Performance analysis of DFIG with PI, PID and FOPID control schemes in Micro grid

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Abstract: Doubly Fed Induction Generator (DFIG) is the most popular variable speed wind energy conversion system. Control of the DFIG is more complicated than the control of a standard Induction motor. To control the DFIG, the rotor current is controlled by a power electronics converter. This paper aims to analyze the performance improvement of DFIG with its controllers such as proportional integral, proportional integral derivative and fractional order proportional integral derivative controllers in micro grid. Design and implementation of these controllers are done in the rotor circuit of DFIG by MATLAB simulation tool. The design, analysis, and MATLAB simulation of a constant grid power wind energy conversion system also discussed. In all abnormal conditions, the required reactive power into the grid is taken care by the horizontal axis wind turbine system. Mathematical modeling of DFIG is addressed. Independent control of active and reactive powers is achieved, and different simulation results under loaded conditions, with variation in prime mover speed and Excitation are presented. The simulation results of the proposed system are discussed with the cases such as transient, post transient conditions, variation of wind speed, fluctuation of electromagnetic torque, active and reactive powers, grid voltage and load contribution of DFIG with its controllers in grid. Based on the extensive simulation results, what type of control scheme gives the effective performance of DFIG in grid is finally concluded. The performances of PID and FOPID controllers are compared with that of PI controller at the end. It is seen that, the closed loop performance of FOPID controller outperforms as compared to conventional controllers.

Keywords: DFIG, PI, PID, FOPID, Complementary sensitivity, Direct Synthesis method

1. Introduction

In the present scenario, requirement of electrical energy is very high, the power generations of existing systems are inadequate to fulfill the demand (**Pratyusha Biswas Deb. 2016- Du. C.L.V.W. et.al. 2015**). Nonconventional energy sources are one among the few options left to meet the supply without exploiting (**Manisha Pal et.al. 2014**) the resources. Wind energy is one of the popular renewable energy sources, which can be obtained from a wind turbine. The mechanical energy produced is fed to a generator using a gearbox and coupling systems. DC Generators are less preferred as compared to AC Generators because it can directly feed to the available grid. To maintain constant wind speed in a wind driven power generation systems, the conventional synchronous generator is not suitable as it cannot maintain synchronism in various loading conditions (**Harmeet Singh Aulakh et. al. 2014- Arun Kumar Datta. 2014**). Therefore, a Doubly Fed Induction Generator (DFIG) can be used for Alternating Current (AC) generation (**Ahmad M. Alkandari et. al. 2011**) where the frequency of the generated voltage is dependent on the speed of the rotor. If the frequency of generated voltage and that of grid are mismatch, then it needs to equalize using power electronic devices before directly feeding to the grid (**Chitti Babu B. et. al. 2009- Amir OstadiY. R. V. et. al. 2009**). Power system stability due to wind power generation system was limited till recent years. By disconnecting major wind farms (**Roberto CardenasS. A. et. al. 2013**) from the grid may result ininstability of the power system. As the wind energy generation is increasing rapidly, reactive power should be maintained within the limit by wind turbines in both steady state as well as transient conditions. Power system deregulation plays an important role for the wind farms to stay connected to the grid during any abnormal conditions by establishing a special regulation and added to the grid codes that specify the number of requirements (**YangH. G. G. 2009- KayikcM. et. al. 2007**). As such, Wind Energy as a reliable source of renewable energy is gaining popularity and interest to bridge the gap of power mismatch [24] and economic factors. Considering various factors like reduced cost, reliability, robust construction, optimal maintenance and for erratic speed operations with a lower rated power converter, DFIGs are commonly used for electromagnetic (**Chen LuH. C. L. 2012- XuW. C. L. 1995**) conversion. DFIG is the best suited variable speed wind generator for high power [14] wind farms. According to the present requirements, wind turbines (**TedN. M. et. al. 2007**) should remain connected and actively support the grid during faults. This requirement became essential because the contribution of power generated by a wind farm can be significant. Earlier, wind turbines were simply disconnected from the grid during faulty condition and reconnected when the fault was cleared, and the voltage returned to normal condition. To model back-to-back Pulse Width Modulation converters, assume ideal and constant DC link voltage between the converters (**MullerR. D. D. S. et. al. 2002**). Consequently, depending on the converter control, a controllable voltage (or current) source can be implemented to represent the operation of the rotor-side of the converter (**Francois BonnetP.E. V. et. al. 2007 - AbadI. P. et. al. 2010**) in the model.

In this paper, ratio of the reactive power to capacitor voltage is considered to find the dynamics of the system using model identification toolbox in MATLAB. The higher order dynamics of DFIG is reduced to two unstable poles with a right half zero using MATLAB/Simulink environment. Simple control methods are developed for all critical conditions of DFIG system. A simple PI controller is designed using complementary sensitivity function. PID controller is designed using direct synthesis method and the parameters of FOPID controller is obtained from Grey Wolf Optimization (GWO) algorithm.

In section 2, the block diagram and Simulink model of DFIG are discussed. Next, Mathematical model of DFIG is explained in section 3. The design of controllers is presented in section 4. Simulation results are provided in section 5. Eventually, the paper ends with the conclusions.

