper, multi-objectives genetic algorithm in MATLAB toolbox is used to determine the optimal five parameters of the controller. Several researchers now are working in order to develop new tuning methods for fractional order PID controllers, by studying the effects of the non-integer order of the derivative and Integral parts in the performance of the controller to be used in different systems as electrical, mathematical, mechanical, and other systems. MATLAB™ software tool box is used in this paper to find out the optimal parameters of classic PID, and FOPID controllers using genetic algorithm and multi-objectives genetic algorithm techniques [12,13].

The fraction order controller form is [14]:

$$G_c(s) = k_p + \frac{k_i}{s^{\lambda}} + k_d\, s^{\mu} \qquad (1)$$

The FOPID controller is more flexible than classical PID controller. Since it has two more fractional values (λ and μ) of the integral part and derivative part respectively. Thus, five parameters can be tuned in this structure (λ; μ; k_p; k_i and k_d), where two more parameters than in the case of a conventional PID controller (λ = 1 and μ = 1). The fractional orders λ and μ can be used to fulfill more specifications of design or other interesting requirements for the controlled system [15, 16].

2. DESIGN STEPS OF FOPID CONTROLLER

For calculating the optimal five unknown parameters (λ; μ; k_p; k_i and k_d) of FOPID as shown in equation (1); there are five steps as follows:

a) Insert the FOPID transfer function in seies with the plant transfer function as shown in Fig. 1.

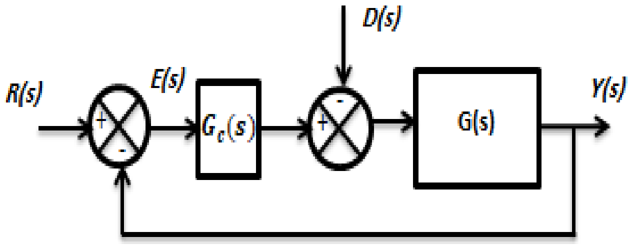

Fig. 1 Closed loop control system

Where :G(s) is the process, $G_c(s)$ is the FOPID controller, R(s) is the reference input, E(s) is the error, D(s) is the disturbance and Y(s) is the output.

b) To Maximize the gain margin to stabilize the system, the gain cross over frequency (ω_{cg}) must be having a specified value using [15, 16].

$$20\log(G_c(w_{cg})G(w_{cg})) = 0db \qquad (2)$$

c) Also for more stability, the phase margin φ_m must be maximized using:

$$-\prod + \varphi_m = \arg(G_c(w_{cg})G(w_{cg})) \qquad (3)$$

d) For rejecting the high-frequency noise, the closed loop transfer function must have a small magnitude at specified frequency ω_h to be less than specified gain H.

$$\left| \frac{G_c(w_h)G\ (w_h)}{1+G_c(w_h)G\ (w_h)} \right| < H \qquad (4)$$

e) For eliminating the steady-state error, let $0 < \lambda < 1$.

f) For rejecting the disturbances in, the sensitivity function must have a small magnitude at low frequencies w_l, its magnitude must be less than some specified gain N:

$$\left|\frac{1}{1+G_c(w_l)G(w_l)}\right| < N \qquad (5)$$

g) For robustness of the controller, the phase angle of the open-loop transfer function must be constant at the gain-crossover frequency using:

$$\frac{d}{dw}angle[G_c(w_{cg})G(w_{cg})] = 0 \qquad (6)$$

From the specifications mentioned above, a set of five nonlinear equations (2, 3, 4, 5 and 6) with five unknown parameters (λ; μ; kp; kd and ki) are obtained. Thus, there are two methods to solve this set of equations the first one is Ziegler and Nichols which isn't accurate enough and can't reach zero steady state condition and the other method is done using multi-objectives genetic algorithm. Genetic Algorithm (GA) is a powerful optimization technique that base on natural selection [17]. Genetic Algorithm is used for searching global optimum of a given objective function like cost, losses, error and performance index.

In this work GA is used for optimizing both the classical PID controller and the FOPID controller of the five parameters (λ , μ , K_p, k_i, k_d) to eliminate the steady-state error and reducing the system overshoots [18].

