Addis Ababa University

Addis Ababa Institute of Technology

School of Electrical and Computer Engineering

Degree of Masters of Science in Control Engineering

Thesis Report

Tuning Fractional Order Proportional Integral Using Genetic Algorithm for Maximum Power Extraction of Wind Turbine

Prepared by:

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Dean, School of Electrical and Computer Engineering

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Abstract

Energy is in high demand and fossil fuels having problems, so current solution is to use renewable out of which wind is one. In using wind, the problem is how to extract the maximum power available in the wind stream. Due to the randomness of wind speed and the fluctuations of wind power. So, to extract the maximum power from the wind well-designed control systems are required.

In this thesis, a 1.5 MW double fed induction generator wind turbine is presented along with new controllers designed to maximize the wind power capturer. The proposed designs mainly focus on controlling the double fed induction generator rotor current in order to allow the system to operate at a certain current value that maximizes the energy capture at different wind speeds. A vector controller for current loop is designed to control the rotor side converter.

The control system design technique considered in this work is genetic algorithm which is used to tune integer order proportional integral and fractional order proportional integral controllers' parameter. The controllers' performance is evaluated using MATLAB/Simulink in related to step response and in overall simulation block of double fed induction generator wind turbine. The obtained results are analyzed to show the performance of the proposed control which is fractional order proportional integral. The step response for rotor current controller evaluation in terms of settling time, rise time, maximum percentage overshoot and steady state error, the responses based on fractional order proportional integral controller has shown better performance when compared to the integer one.

Keywords: IOPI, Genetic algorithm, FOPI, Wind generator, PI Controller, Tuning, DFIG.

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List of Acronyms

GA	Genetic Algorithm
PI	Proportional Integral
FOPI	Fractional Order Proportional Integral
IOPI	Integer Order Proportional Integral
MPPT	Maximum Power Point Tracking
IEEE	Institute of Electrical and Electronics Engineers
k_p	Proportional gain
k_i	Integral gain
DFIG	Doubly fed induction generator
WECS	Wind Energy Conversion System
PWM	Pulse Width Modulation
RSC	Rotor Side Convertor
GSC	Grid Side Convertor
VC	Vector Control
MMF	Magneto-motive Force
CAS	Computer Algebra System
AC	Alternative Current
DC	Direct Current
GW	Giga Watt
β	Pitch angle
ρ	Air density
C_p	Power coefficient

CHAPTER ONE

1. INTRODUCTION

1.1 Background

For several years, traditional power generation plants cause various pollutions and ecological imbalance by using fossil and natural sources such as uranium, hydrocarbons, and water vapor. For example, thermal power plants (coal, oil) are responsible for atmospheric emission of greenhouse gas which cause greenhouse effect. The degradation of air quality is considered as a major problem which has led authorities around the world to take measures to reduce pollutant emissions. As a result, the power generation industry is undertaking to adapt to these new constraints by promoting wind energy. Currently, several wind farms are installed in the world and the one that is both inexpensive and capable of mass production, Wind energy has a higher energy potential and becomes the second source of renewable energy next to hydraulics [1]. Most variable speed wind turbine systems are equipped by the dual-powered asynchronous machine, this type of machine allows a wide range of speed variation (±30%) of the synchronism speed [2, 3]. This is very useful to extract the maximum power during its operation.

Wind turbines have a specific electrical characteristic of a non-linear nature and have a particular point called "Maximum Power Point" where the power generation is maximum. The purpose of any control in this is to track the maximum power point [4, 5], where the MPPT's search in the tip speed ratio verses power coefficient characteristics. This power optimization occurs in the rate of the operating curve of a variable speed wind turbine. In recent decades, several advanced control methods have been developed to control the production processes of electrical energy. However, the performance of the control system has not always been assured due to the complexity of the control algorithms and the non-linearity characteristic of the systems to be controlled.

The conventional PI control techniques cover a wide range of industrial applications; those techniques are linear and have the advantage of simple implementation and the non-complexity synthesis of regulators' gains. In the course of time, these applications have become less efficient, especially if the processes to be controlled have a complex and non-linear structure. Finding an alternative to these conventional techniques is a persistent concern for many researchers because it involves a compromise between the robustness on one side and cost on the other. According to reference [6], conventional or integer order PI controllers have some problems related to nonlinear systems with non-constant parameters; the conventional control laws may be insufficient because they are not robust, especially when the requirements of accuracy and other dynamic characteristics of the system to be controlled are strict. For this, we should use insensitive control laws to the disturbances and nonlinear cases. The main problem in this thesis is the calculation of the parameters of the conventional PI regulator.

In recent years fractional order calculus has gained a lot of attention, especially in the field of system theory and control systems design due to more accurate modeling and control enhancement possibilities [7]. In control practice, it is useful to consider the fractional order controller design for an integer order plant [8].

Genetic Algorithm can optimize parameters of both fractional and integer PI controllers. GA initially generates a random population, which is implemented with small population size in order to allow the controller to be optimized and converge at a faster rate [9].

1.2 Research Motivation

Wind power is the reliable and developed renewable energy source over past decades. The increased awareness of people towards renewable energy, support from governmental institution, and rapid advancement in the power electronics industry, which is the core of wind power systems, are the most contributing factors for the development of wind power systems. As a result, the share of wind power with respect to total installed power capacity is increasing worldwide. Many countries are adopting wind power to generate electricity due to its clean and positive impact on the environment. Wind is considered an endless supply of renewable energy that generates electricity with very little or no pollution. On the other hand, the fossil fuels, such as coal, oil and natural gas, damage the environment by emitting carbon dioxide when burned. According to global wind report of 2021, the total capacity of all wind turbines installed worldwide experienced an increase in the last twenty years. The figure below illustrates the overall installed capacity of wind power generation in the years between 2001 and 2020. All wind turbines, which reached a capacity of 743 GW, installed by end of 2020 cover more than 7% of the global electricity demand.

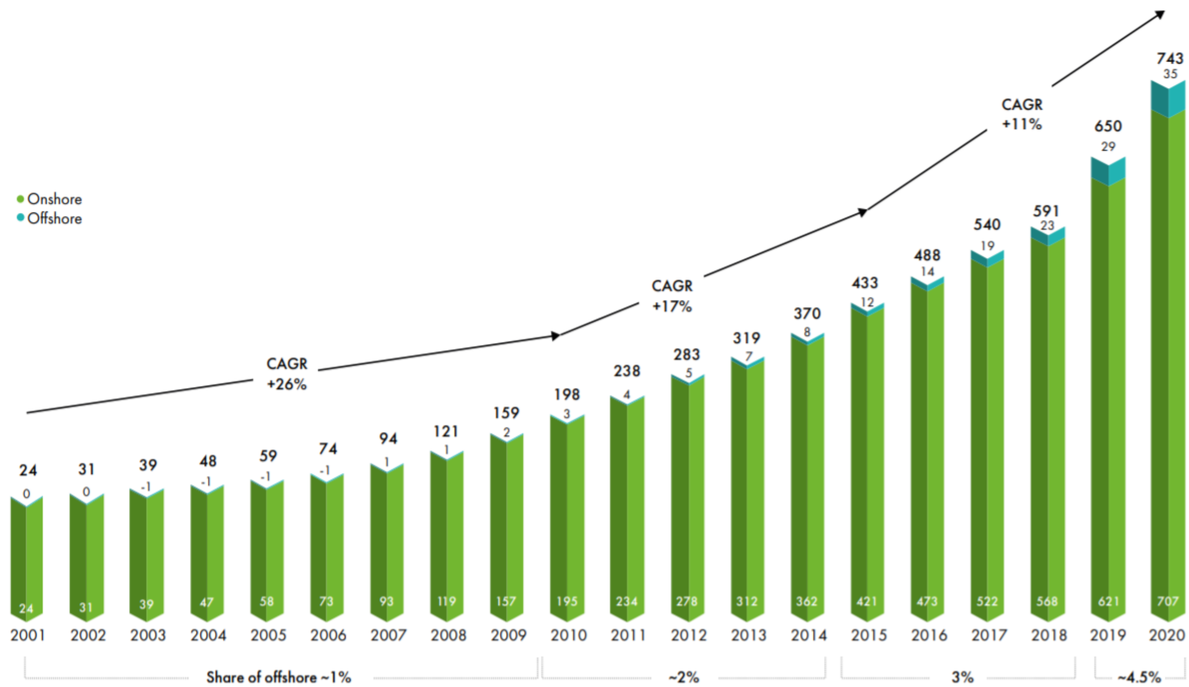


Figure 1.1 the overall installed capacity of wind power generation in the years between 2001 and 2020.

1.3 Problem statement

In recent decades, several advanced control methods have been developed to control the production processes of electrical energy from the wind turbine. However, the performance of the control system has not always been assured due to the complexity of the control algorithms and the nonlinearity characteristic of the wind turbine system.

The conventional or integer order PI control techniques cover a wide range of industrial applications; those techniques are linear and have the advantage of simple implementation and the non-complexity synthesis of regulators' gains. In the course of time, these applications have become less efficient, especially if the processes to be controlled have a complex and nonlinear structure. For this, recently, a novel extension of conventional controller has been attracted considerable attention called Fractional Order PI Controller [10], where the order of the integrator can be fractional value. Hence, this property gives a more freedom than integer order PI controller [11, 12]. Thus, this new approach presents a solution for nonlinear and complex processes. Owing the complexity of studied system, the synthesis of optimal controller parameters is not straight forward. Therefore, this could be solved using genetic algorithm optimization method. One of the optimization techniques adopted in renewable energy processes is Genetic Algorithm [13]. So, Fractional Order PI tuned using GA proposes to minimize the error and getting the optimal parameters of FOPI for wind turbine.

1.4. Objective of the thesis

1.4.1. General Objective

The general objective of this thesis is tuning fractional order PI using genetic algorithm for wind turbine to maximize the energy capture in the wind.

1.4.2. Specific Objectives

The specific aims of this thesis are listed as follows:

- To model wind turbine mathematically
- To tune FOPI parameters by GA
- To use Vector Control (VC) method for wind turbine
- To analyze the efficiency of GA-FOPI

1.5. Methodology

The following methodology will be adopted to carry out this thesis work:

- Modeling of wind turbine
- Modeling of DFIG reference frame
- Design Genetic Algorithm to tune FOPI controller parameters
- Apply FOPI controllers to some control parts such as active power, reactive power, speed, and rotor currents for investigation.
- Analysis and robust performance evaluation of the proposed FOPI controller in comparison with the IOPI controller by means of steady state error, settling time and overshoots.

1.6. Literature Review

There are many types of studies related to wind turbine control system in different engineering departments.

Doubly fed induction generators (DFIG) are extensively used in wind energy conversion systems such as wind turbines. The DFIGs dynamic characteristics requires creating high-performance control schemes. Nevertheless, the dynamic features of such generators mainly depend on certain nonlinear parameters, such as stator flux, stator current, and rotor current, which makes the overall system more complex. Hence, robust controllers are required to be designed in such systems in order to support the dynamic frequencies of wind energy to maintain system stability and good performance. In general, conventional control designs such as the proportional-integral (PI) controllers have multiple disadvantages, such as difficulties in tuning parameters, average dynamic performance, and reduced robustness [7].

In [8], a new rotor current scheme that is implemented in the positive synchronous reference frame is developed. The control system is designed of a standard PI controller and a generalized AC integrator. Their results show that the proposed control scheme leads to significant elimination of either DFIG power or torque oscillations.

The author cited in [10] used the integer order PI controller techniques and concluded as the integer order PI controllers have some problems related to non-linear systems with non-constant parameters; the conventional control laws may be insufficient because they are not robust, especially when the requirements of accuracy and other dynamic characteristics of the system to be controlled are strict. For this, we should use insensitive control laws to the disturbance and nonlinear cases. The main problem in this work is the calculation of the parameters of the convention or integer order PI regulator.

The author cited in [13] compared the integer order PI controller with fractional order PI for wind turbine as: a fractional order PI^{λ} controller is developed as an alternative robust control approach to the integer order PI controller in order to achieve the control objectives. Fractional order PI controllers have been introduced as an extended form of the integer controllers with integrator of real order 'λ'. Such controllers gained considerable attention recently thanks to the flexibility of fractional integral order.

Likewise, the author cited in [14] studied the design of FOPI is founded on extending the analytical procedure so that the parameters of FOPI controller are tuned based on some frequency-domain design specifications. The designed fractional-order PI^{λ} controller is destined for power control of DFIG-generator based on variable speed wind turbine connected in power grid.

The author cited in [15] studied the fractional order modeling and control of dynamic systems. Modeling real dynamic systems using fractional order calculus and control has been presented.

Further, widespread usage of the PI controller has inspired many researchers to look forwarding better design techniques or alternative controllers [16]. In recent days the FOPI took the place of the conventional controller because it provides additional tuning parameter and can provide promisingly good performance and better robustness features compared to classical controllers.

1.7. Scope of the thesis

The scope of this thesis is to improve the efficiency of fractional order PI controller for wind turbine. The thesis is implemented using only MATLAB/SIMULINK simulation with no practical demonstration.

1.8. Thesis Layout

This thesis work is organized in to five chapters. The **first Chapter** deals with an introduction, problem statement, objectives of the study, methodology and literature review leading towards the completion of the thesis. The **second chapter** discusses about mathematical modeling of wind turbine, Modeling of DFIG, MPPT Modeling. The **third chapter** discusses about wind turbine control; concept of vector control and GA. The **fourth chapter** presents about the simulation results obtained using MATLAB/SIMULINK and discussions of the results. Finally, **Chapter five** discuss about conclusion and recommendations for future works.

CHAPTER TWO

2. MODELING OF WIND ENERGY SYSTEM

In this chapter, Mathematical models of Wind turbine, DFIG and MPPT are discussed. To simply the system, the only turbine and generator will be modeled. The drive train and converter are ideal without any losses. Wind turbine and DFIG are mathematically modeled and made the PI controller Fractional. The general scheme of a WTGS is depicted in figure below.

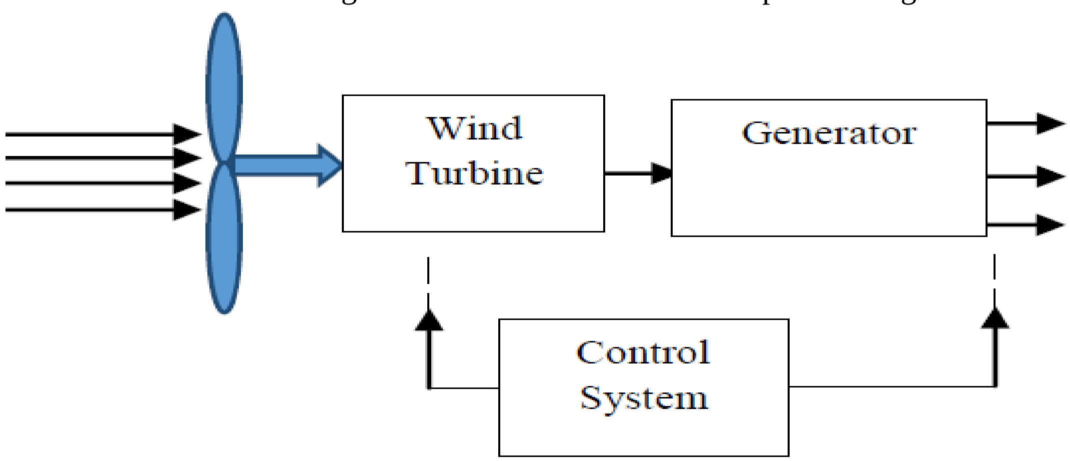


Fig. 2.1 Block diagram of the WTGS

2.1 Modeling of the Wind Turbine

Since the wind turbine is an energy converter, the available energy stored in the wind needs to be determined. The energy in the wind is the kinetic energy of a large amount of air particles with a total mass of M, moving with a speed of V. Let us assume the wind is moving at the same speed and direction before hitting the rotor blades of the wind turbine, and then the kinetic energy stored in the wind can be given by the following expression.

$E=1/2MV^2$ …………………………………………………………………………….. (2.1)

Where, E is the kinetic energy of the air particles, M is the mass of the air particles and V is the wind speed. The total mass of the air particles M, for a period of time t is given by the equation

$M = \rho AV.t = \rho\pi r^2 V.t$ ………………………………………………………………. (2.2)

Where, ρ is the density of the air, A is the area swept by the blades of the wind turbine and r is the radius of the rotor. By substituting (2.2) into (2.1), the kinetic energy of the air particles is given by the following equation [17].

$E = \frac{1}{2}\rho\pi\, r^2\, V^3 t$ ………………………………………………………………………...…. (2.3)

The aerodynamic wind power at time t [18] is given by

$P_{wind} = \frac{E}{t} = \frac{1}{2}\rho\pi r^2\, V^3$ ……………………………………………………………………… (2.4)

Where, P_{wind} is the power of the wind.

From the above equation (2.4), power is directly proportional to the cube of the wind velocity and is directly proportional to the radius of the wind turbine rotor. The power in the above equation (2.4) is the total power of the wind. But the portion of this power can be captured by the wind turbine. In [19] Albert Betz presented the idea that after hitting the wind turbine rotor blades, the wind velocity decreases. It means some kinetic energy is left in the wind after hitting the rotor blades. That means the power captured in the wind turbine is decreased by having power coefficient, C_p. The power coefficient of the wind turbine is the ratio of the power captured by the wind turbine to the maximum power in the wind.

$C_p = \frac{P_{Turbine}}{P_{Wind}}$...................……………………………………………………………… (2.5)

Where, C_p is Power coefficient, $P_{Turbine}$ is the output power of the wind and P_{Wind} is wind power Note that the captured power should always be smaller than the wind power by having C_p.

Moreover, C_p can never be equal to 1, in other words, it is impossible to achieve 100% efficiency. According to Betz limit theory, the maximum value of C_p is 0.593, which means that a maximum of 59.3% of the wind power can be extracted by a conventional wind turbine. If 100% of the wind kinetic energy was converted, a complete stop of the turbine will occur, and hence, there will not be any further energy extraction by the wind turbine. This is known as the Betz Limit, and is the theoretical maximum coefficient of power for any wind turbine type. Moreover, see the below figure for Betz limit detail.

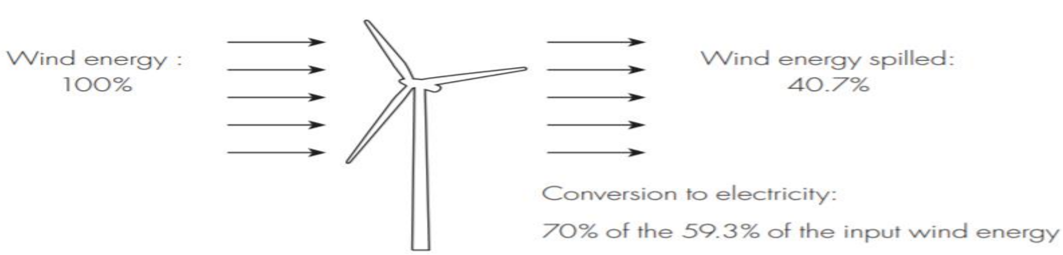


Figure 2.2 Betz Limit

In the figure shown above, the wind turbine converts 70% of the Betz Limit into electricity. Therefore, the C_P of this wind turbine would be 0.7 x 0.59 = 0.41. So, this wind turbine converts 41% of the available wind energy into electricity. This is actually a pretty good coefficient of power. Good wind turbines generally fall in the 35-45% range.