2.Simulink model of DFIG with PI or PID or FOPID controller

The stator of the asynchronous machine is connected directly to the grid, that is, to the supply. In this model, the rotor of the asynchronous machine is integrated with the DC machine. At a different speed of the DC machine, the rotor side converter acts as an inverter or rectifier. The same operation will take place in the grid side converter. Different DFIG speeds are obtained using a prime mover (DC machine) at different speeds using the armature voltage control method. The capacitor bank is connected to the stator terminals of the input machine to provide the magnetic field of operation of the machine.In open loop model of DFIG, the frequency of the systematic power source is set manually so that the EMFs that cause the stator have a frequency equal to the supply frequency (50Hz) at different wind speeds. It is difficult to determine which frequency supply stator voltages will be available at 50Hz frequency.

So, to overcome this, the voltage supplied to the rotor with frequency f must be adjusted continuously until the frequency of the stator side voltages is 50 Hz. This is achieved using an inverter, designed using MOSFET switches; The pulses of these variables are supplied using a PWM generator, the pulses of which are controlled by providing a reference signal with an f frequency and an internal carrier wave (triangular wave) of approximately 1080 Hz.When a sudden inductive load is thrown into the micro grid, the voltage across the grid decreases due to active power drawing. This active power will be compensated, and DFIG achieves this. In this model, an additional load is added to the grid, and after some time, DFIG is connected, and different effects are introduced.

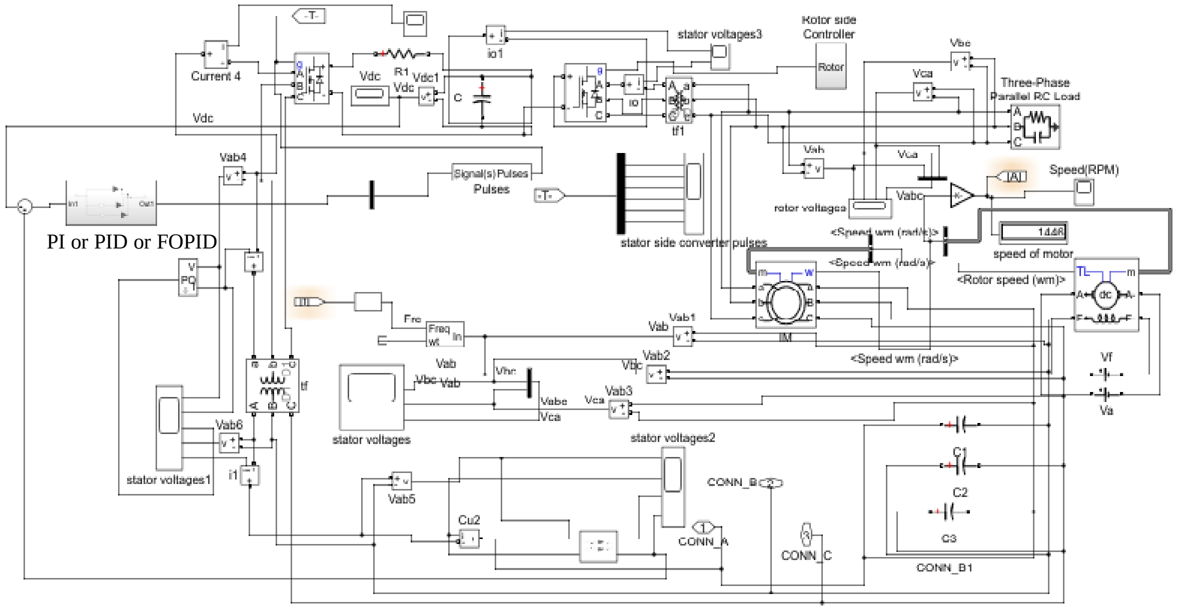

Figure. 1 Simulink model of DFIG connected to grid with PI or PID or FOPID controller

Simulink model of DFIG connected to grid with PI or PID or FOPID controller is shown in Figure. 1. To improve performance the DFIG system, different controllers are introduced between capacitor voltage and reactive power.

3.Mathematical Modelling of DFIG

All the equations (stator & rotor) discussed in this article are with respect to stator reference frame only. Voltage and Flux of Stator can be represented as

$$\left.\begin{aligned}\vec{V}_S &= R_S\vec{I}_S + \frac{d\vec{\psi}_S}{dt}\\ \vec{\psi}_S &= L_S\vec{I}_S + L_m\vec{I}_r\end{aligned}\right\} \tag{1}$$

Voltage and Flux of Rotor can be represented as

$$\left.\begin{aligned}\vec{V}_r &= R_r\vec{I}_r + \frac{d\vec{\psi}_r}{dt} - j\omega_m\vec{\psi}_r\\ \vec{\psi}_r &= L_r\vec{I}_r + L_m\vec{I}_s\end{aligned}\right\} \tag{2}$$

From equation (1) & (2)

$$\frac{d\vec{I}_S}{dt} = \frac{1}{L_rL_S - L_m^2}\left\{L_r\vec{V}_S - \left(L_rR_S + j\omega_mL_m^2\right)\vec{I}_S - L_m\left(\vec{V}_r + (j\omega_mL_r - R_r)\vec{I}_r\right)\right\} \tag{3}$$

$$\frac{d\vec{I}_r}{dt} = \frac{1}{L_rL_S - L_m^2}\left\{L_s\vec{V}_r - \left(R_r - j\omega_mL_r\right)\vec{I}_rL_s - L_m\left(\vec{V}_s + (j\omega_mL_s + R_s)\vec{I}_r\right)\right\} \tag{4}$$