3. MODELING OF THE PROPOSED SYSTEM

Wind energy system is a complex system that converting energy comes from wind to rotational energy using turbine blades and then to electrical energy using generator. As in Fig.2, the proposed system comprises a wind turbine diving three-phase synchronous generator. The synchronous generator is directly connected to the main grid through RL filter and step-up transformer. By measuring the frequency the power system, the turbine blades can be controller using the proposed FOPID controller at different operating conditions. Since in synchronous machine, the frequency and speed are directly related, the controller is used also in protecting the machine from damage against over speed.

The output power or torque of a wind turbine is determined by several factors like; wind velocity, size and shape of the turbine, etc. A dynamic model of the wind turbine, involving these parameters, is required to understand the behavior of a wind turbine over its region of operation. By studying its modeling, it is possible to control a wind turbine's performance to meet a desired operational characteristic.

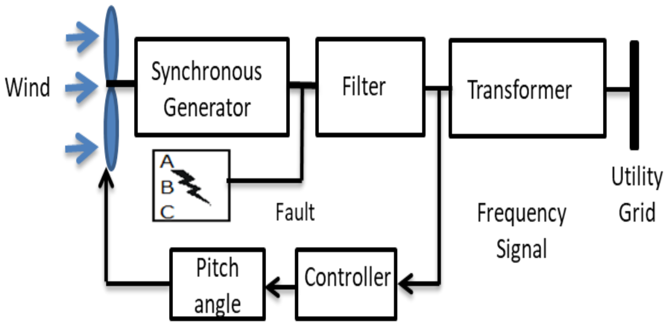

Fig. 2 Block diagram of the proposed system

The conversion of the wind power to mechanical power by the wind turbine rotor can be simulated by the static relation [19]:

$$P_w = \frac{1}{2}\rho C_p(\beta, \lambda_i)AV_w^3 \qquad (7)$$

Where:

P_w is the rotor mechanical power (W)
V_w is the wind speed at the center of the rotor (m/s)
$A=\pi R^2$ is the rotor surface (m^2), and R is the rotor radius (m)
ρ is the air density (kg/m^3) and,
And C_p is the rotor aerodynamic power coefficient.

The rotor mechanical torque can be calculated from Pw by

$$T_w = \frac{P_w}{\omega_R} \qquad (8)$$

Where ωR is the rotor angular velocity, in rad/sec.

The rotor aerodynamic power coefficient, C_p, is the percentage of the kinetic energy of the incident air mass that is converted to mechanical energy by the rotor, and it is expressed as follow [3]:

$$C_p = C_p(\beta, \lambda_i) \qquad (9)$$

Where:

$$\lambda_i = \frac{1}{\frac{1}{(\lambda + 0.08\beta)} - \frac{0.035}{(\beta^3 + 1)}} \tag{10}$$

Where λ is the tip speed ratio of the blades if the pitch angle of the blades is constant and defined as

$$\lambda = \frac{R\omega_R}{V_w} \tag{11}$$

Considering the torque coefficient Ct(λ), the wind turbine mechanical torque is given by:

$$T_w = \frac{1}{2}\rho R^3 V_w^2 C_t(\beta, \lambda_i) \tag{12}$$

$$C_p(\beta, \lambda_i) = \lambda C_t(\beta, \lambda_i) \tag{13}$$

The following table shows the main parameters of the proposed wind turbine in this work.

Table -1 Typical parameters for 0.5 MW wind turbine

The rotor mechanical power [MW]	0.5
The rotor blade radius [m]	17
The rotor angular speed [rad/sec]	4.5
The air density [kg/m^3]	1.225
The rated wind speed [m/sec]	13
Cut-off wind speed [m/sec]	5
Number of rotor blades	3

Fig. 3 shows the wind turbine model that build using MATLAB™ software.

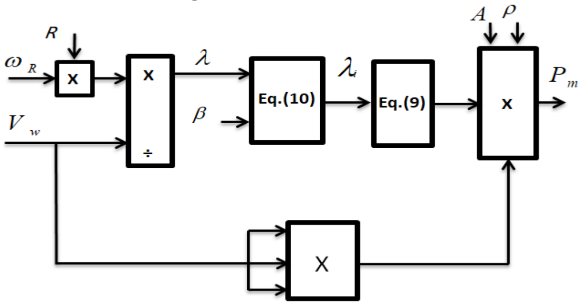

Fig. 3 Wind turbine model.