The power coefficient of the wind turbine can be expressed by [20]:

$$C_P = c_1\,(c_2 \frac{1}{\lambda i} - c_3\beta - c_4)e^{-c_5\frac{1}{\lambda i}} + c_6\lambda \quad (2.6)$$

Where the values of c_1= 0.5176, c_2= 116, c_3= 0.4, c_4= 5, c_5= 21, and c_6= 0.0068.

The values of the coefficients c_1; c_2; c_3; c_4; c_5; c_6 depends on the type of the wind turbine and given from manufacturer.

$$\frac{1}{\lambda i} = \frac{1}{\lambda+0.08\beta} - \frac{0.035}{1+\beta^3} \quad (2.7)$$

Where, β is the pitch angle of the blade space. The pitch angle is the angle between the orientation of the blade and the wind velocity. When the pitch angle is zero, the blade is fully impacted by the wind velocity, and the wind turbine will capture the maximum power in the wind. λ is the tip speed ratio which is defined as the ratio between the rotor speed and the wind speed. The tip speed ratio is given by the equation [20]:

$$\lambda = \omega_m \frac{R}{V} \quad (2.8)$$

Where, ω_m is the angular speed of the wind turbine generator and R is the rotor radius.

The wind turbine is used to convert the wind kinetic energy to mechanical energy. Wind passes over the blades, starts rotating the blades and exerting a turning force. The rotating blades of the wind turbine turn a shaft inside the nacelle that goes into the gear box. The gear box is used to increase the rotational speed which is appropriate for the generator. In small turbines the gear box ratio is 1:1 that is the angular speed of the wind turbine rotor is equal to the rotor speed of the generator. The mechanical torque T_m is defined by [18]:

$$T_m = \frac{P_m}{\omega_m} = \frac{1}{2\omega_m}\rho\,\pi r^2 V^3 C_P\,(\lambda, \beta) \quad (2.9)$$

The mechanical dynamic of the system also modeled as:

$$J\,\frac{d\omega_m}{dt} = T_m = T_{aef} - T_{em} - f_v\,\omega_m \quad (2.10)$$

Where, J: system total inertia

ω_m: mechanical speed of DFIG

T_{em}: electromagnetic torque

f_v : coefficient of friction

T_{aef} : aerodynamic torque on the fast axis of the turbine

T_{aes} : aerodynamic torque on the slow axis of the turbine

The above equations are used to prepare the block diagram of the turbine model figure below.

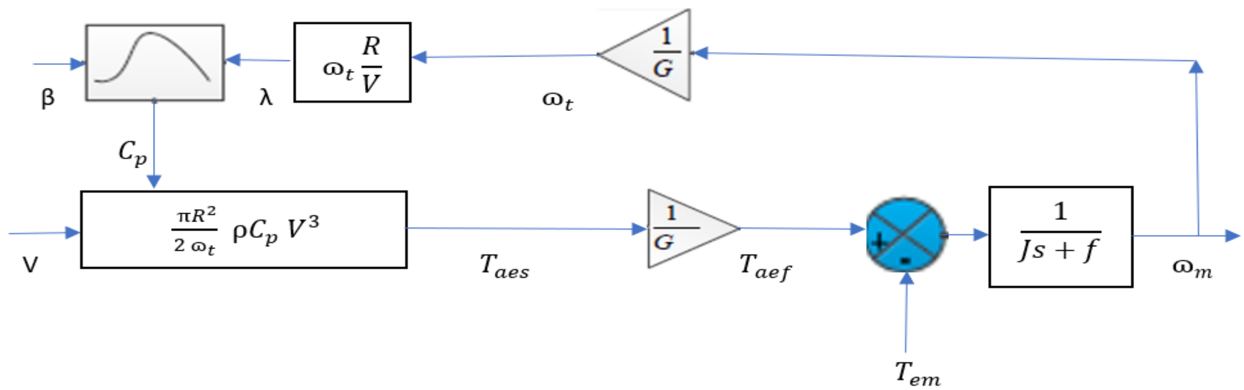


Figure 2.3 Wind-turbine model

Here the block diagram consists of blades, gearbox, and shaft. As equation (2.8) above and represent in this block, the tip speed ratio (λ) is the ratio of turbine speed and wind speed where R is the radius of the rotor blade which is constant. To extract λ_{opt}, optimizing torque is very important to generate the optimized ω_m which is responsible to produce λ_{opt} through gearbox ratio as this representation. C_P is the function of λ and β as equated in (2.6) above. But β is zero in this work and C_P is only based on tip speed ratio (λ). So, $C_{P_{max}}$ should be obtained by finding the optimal, λ_{opt} and the power from the turbine will be maximized which is determined using MPPT control strategy as plotted in figure 2.4 below.

The optimal, λ_{opt} is equated as:

$$\lambda_{opt} = \frac{R\omega_t}{V} \quad \text{.......} \quad (2.11)$$

The aerodynamic torque extracted by the turbine is then given by

$$T_{aer} = \frac{1}{2}\rho\pi R^3 \frac{R^2\,\omega_t^2}{\lambda_{opt}^{\;2}}\,\frac{C_{P_{max}}}{\lambda_{opt}} \quad \text{.......} \quad (2.12)$$

That is,

$$T_{aer} = \frac{1}{2}\rho\pi\frac{R^5}{\lambda_{opt}^{\;3}}\,C_{P_{max}}\,\omega_t^2 \;=\; K_{opt}\,\omega_t^2 \quad \text{.......} \quad (2.13)$$

Where, $K_{opt} = \frac{1}{2}\rho\pi\frac{R^5}{{\lambda_{opt}}^3} C_{P_{max}}$ and ω_t is aerodynamic speed.

2.2 Modeling of MPPT

The produced power from a given wind turbine depends mainly on wind speed and tip speed ratio. As these quantities vary with time, maximum power point tracking control algorithm is necessary to control and adjust continuously the rotational speed of the DFIG which assures the variable speed operation that maximizes the output power for a wide range of wind speeds. The optimal generator speed corresponds has λ_{opt} and β = 0°. At this value, the power coefficient C_p is equal to its maximum value. Thus, the electromagnetic torque reference determined by MPPT control strategy is expressed by (2.14) [31]. From figure 2.10, there is a unique operating point called the maximum power point (MPP), where the power generation is maximum at which λ_{opt} and $C_{P_{max}}$ by making β zero. The block diagram of speed ratio (TSR) MPPT controller using FOPI controller tuned by genetic algorithm is shown in Figure 2.4.

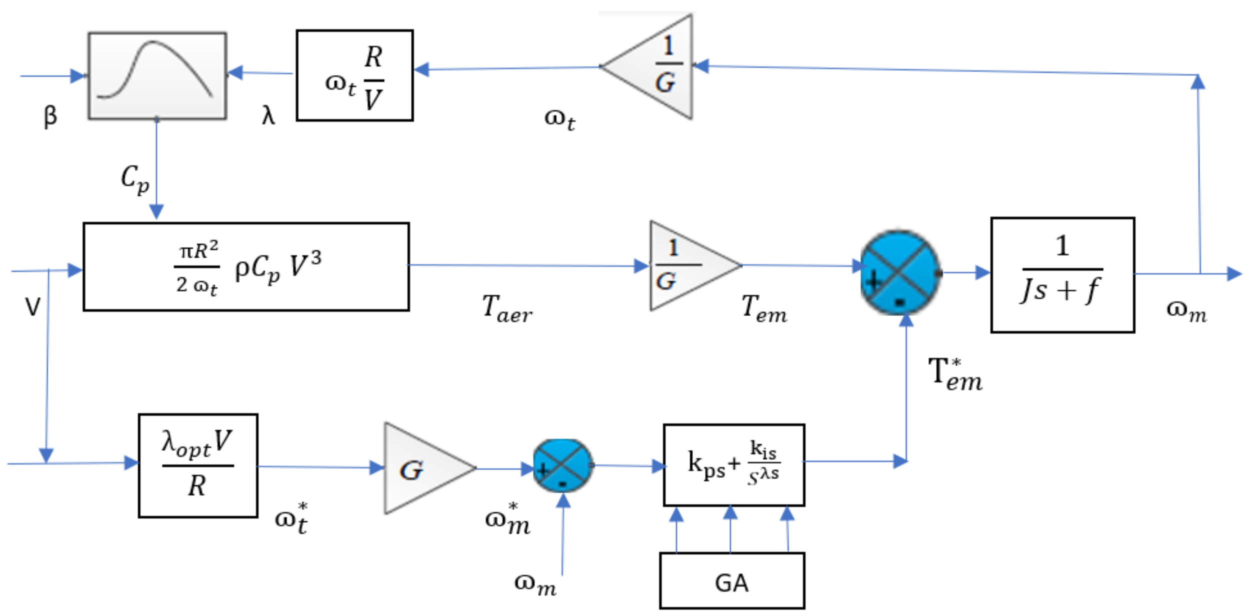


Figure 2.4 Proposed MPPT controller

From this, the electromagnetic torque reference determined by MPPT is expressed as:

$T^*_{em} = k_{ps}\ (\omega^*_m - \omega_m) + k_{is}\int(\omega^*_m - \omega_m)dt$ ……………………………………………. (2.14)

Where, k_{ps} and k_{is} is the proportional and integral gains of the rotor speed respectively.

λ_s is the value of λ for speed.

The reference electromechanical torque, T_{em}^* is obtained from rotor speed after tuning FOPI controller parameters using genetic algorithm. As equated in (2.9) above, mechanical power, P_m depends on power coefficient, C_p and wind speed, V where C_p is the function of λ since β is zero in this work. So, to maximize power, finding the λ_{opt} and $C_{P_{max}}$ when wind speed is varying. The λ_{opt} is extracted when optimal rotor speed, ω_m is applied from the optimized torque in this block diagram. Then the λ_{opt} is applied to power coeffiecent, C_p to produce $C_{P_{max}}$. The peak point at which λ_{opt} and $C_{P_{max}}$ intersect each other when beta zero can be expressed as maximum power point as plotted in figure 2.10. At this point the maximum power has extracted.

2.3 Double Fed Induction Generator Modeling

For the DFIG-based wind turbine, it has many advantages. Principally, DFIG makes the system easily operate in variable speed, lower the converter costs, and power losses. To control the active and reactive power without coupling, DFIG is generally defined in the synchronously d–q frame. Consequently, the model in the d–q coordinate axis of the stator and the detail of the block diagram description is shown in the figure below.

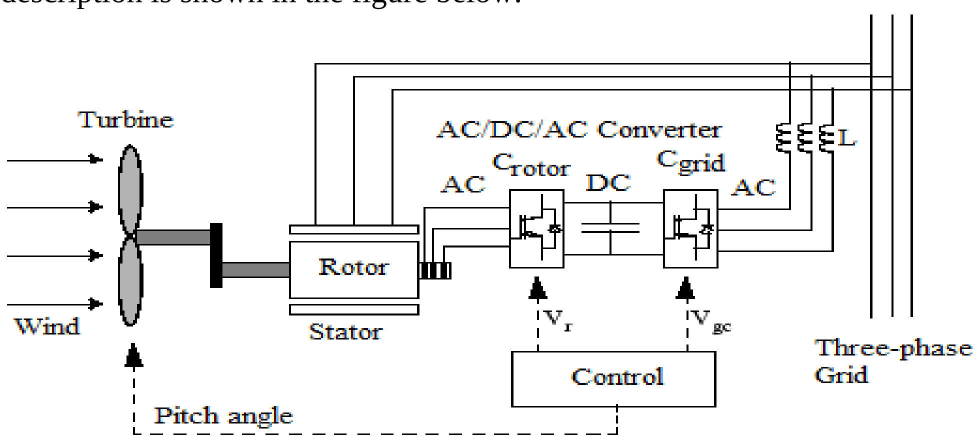


Fig. 2.5 Configuration of DFIG based wind turbine system.

Voltage Equations

$$\begin{cases} V_{sd} = R_s . I_{sd} + \frac{d}{dt}\varphi sd - \omega_s . \varphi sq \\ V_{sq} = R_s . I_{sq} + \frac{d}{dt}\varphi sq + \omega_s . \varphi sd \\ V_{rd} = R_r . I_{rd} + \frac{d}{dt}\varphi rd - (\omega_s - \omega_r) . \varphi rq \\ V_{rq} = R_r . I_{rq} + \frac{d}{dt}\varphi rq + (\omega_s - \omega_r) . \varphi rd \end{cases} \quad \ldots\ldots (2.15)$$

Flux Equations

$$\begin{cases} \varphi sd = L_s \,.\, I_{sd} + M.\, I_{rd} \\ \varphi sq = L_s \,.\, I_{sq} + M.\, I_{rq} \\ \varphi rd = L_r \,.\, I_{rd} + M.\, I_{sd} \\ \varphi rq = L_r \,.\, I_{rq} + M.\, I_{sq} \end{cases} \quad \ldots\ldots (2.16)$$

Power Equations

$$\begin{cases} P_s = V_{sd} \,.\, I_{sd} + V_{sq} \,.\, I_{sq} \\ Q_s = V_{sq} \,.\, I_{sd} - V_{sd} \,.\, I_{sq} \\ P_r = V_{rd} \,.\, I_{rd} + V_{rq} \,.\, I_{rq} \\ Q_r = V_{rq} \,.\, I_{rd} - V_{rd} \,.\, I_{rq} \end{cases} \quad \ldots\ldots (2.17)$$

Torque Equations

$$\begin{cases} T_{em} = p \frac{M}{Ls} (\varphi sd.\, I_{rq} - \varphi sq.\, I_{rd}) \\ T_{em} = (\frac{3}{2}) (\frac{p}{2}) [(\varphi rq\, I_{rd} - \varphi rd.\, I_{rq})] \\ = (\frac{3}{2}) (\frac{p}{2}) [(\varphi ds\, I_{qs} - \varphi qs.\, I_{ds})] \\ = (\frac{3}{2}) (\frac{p}{2}) L_m [(I_{dr}\, I_{qs} - I_{rq}.\, I_{ds})] \end{cases} \quad \ldots\ldots (2.18)$$

Where, $L_s = L_{ls} + L_m$, $L_r = L_{lr} + L_m$

Fractional Voltage Equations

$$\begin{cases} V_{sd} = R_s \,.\, I_{sd} + \frac{d^\alpha}{dt^\alpha} \varphi sd - \omega_s \,.\, \varphi sq \\ V_{sq} = R_s \,.\, I_{sq} + \frac{d^\alpha}{dt^\alpha} \varphi sq + \omega_s \,.\, \varphi sd \\ V_{rd} = R_r \,.\, I_{rd} + \frac{d^\alpha}{dt^\alpha} \varphi rd - (\omega_s - \omega_r).\, \varphi rq \\ V_{rq} = R_r \,.\, I_{rq} + \frac{d^\alpha}{dt^\alpha} \varphi rq + (\omega_s - \omega_r).\, \varphi rd \end{cases} \quad \ldots\ldots (2.19)$$

For other equations, the integer equations and fractional equations are the same. In other word, Power equations, Torque equations and Flux equations have the same integer equation and fractional equation. Because these equations have no derivative term.

2.4 Wind Energy System Model Validation

The above Mathematical model equations can be investigated using MATLAB/SIMULINK and the characteristic relationship is investigated based on the given parameters, such as: Wind turbine Parameters and DFIG Model parameters. After setting the values of the parameters of wind speed, air density, blade swept area and radius of the rotor. To validate the mathematical formulation approach discussed above, the below listed parameters are used to present an operating point when the wind speed is constant equal to 12m/s and pitch angle maintained to zero.

Table 2.1. DFIG Parameters' [30]

parameter	Value
Stator resistor per phase	0.00406 p.u.
Rotor resistor per phase	0.021 p.u.
Inductance of the stator winding	0.0137p.u.
Inductance of the rotor winding	0.0136 p.u.
Magnetizing inductance	0.0135 p.u.
Number of pole pairs	2
Stator power, P_s.	1.5MW
Stator voltage, V_s	690V
Grid frequency	50Hz
Friction factor	0.001p.u.

Table 2. 2.The Parameters of Wind Turbine

parameter	Value
Number of blades	3
Inertia	5.04kg.m^2
Cut in speed.	5m/s
Rated speed	12m/s

Let us see the turbine speed verses output power characteristics by setting wind data such as: wind speed, pitch angle controller gain, maximum pitch angle and nominal power from MATLAB. The simulation figures below show the wind turbine characteristics by varying pitch angle without the controller.

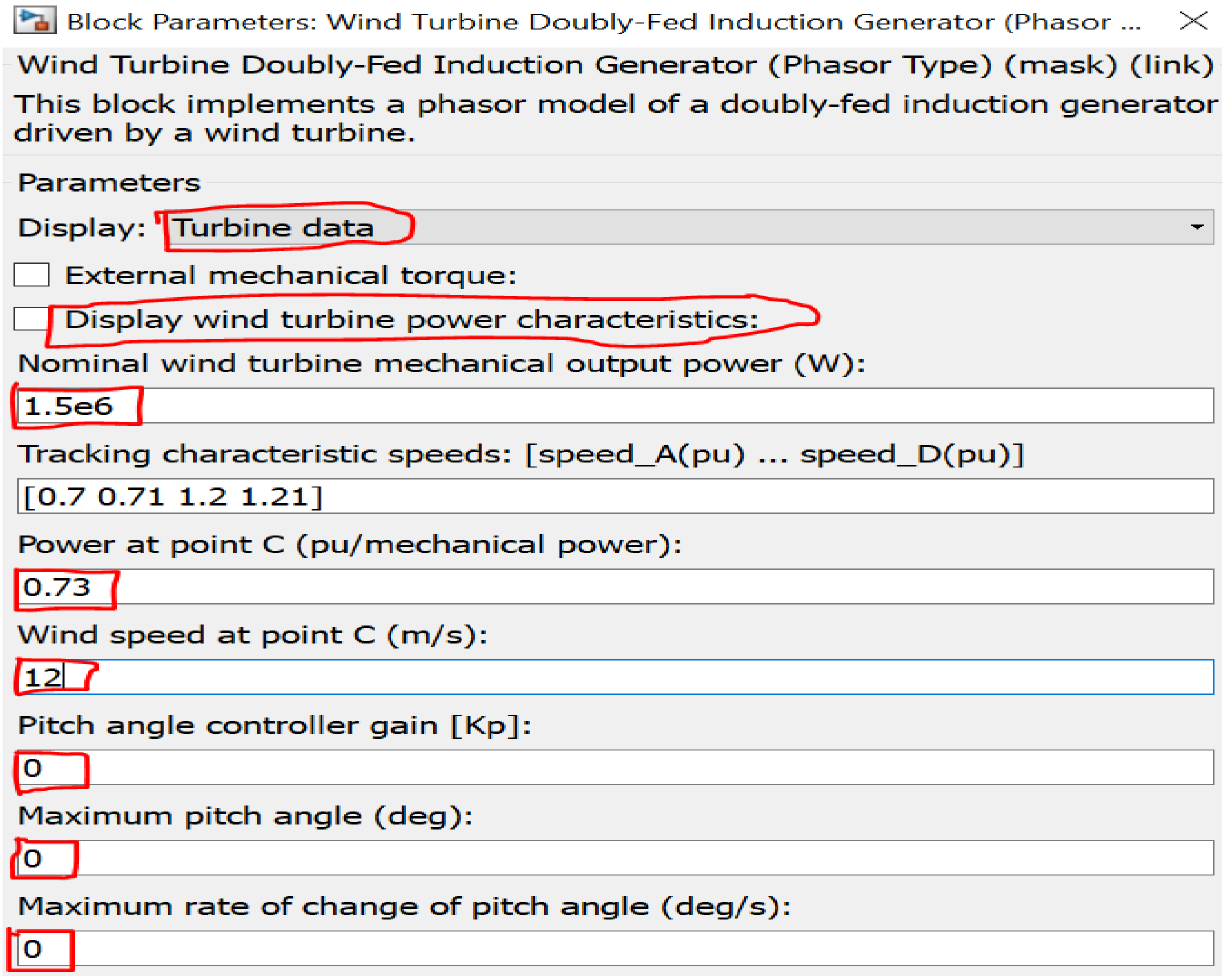


Fig. 2.6 The wind turbine parameters setting block.