Rotor Voltage of DFIG

$$V_r = R_r\vec{I}_r + sj\omega_sL_{\sigma r}\vec{I}_r + sj\omega_sL_m\left(\vec{I}_r + \vec{I}_s\right) \tag{5}$$

Stator Voltage of DFIG

$$V_s = R_s\vec{I}_s + sj\omega_sL_{\sigma s}\vec{I}_s + sj\omega_sL_m\left(\vec{I}_r + \vec{I}_s\right) \tag{6}$$

where $s = \omega_s - \omega_m / \omega_m$

Stator Active Power is $P_s = \frac{3}{2}\mathrm{Re}\left(\vec{V}_s * \vec{I}_s^*\right)$ (7)

Rotor Active Power is $P_r = \frac{3}{2}\mathrm{Re}\left(\vec{V}_r * \vec{I}_r^*\right)$ (8)

4.Controllers Design

4.1 PI Controller Design

The entire system of DFIG can be reduced to a single loop control system. Consider a single loop control scheme as shown in Figure. 2 where input is capacitor voltage and output is reactive power.

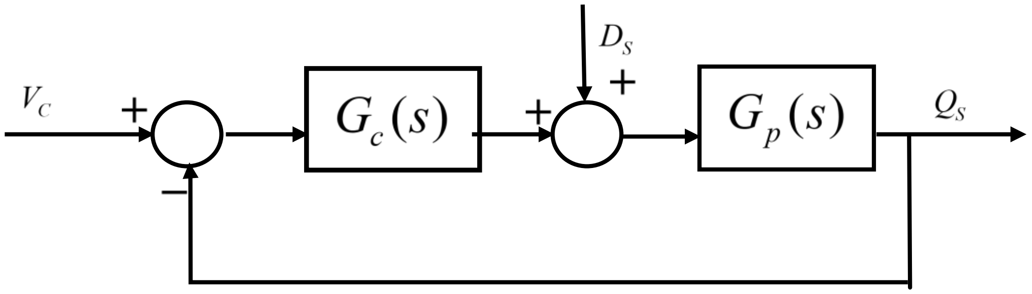

Figure. 2. Block diagram representation of Control scheme

$$G_p(s) = \frac{K(s-z)}{(\tau_1 s - 1)(\tau_2 s - 1)} \tag{9}$$

$G_p(s)$ is second order DFIG system with two unstable poles and a right half plane zero. Where *K* is the gain, τ_1 and τ_2 are the time constants, z is right half plane zero.

The complementary sensitivity function (**Padhan D.G. et. al. 2013**) of the loop for set point or disturbance rejection is given by

$$T(s) = \frac{G_c(s)G_p(s)}{1+G_c(s)G_p(s)} \tag{10}$$

The following condition should be satisfied in order to track the input signal or reject step load disturbances injected into the secondary process input.

$$\lim_{s\to 1/\tau_1, 1/\tau_2} \left(1 - T(s)\right) = 0 \tag{11}$$

According to robust IMC theory, the desired closed loop complementary sensitivity function is proposed as

$$T(s) = \frac{\beta_2 s^2 + \beta_1 s + 1}{\left(\lambda s + 1\right)^4} \tag{12}$$

Where λ is the tuning parameter to achieve satisfactory closed loop performances.

The controller $G_c(s)$ is considered as PI controller, given as

$$G_c(s) = G_{pi}(\mathrm{s}) = K_p + \frac{K_i}{s} \tag{13}$$

After doing a simple calculation, the parameters of PI controller are obtained as

$$K_p = \frac{\beta_1 - (\tau_1 + \tau_2)}{K\left(\beta_1 z - 4\lambda z\right)} \tag{14}$$

$$K_i = \frac{1}{K(\beta_1 z - 4\lambda z)} \tag{15}$$

The main requirement for the selection of the tuning parameter λ. It is selected in such a way that the proposed PI controller provides good performance in nominal and system parameter perturbation cases. By comparison, the value of the tuning parameter that provides optimal control performance is selected between the range 0.4 to 1.9.

4.2 PID Controller Design

The PID control structure is considered as

$$G_c(\mathrm{s}) = G_{pid}(s) = K_c\left(1 + \frac{1}{T_i s} + T_d s\right) \tag{16}$$

The parameters K_c, T_i and $\mathrm{T_d}$ are obtained using direct synthesis approach.

From Figure 2, the closed-loop transfer function for the loop is

$$\frac{Q_s}{V_c} = \frac{G_{pid}(s)G_p(s)}{1+G_{pid}(s)G_p(s)} \tag{17}$$

Using direct synthesis method (**Seshagiri Rao A. et. al. 2009**), the desired closed loop response is specified and the corresponding PIDcontroller is obtained.