Fig. 4 displays the relation between the power coefficient C_p and the tip speed ratio, it can be seen from the figure that the maximum power coefficient is 0.44 and the optimum tip speed ratio is 5.8, these values depend on the wind speed and the turbine design.

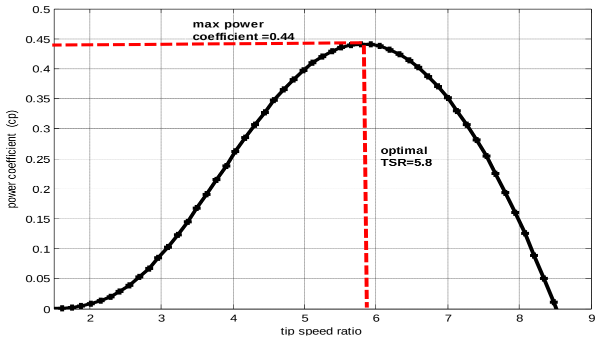

Fig. 4 Performance curve for a modern three blades wind turbine.

4. THE CONTROLLERS TUNING TECHNIQUES

At first, the classical PID controller is tuned using Ziegler and Nichols method, the tuned controller gains are: k_p= 652, k_i=740 and k_d=99. The controller transfer function becomes:

$$G_c(s) = 652 + \frac{740}{s} + 99s$$

By using genetic algorithm optimization in MATLAB toolbox, the optimal parameters of the classical PID controller k_p=413 , k_i=0.32 and k_d=0.56. The controller transfer function becomes:

$$G_c(s) = 413 + \frac{0.32}{s} + 0.56\,s$$

Finally when using the multi-objective genetic algorithm in MATLAB™ toolbox with the fractional order $PI^{\lambda}D^{\mu}$ controller , the optimal parameters of the controller are: k_p=898 , k_i=1.6 , k_d= 2.97 , λ=0.96 and μ= 0.88 . The controller transfer function becomes:

$$G_c(s) = 898 + \frac{1.6}{s^{0.96}} + 2.97\,s^{0.88}$$

5. SIMULATION RESULTS

The power system performance will be tested with using the two controllers and the three different optimization techniques at different operating cases as shown in the next subsections.

A) PERFORMANCE OF THE WIND SYSTEM AT CONSTANT AND STEP CHANGE IN WIND SPEED

At constant wind speed of 16 m/sec as shown in Fig.5 (a), the performance of the power system will be tested with the PID controller tuned by Ziegler-Nichols, genetic algorithm , and fractional order controller. The PID controller is used to control the turbine blades pitch angle as seen in Fig.4.b. Fig.6 shows the wind farm active and reactive power, and Fig.7 displays the frequency at the generator terminals. It can be noticed that the wind farm performance is best in case of using FOPID controller, where the oscillations in power and frequency are reduced and the steady-state error is minimized.

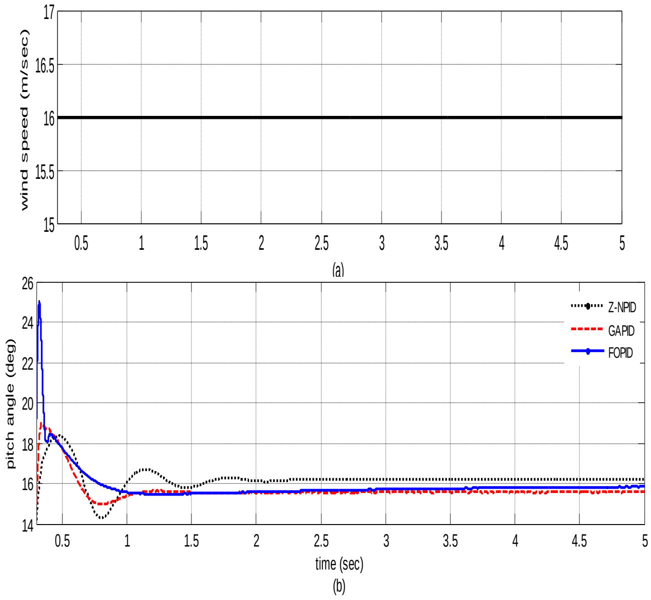

Fig. 5 (a) Wind speed (b) blades pitch angle

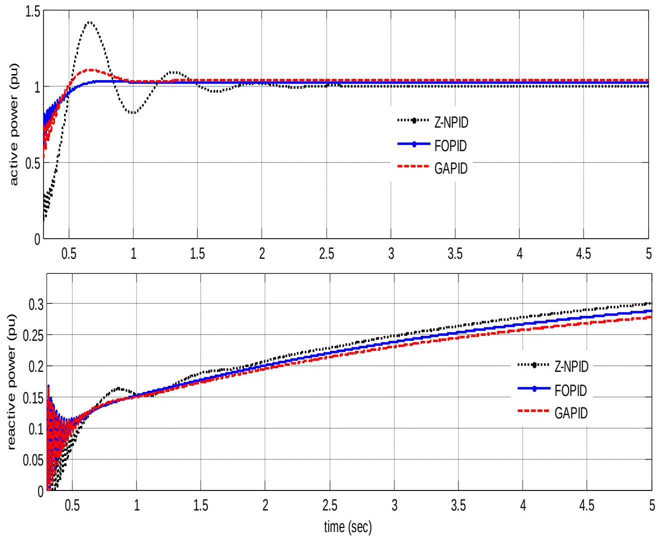

Fig. 6 Active and reactive power of the wind farm at constant wind speed

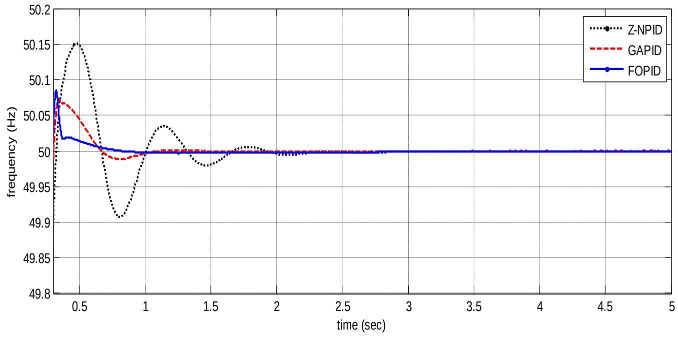

Fig. 7 Generator frequency at constant wind speed

The performance of the wind farm and the robustness of the PID controller will be cheeked when the wind speed is suddenly stepped down from 16 m/sec to 8 m/sec and suddenly stepped back to 16 m/sec as shown in Fig. 8.

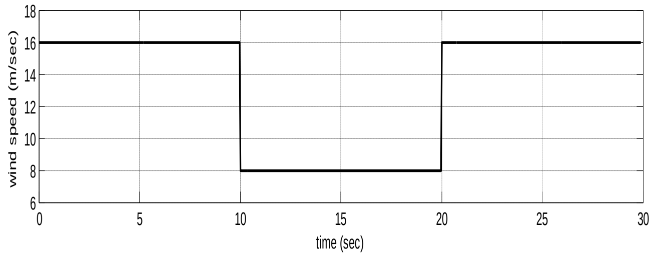

Fig. 8 Step change in wind speed.

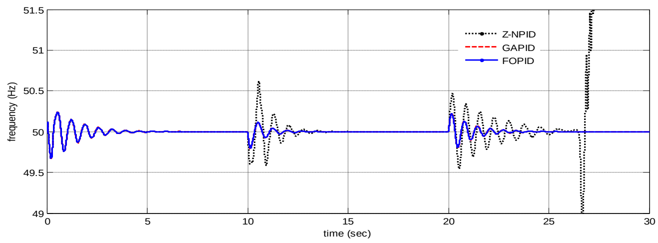

Fig. 9 Generator frequency at step change in wind speed

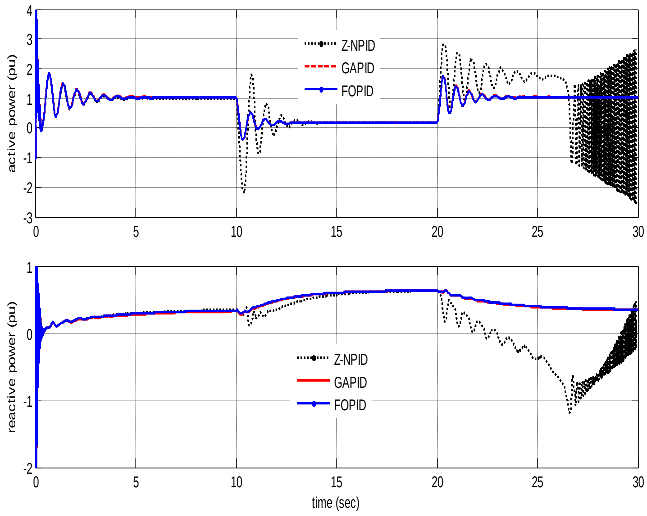

Fig.10 Active and reactive power of the wind farm at step change in wind speed

It can be seen from Fig. 8 and Fig. 9 that the wind farm becomes unstable with the PID controller tuned by Ziegler and Nichols method, but still stable with better performance in case of GAPID controller and FOPID controller.

B. PERFORMANCE OF THE WINDSYSTEM AT THREE-PHASE SHORT CIRCUIT AT THE GENERATOR TERMINALS

The three-phase short circuit is the most severe fault and may lead the power system to instability, i.e. the grid cannot supply enough reactive power to let the voltage recover quickly and hence suppress the oscillations.

Since the rotor in the synchronous generator rotates synchronously with the stator field, the rotor speed is the same as the electrical frequency. Hence, rotor speed oscillations are grid frequency oscillations, which have to be dampened during faults before the whole system becomes unstable [20]. In a conventional power plant, SG equipped with power system stabilizers dampens these oscillations. In this work the designed controller is used to control the pitch angle of the wind turbine pre-and after fault occurrences [21,22].

In this case the performance of the wind farm and the robustness of the designed controller will be cheeked when a three-phase short circuit for 300msec at generator terminals is occurred and naturally cleared.

It can be seen from Fig.11 and Fig.12 that the wind farm becomes unstable with the PID controller tuned by Ziegler and Nichols method, but still stable with better performance with GAPID controller. The performance of the wind farm with the FOPID controller is the best where the system is stable, fast response and minimum steady-state error.

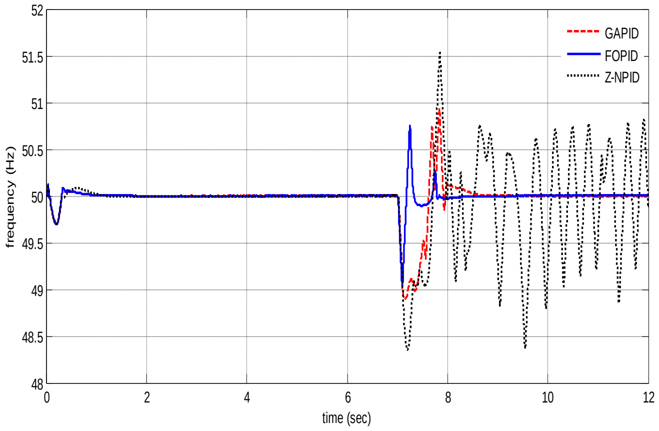

Fig.11 Generator frequency in case of three-phase short circuit at generator terminals

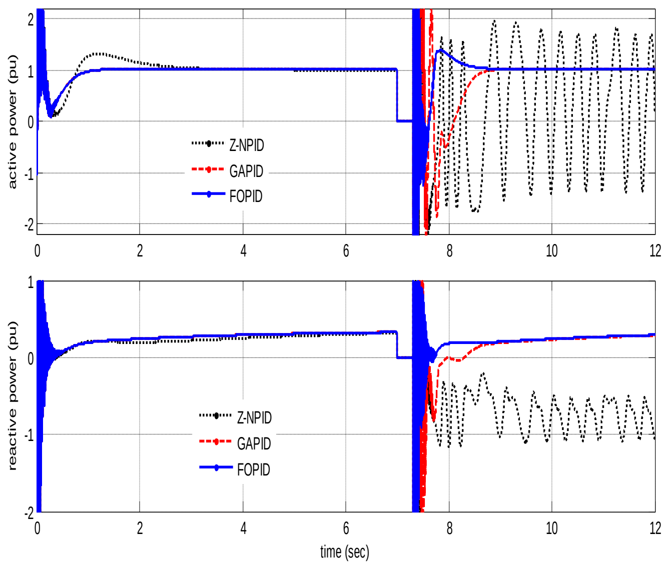

Fig.12 Active and reactive power of the wind farm in case of three-phase short circuit at generator terminals

C. PERFORMANCE OF THE WIND SYSTEM AT INCREASING THE MOMENT OF INERTIA BY 20%

In this case the performance of the wind farm and the robustness of the designed controller will be cheeked when a moment of inertia of wind turbine and the synchronous generator together increased by 20%. It can be seen from Fig.13 the generator frequency has a large oscillations and long settling time in case of Z-NPID. The performance becomes better in case of GAPID and the best in case of using FOPID. GAPID controller. The performance of the wind farm with the FOPID controller is the best where the system is stable, fast response and minimum steady-state error.

Fig.14 displays the wind farm active and reactive power (in pu); in this case, the best performance (minimum overshoot, short settling time, and minimum steady-state error) is done when using the FOPID controller.

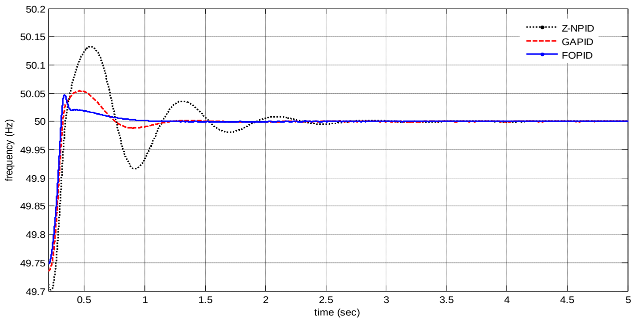

Fig.13 Generator frequency at 20% increasing in system moment of inertia

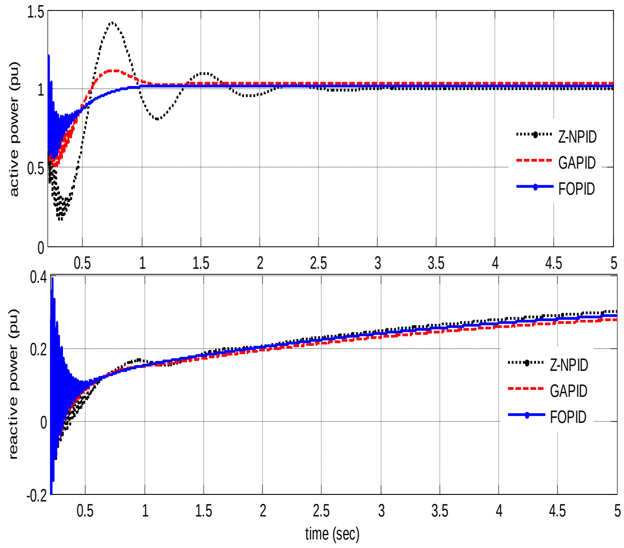

Fig.14 Active and reactive power of the wind farm at 20% increasing in system moment of inertia

6. CONCLUSION

In this paper, fractional order proportional integral derivative (FOPID) controller was designed for controlling a wind farm at normal and abnormal conditions by controlling the turbine blades pitch angle. The designed fractional order proportional integral derivative (FOPID) controller can provide better results as compared with the traditional PID controller in simulation. The FOPID controller was designed following a set of imposed tuning constraints, which can guarantee the desired control performance and the robustness of the designed controllers to the loop gain variations. From the simulation results, it is observed that the designed fractional order PID controller works efficiently.

The FOPID gives much better system performance than conventional PID due to controlling two more parameters beside the three which are found in conventional one. This performance achieved by reaching zero steady state error faster than the conventional one with very small settling time, and very small overshoot which means a lot when used this in power system. The proposed controller succeeded in protecting the synchronous generator against over speed and achieved the system stability after sever faulted conditions.

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