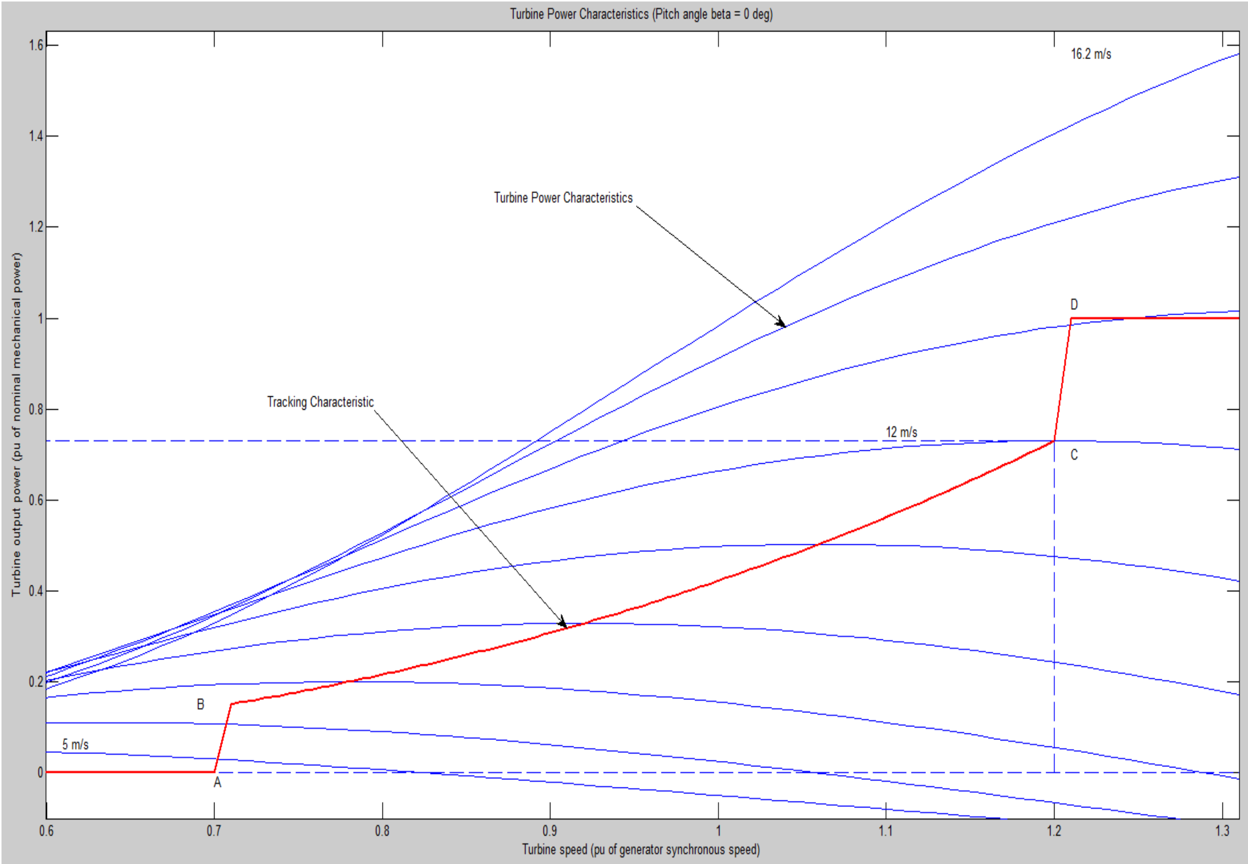


Fig. 2.7 Turbine speed vs. o/p power for pitch angle equal to zero.

Here, section BC represents the optimum operation range. Within this range, the rotor speed is adjusted in proportion to the wind speed so that the optimal tip speed ratio is maintained which leads to a maximum wind power capture, while the pitch angle is zero.

It is not practicable to maintain optimum power extraction from cut-in up to the rated speed. Therefore, section AB and CD account for the transition ranges. The reason why section AB and CD are not vertical is that, if so, there will exist some problems because the desired power is not uniquely defined at minimum and rated generator rotor speed. The slight changes of the generator rotor speed around its minimum or its rated value will cause large power fluctuations. From zero speed to speed of point A the reference power is zero. Between point A and point B the tracking characteristic is straight line; the speed of point B must be greater than the speed of point A. Between point B and point C the tracking characteristic is the locus of the maximum power of the turbine (maxima of turbine power vs turbine speed curves). The tracking is straight line from point C to point D. The power at point D is per one unit (1pu) and the speed of point D must be greater than the speed of point C. Beyond point D the reference power is constant equal to one per unit (1pu).

For this, when the pitch angle is zero and wind speed is 12 m/sec we get maximum power. But if we change the pitch angle to 5 and 10 respectively for the same wind speed the output power is decreased and this indicate the effect of pitch angle on the output power as shown in figure (2.8, 2.9) below. So, to extract maximum power by reaching power coefficient, C_P at maximum value, pitch angle must be maintained to zero.

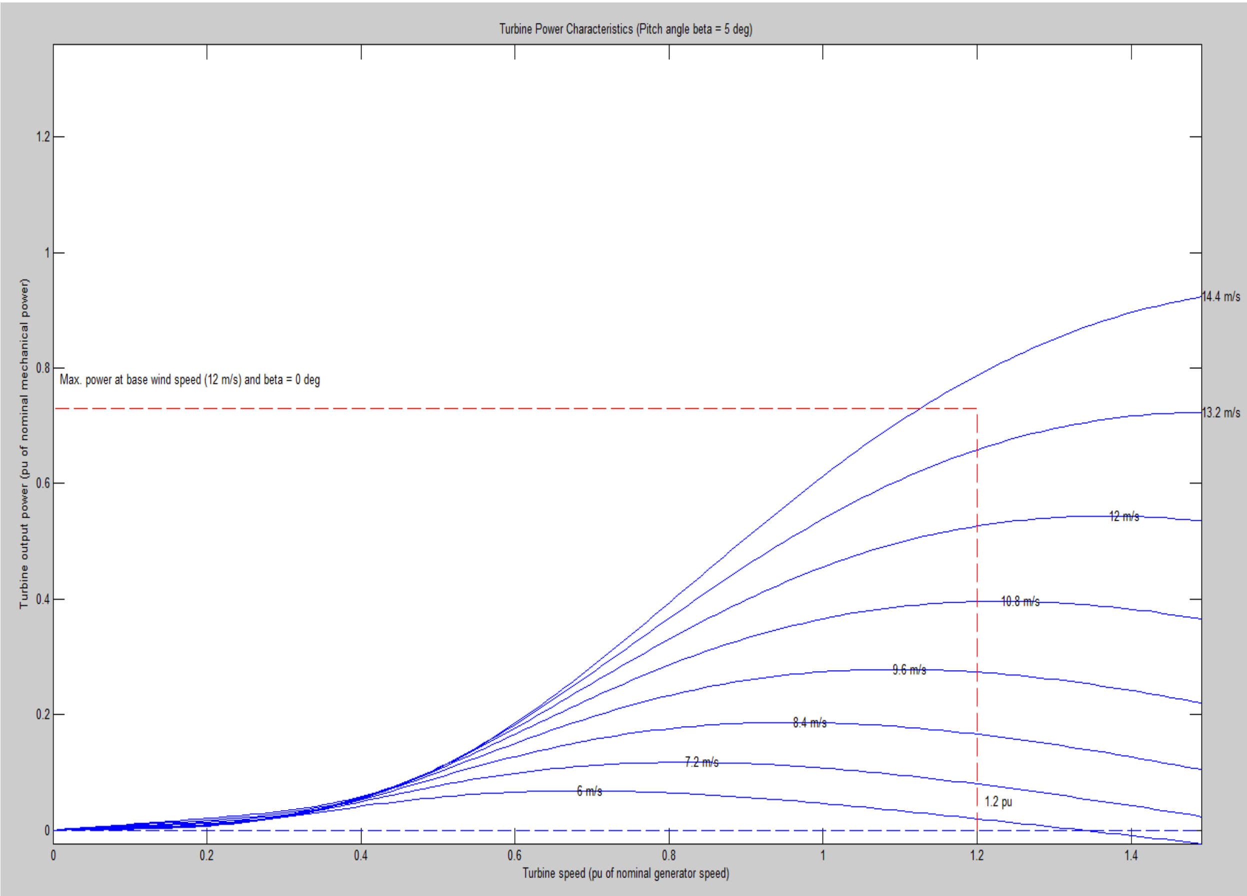


Fig. 2.8 Turbine speed vs. output power for pitch angle equal to 5.

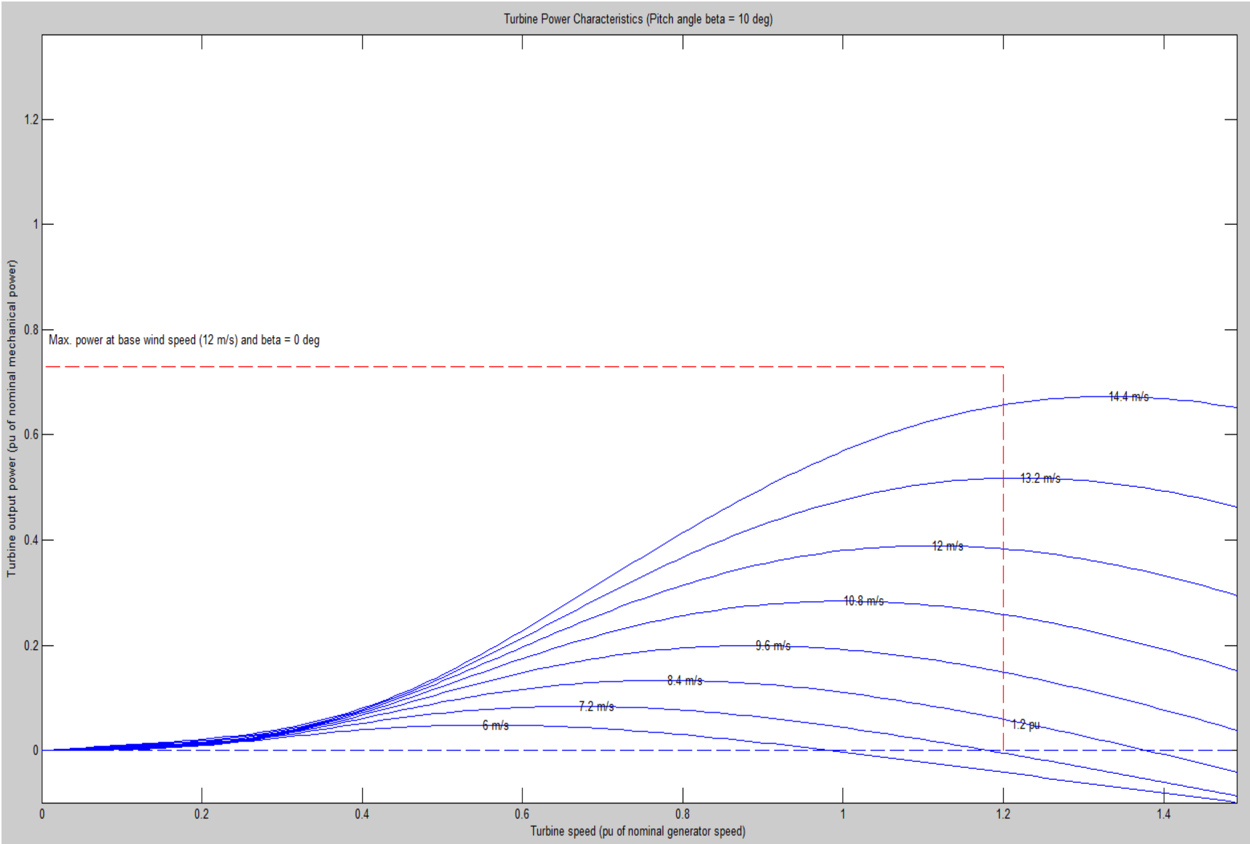


Fig. 2.9 Turbine speed vs. o/p power for pitch angle equal to 10.

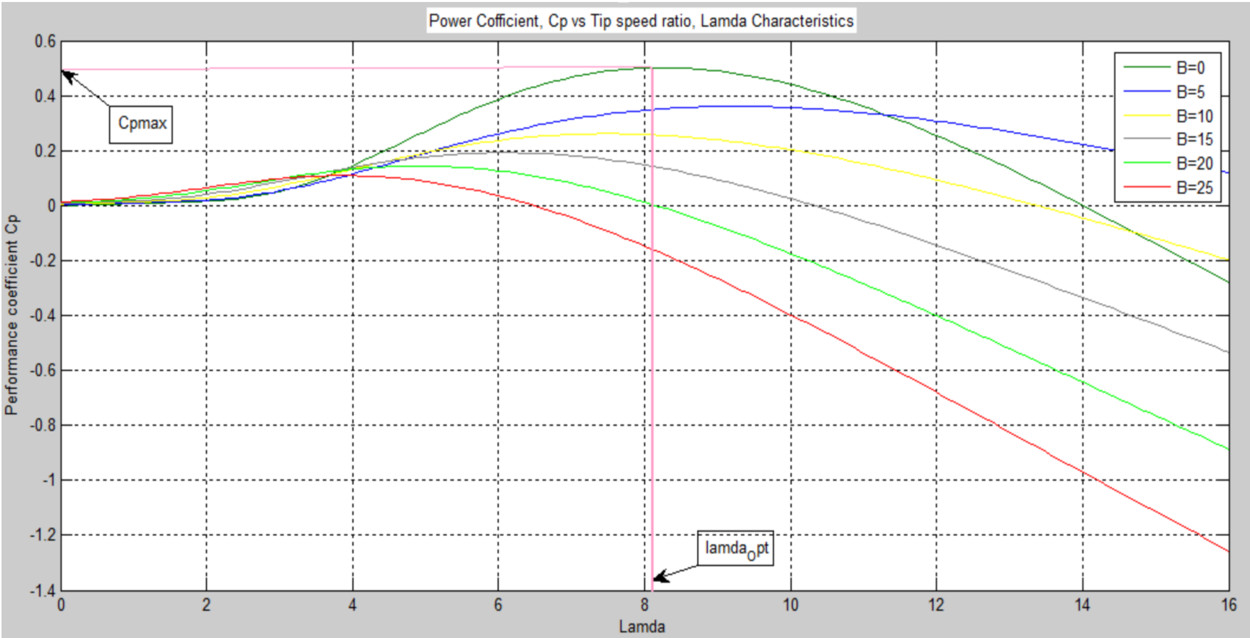


Fig. 2.10 C_P verses λ characteristics when pitch angle varies.

From fig. 2.10, above as the value of pitch angle is varying from 0 to 25. Power coefficient, C_p is small. Here, Pitch angle beta is increasing from 0 to 25 by the interval of 5. During this, the power coefficient C_p is decreasing. The values are approximated as: C_{Pmax}=0.48 and $\lambda_{opt} = 8.1$ (at β is zero).

CHAPTER THREE

3. CONTROL SYSTEM DESIGN

In this chapter wind turbine control strategies and Genetic algorithm optimization technique will be discussed. Integer and fractional order PI controller will be designed. GA optimization technique will be used to get optimized parameters of both fractional and integer order PI controllers. Fractional order PI controller will be designed using FOMCON toolbox.

3.1 Introduction to wind turbine control strategies

Control systems technology has been playing an important role in wind turbine operation. For the case of DFIG, control system is used to maintain magnitudes of the high-speed shaft torque, active and reactive power of the generator, and grid side converter magnitude such as the DC bus voltage and the reactive power, close to their optimum values, in order to achieve an effective energy generation and high performance. Basically, vector control is the most appropriate control method as it makes it possible to regulate separately the reactive and active powers exchanged between the WGS and the electrical grid.

For DFIG-based wind, the controller of the machine side mainly aims to extract the maximum energy from wind. The complete control strategy of the DFIG based wind turbine is also divided in two ways. one is scalar control, and the other is vector control. The limitations of scalar control give a significance to vector control. Though the scalar control strategy is modest to implement but the natural coupling effect gives sluggish response. The inherent problem is being solved by the vector control strategy.

3.2 Vector control of wind turbine

In order to control the direct and quadrature currents, stator flux-oriented vector control scheme is applied based on the following assumptions:

- ✓ Stator voltage drop across resistance has been neglected as the effect of stator resistance is quite low compared to the grid voltage.
- ✓ The DFIG is connected to a stiff grid, i.e., the frequency and amplitude of the stator or grid voltage is assumed constant.
- ✓ Magnetizing current of the stator is assumed to be determined by the grid.
- ✓ The q-axis is ninety degree ahead of the d-axis and rotating at synchronous speed in the direction of rotation.
- ✓ The stator flux vector is aligned with the d-axis of the stator.

The above assumptions lead to the following.

$$\begin{cases} \varphi_{sd} = \varphi_s \\ \varphi_{sq} = 0 \end{cases} \quad \text{(3.1)}$$

$$\begin{cases} V_{sd} = 0 \\ V_{sq} = \omega_s \varphi_{sd} \end{cases} \quad \text{(3.2)}$$

Using (3.1) and (3.2) in (2.15) - (2.18) the electromagnetic torque, the rotor voltages and the stator active and reactive power can be expressed in function the rotor currents as follows:

$$T_{em} = p \frac{M}{Ls} \varphi s . I_{rq} \quad \text{(3.3)}$$

$$\begin{cases} V_{dr} = R_r I_{dr} + \sigma L_r \frac{dI_{dr}}{dt} - \omega_s g \sigma L_r I_{qr} \\ V_{qr} = R_r I_{qr} + \sigma L_r \frac{dI_{qr}}{dt} + \omega_s g \sigma L_r I_{dr} + g \frac{M}{L_s} V_s \end{cases} \quad \text{(3.4)}$$

$$\begin{cases} P_s = -V_s \frac{M}{L_s} I_{rq} \\ Q_s = -V_s \frac{M}{L_s} I_{rd} + V_s \frac{\varphi_s}{L_s} \end{cases} \quad \text{(3.5)}$$

Where, $\sigma = 1 - \frac{M^2}{L_s Lr}$, M= L_m and $g = \frac{(\omega_s - \omega)}{\omega_s}$ is the generator slip.

At equation (3.5), the obtained a model of DFIG in synchronous d-q reference frame and stator flux orientation shows that the active and reactive powers injected into the grid can be controlled independently. Indeed, the direct component I_{dr} of the rotor current controls the reactive power while the quadrature component I_{qr} controls the active power.