Hence equation (17) gives

$$G_{pid}(s)=\frac{1}{G_p(s)}\frac{1}{\dfrac{1}{\left(Q_s/V_c\right)_{desired}}-1} \tag{18}$$

Choosing the desired closed loop dynamics as

$$\left(\frac{Q_s}{V_c}\right)_{desired}=\frac{1}{\beta_c s+1} \tag{19}$$

Where β_c is the closed loop tuning parameter. Thus,

$$G_{pid}(s)=\frac{(\tau_1 s-1)(\tau_2 s-1)}{K(\mathrm{s-z})(\beta_c s+1)} \tag{20}$$

After simplification, the following PID controller parameters were obtained

$$\left.\begin{aligned} K_c &= \frac{0.5(\tau_1+\tau_2)}{Kz} \\ T_i &= (\tau_1+\tau_2)\beta_c \\ T_d &= \frac{\tau_1\tau_2}{\tau_1+\tau_2} \end{aligned}\right\} \tag{21}$$

4.3FOPID Controller Design

The transfer function of the proposed FOPID controller can be described as follows:

$$G_c(s)=K_p+\frac{K_i}{s^{\lambda}}+K_d s^{\mu} \tag{22}$$

Gray Wolf Optimization (GWO) Algorithm is used to obtain the parameters of FOPID for satisfactory DFIG control.The gray wolf optimizer is a meta-heuristicalgorithm, and the wolves belong to the Canidae family asmentioned in (**S. Mirjalili et.al.2010**). A fascinating history ofwolves search for their prey for survival, it depends on the strength of thewolf. The strong wolf has morechances of survival. They usually hunt by group size5-12 wolves. The chances of catching the prey depend on itat the wolf level. Hunting process in GWOalgorithm follows the sequence level accordinglyof wolves. The highest level is assigned to the leader ofgroup represented as alpha (α) Next levelof the wolf represented beta (β)ruling less than a leader. This is the third level. The delta (δ)wolf plays a prominent role during the search process as it isencourages other wolves to follow an inclusive leader.Some wolves share the final level of the classknown as omega (ω), and its movement toward animalsdepending on the location of the above positions. Social hierarchy and pseudo codes of GWO algorithm can be found in (**Bhavandla Bhanupradeep et. al. 2020**).

5.Simulation Results

The waveforms shown in Figure. 3 represent the dc output voltage across dc link.

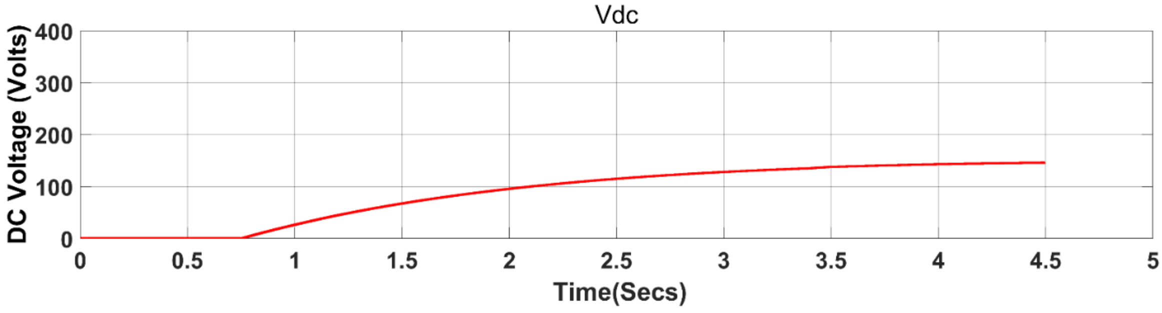

Figure. 3 DC output voltage

The waveforms shown in Figure. 4 represent the active power and reactive power of grid and DFIG when the loadis added.