The reference rotor currents $I_{dr}*$ and $I_{qr}*$ are given by:

$$\begin{cases} I_{qr} * = - \frac{L_s}{M V_s} P_s * \\ I_{dr} *= \frac{V_s}{M \omega_s} - \frac{Ls}{MV_s} Q_s * \end{cases} \quad \text{(3.6)}$$

In the form of two separate loops, the active and reactive powers generated are controlled in the d and q axes.

$$\begin{cases} I_{sd} = -\frac{Lm}{L_s} I_{rd} + \frac{\varphi_s}{L_s} \\ I_{sq} = -\frac{Lm}{L_s} I_{rq} \end{cases} \quad \text{(3.7)}$$

It is well known that MPPT control strategy improved energy efficiency of WGS and consequently active power generated. In this thesis, another possible improvement concerning this time the reactive power control is proposed. Indeed, the stator reactive power is controlled to protect windings against the aging phenomenon, it is controlled to reduce of generator copper losses. Generator copper losses can be expressed as:

$$P_{cu} =(I_{sd}^2 + I_{sq}^2)R_s + (I_{rd}^2 + I_{rq}^2) R_r \quad \text{………………………………………… (3.8)}$$

Substituting the expressions of I_{sd} and I_{sq} in (3.8), we get:

$$P_{cu} = (R_{r+\frac{L_m^2}{L_s^2}} R_s) I_{rd}^2 + \frac{\varphi_s^2}{L_s^2} R_s - \frac{2L_m \varphi_{s\,Rs}}{L_s^2} I_{rd} + (R_{r+\frac{L_m^2}{L_s^2}} R_s) I_{rq}^2 \quad \text{…………………………..(3.9)}$$

In (3.5), I_{rq} has been used to control stator active power, and φ_s remains approximately constant as described above, then the generator copper loss is a function of direct rotor current I_{rd}. For the copper loss to be minimal, it is necessary that:

$$I_{rd} = \frac{L_m \varphi_{s\,Rs}}{L_s^2 R_r + L_m^2 R_s} \quad \text{…………………………………………………………… (3.10)}$$

As R_s very small and I_{rd} becomes zero, the reactive power also approaches to zero.
By substituting the expression of direct rotor current I_{rd} in (3.5), we get the expression of reactive power optimal exchanged between the stator of DFIG-generator and grid as:

$$Q_{s-opt} = Q_s^{ref} = \frac{V_s}{L_s} L_m \left(\frac{L_m \varphi_{s\,Rs}}{L_s^2 R_r + L_m^2 R_s} \right) + V_s \frac{\varphi_s}{L_s} \quad \text{…………………………………………… (3.11)}$$

As explained in chapter two, the power captured through turbine from the wind is maximized if the machine speed is adapted such that the power coefficient is maximum ($C_P = C_{Pmax}$), which occurs for a determined tip speed ratio (λ_{opt}). The DFIG control aims to keep the machine speed in its optimum value and hence, to maximize the produced power in a vast range of wind speeds, according to the following expression:

$$\Omega_{mec}^{ref} = G \frac{\lambda_{opt} V}{R} \quad \text{………………………………………………………………… (3.12)}$$

Therefore, the stator active power reference injected to the electric power grid can be obtained as:

$$P_s^{ref} = P_{opt} = 0.5\rho\pi R^5 \frac{\Omega_m^2}{\lambda_{opt}^3} C_{P_{max}} \quad \text{……………………………………… (3.13)}$$

Where, P_{opt} is the optimal power that can be captured from the wind.
Based on the control strategy discussed above, figure. 3.1 shows an implementation of the control of the RSC.

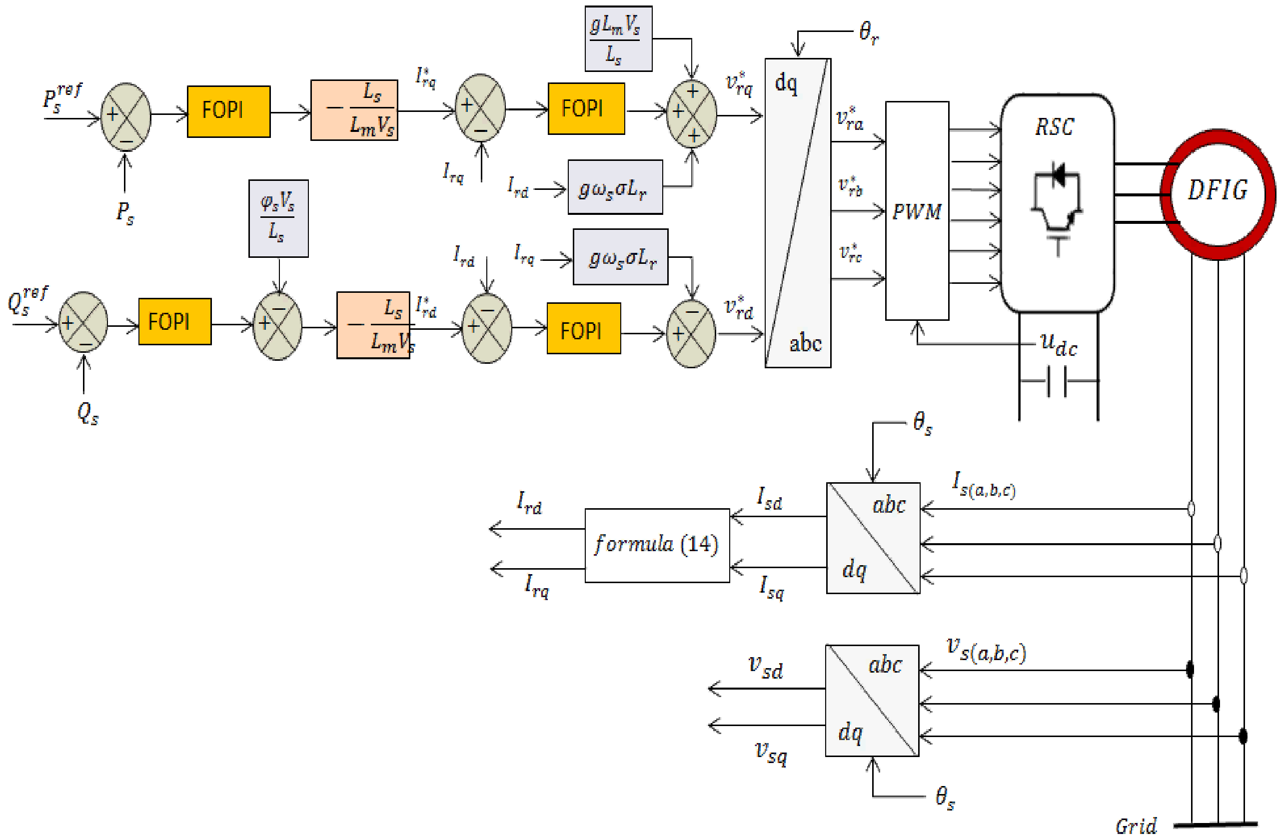


Fig. 3.1 Implementation of RSC control system

Where, the formula (14), represents equation (3.7) in my scenario.

3.2.1 Current and Power control loop

Here, the objective is to control current loop, I_{qr} to evaluate the controller performance and extract maximum power. The control system has inner current quadrature loop I_{qr} and outer power loop, P_s . To regulate the power optimally, it will set up two control loops one ach axis with a fractional order proportional integral regulator for each, a loop for power and one for the current while compensating for interference terms and coupling of the d and q axes.

The figure.3.2 shows the proposed control diagram of the RSC control using fractional order PI controllers in the q axis according to vector control approach. In this figure, the term C_d→q = $\omega_s\, g\sigma L_r I_{dr}$ represented the cross coupling between d and q axis and $F_q = gL_m V_{rs}/L_s$ is the disturbance term. These two terms depend strongly on DFIG slip; but, in most operating cases, DFIG operates around synchronous speed; accordingly, these terms do not have significant effect in the steady state working mode and could be compensated by adding fed forward terms, as shown in block diagram.

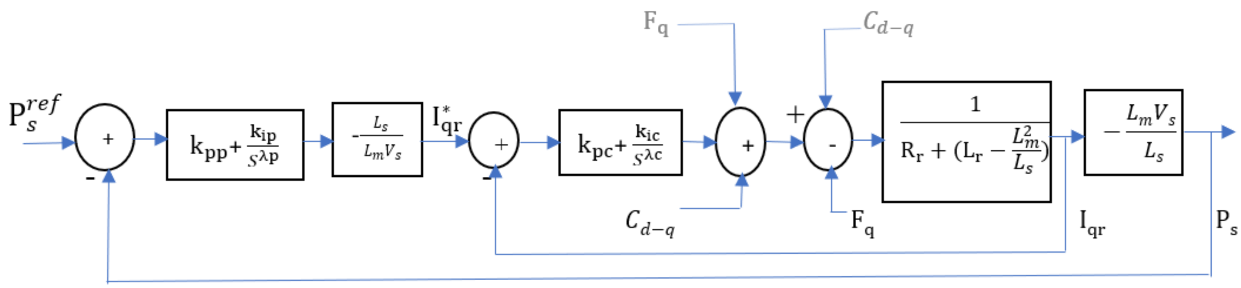


Fig.3.2 The proposed block diagram for applying FOPI controllers for current and power

Where,

k_{pp} and k_{ip} are the proportional and integral controller gain for power respectively

k_{Pc} and k_{ic} are the proportional and integral controller gain for current respectively

λ_p and λ_c are the λ values for power and current respectively

From this block diagram, the two loops are Current control loop (Inner) and Power control loop (Outer). Both contains FOPI controller and the same plant. The plant transfer function for both current loop and power loop are calculated from this block.

3.2.2 Speed control loop

If the mechanical torque, T_{em} is set equal to the reference torque, T_{em}^* as is common to do, the steady state difference between the two will result in a continuous increase or decrease of the rotor speed due to the swing equation defined in equation (3.14) below. This can be corrected with a speed controller in cascade with the current controller that is used to adjust T_{em}^* in order to keep the rotor speed constant. The rotor speed reference value can be obtained based on the power speed relationship of the wind turbine, typically in the form of a table that shows the relationship of rotor speed and the input mechanical power (or mechanical torque). The actual rotor speed can thus be measured and compared to the reference value.

$$T_{em} - T_L = J\frac{d\omega_m}{dt} + f\omega_m \quad (3.14)$$

Where, T_{em} is the electromechanical torque and T_L is load torque.

Assume T_L is zero here,

$$\frac{\omega_m}{T_{em}} = 1/(Js + f) \quad (3.15)$$

Which is equal to the transfer function of the speed as expressed on the figure below.

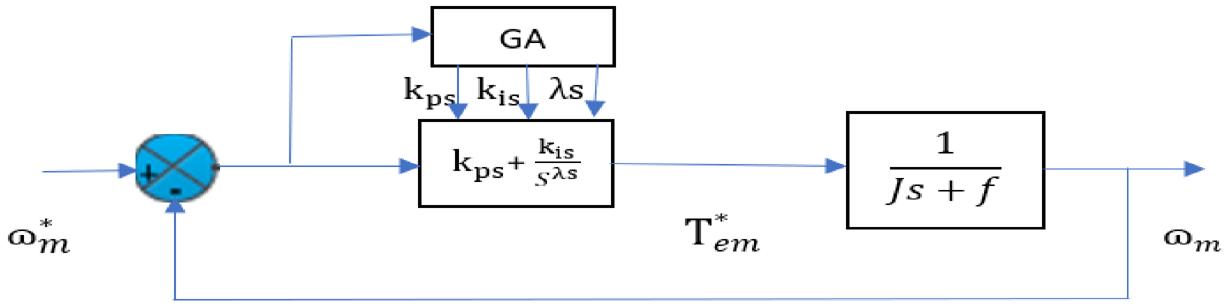


Fig. 3.3 Speed control block diagram

Using this block diagram with the designed values of J and f values, the values of the FOPI parameters (k_{ps}, k_{is} & λs) are optimized by GA optimization technique which will be discussed in the next section.

3.3 Genetic Algorithm optimization technique

The most popular evolutionary algorithm is the Genetic Algorithm (GA), invented by John Holland at the University of Michigan in 1975 [26]. The basic element of GA is the chromosome. This contains the generic information for a given solution and is typically coded as a binary string. Initially, population of chromosomes created randomly represent number of solutions to a given problem. A fitness function, which is in effect a performance index, is used to select the best solutions in the population to be parents to the offspring's that will comprise the next generation. The fitter the parent, the greater the probability of selection. This emulates the evolutionary process of "survival of the fittest" [27]. GA repeatedly modifies a population of individual solutions.

The basic steps of genetic algorithm are as follows.

1. **Start**: Generate a random population of n chromosomes which have a proper form for the problem.

2. **Run fitness function**: Evaluate the fitness function using each chromosome in the population.

3. **Result test**: Judge the n evaluated results. If conditions are satisfied, then GA stops and outputs the best chromosome of current population.

4. **Selection**: Select two or more parent chromosomes from a population according to their fitness (the better the fitness of a chromosome, the greater is its chance of being selected).

5. **Crossover**: With a crossover probability cross over the parents to form a new offspring (children). If no crossover was performed, the offspring is an exact copy of the parents.

6. **Mutation**: With a mutation probability mutate new offspring at each locus (position in chromosome).

7. **Replace**: Place new offspring in the old population to create a new population and use a new generated population for a further run of the algorithm.

8. **Loop**: Go to step 2.

To implement the GA optimization, first the fitness function must be defined. The fitness function is the objective function that needs to be minimized. In this thesis the objective function contains the function that represents the integral time absolute error between desired and actual output. Besides the fitness function the number of variables to be optimized should also be specified. The variables to be optimized are PI current and Power controller's gains (k_p , k_i) and λ in case of fractional order controller to ensure optimal control performance for the wind turbine. The flowchart of GA and the block diagram of the controller structure is given below in figure 3.2 and 3.3 respectively.

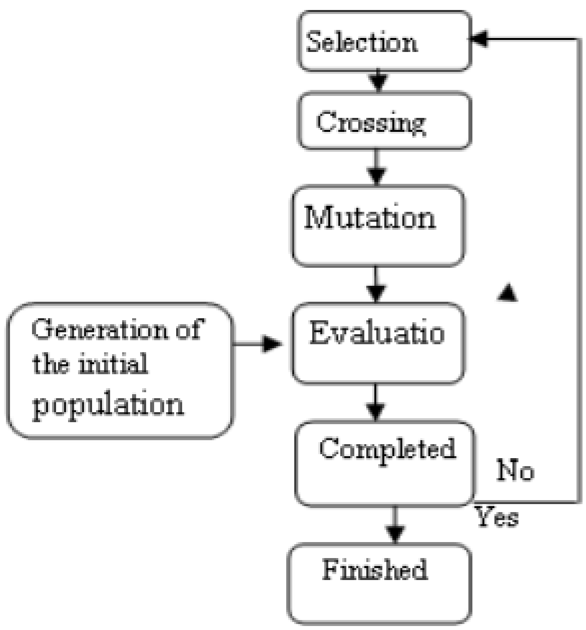


Fig. 3.4 Flowchart of Genetic Algorithm

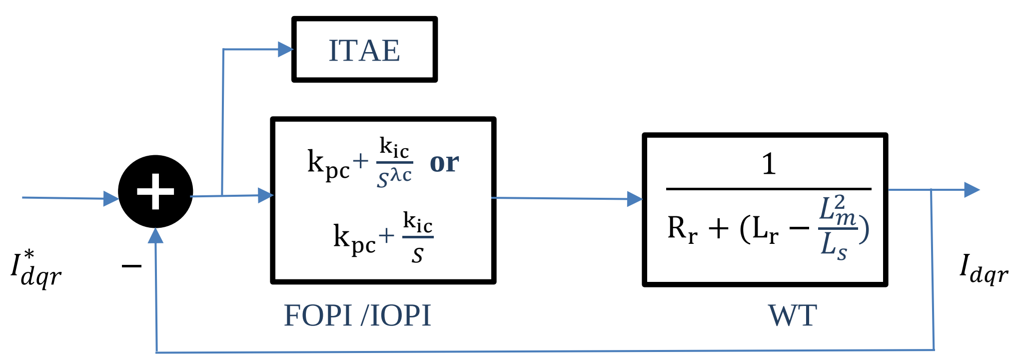


Figure 3.5 Structure of FOPI and IOPI controller with fitness function

Where, FOPI is the fractional order proportional integral rotor current controller transfer function

IOPI is integer order proportional integral of rotor current controller transfer function

Turbine is the plant transfer function

I_{dqr} is the direct and quadrature of rotor current

WT is wind turbine

Since the objective is to minimize the error between the reference and actual values, the fitness function selected in the GA optimization was considered as the integral time absolute error (ITAE). This well-known index could be used for optimization and controller tuning of current and equated as below:

$$ITAE = \int_0^t t|\Delta I_{dqr}|\, dt \quad (3.14)$$

Where, $\Delta I_{dqr} = I_{dqr}^{*} - I_{dqr}$ is the error between reference and measured current.

The FOPI/IOPI controllers' parameters are tuned using GA optimization technique and then applied to the system to minimize the error between reference current and the measured one. Then the total error is expressed using ITAE.

3.4 Design of FOPI and IOPI controllers using GA optimization technique

One of the main challenges in the design of controller for real time applications is getting the optimal values of controller parameters, which play a vital role in determining the performance and optimality of the controller. Commonly, trial and error approach is employed for selecting the parameters of controller, which is not only burdens of design but also results in non-optimal response. Hence, to find the optimal values of controller parameters, the genetic algorithm parameters of are designed and applied for current control of turbine. The transfer function of PI controller is

$$G_c(s) = k_p + \frac{k_i}{s} \quad (3.15)$$

Mostly for industrial applications, integer order controllers are used for controlling purpose. Now day's fractional order PID (FOPID) controller is used for industrial application to improve the system control performances. The most common form of a fractional order PID controller is the $PI^{\lambda} D^{\mu}$ controller [28]. FOPID controller provides extra degree of freedom for not only the need of design controller gains but also design orders of integral and derivative. The orders of integration and derivation are not necessarily integer, but any real numbers. As shown in figure 3.4, the FOPID controller generalizes the conventional integer order PID controller and expands it from point to plane. This expansion could provide much more flexibility in PID control design. The transfer function of such a controller has the following form [29].

$Gc(s) = k_p + \frac{k_i}{s^{\lambda}} + k_d S^{\mu}$ ………………………………………………………………… (3.16)

By making μ=0, and k_d=0 fractional order PI will result as

$Gc(s) = k_p + \frac{k_i}{s^{\lambda}}$ …………………………………………………………………………. ….(3.17)

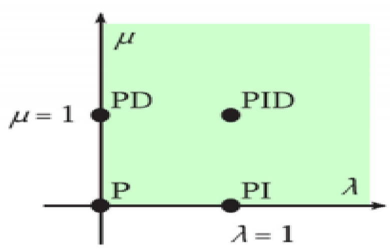


Figure 3.6 General form of a fractional order PID controller

It is Clear, by selecting λ = 1 and μ = 1, a classical PID controller can be recovered. Using λ = 1, μ = 0, and λ = 0, μ = 1, respectively corresponds to the conventional PI & PD controllers. All these classical types of PID controllers are special cases of the $PI^{\lambda} D^{\mu}$ controller. Fractional and integer order PI controllers are optimized by Genetic Algorithm function 'ga' of MATLAB 2018a. The parameters are initialized by MATLAB programming first and integrated to the GA optimization after designing of GA. GA optimization tool calls the initialized function from MATLAB programming code and set the parameters' values based on the designed parameter. Then the IOPI controller parameters gain (k_p & k_i) and the FOPI (k_p, k_i & λ) are obtained using GA optimization techniques and applied to the controller. The below table 3.1 shows the GA parameters designed to tune both IOPI and FOPI controllers' parameters for speed, Power and Current using the above figure 3.2 & 3.3 block diagrams and ITAE as objective function.

Table 3.1 Parameters of GA

GA Property	Values/Descriptions
Population Size	80
Selection Function	Tournament Selection
Mutation Function	Uniform
Crossover Function	Intermediate
Number of Generation	200 for PI and 300 for FOPI
Crossover Probability	0.8
Mutation Rate	0.1
Tolerance	1e-6
Number of Iteration	51

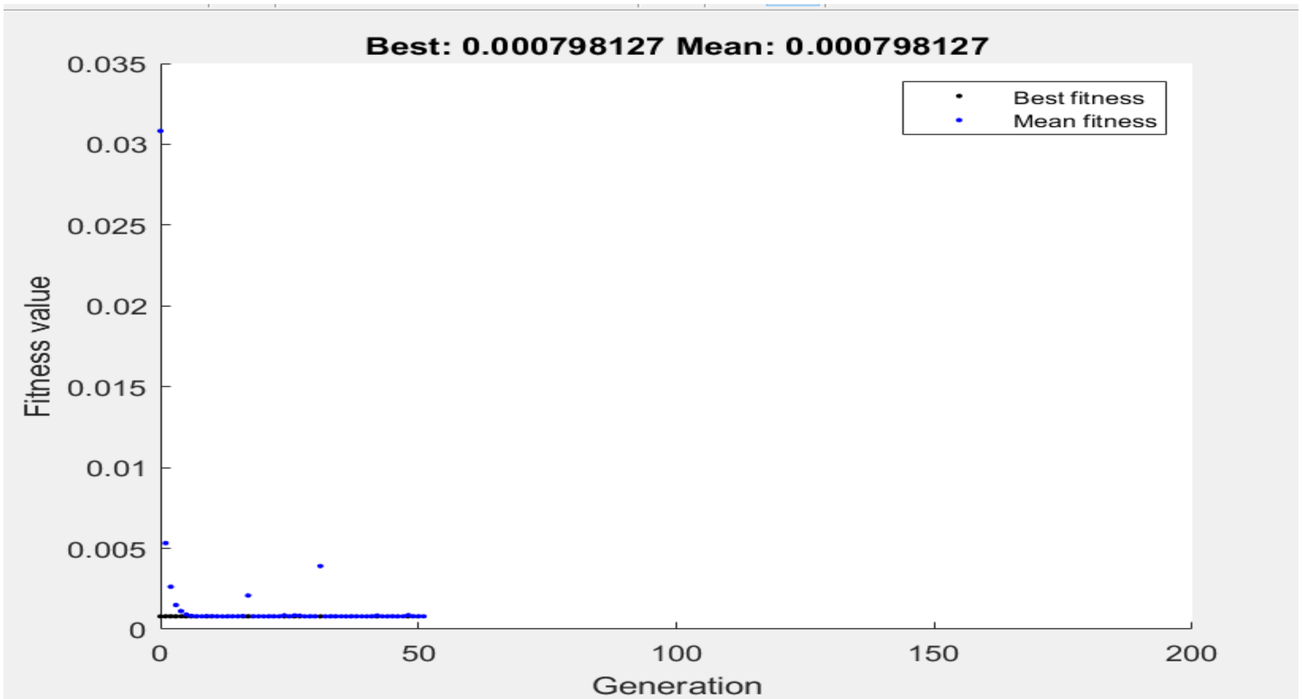


Figure 3.7a Best evaluated outputs of fitness function for PI Current controller

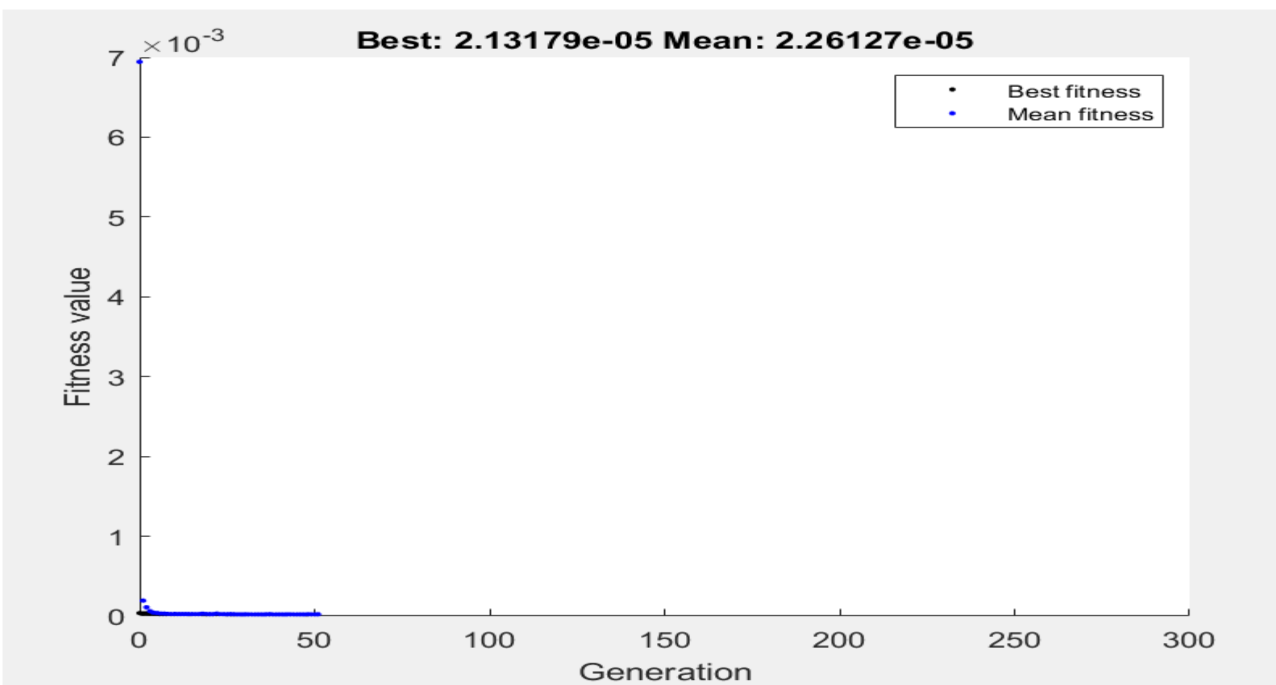


Figure 3.7b Best evaluated outputs of fitness function for FOPI Current controller

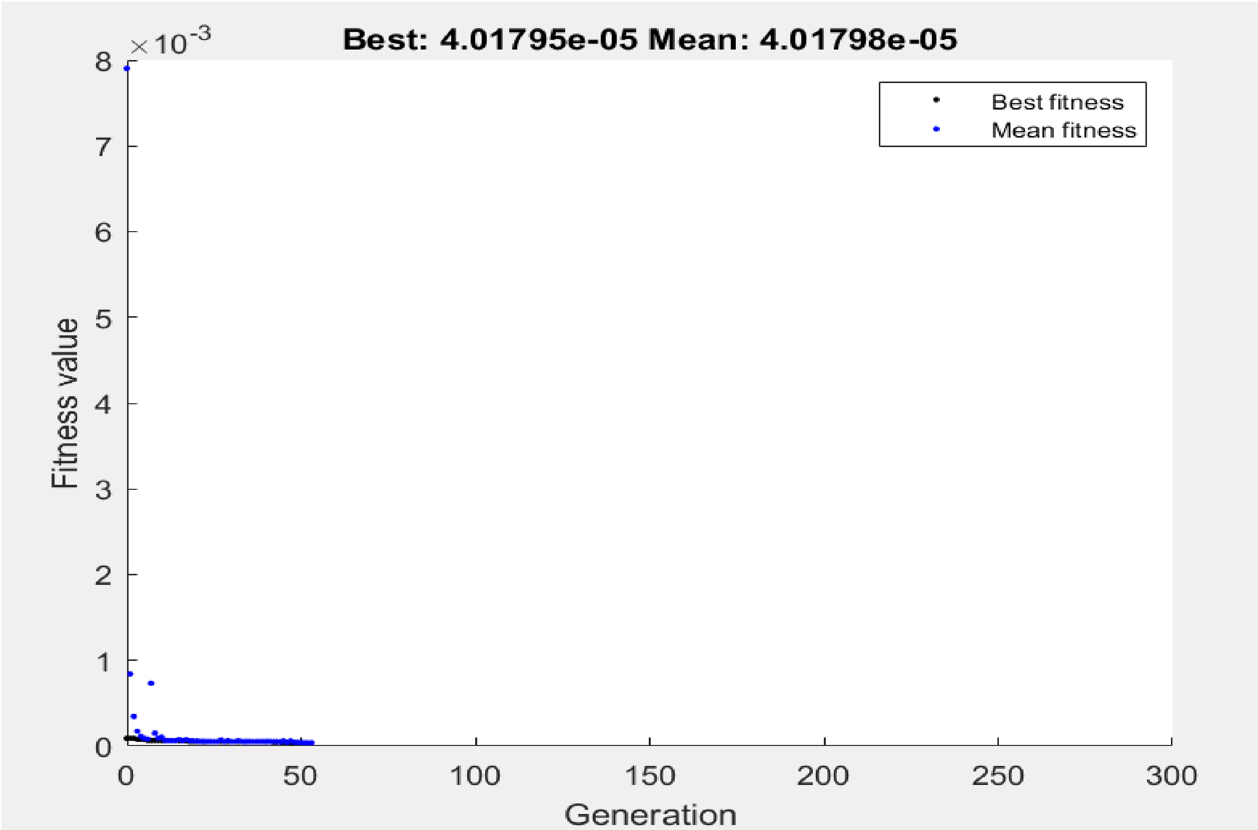


Figure 3.7c Best evaluated outputs of fitness function for FOPI Power controller

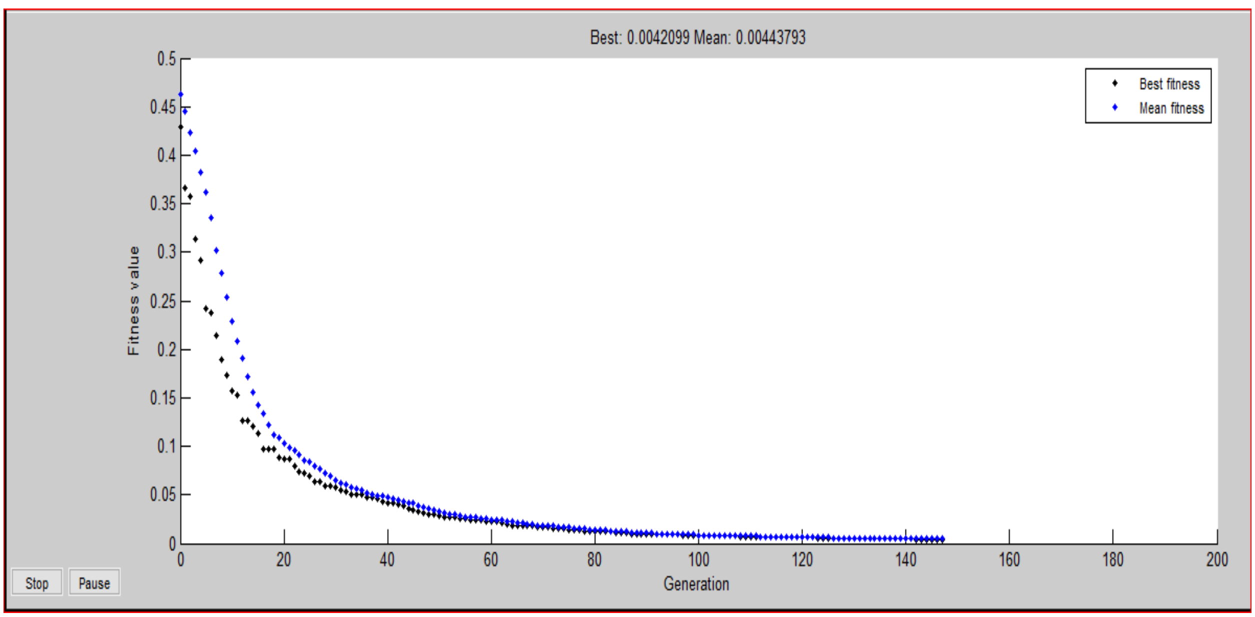


Figure 3.7d Best evaluated outputs of fitness function for PI speed controller

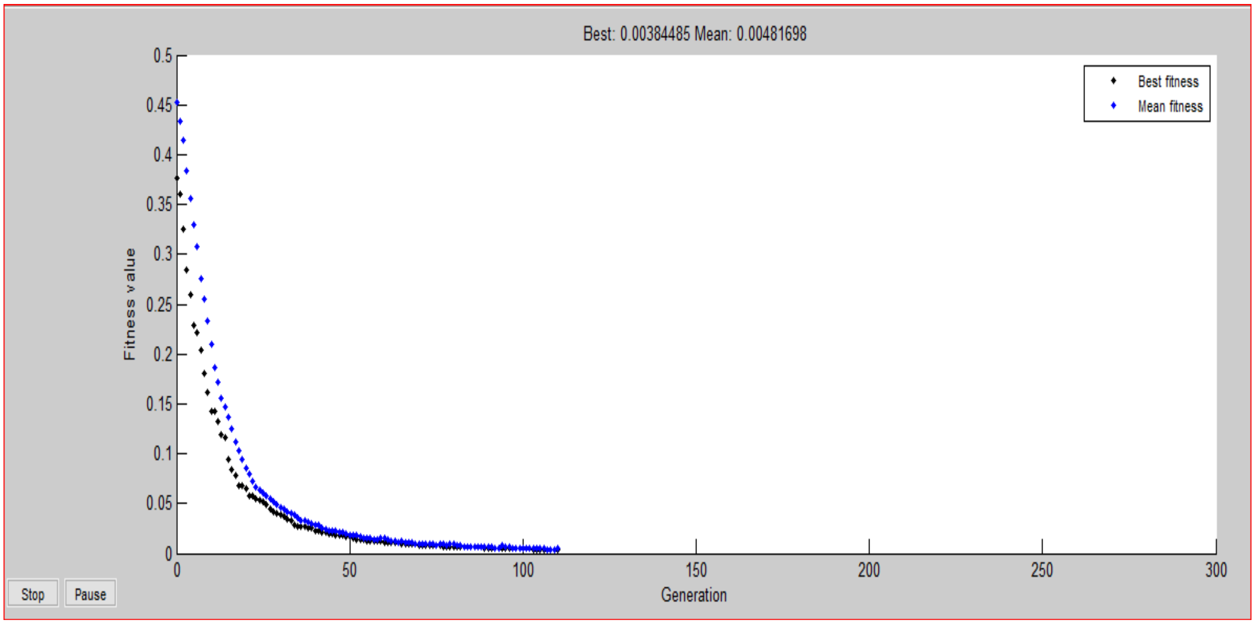


Figure 3.7e Best evaluated outputs of fitness function for FOPI speed controller

The parameters of PI and FOPI for current, power and speed controllers obtained according to the procedure of optimization by the technique of GA are given below in table 3.2, table 3.3 and table 3.4 respectively.

Table 3.2 PI & FOPI Current controller gain values

PI Controller			
Parameter	k_{pc}	k_{ic}	
Value	0.111	39.724	
FOPI Controller			
Parameter	k_{pc}	k_{ic}	λ_c
Value	0.565	38.752	0.989

Here, the values of k_{pc}, k_{ic} and λ_c are extracted after tuned by GA using the current, I_{qr} transfer function.

Table 3.3 PI & FOPI Power controller gain values

PI Controller			
Parameter	k_{pp}	k_{ip}	
Value	0.328	435.075	
FOPI Controller			
Parameter	k_{pp}	k_{ip}	λ_p
Value	0.384	468.947	0.994

Here, the values of k_{pp}, k_{ip} and λ_p are extracted after tuned by GA using the power, P_s transfer function.

Table 3.4 PI & FOPI Speed controller gain values

PI Controller			
Parameter	k_{ps}	k_{is}	
Value	79.8905	0.2348	
FOPI Controller			
Parameter	k_{ps}	k_{is}	λ_s
Value	46.0978	49.4395	0.0389

Here, the values of k_{ps}, k_{is} and λ_s are extracted after tuned by GA using the speed, ω_m transfer function.

The chromosomes for the PI controller parameters are [x1, x2] and for fractional order PI controller are [x1, x2, x3]. Parameters of GA use values of the ‘ga’ function which are listed in table 3.1. When the performance needs to be improved, the parameters may be changed by ‘gaoptim tool’ function.

CHAPTER FOUR

4. SIMULATION RESULTS AND DISCUSSION

In this chapter, the simulation results are obtained beneath various operating conditions to evaluate performances of designed FOPI controller, and to validate the advantages of proposed fractional order PI controller in comparison with the integer one for the studied wind energy generation system. In this case, the step response of rotor current, rotor speed and power are studied based on the designed in the previous chapter for both IOPI and FOPI. Then the performances of IOPI and FOPI controllers are evaluated in terms of rise time, settling time and percentage overshoot in related to the step response. The overall simulation performance is evaluated and discussed by varying Wind speed.

4.1 Step Response Simulink Model

The mathematical equations presented in chapter two and three are used to model the WGS in MATLAB/Simulink R2018a environment. Firstly, I have tried to model the simple block diagram of rotor current, rotor speed and power in related the step response which are tuned in chapter three using GA. Then the overall system Simulink block diagram has been developed in MATLAB/Simulink.

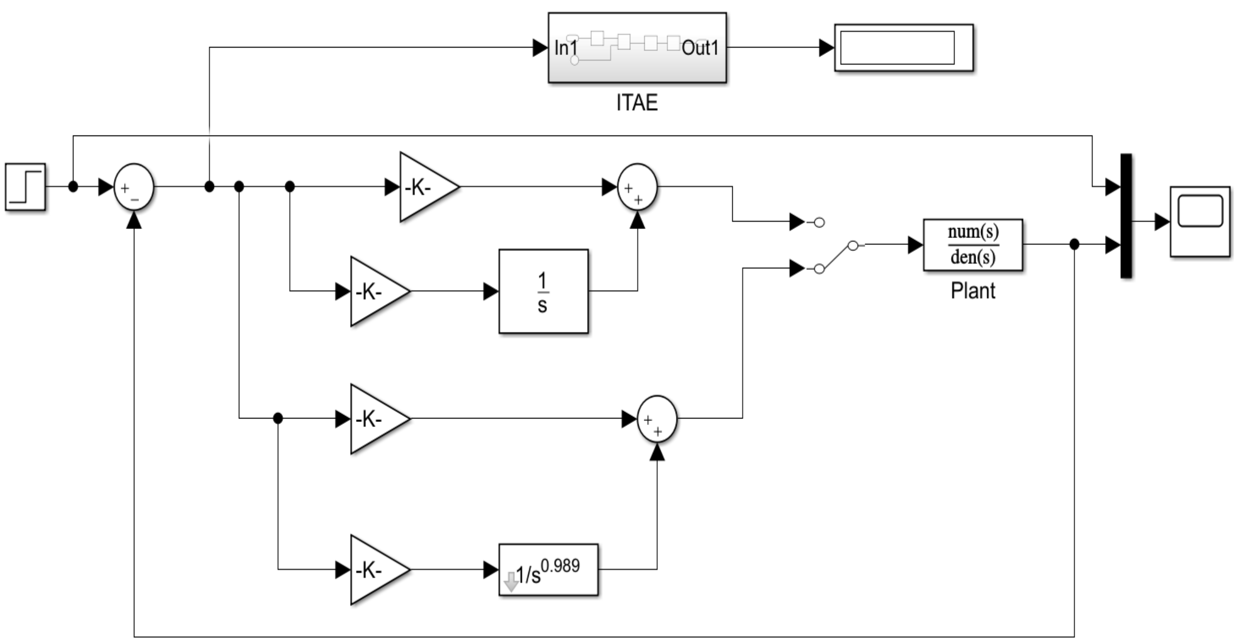


Fig. 4.1a IOPI & FOPI for current controller Simulink block for step response

Where, 0.989 is the value of λ for current after tuned and $\frac{num(s)}{\mathrm{den(s)}}$ is transfer function of the plant which is equal to $\frac{1}{0.0003s+0.021}$.