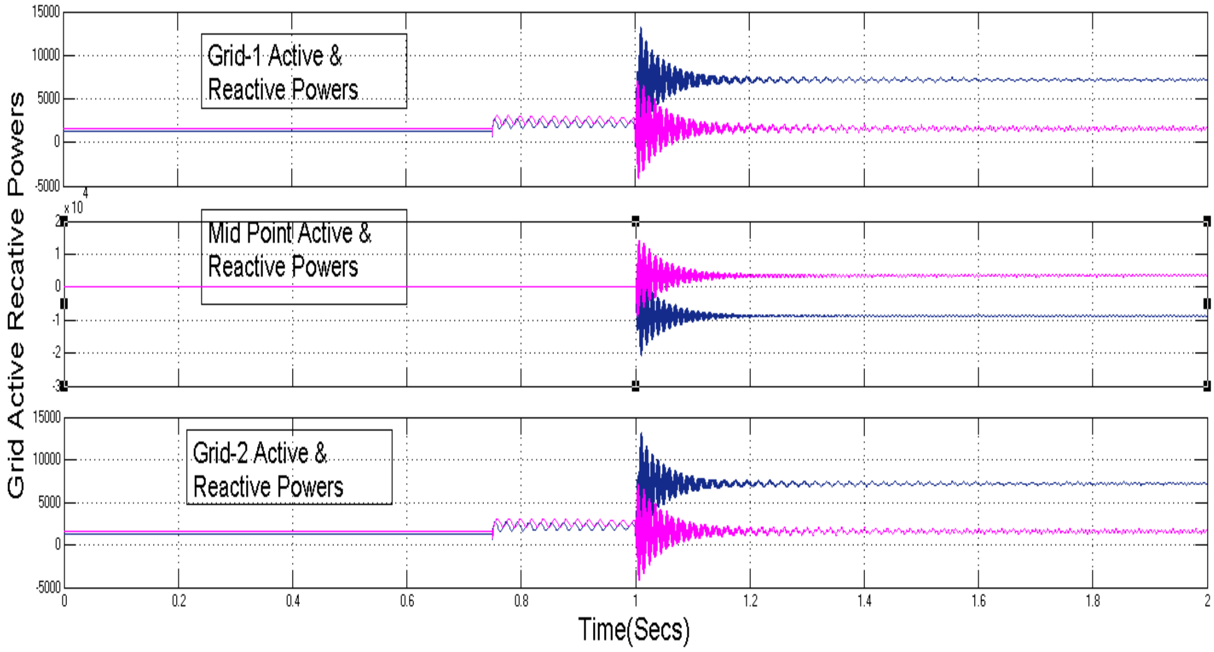

Figure. 4 Active and Reactive power grid and DFIG without controllers

The specifications for DFIG system are given by

f=50 Hz, J=0.05 kg m^2, R_s=50 Ω, L_s=0.00589 H, $X_m=2\pi f L_m = 2\pi\times50\times0.1722 = 54.07$ Ω, L_m= 0.1722 H, R_r= 45 Ω, L_r= 0.005839 H, R_g= 0.0001 Ω, L_g=0.0006 H, $X_g= 2\pi\times50\times0.0006 =0.1884$ Ω, $C_{dc} = 1\times 10^{-2}$ F, V_s=440 V RMS, V_r=180 V, V_{dc}=45 V, i_{qs}=0.8 A, i_{ds}=1.95 A, i_{qr}=0.09 A, i_{dr}=0.155 A, i_{qg}=1.76 A, i_{dg}=1.481 A, V_{qr}=97 V, V_{dr}=151.6 V, V_{qg}=230.56 V, V_{dg}=374.75 V, V_{qs}=245 V, V_{ds}=365.48 V, L_{ss}= 0.17809 H, L_{rr}= 0.17839 H, $\omega_s=2\pi f = 2\pi\times50 =$ 314 rad/sec

The proposed controller settings of PI controller are obtained as: $K_p = 4.382$, $K_i = 32.26$.
The proposed controller settings of PID controller are obtained as: $K_c = 220.44$, $T_i = 12.59$, $T_d = 5.33$. And the proposed controller settings of FOPID controller is obtained as: $K_p = 190.16$, $K_i = 49.97$, $K_d = 2.28$, $\lambda = 1.27$ and $\mu = 0.98$

Active and Reactive power grid and DFIG with PI controller is shown in Figure. 5.

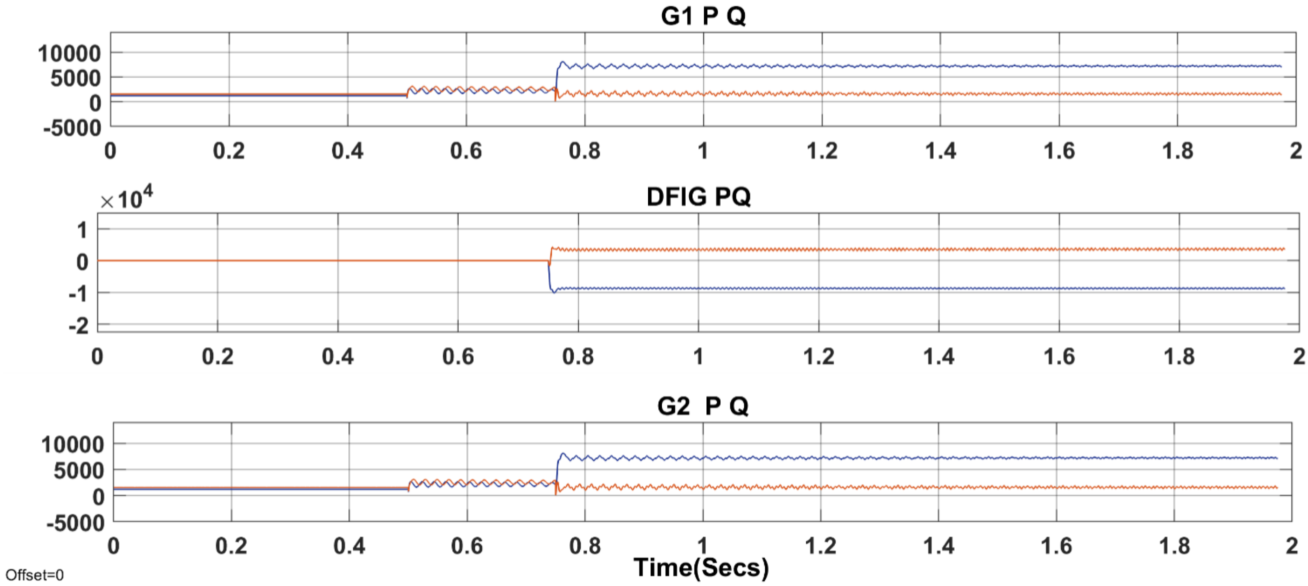

Figure. 5 Active and Reactive power grid and DFIG with PI controller

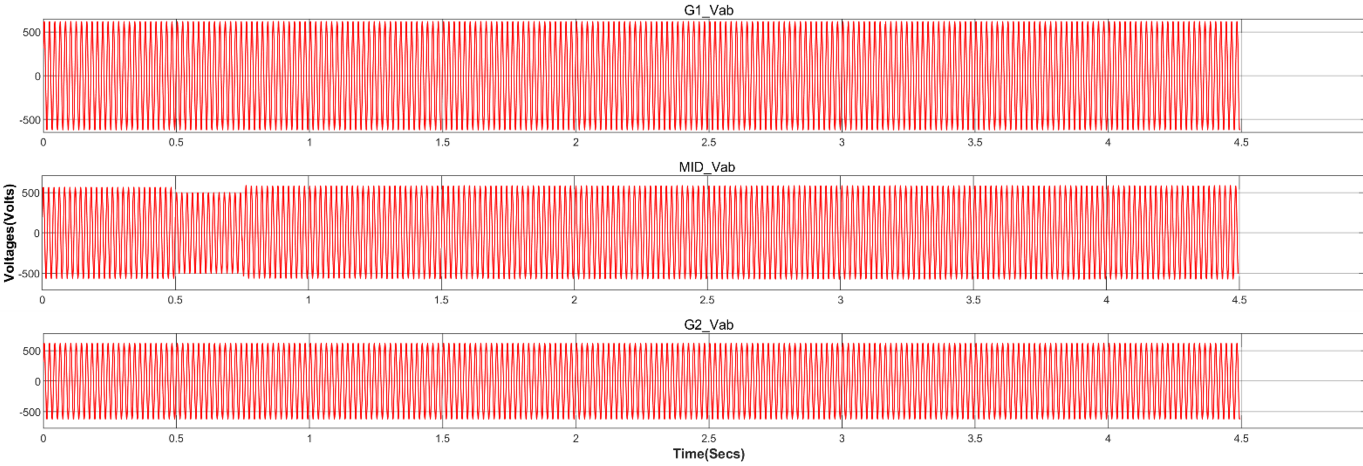

Figure. 6. Grid side voltages with PI, PID and FOPID controllers

Grid side voltages with PI, PID and FOPID controllers are shown in Figure. 6.

Apparent power generated below synchronous speed and above synchronous speed using PI controller are shown in Figure. 7 and Figure. 8 respectively.

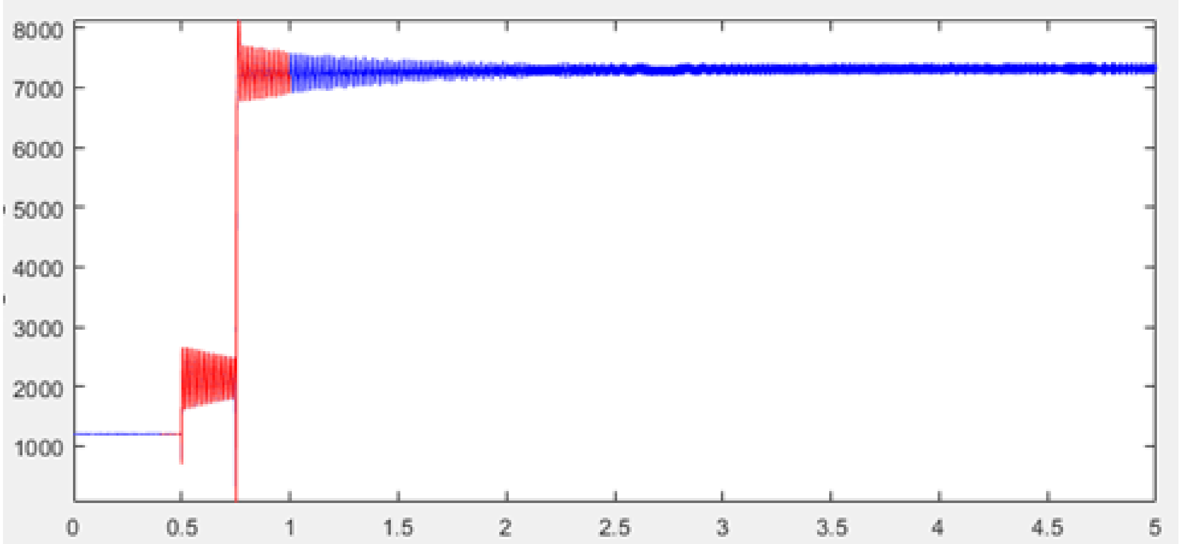

Figure. 7 Power generated using PI controller at 1400 RPM

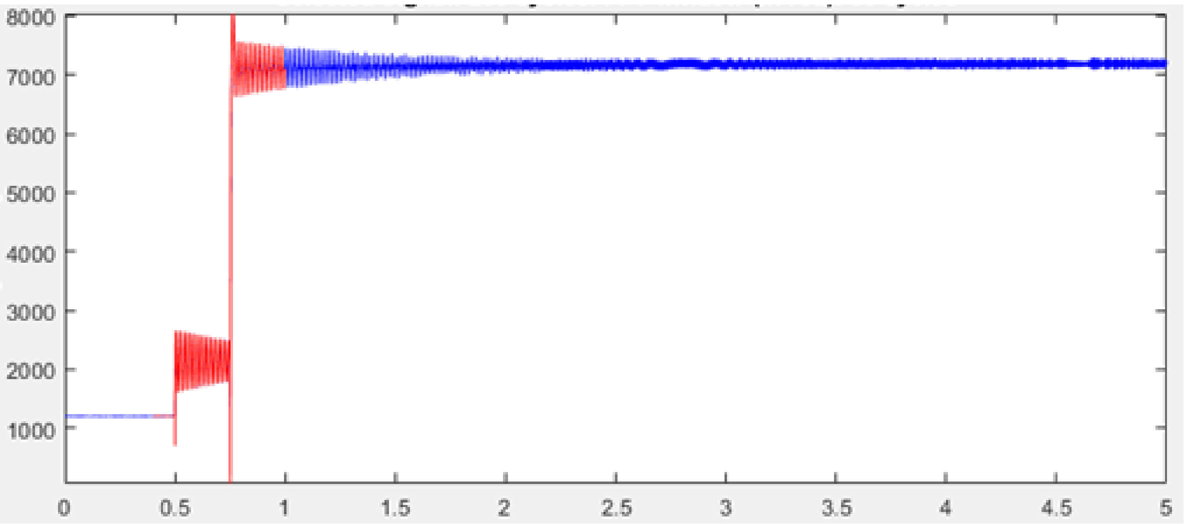

Figure. 8 Power generated using PI controller at 1700 RPM

Apparent power generated below synchronous speed and above synchronous speed using PID controller are shown in Figure. 9 and Figure. 10, respectively.

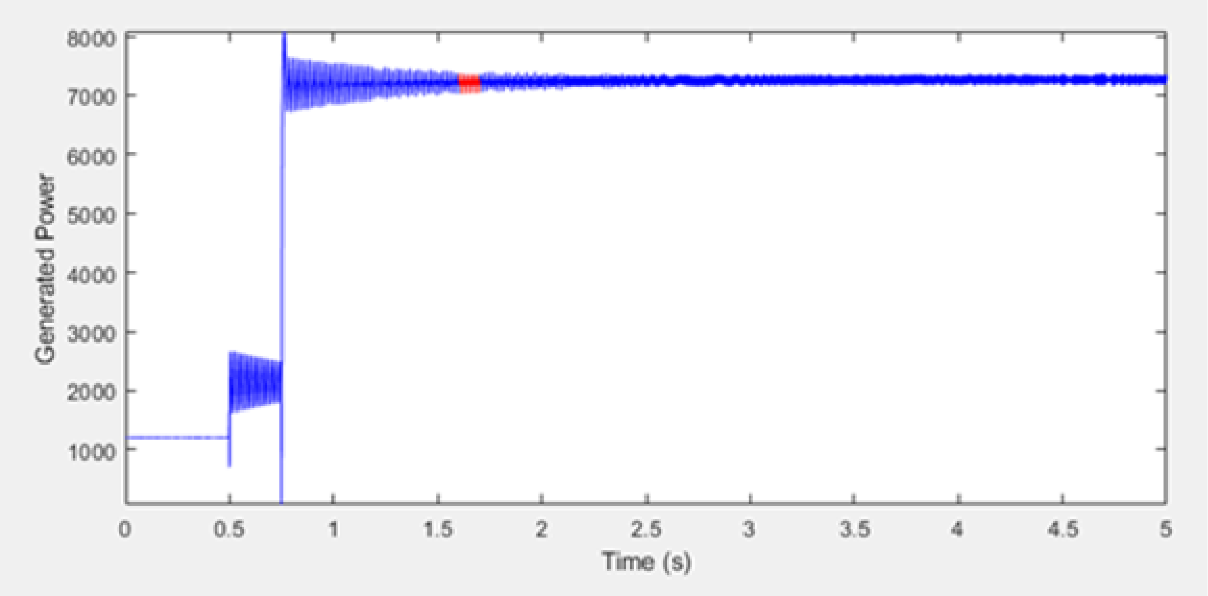

Figure. 9 Power generated using PID controller at 1400 RPM

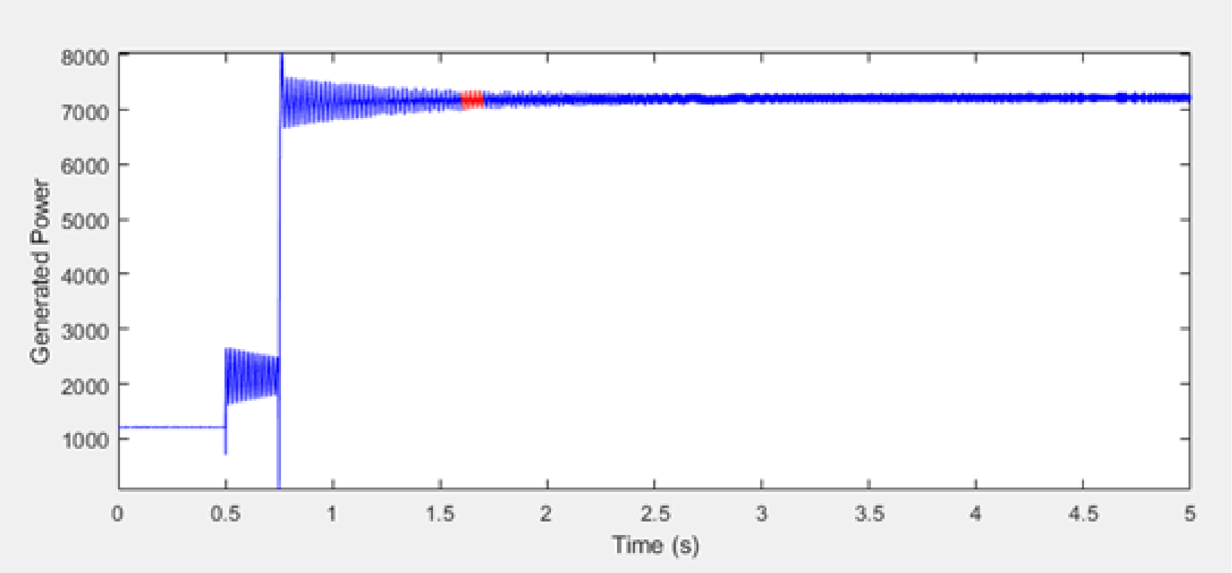

Figure. 10 Power generated using PID controller at 1700 RPM

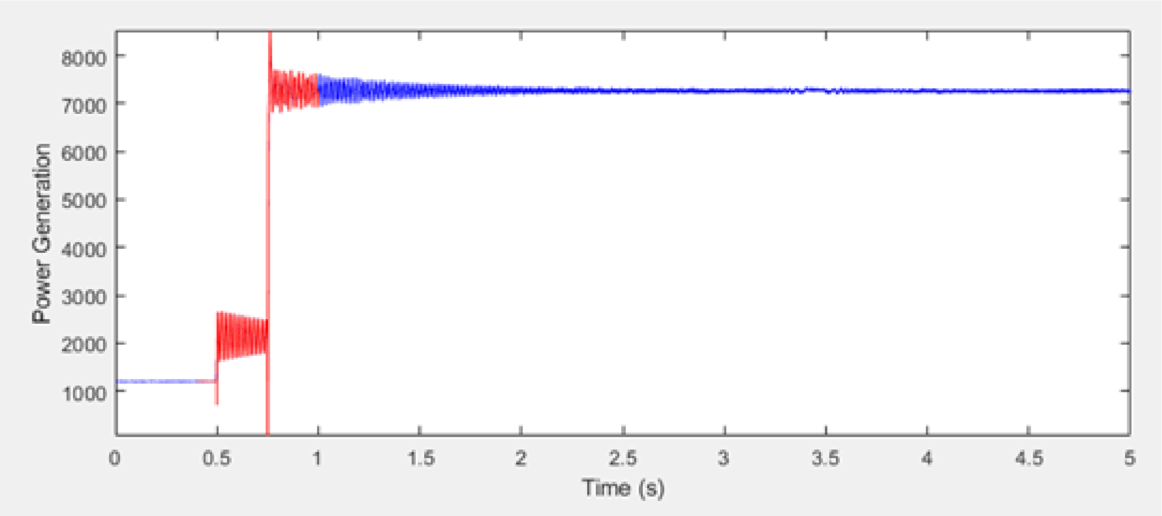

Figure. 11 Power generated using FOPID controller at 1400 RPM

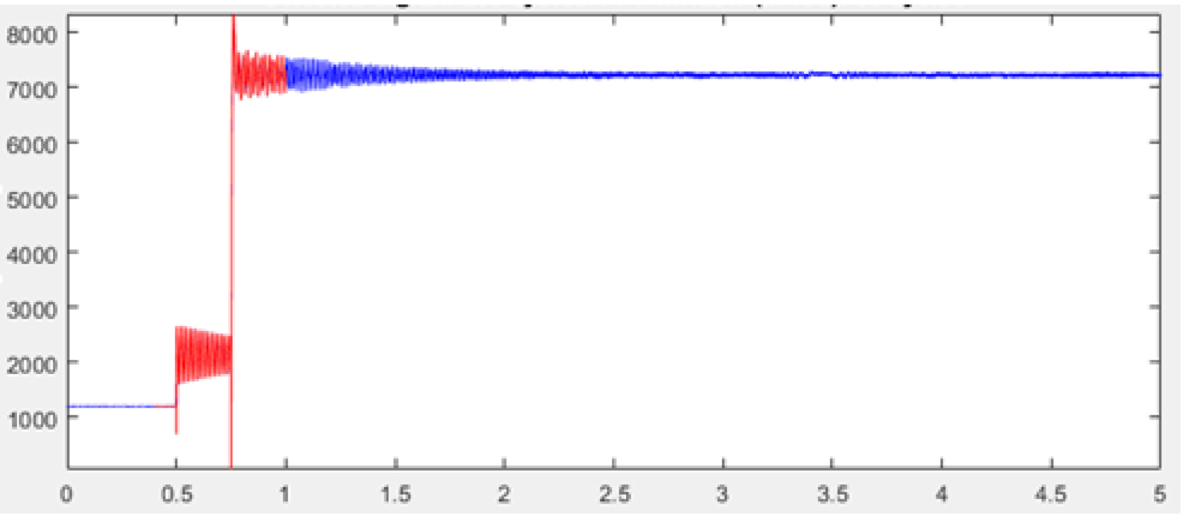

Figure. 12 Power generated using FOPID controller at 1700 RPM

Apparent power generated below synchronous speed and above synchronous speed using FOPID controller are shown in Figure. 11 and Figure. 12, respectively.

Table 1: Performance Specifications

	Generated Power Settling Time (Sec)
PI Controller	4
PID Controller	3.5
FOPID Controller	2

The proposed FOPID method has less settling time and less oscillations as compared to PI and PID controllers. From Table 1, it can be seen that the FOPID control approach provides better control performance.

6.Conclusions

Modeling and control of the DFIG using PI, PID and FOPID controllers are presented. Independent control of apparent power is achieved when DFIG is connected to the grid, and different simulation results under loaded conditions are executed and validated in the closed-loop system. The dynamics of DFIG system is obtained and the corresponding reduced order model found using MATLAB/Simulink environment. PI, PID and FOPID controllers are proposed for a variable speed DFIG-based WECS to prevent system breakdown under extreme conditions. The controllers design methods are also discussed. Simulation results show that WECS with FOPID control show better performance even in critical situations. From the simulation results, it is confirmed that the FOPID controller out performs compared to PI and PID controllers.

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