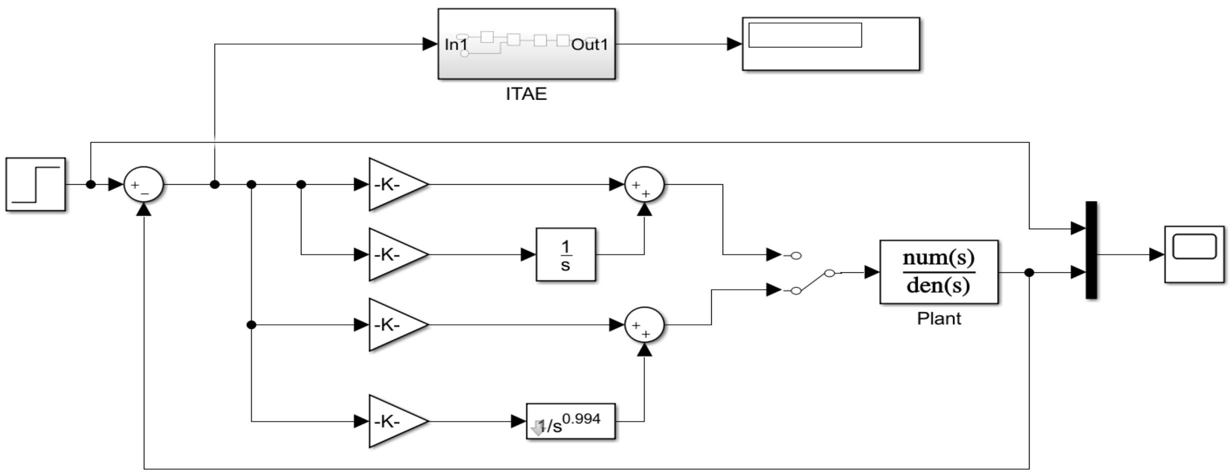


Fig. 4.1b IOPI & FOPI Power controller Simulink block for step response

Here, $\frac{num(s)}{\mathrm{den(s)}}$ is the transfer function which is $\frac{s+5}{0.0012s^2+s+5}$ and 0.994 is the value of λ extracted after tuned.

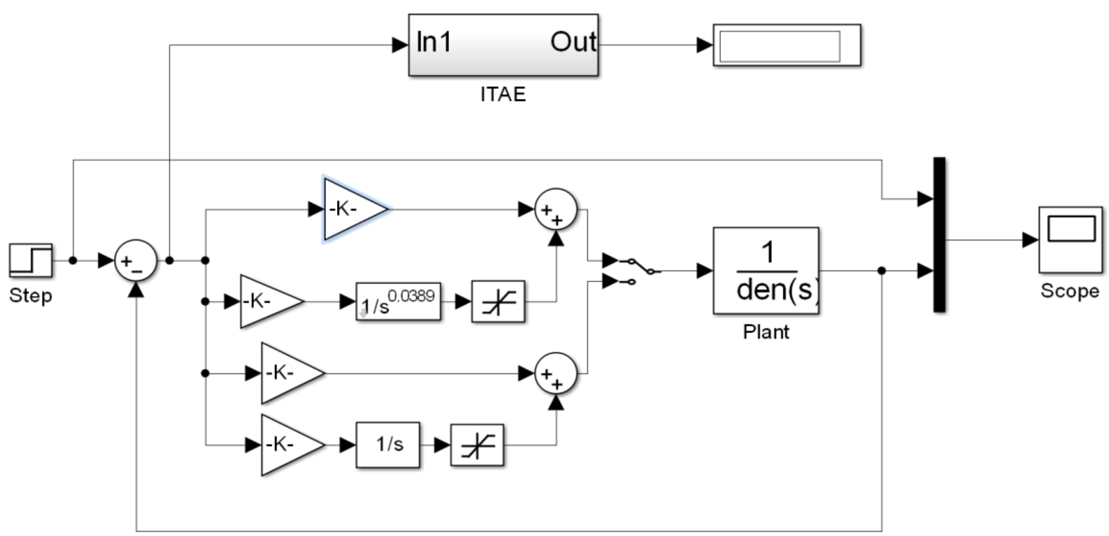


Fig. 4.1c IOPI & FOPI Speed controller Simulink block for step response

Where, $\frac{1}{\mathrm{den(s)}}$ is the transfer function which is $\frac{1}{5.04s+0.001}$ and 0.0389 is the value of λ_s.

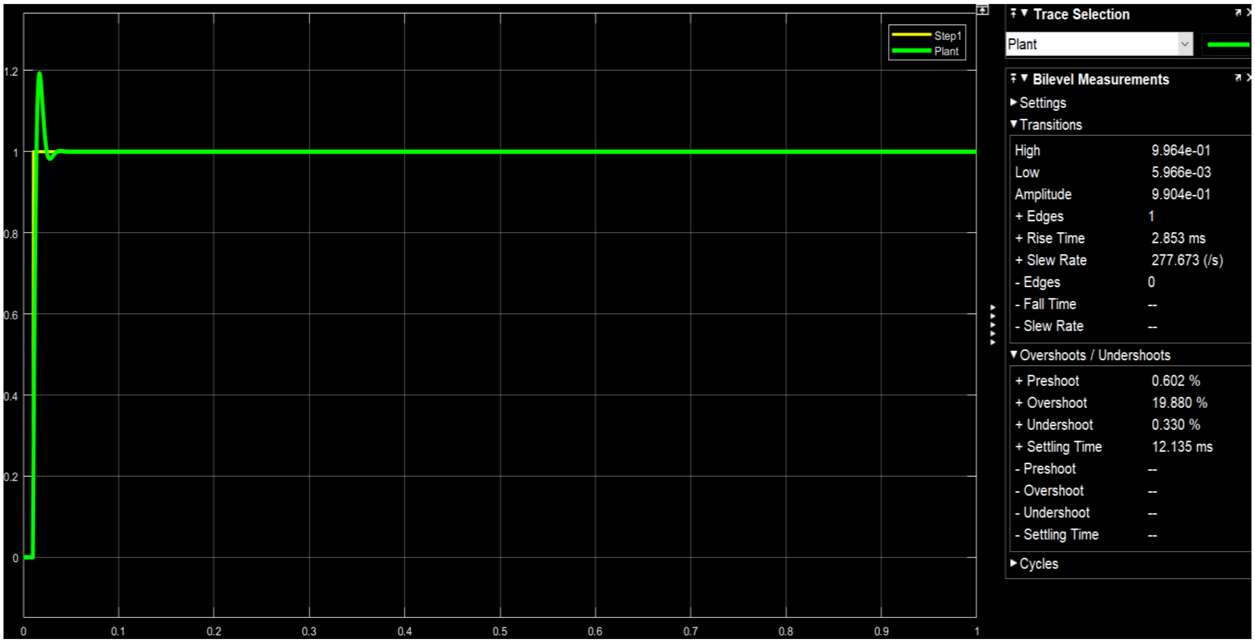


Fig. 4.2a IOPI step response current controller

From this, the IOPI step response for current has evaluated in terms of rise time, settling time and overshoot. Where, rise time = 0.002853s, settling time=0.012135s, overshoot=19.88%, undershoot =0.330, and ITAE=0.00004269.

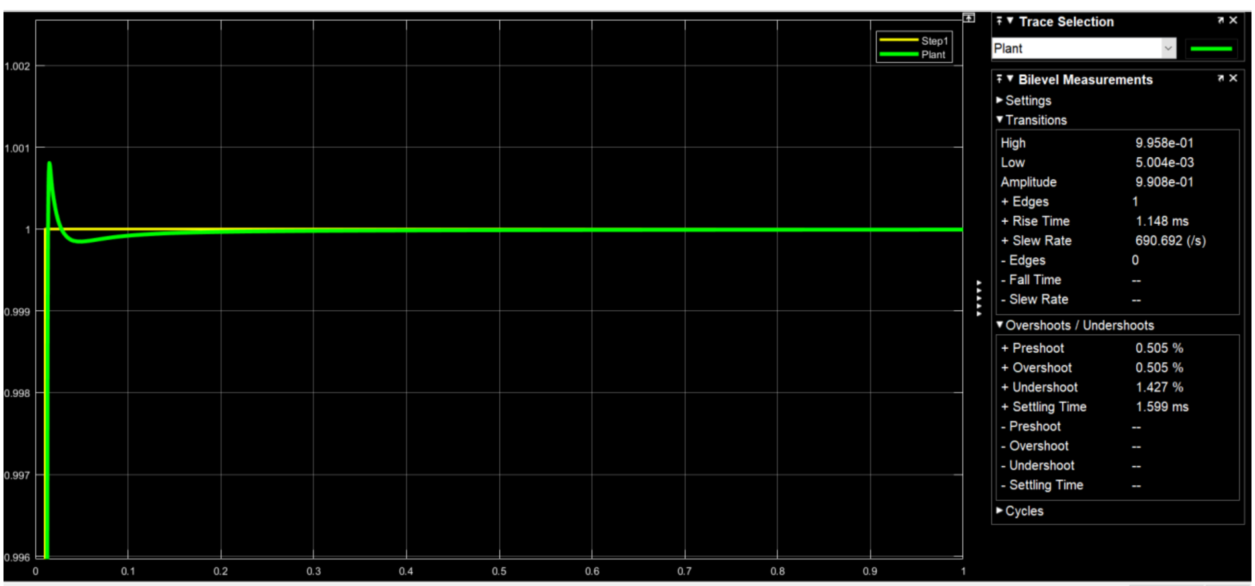


Fig. 4.2b FOPI step response current controller

From this, FOPI step response for current has shown some improvements when compared to IOPI in terms rise time, settling time and high improvement on the percentage overshoot. Where, rise time = 0.001148s, settling time = 0.001599s, overshoot = 0.505%, undershoot=1.427%, and ITAE = 0.000001216. Here, the fractional order PI has shown good performance in current control related step response.

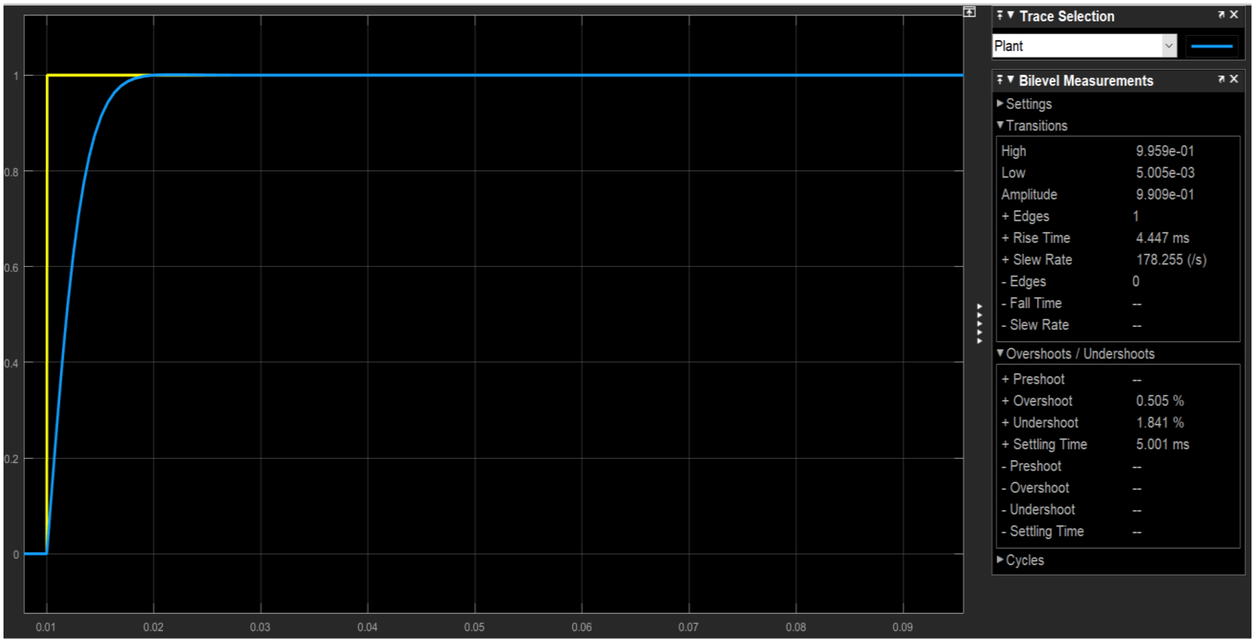


Fig. 4.2c IOPI step response power controller

From fig. 4.2c, IOPI step response for power controller has the following values in terms of rise time, settling and overshoot. Which is, rise time = 0.004447s, settling time = 0.005001s, overshoot = 0.505% and ITAE = 0.00003006.

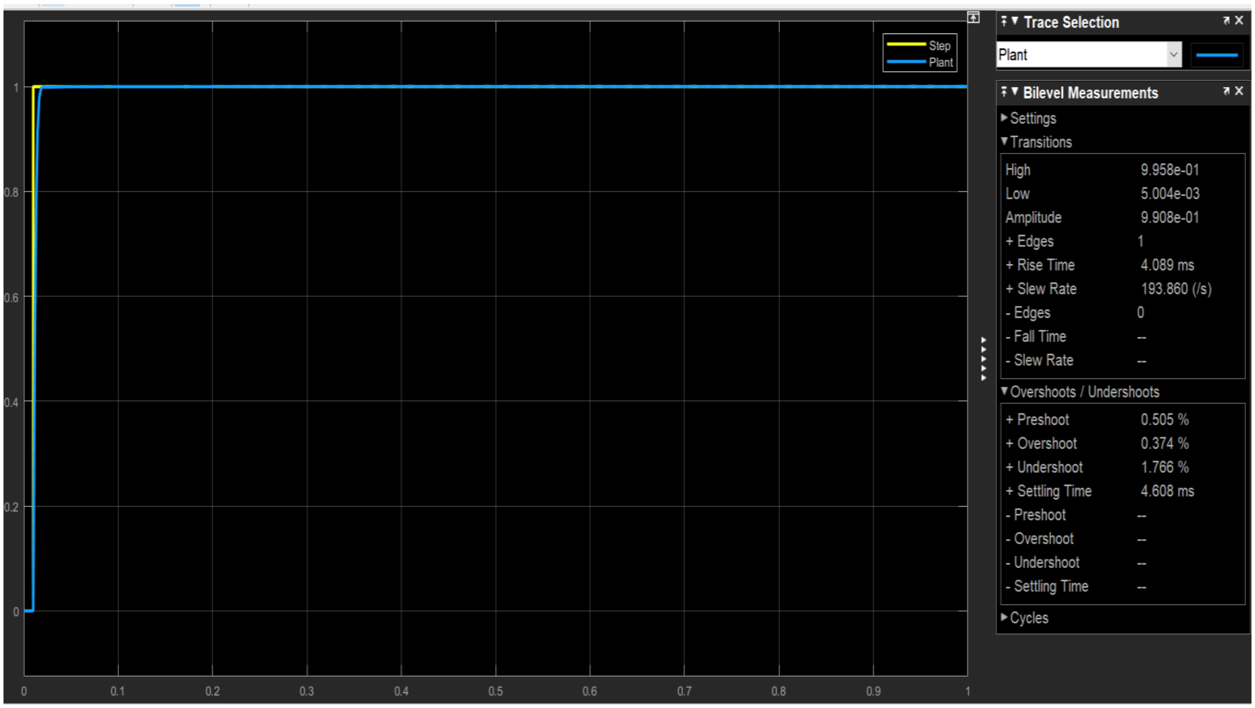


Fig. 4.2d FOPI step response power controller

From this, FOPI step response for power controller has shown some improvements when compared to IOPI in terms of rise time, settling time and percentage of overshoot. Where, rise time = 0.004089s, settling time = 0.004608s, overshoot is 0.374% and ITAE = 0.00001348.

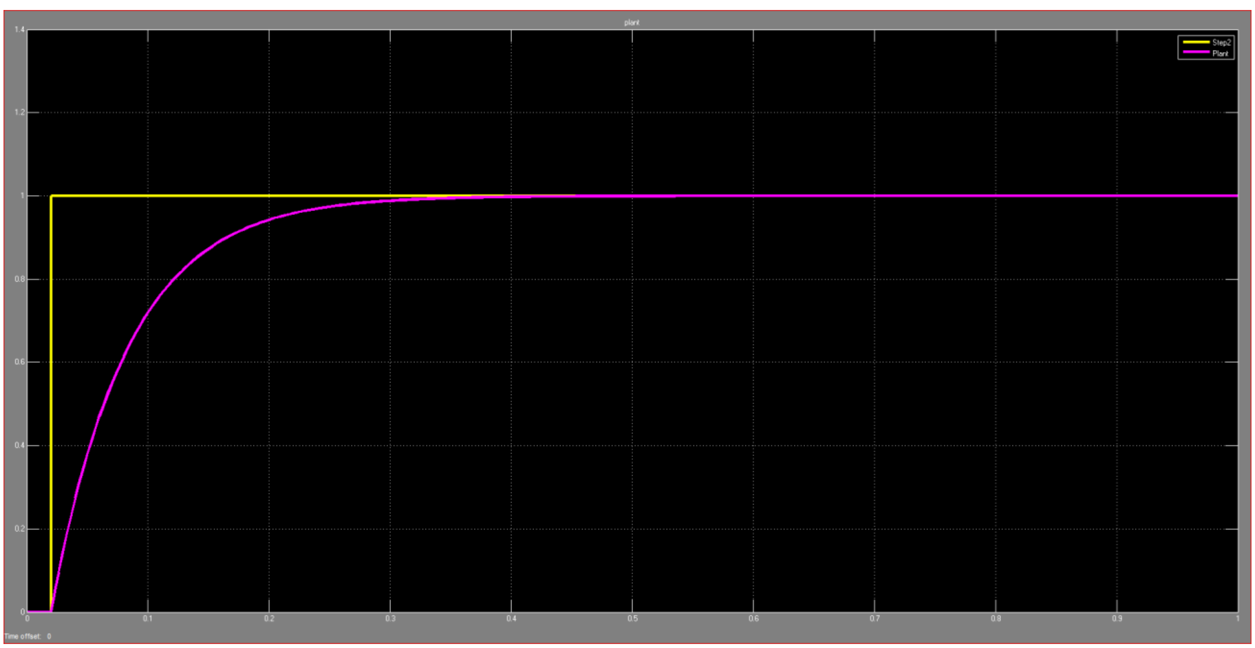


Fig. 4.2e PI step response Speed controller

PI step response for speed controller has the following values in terms of rise time, settling and ITAE. Which is, rise time = 0.2667s, settling time = 6.9800s, and ITAE = 0.005261.

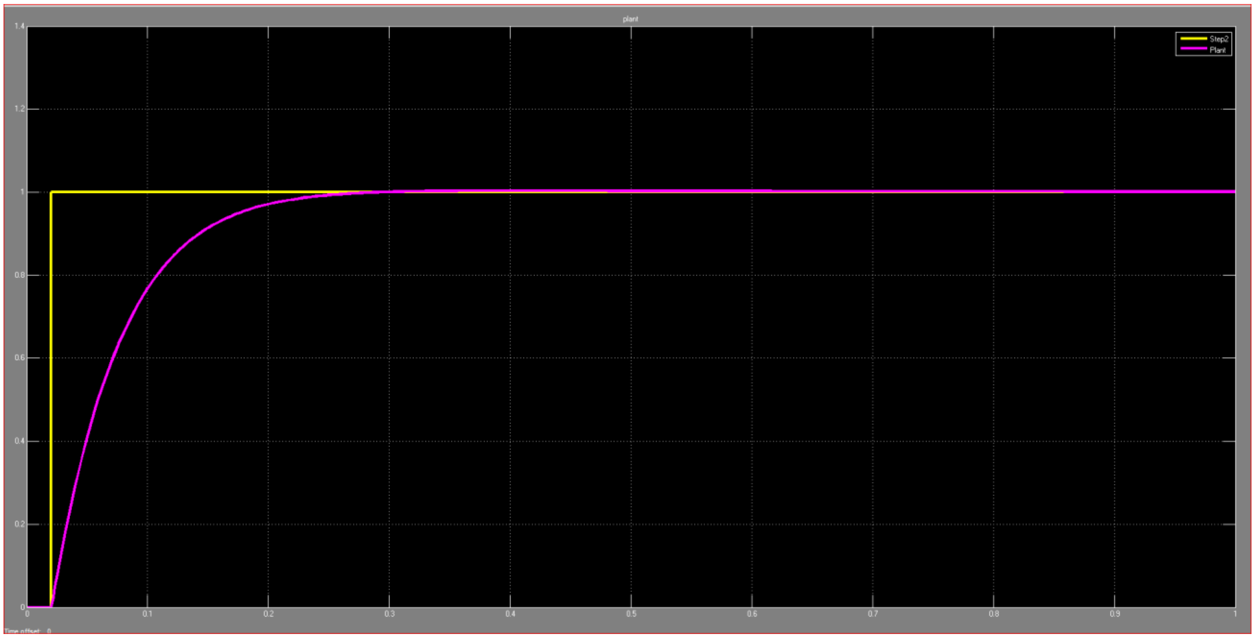


Fig. 4.2f FOPI step response Speed controller

FOPI step response for speed controller has the following values in terms of rise time, settling and ITAE. Which is, rise time = 0.6857s, settling time = 6.8700s, and ITAE = 0.004619.

The settling time and ITAE are improved in this controller when compared the integer order.

Here the step response for current and power of wind turbine, the current response has shown best performance rather power. This means current has good response in terms rise time and settling time while power has good performance in minimizing the percentage overshoot.

In all, Current, Power and Speed control loop above, FOPI has shown an improvement when compared to IOPI in terms of rise time, settling time and integral time absolute error (ITAE).

The table below shows the overall responses in terms of settling time, rise time, overshoot and ITAE.

Table 4.1 The step responses for Current, Power and Speed

Current				
Parameters	Settling time (s)	Rise time (s)	Overshoot (%)	ITAE
IOPI	0.012135s	0.002853	19.88	0.00004269
FOPI	0.001599s	0.001148s	1.427	0.00001216
Power				
Parameters	Settling time (s)	Rise time (s)	Overshoot (%)	ITAE
IOPI	0.005001	0.004447	0.505	0.00003006
FOPI	0.004608	0.004089	0.374	0.00001348
Speed				
Parameters	Settling time (s)	Rise time (s)	Overshoot (%)	ITAE
IOPI	6.9800	0.2667	---	0.00552
FOPI	6.8700	0.6857	---	0.004619

4.2 The Overall Simulink Model of WGS

The overall wind turbine Simulink model includes the aerodynamic, mechanical, electrical and control system Simulink model. Here is the regulation of the rotor currents (I_{dr} and I_{qr}) to control the active and reactive power using vector control method respectively.

4.2.1 Wind Speed Model Simulation

The wind speed model consists of average wind speed component, ramp component, gust component and turbulence component. The Simulink wind speed model is represented in below. Where the transfer function of the first order filter is given by: $\frac{300s}{300s+1}$, which is used to keep the shape of the turbulence when speed is varying.

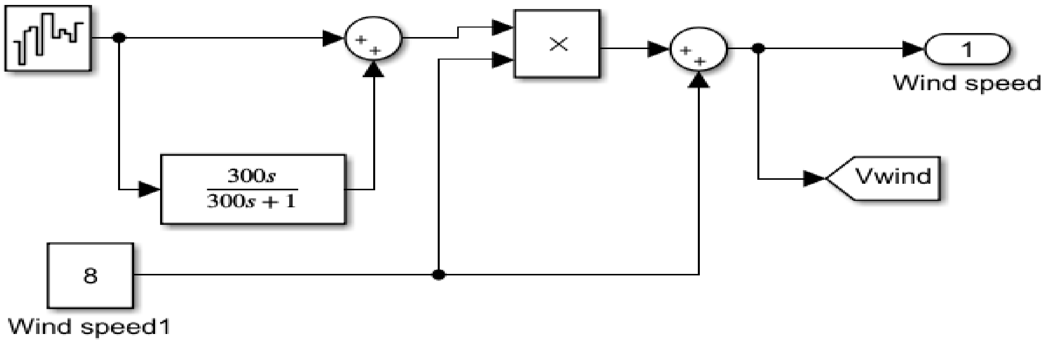


Fig. 4.3a Wind speed model simulation with average speed of 8m/s.

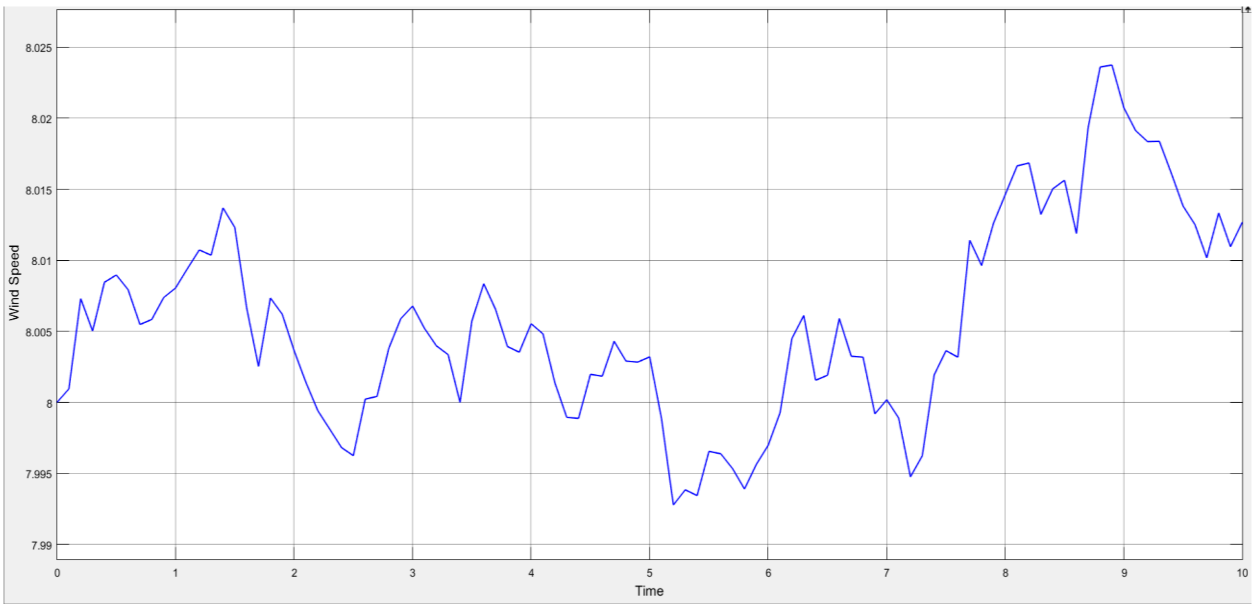


Fig. 4.3b Wind speed characteristics

Here is the wind speed profile including the above components using 8m/s as average wind speed.

4.2.2 Aerodynamic Model Simulation

The aerodynamic model, represented in Fig. 4.4. below is designed to evaluate the aerodynamic torque of the turbine shaft T_t as modelled in equation (2.13) in pervious chapter.

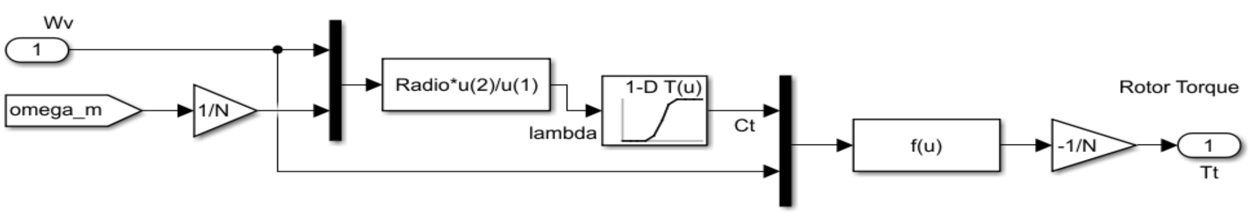


Fig. 4.4 Aerodynamic system simulation of a wind turbine

Where, Radio*u (2)/u (1) in simulation equation represents as: u (2) represents W_v, u (1) represents omega_m and Radio represents radius of turbine blade.

4.2.3 Electrical Model Simulation

Fig. 4.5 below represents the electrical system model which includes the DFIG that has its rotor connected to the rotor side convertor from the right, and its stator to the grid from the left. The grid side converter is replaced by a DC voltage source in this thesis for simplicity.

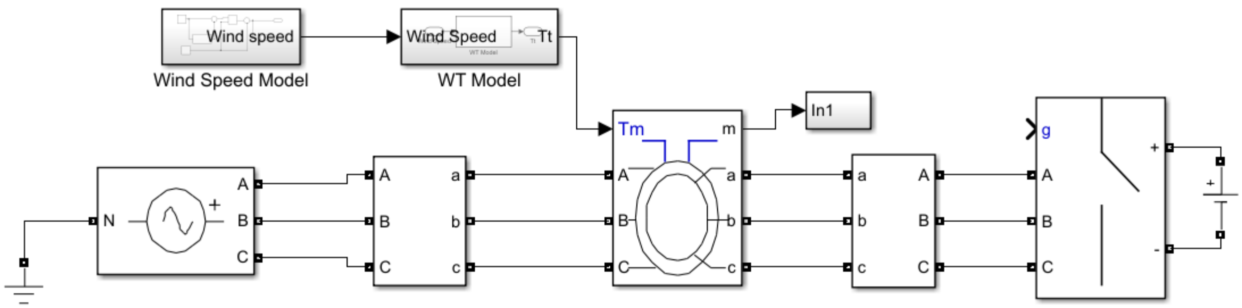


Fig. 4.5 Electrical system simulation of a DFIG wind turbine

4.2.4 Control System Simulation

In this work, an indirect speed control is designed to force the aerodynamic torque, T_{aer} to follow the maximum power curve in response to wind variations. Moreover, a vector controller for current loops (I_{dr} & I_{qr}) is used to control the rotor side converter. Fig. 4.6 shows the control system of DFIG wind turbine while Fig. 4.7 exhibits the overall Simulink design. The design consists of a DFIG that is equipped with a wound rotor induction generator that has a voltage source converter connected to the sliprings of the rotor the grid is directly coupled to the stator winding while the power converter is connected to the rotor winding.

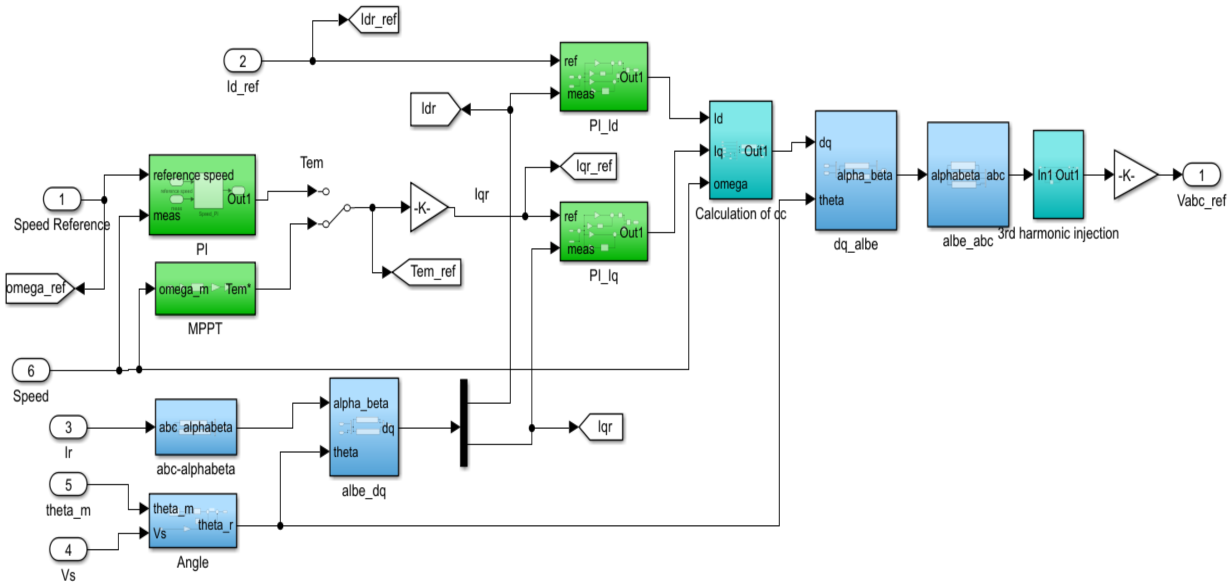


Fig. 4.6 Control System Simulation of a DFIG WT

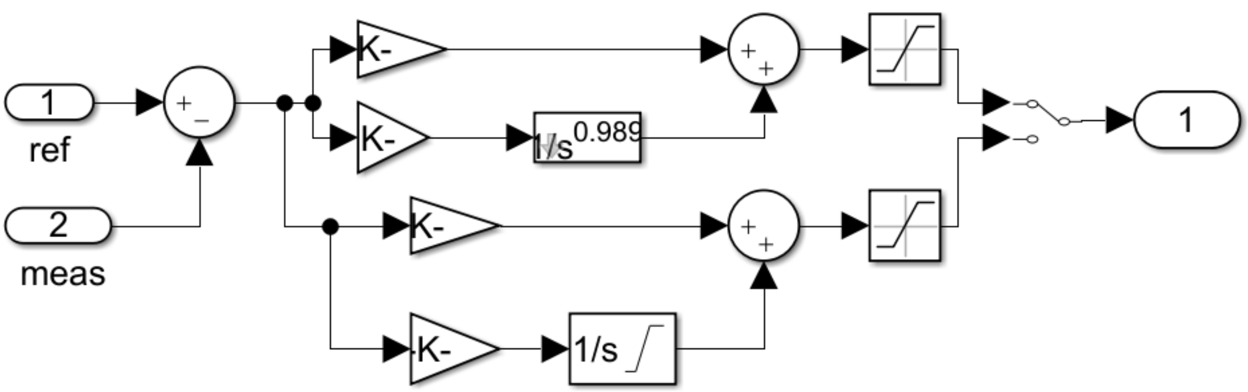


Fig. 4.6a IOPI and FOPI controller design of the DFIG wind turbine.

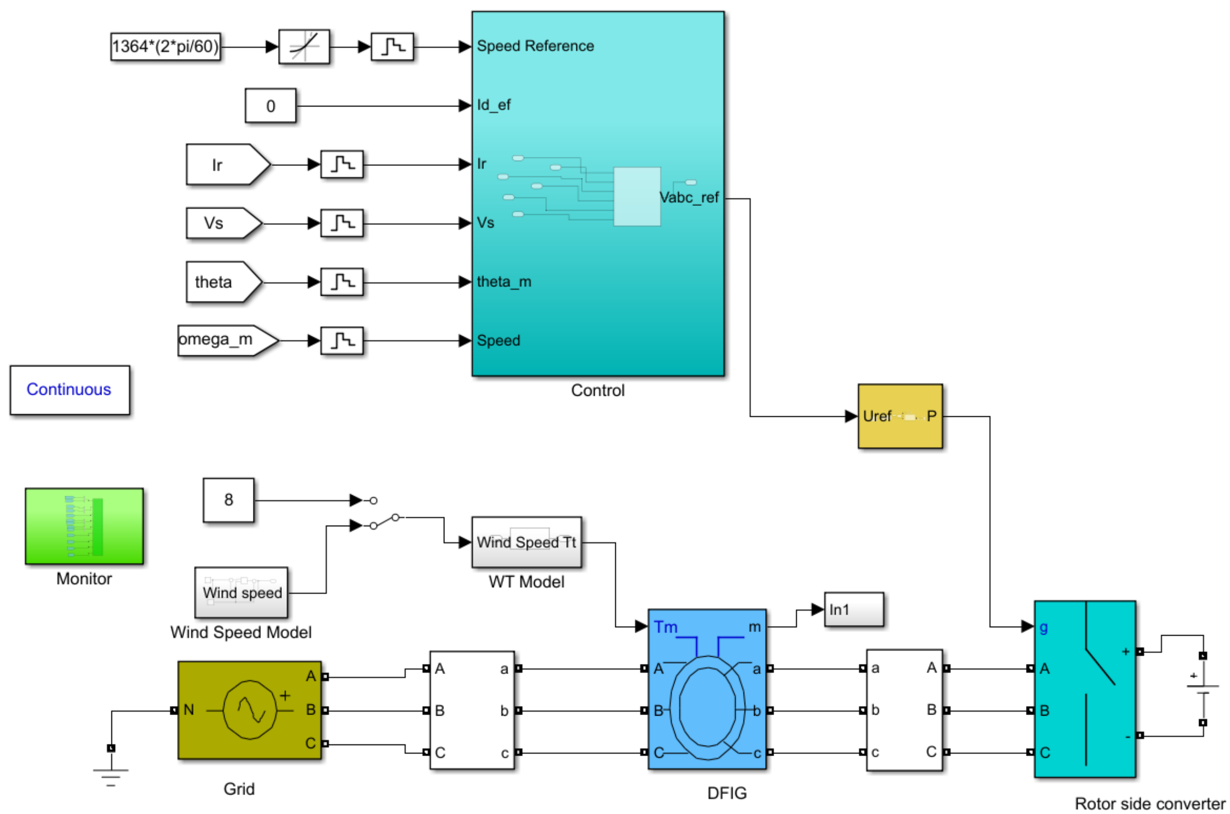


Fig. 4.7 Overall WT dynamic model design in Simulink.

Where, 1364*(2*pi/60) is the reference speed in revolution per minute which is 142.8 rad/s. The overall MATLAB/Simulink block diagram contains fractional and integer order PI controllers for both current and speed control.

4.3 Performance Analysis

In this section, the simulation results of the DFIG-Based wind turbine system using the two proposed controllers are analyzed and discussed.

4.3.1 Simulation Results for different wind speeds using GA_IOPI controller

Here is the simulation of the overall wind turbine control response, which was focused on the response of rotor currents, I_{dr} & I_{qr} in terms of rise time, percentage overshoot, under shoot and steady state error. The steady state analysis of the simulated system by using 1364 rev/min speed as reference. It is noticed that the steady state values of speed, torque, rotor current, stator current and rotor voltage are checked to match with the reference values. The rotor speed is 142.8 rad/s which is equal to 1364 rev/min that was set as reference speed. The electromagnetic torque at steady state is -5401 that is very close to the reference which is -5402. The torque is negative since it is generating mode. The d-axis rotor current is referenced to zero and it matches to steady state as described on below simulation result. Let us see the following responses for detail.

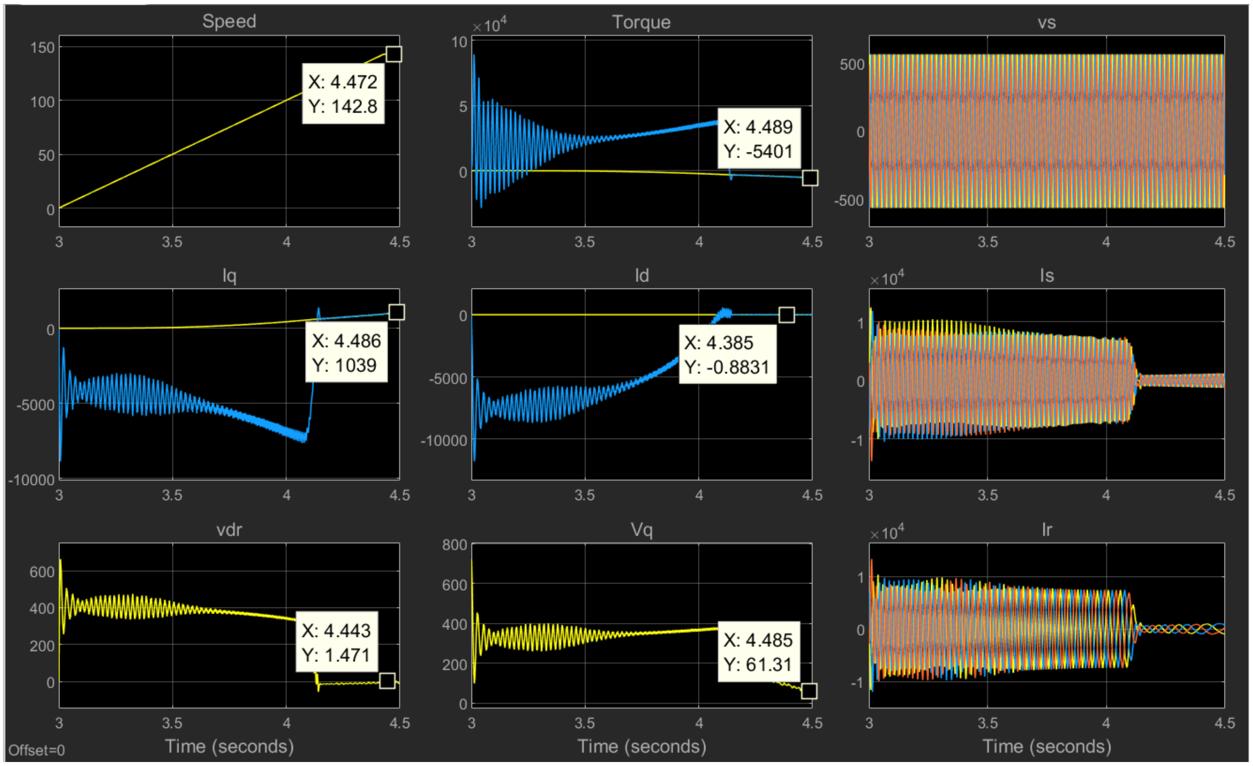


Fig. 4.8 Steady state response of the GA_IOPI simulated system with average speed 8m/s

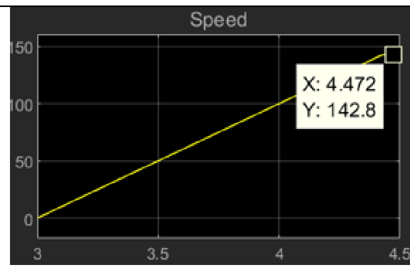
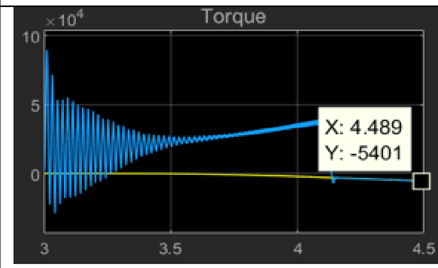
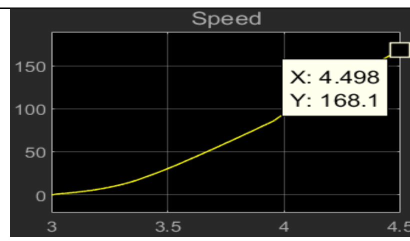
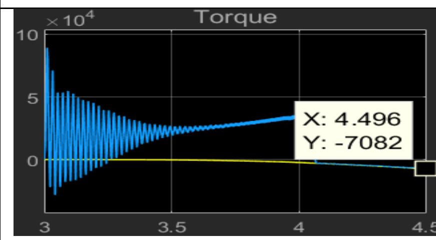
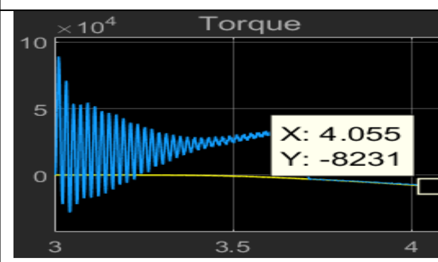
Here is the analysis of percentage overshoot/undershoot, steady state error and rise time of rotor speed, electromagnetic torque, rotor currents are presented. As compared the response of rotor currents in related to step response above, the overall response is also approximately the same as you can see from this simulation result. The detail is presented on below table.

Table 4.2 Steady state analysis for DFIG wind turbine with GA_IOPI controller.

Parameters	I_{dr}	I_{qr}
Peak Overshoot (%)	4.167	16.3
Peak Undershoot (%)	14.372	3.94
Rise time (s)	0.336	0.316

By using this steady state values of rotor speed and electromagnetic torque corresponding to different wind speeds, I have tried to show how much amount of power is extracted from wind based on the GA_IOPI controller as below.

Table 4.3 Extraction of Power with GA_IOPI at different wind speed

Wind speed (m/s)	Power (MW)	Rotor Speed	Electromagnetic Torque
8	142.8*5401=0.77		
10	168.1*7082=1.19		
12	181.7*8231=1.495		

As the simulation result shows here, by using GA_IOPI controller and taking 12m/s as rated wind speed the power extracted is around 1.495MW. The extracted power is almost around the rated one which is 1.5MW.

4.3.2 Simulation Results for different wind speeds using GA_FOPI controller

Here are the simulation responses of wind turbine in terms of Overshoot/Undershoot, Rise time and steady state error in related to rotor currents, Electromagnetic torque, rotor speed using 8 m/s as average wind speed.

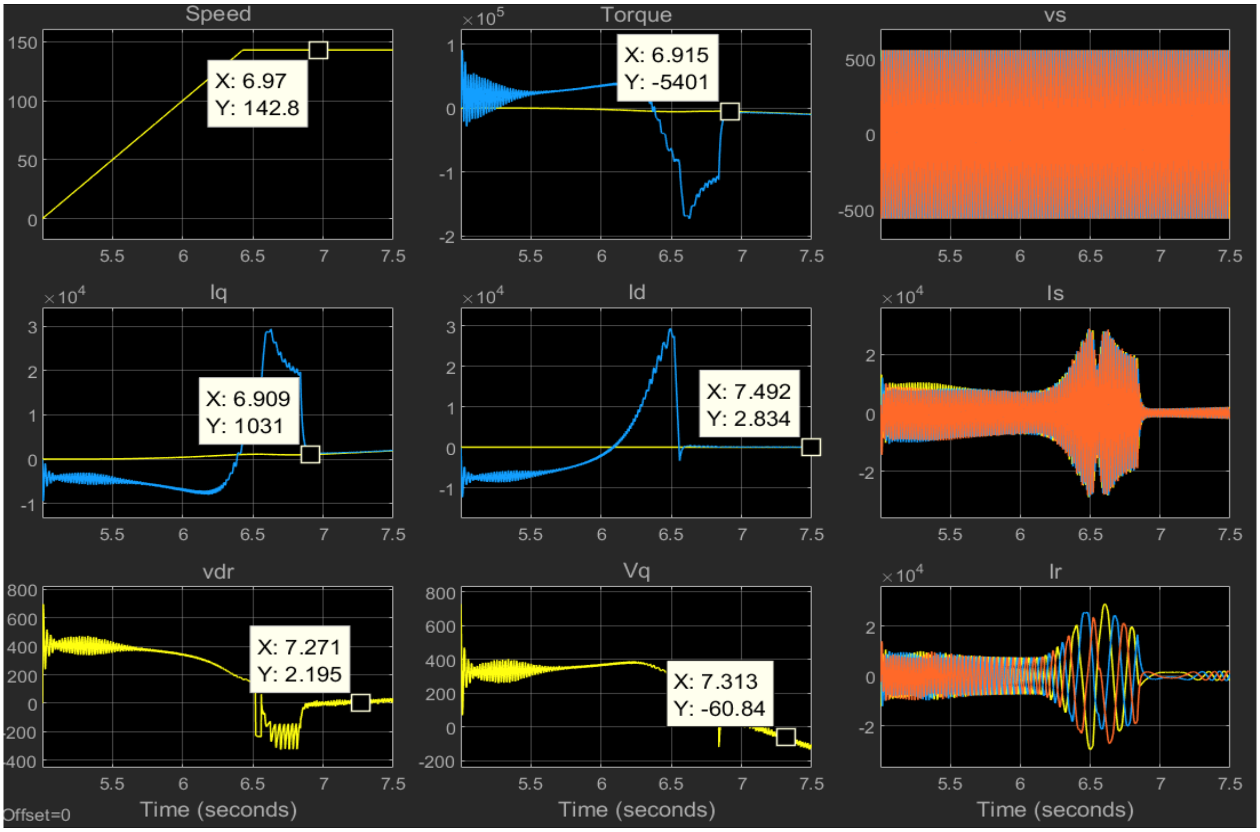


Fig. 4.9 Steady state response of the GA_FOPI simulated system with average speed 8m/s

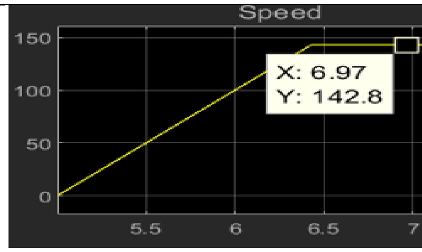
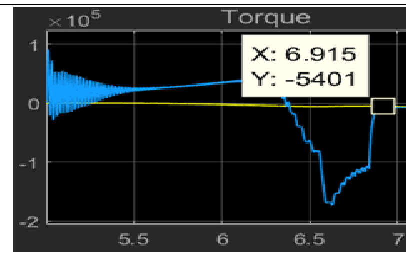
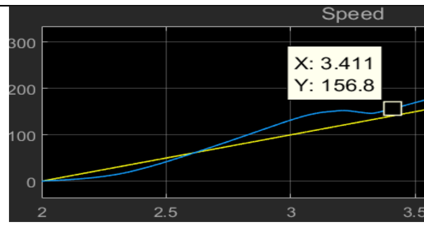
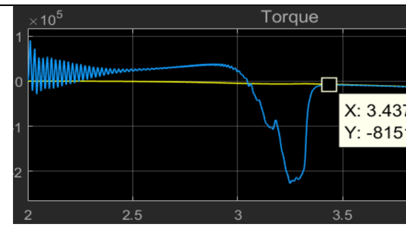
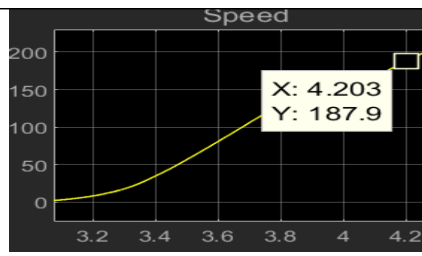
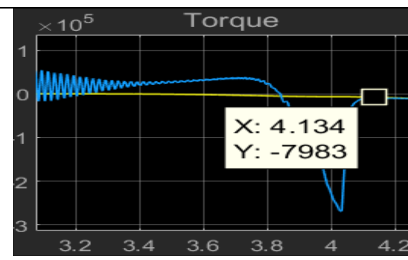
Here is the analysis of percentage overshoot/undershoot, steady state error and rise time of rotor speed, electromagnetic torque, rotor currents (I_{dr} & I_{qr}) are presented. As compared the response of rotor currents in related to step response above, the overall response is also approximately the same as you can see from this simulation result. The detail is presented on below table.

Table 4.4. Steady state analysis for DFIG wind turbine with GA_FOPI controller.

Parameters	I_{dr}	I_{qr}
Peak Overshoot (%)	13.71	2.027
Peak Undershoot (%)	5.677	1.967
Rise time (s)	0.27	0.162

By using this steady state values of rotor speed and electromagnetic torque corresponding to different wind speeds, it has tried to show how much amount of power is extracted from wind. Based on the GA_FOPI, the below table 4.3 shows amount of power extracted from the wind with varying wind speed.

Table 4.5 Extraction of Power with GA_FOPI at different wind speed

Wind Speed (m/s)	Power (MW)	Rotor Speed	Electromagnetic Torque
8	142.8*5401=0.771		
10	156.8*8151=1.278		
12	187.9*7983=1.500		

Here using GA_FOPI controller, the power produced from the wind at different wind speed is 1.5MW. If the wind speed strongly increases, the power produced could be above the rate. During this the pitch angle is enabled for protection purpose. But in thesis pitch angle is inactive because the aim is to extract maximum power from the wind up to the rated one.

4.3.3 Fractional order PI controller efficiency

By comparing the corresponding parameters listed in Table 4.1 and Table 4.3, it is observed that the DFIG wind turbine response with fractional order PI controller shows enhancements in terms of peak overshoot, peak undershoot and rise time when compared to system with integer order PI controller. This show that the fractional order PI is efficient for turbine control.

CHAPTER FIVE

5. CONCLUSION AND RECOMMENDATION

5.1 Conclusion

In this thesis, 1.5 MW DFIG wind turbine controller design types of integer order PI and fractional order PI are used to enhance the performance of DFIG wind turbines. It is assumed that the wind turbine has a general model consisting of electrical, aerodynamic, mechanical and control system models. Indirect speed controller is designed to force the aerodynamic torque Tae to follow the maximum power curve or MPPT in response to wind variations, while a vector controller for current loops is designed to control the rotor side converter. PI controller was designed to control the rotor current components. The gain parameters of the IOPI controller coefficients, k_p and k_i were tuned using genetic algorithm until the desired performance values were obtained. However, the IOPI design could not satisfy the required system performance as peak overshoot, peak undershoot and rise time for all parameters. Therefore, a modern efficient controller, namely fractional order PI controller was introduced. The gain parameters of the FOPI controller coefficients, k_p, k_i and λ were tuned using genetic algorithm until the desired performance values were obtained. Fractional order PI controller showed performance enhancements in terms of the system parameters peak overshoot, peak undershoot and rise time compared to system with integer order PI controller. Finally, it has been demonstrated that the parameters optimization of fractional order controller based on GA is highly effective in DFIG wind turbine. The steady state values of currents for DFIG wind turbine were evaluated to assure that the simulation results follow the reference values.

5.2 Recommendation

As a recommendation, pitch control can be used to overcome any oscillations in rotor speed of DFIG for wind turbine speed higher than the rated speed which is 12m/s and hence increase the study range of wind speed values. Moreover, it may be useful to extend the design to a wind farm that consists of multiple wind turbines.

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Appendices

Appendix-A. MATLAB codes of Controllers' Parameter optimization using GA.

A.1. Programming a function to optimize the IOPI controller

```
function [J] = IOPI_Optim(x)
s=tf ('s');
plant= tf ('s');
kp = x (1)
ki = x (2)
cont = kp + ki/s;
 %step(feedback(plant*cont,1));
 dt=0.01;
 t=0: dt: 1;
 e=1-step (feedback(plant*cont,1), t);
  J = sum (t'.*abs(e)*dt);
```

A.2. Genetic algorithm optimization tools to run the IOPI controller

⇒Optimization ➡ Optimization tool

Solver: ga – Genetic algorithm

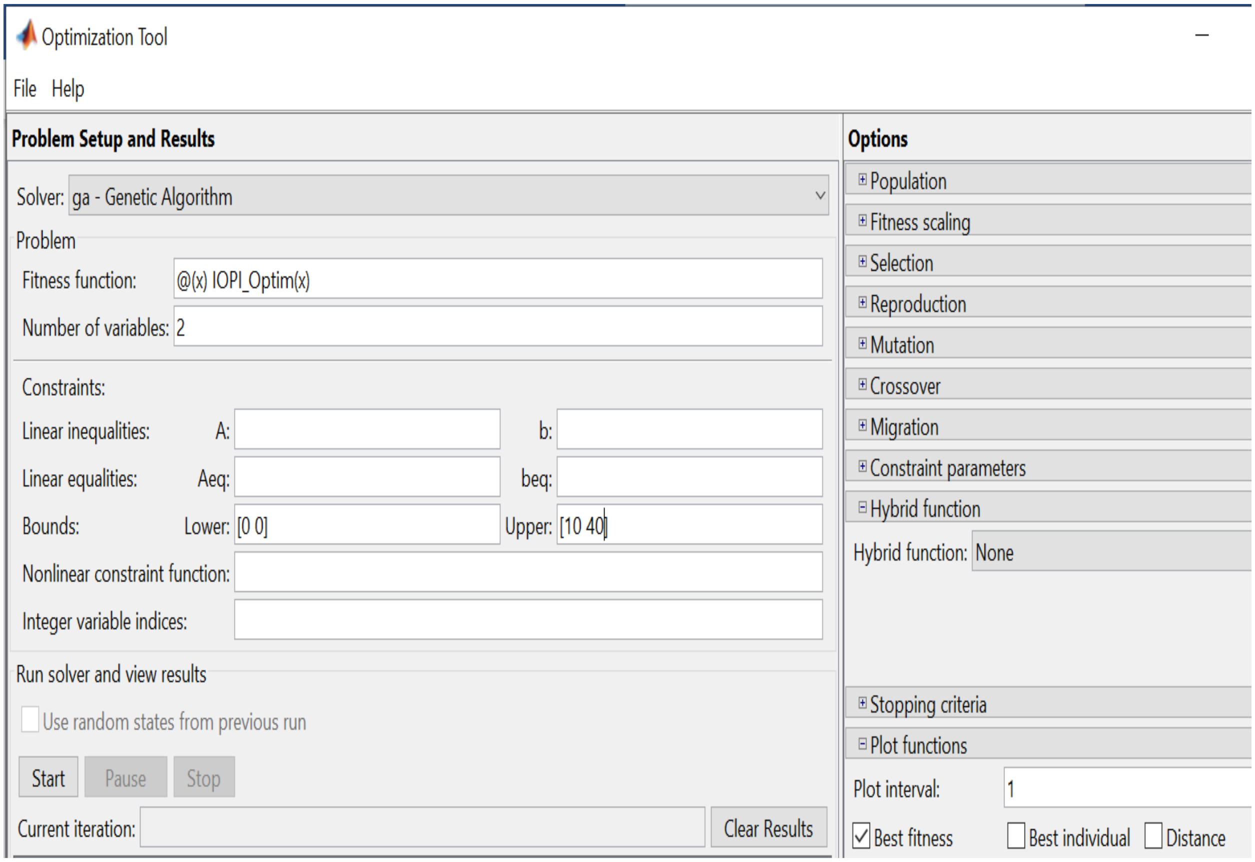
Fitness function: @(x) IOPI_Optim(x)

Number of variables=2

Lb= [0 0]

Ub = [10 40]

%Set the parameters of GA listed on table 3.1 using ga optimization tool as:



A.3. Programming a function to optimize the FOPI controller

```
function [J] = FOPI_Optim(x)
s=fotf ('s');
plant= tf ('s');
kp = x (1)
ki = x (2)
lambda= x (3)
cont = kp + ki/s^λ
 %step(feedback(plant*cont,1));
 dt=0.01;
t=0:dt:1;
 e=1-step(feedback(plant*cont,1),t);
  J = sum(t'.*abs(e)*dt);
```

A.4. Genetic algorithm optimization tools to run the FOPI controller

➡Optimization ➡ Optimization tool

Solver: ga – Genetic algorithm

Fitness function: @(x) FOPI_Optim(x)

Lb= [0 0 0]

Ub = [10 40 1]

%Set the parameters of GA listed on table 3.1 using ga optimization tool as: