MPPT Based On-off Control for DFIG Driven by Variable Speed Wind Turbine

Om Prakash Bharti, R.K. Saket*, and S.K. Nagar

Abstract— *This manuscript deals an on-off Control method which is based on maximum power point tracking and expected to control the rotor side converter of DFIG based wind turbine associated with the grid. The Grid Side Converter is controlled in such a manner to make certain a flat DC voltage as well as ensure sinusoidal current on the network. The modeling and testing of the system demonstrate that the individual block of MPPT, DFIG, and Rotor controllers are functioning to achieve the desired objective. The MPPT blocks are in coordination with the rotor controller block of DFIG based wind turbine, which is trying to keep the torque within the optimal value at which the maximum power is obtained. The performance analysis to the new developed DFIG based WT Matlab Simulink model with MPPT based on-off control is assessed with the conventional (asynchronous) Matlab Simulink model, which demonstrate the enhanced performance output of newly developed model as compared to the traditional model. The performance of the standard Matlab / Simulink model at different wind velocities illustrate that the system has excellent achievement at average wind speeds than that at lower and higher wind speeds.*

Keywords— **Wind turbine, DFIG, Grid Side Converter (GSC), Matlab Simulink Models, ON-OFF control, MPPT.**

1. INTRODUCTION

Energy utilization has always been of significant importance looking into the history of humankind. From the beginning, humans have searched for ways to extract the energy available either by rubbing the stone to light the fire or relying on the firewood for cooking purpose. With the advancement and development, the kind of resources human relied on changed and has been changing even today. Science and technological progress have made today's age very much more accessible but at the expense of energy. The primary source of energy extraction till date has been the petroleum extracts. These sources are going to dry up now and then looking into the developmental works that have been carried forward at present age. Also with the growing population has caused the increase in the industrial and domestic demands of energy and resources. In the planet of limited resources, such growth in demand can cause the exhaustion of the earth's energy resources [1]. Long ago, the need to generate large amounts of electrical energy and the realization that giant power plants were more efficient than smaller ones encouraged the construction of massive power plants. However, the construction of such bigger plants accompanies with massive floods, large power transmission lines, and towers, air pollution, modified waterways, devastated forests, etc. This trend in development has caused the material capacities to reach their limits and widespread, increasing pollution. The novel alternative has to be device if humankind is to stay alive today, moreover for centuries to come. In the ancient times century, it has been seen that the expenditure of non-renewable sources of energy has caused an ecological damage than any other human activity. Electrical power generated from fossil fuels such as coal and crude oil has led to the high attentiveness of harmful gases in the atmosphere. It has, in turn, resulted in a lot of problems being faced nowadays such as ozone exhaustion along with global warming. Vehicular toxic waste has also been a significant problem [3,4]. Consequently, alternative sources of energy have become very relevant and applicable today's world. These sources, such as the sun as well as the wind, can never be fatigued and consequently are called renewable sources. Generally of the renewable sources of energy are relatively non-polluting and considered clean though biomass, a renewable source, is a significant polluter indoors. The source of energy which comes from natural resources such as sunlight, wind, rain, tides, and geothermal heat, and is naturally renewed is termed as renewable energy. Renewable sources of energy have been in the limelight considering the advantages they offer and also the technical and economic benefits entailed with them. Even though renewable in nature, it is of utmost importance to search for the best method that can maximize the power extraction from any chosen renewable source. Therefore, it also becomes necessary to look into the best ways that can increase the extraction to available energy ratio with the use of proper technology. Wind power is the exchange of wind energy into an appropriate form of energy, for instance using wind turbines to generate electrical energy, windmills for mechanical power, wind pumps for water pumping, or

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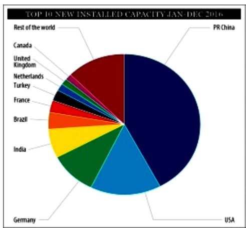
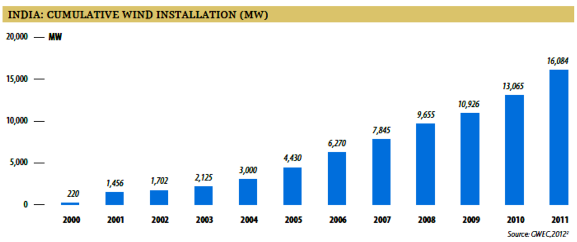
sails to drive ships. The whole amount of cost-effectively extractable power available from the wind is significantly more than present human power use from all sources. Wind power, as an option to vestige fuels, is plentiful, renewable, extensively extent, clean, and produces no greenhouse gas emissions for the duration of the process.Windpower is the world's fast-growing source of energy [2].The favorite of electricity is generated by burning coal, rather than an eco-friendlier scheme like hydroelectric power. This use of coal causes untold ecological harm through CO_2 and other toxic emissions. The energy division is by far the largest source of this radiation, together in the India as well as globally, and if we are to tackle climate change, it is evident to move limited fossil fuel reserves to more sustainable and renewable sources of energy. The beneficial characteristics of wind energy include Clean and endless fuel, Local economic expansion, Modular and scalable technology, Energy price stability, Concentrated dependence on imported fuels.With the rapidly increasing demand intended for power along with importance on clean energy, India has also taken a step forward along with other countries. Whereas in [1],The statical data of global cumulative wind capacity along with India's wind energy installation has been described. According to the Global Wind Report 2016, the total installed wind capacity at the end of 2016 is shy of 486 GW. Out of the full capacity, India established wind power generation capacity stood at about 28,700 MW constitute 5.9% of global wind power capacity as shown in Fig. 1(a).



Country	MW	% Share
PR China*	23,328	42.7
USA	8,203	15.0
Germany	5,443	10.0
India	3,612	6.6
Brazil* *	2,014	3.7
France	1,561	2.9
Turkey	1,387	2.5
Netherlands	887	1.6
United Kingdom	736	1.3
Canada	702	1.3
Rest of the world	6,727	12.3
Total TOP 10	**47,873**	**88**
World Total	**54,600**	**100**

Source: GWEC

(a)



(b)

Fig.1 (a) Statistical data of Global cumulative wind capacity [1]; (b) Statistical data of India's wind energy installation [1]

In the 1980s, the government of India demonstrated the Ministry of Non-Conventional Energy Sources (MNES) to push diversification of the country's energy supply and satisfy the ever-increasing energy demand of its quickly rising financial system. In 2006, this department was appointed by the Ministry of New and Renewable Energy (MNRE).throughout the first decade of the 21st century; India came out as the 2nd contributing wind power market in Asia. More than 2,100 MW wind capacity manuscripts were added in the financial year 2010–11. The installed capacity increased from a modest base of 41.3 MW in 1992 to reach 28,700 MW by December 2016. India had an additional documentation year of different wind energy installation stuck between January as well as December 2011, installing extra than 3 GW different capacity for the first time to reach a total of 16,084 MW shown in Fig. 1(b). As for March 2012, renewable energy accounted for 12.2 percent of total established capacity, up to from 2 percent in 1995. Wind power explains about 70 percent of this installed capacity. The wind power installations in India had arrived at 17.9 GW on August 2012 ending.

Modern wind power technology has come a long way in the last two decades, both globally and India. Enhanced technology has slowly and steadily improved capability efficiency. An essential drift in the Indian industry which is the expansion of multi-megawatt turbines established at more considerable hub heights. Larger diameter rotors allow a single wind power generator to capture more energy or power per tower. That enables WTGs to take advantage of higher altitudes with stronger winds and less turbulence (wind speed enhance with height above the earth). The more significant machines had resulted in a substantial improvement in the capacity factor on the standard as of 10-12% in 1998 to 20-22% in 2010. Intended for two decades worldwide standard WTG power ratings have developed approximately, with modern industrial machines rated on the standard in the range of 1.5 MW to 2.1 MW.

The paper includes Introduction in section I. Section II involves an overview and theoretical concepts of the wind energy conversion systems for wind turbine systems. Part III contains ideas of the Wind Energy generating system as well as a doubly fed induction generator. Section IV incorporates the Methodology being followed in implementing the models of on-off control based MPPT along with MPPT concept and methods as well as MPPT controllers and their MPPT type's technique with on-off control. Section V gives the brief operation of the whole system, how each of the blocks performs to achieve the desired objective and finally, results of the simulation are presented with the analysis of the obtained result. Based on the results and analysis, Conclusion has been drawn in Section VI.

2. WIND ENERGY CONVERSION SYSTEMS FOR WIND TURBINE: AN OVERVIEW

Demand seems to increase continuously with the increasing population and technological advancement. With the growth of the request, the generating systems should be able to generate sufficiently to meet the demand. The only one way to achieve this requirement is to increase the generation by increasing the number of producing stations, which is not feasible to construct instantaneously to meet the current demand. Therefore, the best solution is to make the maximum utilization of the available energy. From various possible options make efficient use of available power, to shift from conventional fossil-based energy sources to renewable energy. The growing interest in the field of wind energy has motivated many of the researchers to focus on the area of extraction of power from the wind. The primary question for the research to carry forward is the ways by which the available energy at a given wind velocity can be harnessed to its maximum. The general equation governing the power output of the wind turbine is provided by; [3]

$$P_m = \frac{1}{2}\rho A_r v^3 C_p(\lambda, \beta) \tag{1}$$

where,

- P_m Mechanical power extracted from turbine rotor,
- ρ Air density [kg/m^3],
- A_r Area covered by the turbine blade; πR^2; R being the radius of turbine blade in meters (m),
- C_p Power coefficient or performance coefficient,
- β Pitch angle,
- λ Tip speed ratio Rw_r/v;
- ω_r Turbine rotation speed,
- v Wind velocity.

The power output from the turbine as given by the power equation depends on factors like the radius of the turbine blade, wind velocity, and power coefficient. Among these factors, wind velocity is not under human control to maximize the power output, and it is not a feasible option to change the radius to maximize the output, so the only alternative available to maximize the production is by optimizing the power coefficient C_p. C_p is again the function of pitch angle β and tip speed ratio λ. Pitch angle control is beyond the scope of this manuscript work so the only variable that can be controlled is tip speed ratio which can only be controlled by controlling the shaft speed ω_r.Wind energy conversion system as a whole is the unit which transfers the wind energy, through the wind turbine coupled to the generators, to the form that can be utilized by the consumers. The final way of energy to be converted is the electrical power. Therefore, the wind energy conversion system should have all the components necessary to extract the available energy from the wind and convert it to equivalent electric power. In [5, 6], the wind energy conversion systems are composed of blades; a power generator, a power electronic converter, and a control system have been stated, as shown in Fig 2(a). There are synchronous or asynchronous machines based different type of WECS cofigurations have been installed for pitch regulated systems. On the other hand, the useful objective of these systems is the same: convert the wind kinetic energy into electric power and injecting into the utility grid.

As shown in the block diagram in Fig.2(a), the WECS have in general two conversion processes. The first conversion extracts the wind energy, with the help of wind turbines, into the mechanical power output. The wind turbine shaft is coupled to the generator shaft with or without gearbox depending upon the type of generator and technology used. The generator converts the available or inputs mechanical power to the form that can be utilized by the consumers known as secondary conversion. The generator output being electrical can either be supplied to the grid or can be fed directly to the consumers depending upon the requirement. While providing the power to the grid, the generator output should be synchronized with the grid voltage/frequency. For this proper controller and converter should be connected to the generator before feeding the power into the grid.

2.1 Aerodynamic Power Conversion and Control

The aerodynamic power conversion involves the wind turbine blade design and its operation to harness the mechanical power within certain wind velocity. The aerodynamic power conversion includes the interaction of air flow to create drag force (F_D) and lift force (F_L). Where is the pitch angle, β, is the angle between the chord line of the blade and the plane of rotation. The angle of attack, κ, is the angle between the chord line of the blade and the relative wind direction [7]. It can be understood from the Fig.2 (b) below.

The power extract from the wind is given as a fraction of the total power in the wind. The portion is described by a coefficient of performance, C_p [7]. The power coefficient determines the power to be extracted for given wind velocity. At the high wind speed, it is essential to limit the input power to the turbine, i.e., aerodynamic power control. There is three primary behavior of performing the aerodynamic power control, i.e., through stall, pitch or active stall control. Stall control involves that the blades are designed to stall in high wind speeds, and no pitch mechanism is thus required [8].The pitch control can be used to maximize the power output from the turbine by changing the pitch angle. At higher wind speeds, the pitch angle is controlled to decrease the angle of attack which reduces aerodynamic power extracted [8]. The control of pitch angle to maximize the power is beyond the scope of the manuscript. Therefore, only tip speed ratio, i.e., generator speed is controlled to achieve the maximum output power.

2.2 Power Coefficient (Cp)

Equation 1gives the mechanical power extracted from the turbine. In Fig. 2(c) the variation of C_p according to tip speed ratio is shown.

C_p can be computed either by measurements or by theoretical computations. Based on theoretical calculations, the empirical relation of C_p has been derived in [9] and [10]. In [9], the observed relationship of C_p as a function of tip speed (λ) and pitch angle (β) has been given. As the pitch angle control is not studied in this manuscript work, β becomes 45 degrees.

2.3 Wind Turbine Systems

Wind turbine system can be categorized by the nature of their operation, i.e., either fixed speed or variable speed. Based on the nature of operation the selection of energy transformation device generator is made. In support of fixed-speed wind turbines, the generator (induction generator) is directly connected to the grid. Since the speed is approximately fixed to the grid frequency, and most definitely not controllable, it is not probable to store the turbulence of the wind in the form of rotating energy [11]. For a varying-speed wind turbine, the generator is controlled by power electronic equipment, to control the rotor speed. And the power fluctuations caused by wind variations can be more or less absorbed by changing the rotor speed. Thus, the power quality brunt stimulated by the wind turbine can be enhanced equated to a fixed-speed turbine.

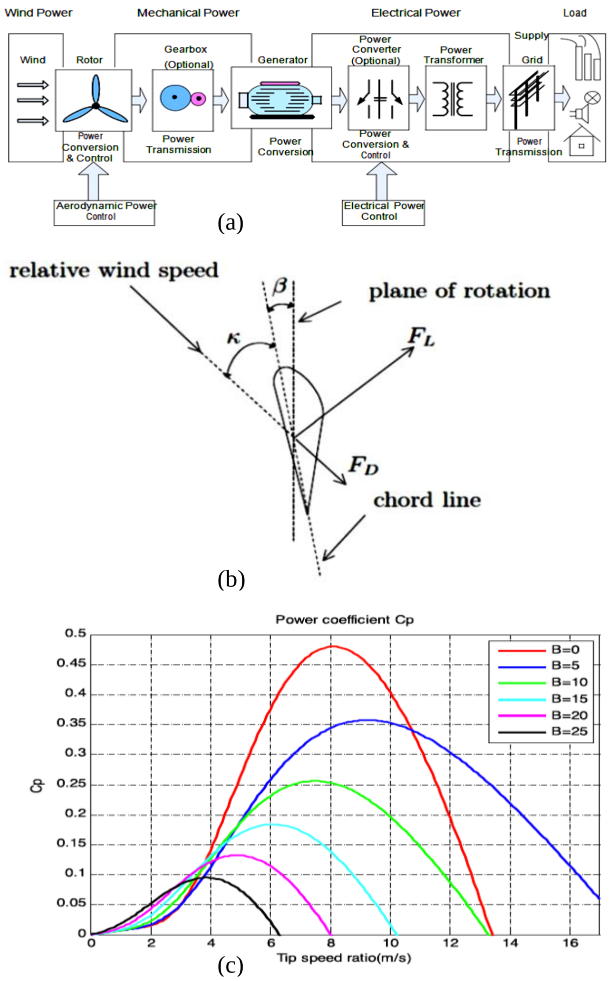


Fig.2 (a) Basic Block of WECS [3]; (b) Pitch Angle and Angle of Attack [4]; (c) C_p vs. λ [18]

In general, wind turbine systems are classified into four different groups [6].

(I) Fixed-SpeedWindTurbine with an Induction Generator

(II) Variable-Speed Wind Turbine with an Induction Generator or Synchronous Generator

(III) Variable Speed Wind Turbine Equipped with Multiple-Pole Synchronous Machine Variable

(IV) Speed Wind Turbine Equipped with a Doubly-Fed Induction Generator.

3. WIND ENERGY GENERATING SYSTEMS

3.1 Wind Turbines

Wind turbines produce electricity by using the power of the wind to drive an electrical generator passing the blades, the wind generates pick up plus exerts a turning force. The revolving blades turn a shaft inside the nacelle, which goes into a gearbox. The gearbox adjusts the rotating speed to that which is suitable intended for the generator, which uses magnetic fields to exchange the rotating energy into electrical energy. The power production goes to a transformer, which converts the electricity from the generator at approximately 700V to the suitable voltage for the electrical power collection system, usually 33 Kv [15]. The wind turbine takes out kinetic energy from the swept area of the blades. The power comprised in the wind is given by the kinetic energy of the flowing air mass per unit time. That is

$$P_{air} = \frac{1}{2}\rho\pi R^2 v^3 \tag{2}$$

where P_{air} is the power contained in the wind (in watts), ρ is the air density (1.225 kg/m^3 at 15°C and standard pressure), R is the blade radius of the wind turbine, and v is the wind velocity without rotor disturbance. That is preferably at an infinite distance from the rotor (in meter per second). Even though the above equation gives the power accessible to the wind, the power transfer to the wind turbine rotor is concentrated by the power coefficient, C_p.

$$C_p = \frac{P_{windturbine}}{P_{air}} \tag{3}$$

$$P_m = \frac{1}{2}\rho\pi R^2 v^3 C_p(\lambda,\beta) \tag{4}$$

Here, R is the radius of the blade of a wind turbine . is the air mass density, v is the wind speed, λ is the tip speed ratio, β is the pitch angle, C_p is the wind turbine energy coefficient. The maximum value of C_p is determined by the Betz limit, which states a turbine cannot extract more than 59.3% of the power from the air stream. Actually, wind turbine rotors have highest C_p measures in the series 25-45%. Several numerical approximations exist for $C_p(\lambda,\beta)$ characteristics, for different values of the pitch angle β, are illustrated in above Fig. 2. This figure indicates that there is one particular λ at which the turbine is most efficient. Normally, a variable-speed wind turbine follows C_{Pmax} to capture maximum power up to the rated speed by varying the rotor speed to keep the system at λ_{opt}. However, the Tip Speed Ratio (λ) is defined for WT [19] as follows:

$$\lambda = \frac{\omega_r R}{v} \tag{5}$$

(a)

where w_r is a wind turbine rotor speed, R is the radius of the swept area of the blade (in meter). However tip speed ratio λ and the power coefficient C_p is the dimensionless quantity and can be used to explain the performance of any size of wind turbine rotor. On another hand, the Specified Rated capacity (SRC) is an important index which is used to compare a variety of wind turbine designs in [16] is formulate as follows.

$$SRC = \frac{Generator Power Regulation}{Rotor Swept Area} \quad (6)$$

It varies between from 0.2 (for small rotors) to 0.6 (large rotors).

3.2. Doubly Fed Induction Generator

At this time, DFIG wind turbines are more and more used in generally find farms. A typical DFIG scheme is exposed in the under the figure. The AC/DC/AC converter comprises two apparatus: the rotor side converter C_{rotor} as well as a Grid side converter C_{grid}. These converters are voltage source converters that employ forced commutation power electronic devices (IGBTS) to synthesize AC voltage from DC voltage source. A capacitor linked to DC side acts as a DC voltage source. The generator slip rings are associated with the rotor side converter, which aids a DC link with the grid side converter in such a manner so-called back-to-back arrangement. The wind power captured by the turbine is transformed into electrical energy by the IG and is transferred to the grid by stator and rotor windings. The control system gives the pitch angle command, and the voltage controls for C_{rotor} as well as C_{grid} to control the power of the wind turbine, DC bus voltage and reactive power or voltage at grid terminals [17], [22]. The DFIG based WT scheme is shown in Fig.3.

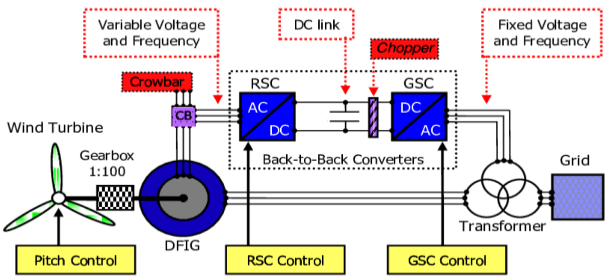


Fig.3. A DFIG based Wind turbine system.

3.2.1 Operation: while the rotor speed is larger than the revolving magnetic field from the stator, the stator induces a high current in the rotor. The quicker the rotor rotates, the more power will be transferred as an electromagnetic force to the stator, and in turn, transformed into electricity which is fed to the electric grid. The speed of a synchronous generator will differ with the rotational force functional to it. Its dissimilarity from synchronous speed in percent is called generator's slip. With rotor winding short-circuited, the generator at full load is only a small number of percent. With the DFIG, slip control is an offer by the rotor and grid side converters. At high rotor speeds, the slip powers are improved and deliver to the grid, resultant in high on the whole system efficiency. If the rotor speed range is imperfect, the ratings of the frequency converters will be small compared to the generator rating, which helps in reducing converter losses and the system cost [20].Since the mechanical torque functional to the rotor is active for power generation and since the rotating speed of the magnetic flux in the air gap of the generator is active and steady for a constant frequency grid voltage, the sign of the rotor electric power output is a function of the slip sign. C_{rotor} and C_{grid} can generate or engrossing reactive power and be able to be used for controlling the reactive power or the network terminal voltage. The pitch angle is controlled to limit the generator output power to its standard value for high wind speeds. The network offers the necessary reactive power to the generator.

3.2.2 DFIG model: The model of the doubly fed induction generator is given by the following set of equations; Equations of stator voltage components [20]:

$$v_{ds} = R_s i_{ds} + \frac{d}{dt}\varphi_{ds} - w_s\,\varphi_{qs} \quad (7)$$

$$v_{qs} = R_s i_{qs} + \frac{d}{dt}\varphi_{qs} - w_s\,\varphi_{ds} \quad (8)$$

Equations of rotor voltage components:

$$v_{dr} = R_r\, i_{dr} + \frac{d}{dt}\varphi_{dr} - w_r\,\varphi_{qr} \quad (9)$$

$$v_{qr} = R_r\, i_{qr} + \frac{d}{dt}\varphi_{qr} - w_r\,\varphi_{dr} \quad (10)$$

Equations of stator flux components:

$$\varphi_{ds} = L_s i_{ds} + M i_{dr} \quad (11)$$

$$\varphi_{qs} = L_s i_{qs} + M i_{qr} \quad (12)$$

Equations of rotor flux components:

$$\varphi_{dr} = L_r i_{dr} + M i_{ds} \quad (13)$$

$$\varphi_{qr} = L_r i_{qr} + M i_{qs} \quad (14)$$

Equations of electromagnetic torque:

$$T_{em} = \frac{3}{2} P(\varphi_{ds} i_{qr} - \varphi_{ds} i_{dr}) \quad (15)$$

Mechanical equation:

$$T_{em} = T_r + J\frac{d\Omega}{dt} + f\Omega \quad (16)$$

Whereas the active and reactive powers at the stator side and at the rotor side are defined as

$$P_s = \frac{3}{2}\left(v_{ds} i_{qs} + v_{qs} i_{ds}\right)$$
$$Q_s = \frac{3}{2}\left(v_{qs} i_{ds} - v_{ds} i_{qs}\right) \quad (17)$$

$$P_r = \frac{3}{2}\left(v_{dr} i_{qr} + v_{qr} i_{dr}\right)$$
$$Q_r = \frac{3}{2}\left(v_{qr} i_{dr} - v_{dr} i_{qr}\right) \quad (18)$$

where, V_{ds}, v_{qs}, v_{dr}, v_{qr} represent the measured stator and rotor voltages components; i_{ds}, i_{qs}, i_{dr}, i_{qr} are respectively the elements of the stator and rotor currents. While φ_{ds}, φ_{qs}, φ_{dr}, φ_{qr} are the components of the stator and rotor flux vectors; R_s, R_r is the stator and rotor phase resistances; L_s, L_r are the cyclic stator and rotor inductances; p is pole pairs number; M is the cyclic mutual inductance; T_r is the load torque; f is friction constant; J is moment of inertia; w_r is the synchronous rotor speed; Ω is the mechanical rotor speed, and T_{em} is the electromagnetic torque. The wind turbine is used for the production of high power generators. The stator resistance of the DFIG is neglected, and the stator flux ϕ_s is set aligned with the d-axis and assumed to be constant [20].

Then, one can write $\phi_{ds} = \phi_s$ and $\phi_{qs} = 0$. Consequently, Equations 19- 24, become respectively:

$$v_{ds} \approx 0 \tag{19}$$

$$v_s = v_{qs} \approx w_s \phi_s \tag{20}$$

$$\varphi_s = L_s i_{ds} + M i_{dr} \tag{21}$$

$$0 = L_s i_{qs} + M i_{qr} \tag{22}$$

$$v_{dr} = R_r i_{dr} + (Lr - \frac{M^2}{L_s})\frac{di_{dr}}{dt} - g w_s (Lr - \frac{M^2}{L_s}) i_{qr} \tag{23}$$

$$v_{qr} = R_r i_{qr} + (Lr - \frac{M^2}{L_s})\frac{di_{qr}}{dt} - g w_s (Lr - \frac{M^2}{L_s}) i_{dr} + \frac{M v_s}{L_s} \tag{24}$$

Equations (19), (20), (21) and (22) are used to rewrite the stator active and reactive powers as follow: [20].

$$P_s = -\frac{3Mv_s}{2L_s} i_{qr}$$

$$Q_s = \frac{3v_s}{2L_s w_s}(v_s - M w_s i_{dr}) \tag{25}$$

Moreover, the electromagnetic torque is given by:

$$T_{em} = -\frac{3}{2} p \frac{M}{L_s} \phi_s i_{qr} \tag{26}$$

where v_s is the stator voltage magnitude assumed to be constant, w_s Synchronous angular speed.

4. MAXIMUM POWER POINT TRACKING CONCEPT AND METHODS

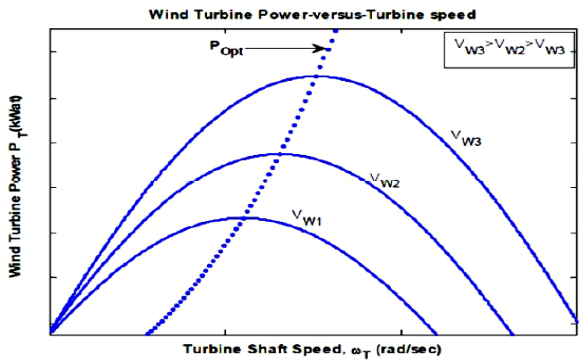
At a given wind velocity, the mechanical power available from a wind turbine is a function of shaft speed. Capitalize on the power captured from the wind; the shaft speed has to be controlled by a variable-speed method. The wind turbine mechanical output power, P_T is affected by the ratio of the turbine shaft velocity and the wind velocity, i.e., tip-speed-ratio (λ=R.ω_r/v). As a result of variations in wind speed, the turbine shaft speed ω_r (or generator shaft speed ω_g), and wind turbine power P_T will change. Fig.4 (a) shows a family of typical P_T versus ω_r curves for different wind velocities for a standard system, as seen in this figure. Various power curves have different maximum power, P_{max} (or optimal power, P_{opt}) [14].

4.1 Various kinds of MPPT Control techniques

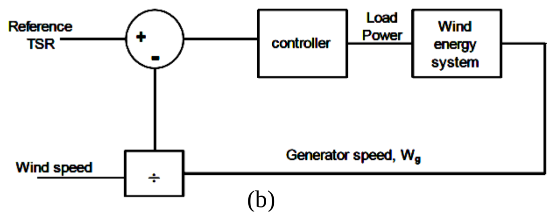
Maximum power point tracking is an efficient method of extracting generated power from generating systems used by grid-connected inverters, solar battery chargers, and wind energy conversion system. Wind power is dependent on weather, topology, and environment. It is essential to choose the best place where the quality of air can produce more electricity. Then it's hard to wind turbine to provide 60% of power from wind speed. Wind energy conversion system also has other losses similar to mechanical resistance and small generator efficiency. So the total output power from WECS depends on tracked wind power. Hence, a maximum power point tracking control is needed. [21].The various Types of MPPT control techniques are described as follows:

(i) Tip speed ratio (TSR) control

The optimal TSR is constant for a given wind turbine irrespective of variable wind speed as shown in Fig 4(b). While the wind turbine works at this optimum TSR, the power so extracted from the WECS is maximized. Hence MPPT method forces the energy conversion system to perform at optimized TSR by comparing it with the actual value and supplying this error to the MPPT controller. The system reacts by varying the generator speed to decrease this error. This optimized TSR can be computed experimentally and used as a reference. Though this method is simple as wind speed is measured directly, a precise measurement of wind speed is not possible and also the cost of the system increases. The block diagram of the tip speed ratio for MPPT control method is as shown in Fig. 4(b) [23]. And Plot of Power coefficient vs. Tip speed ratio [23] is shown in Fig. 4(c).



(a)



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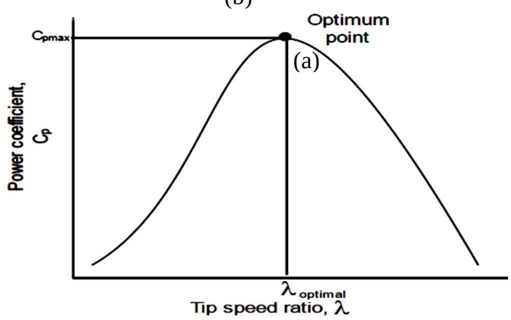

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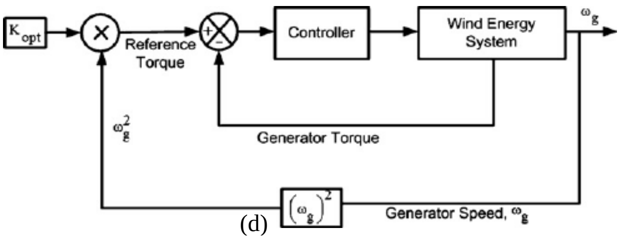


(d)

Fig. 4(a) Maximum PowerPoint Tracking [12]; (b) Block diagram for Tip speed ratio MPPT control [23]; (c) Plot of Power coefficient vs. Tip speed ratio [23]; (d) Block diagram for optimal torque control [23].

(ii) Optimal torque control (OT)

As talked about in TSR MPPT technique of control, preserving the action of the system at optimized TSR ensures maximum conversion of the available wind energy into mechanical energy. It can be seen from Fig 4(d) that the objective of this method is to adjust the PMSG torque about maximum power reference torque of the wind turbine at given wind speed. The turbine power as a function of λ and w_r is determined mathematically. The block diagram as shown in Fig.4 (d) describes the working of the OT controller [21].

(iii) Power signal feedback control (PSF)

In this controlling method, the reference optimum power curve of the wind turbine is obtained first from the experimental results. The functioning points for highest output power along with the consequent wind turbine speed are saved in a lookup table. The block diagram of the power signal feedback control is shown in Fig 5(a).

(iv) Mechanical Speed-Sensor less PSF control

This method has the capability of providing a power reference for the controller analogous to maximum power point without measuring the turbine shaft speed. Whereas for PSF control, neither wind velocity neither sensor nor turbine speed sensors are required. That is the significant advantage of this approach. The process can be developed for all wind turbine system including an induction generator (IG) [14].Fig 5(b) illustrates the block diagram of a mechanical speed-sensor less PSF control system. In this method, a look-up table containing induction generator synchronous speeds (ω_s) corresponding to the optimal generator powers ($P_{gen-opt}$) is used. As the wind speed varying with time, then the wind turbine adjusts the speed to track the optimum wind turbine speed.

(v) Perturbation and observation control (P&O)

The perturbation and observation method of control is an efficient optimization method which uses the principle of searching for the local optimum point of a given function. It is used to examine the optimal operating point, and hence it will help to maximize the extracted energy. This control method is based on inserting a little step size difference in a control variable and observing the changes in the target function till the slope of the function becomes zero. As shown in Fig.5(c), the controller guides the operating point by locating the position and the distance of the functioning point from the peak point. The operating point moves towards the right if it is on extreme left side and vice versa. In this process, the duty cycle of the boost converter is perturbed, and the dc link power is observed. In this method, wind speed measurement is not required hence the mechanical sensors are not used. Therefore, this method of control is more reliable and cost-efficient [21].

(vi) Wind Speed Measurement control

The wind turbine speed control aims to maintain wind turbine shaft speed at an optimal value, i.e., ω_{Pmax}, so that maximum mechanical power can be captured at any given wind velocity (V_W). In the wind speed measurement (WSM) method, both wind speed and shaft speed (ω_T) should be measured which is shown in Fig.5 (*d*). Also, optimal tip-speed-ratio (λ_{opt}) must be determined by the controller.

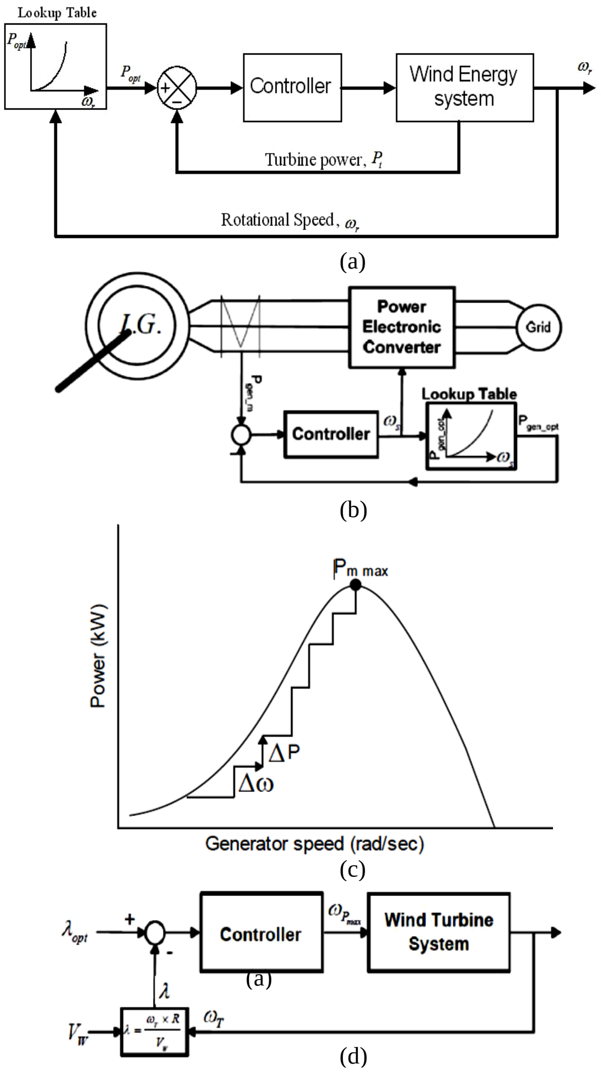


Fig. 5(a) Block diagram for PSF MPPT control [23]; (b) Mechanical speed-sensors less PSF control [12]; (c) Plot of generated power in KW vs. generator speed in rad/sec [23]; (d) Wind speed measurement method [12]

4.2. MPPT based ON-OFF Control Technique for DFIG Systems

Several research works have been presented with different power/voltage control of DFIG based wind energy conversion system associated to the grid. These control diagrams are based on vector control notion with conventional PI controllers [23]. Fuzzy logic and adaptive fuzzy controllers have also been used in the power/voltage control loop [24]. Traditional controllers for wind energy conversion systems (WECS) can be developed for more well-organized strategies based on intelligent control technique. On-Off control is a robust scheme aiming at captured power maximization of DFIG-based WECS connected to the grid. This approach superposes the tracking of the optimal torque value [25]. The control objective can be formulated as an optimization problem, in which an objective function is maximized or minimized, to extract the maximum power from the wind energy. There is a particular difficulty about the On-Off control, concerning the meaning of a switched module (follow the sign of the tip speed ratio inaccuracy) with guaranteed properties of attractiveness and stability. On-Off Control is based on maximum power point tracking method which is anticipated to control the rotor side converter of wind turbine equipped using the DFIG connected to the grid.

4.2.1 Controller Design: This approach supposes that the WECS reacts sufficiently fast to the variation of the low-frequency wind speed; this happens in the case of low-power WECS. Thus, for ensuring the optimal energy conversion, it is sufficient to feed the electrical generator with the torque control value corresponding to the steady-state operating point. To this end, an on-off-controller-based structure can be used to zero the difference $\sigma = \lambda_{opt} - \lambda$, where λ is given by the low-frequency component of the wind speed v [25].

$$\lambda = \frac{\omega_r R}{v} \tag{27}$$

4.2.2 Rotor side converter based On-Off control: From Equation (26), the electromagnetic torque can be controlled directly by acting current component. Then; the rotor current is given by:

$$I_{q\_ref} = -\frac{2L_s w_s}{3pv_s M_{Temref}} \tag{28}$$

From Equation (25), the stator reactive power can be controlled by acting on I_{dr}. Then, the d-reference rotor current is given by:

$$I_{dr\_ref} = \frac{2L_S}{3v_s M}\left(\frac{3v_s^2}{2L_s w_s} - Q_{s\,ref}\right) \tag{29}$$

For ensuring the maximum power point tracking an On-Off supposes that the WECS reacts sufficiently fast to the variation of wind speed (see Fig. 6(a)). An On-Off controller can be used to zero the difference between the optimal tip speed ratio and the actual tip speed ratio σ [26]:

$$\sigma = \lambda_{opt} - \lambda \tag{30}$$

The on-off objective is to make the difference between the optimal tip speed ratio and the actual tip speed ratio as small as possible with regulating the rotor speed according to the wind speed.

The control law u has two components:

$$T_{emref} = u^{eq} + u^{n} \tag{31}$$

where the equivalents control u^{eq} as defined:

$$u^{eq} = 0.5\pi \rho R^3 \frac{C_P R^3(\lambda_{opt})}{i\lambda_{opt}} v_s^2 = A v_s^2 \tag{32}$$

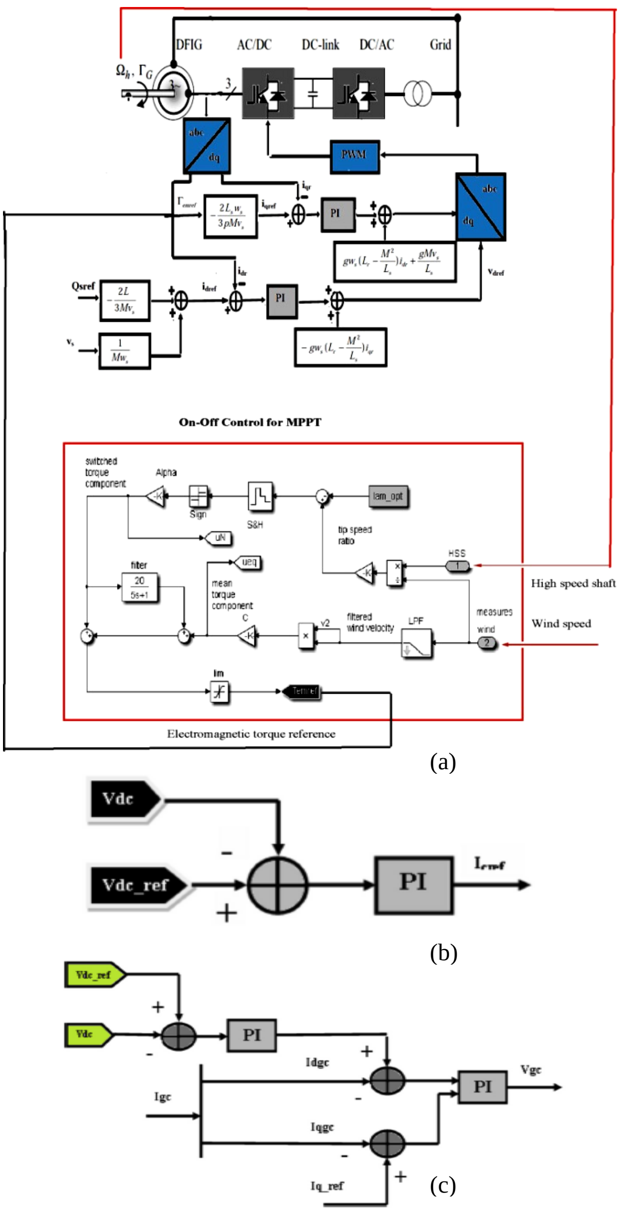


Fig. 6(a) Rotor side converter based on-off control scheme For DFIG; (b) Direct bus control scheme [18]; (c) Grid side control scheme [18].

With $A = 0.5\pi \rho R^3 \frac{C_P(\lambda_{opt})}{i\lambda_{opt}}$ and i is the gearbox ratio,

u^n is an alternate, high-frequency component, which switches between two values, -α and +α, α>0:

$$u^n = \alpha sign(\sigma) \tag{33}$$

Component u^{eq} makes the system operated at the optimal point, whereas u^n has the role of stabilizing the system behaviour around this point, once reached. The control law associated with the diagram in Fig. 6(a) provides the steady state torque reference. The control input has, in this case, a large spectrum; the zero-order sample-and-hold (S&H in Fig. 6(a)) has been introduced to limit the loop switching frequency. If this frequency is too large, the control circuit becomes inefficient. The zero order S&H element is approximated as a first order low-pass filter with a time constant $T_{S\&H} = T_s/2$, where T_s is the sampling period of the S&H. In Fig. 6(a) the nonlinear part consists of an On-Off relay ("sign" block). The control of the rotor side converter is illustrated in Fig. 6(a); the reference i_{qref} is derived from the high-speed shaft Ω_h and measured wind speed v by tuning the On-Off controller based maximum power point tracking (MPPT). Also, a current command i_{dref} is derived from Equation (25) to control the reactive power to the required value, as shown in Fig. 6(a). Elsewhere; Equations (23) and (24) has been used to design the current control loops along the two axes. Thus, by adding a PI regulator in the loop control of the d-axis and q-axis rotor currents is realized, as shown in Fig. 6(a) [26].

4.2.3 Inverter and direct bus voltage control:

The direct bus voltage is given by the following equation [26]:

$$V_{dc} = \int \frac{1}{c} I_c dt \tag{34}$$

with, $I_c = I_{dc} - I_n$ (35)

With V_{dc} and I_{dc} are the direct bus voltage and current respectively and I_n is the three-phase currents supplied to the grid. The control scheme of the direct bus voltage is presented in Fig. 6(b). The grid-side converter is used to monitor the voltage of the DC bus capacitor. On behalf of the grid-side controller, the d-axis of the revolving reference frame used for d-q transformation is associated with the actual sequence of the grid voltage. This controller consists of measuring the d-q components of AC currents to be controlled as well as the DC voltage. This converter maintains constant dc-link voltage as a reference value during discharge/charge current [26].

The output DC voltage regulator is fed into the current reference I_{dgc_ref} for the current regulator. Then the current corrector controls the magnitude and phase of the voltage generated by the converter $C_{grid}(V_{gc})$. The grid side controller is presented in Fig. 6(c).

5. SIMULATION RESULTS AND INTERPRETATION

The simulation results in the study state are carried out with MATLAB / Simulink to verify the effectiveness of the considered system using On-Off control for the designed WECS with doubly fed induction generator. Wind speed is typical to assume that the mean value of the wind speed is constant at some intervals. To evaluate the control method aiming at captured power maximization for DFIG based wind turbine using an On-Off controller, MATLAB is used to carry out the simulation.

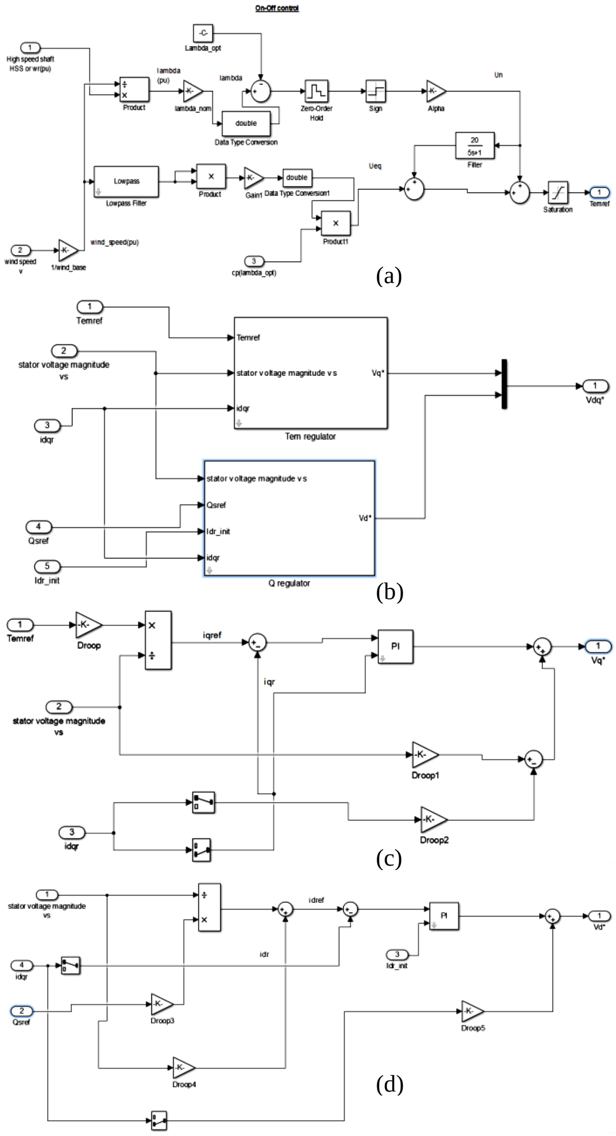


Fig. 7(a) MPPT Model for calculating torque reference; (b) MPPT Model for V_{dq} reference; (c) MPPT Model for i_{qref}; (d) MPPT Model for i_{dref}.

5.1 MPPT Controller Block

The MPPT block has its input as wind velocity and rotor speed as well as calculates the output as optimal torque reference for maximum power. The developed model of MPPT in SIMULINK workspace is shown in Fig 7(a). The control of the rotor side converter is illustrated in Fig. 7(b).The reference i_{qref} is derived from the high-speed shaft Ω_h and measured wind speed V by turning the On-Off controller based maximum power point tracking (MPPT) as shown in Fig 7 (c). Also, a current command i_{dref} is derived from Equation (29) to control the reactive power to the required value, as shown in Fig. 7(c). Elsewhere; Equations (27) and (28) was used to design the current control loops along the two axes. Thus, by adding a PI regulator in the loop control of the d-axis and q-axis rotor currents is realized.

5.2. MPPT based DFIG System model with on-off control scheme Description

The system model, Fig. 8, can track the torque output from the wind turbine at a given wind velocity. The torque tracked is fed into energy conversion device which converts the available mechanical power into equivalent electrical with the help of a Doubly Fed Induction Generator. It is modeled with a speed control mechanism. The speed control device is achieved with the combination of rotor controllers. The system under study is not only able to track the torque but can maintain a speed of the generator and the coupled turbine shaft to a speed that maximizes the power extracted at given wind speed. Hence, the outcome is the system that at any time tracks the maximum power from the wind turbine at a given wind velocity. Towards achieving the process, the system modeled works in a three-step operation. In the direction of minimizing the complexity, each block was tested individually, and finally, these blocks are connected to achieve the desired objective. Therefore, based on the sequence of operation, the first operation is performed by the first block the MPPT controller block. The MPPT controller block can generate a reference torque at which the maximum power is extracted from the wind. The second block is a Double fed induction machine which converts the input mechanical power into electrical energy. The double fed induction machine block is constructed of many other blocks to calculate the rotor currents, stator currents, electromagnetic torque and rotor speed as its output. The third block consists of rotor converter and controller for the rotor circuit converter. The rotor controller has its input as optimal torque from the MPPT block and the actual speed from the generator block. The rotor currents output from the induction generator block also acts as an input to the rotor controller block. The input to the inverter is a DC link voltage which is maintained by a controlled voltage source.

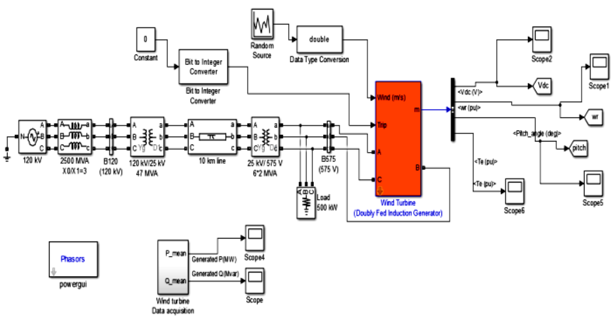


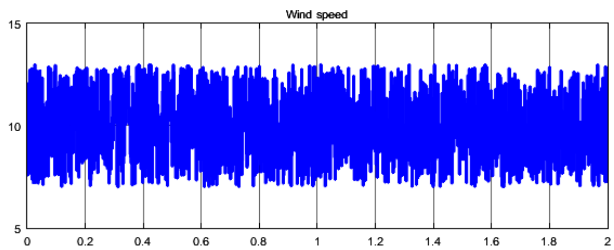
Fig. 8. DFIG Based WT Matlab/Simulink Developed Model

5.3. Performance of Rotor Side controller/Converter

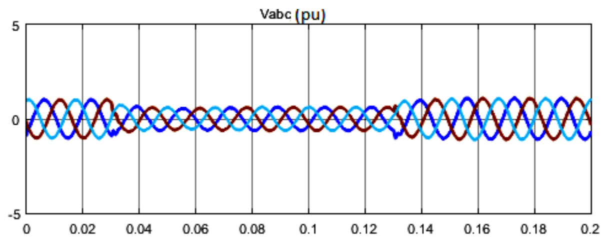
Performance analysis of Rotor side converter includes the observations obtained from the developed model. The view obtained from each block is to be compared with the expected value to check the accuracy obtained from the model. The factor that decides the performance of rotor side controller is the selection of the gain in the PI controller used in the Speed control loop and Current control loop. For a given wind velocity of 10m/s, the optimal value of torque obtained from the MPPT block is around 25.35 NM, therefore, to get the maximum power the amount of torque should be fixed around 25.35 NM. Along with the torque, the amount of speed should also be at its optimal value. For wind velocity of 10m/s, the value of optimal rotor speed from the MPPT block is 130.9 rad/s, i.e., 1250 R.P.M. Therefore, to obtain the maximum power point the value of generator speed should be maintained at 1250 R.P.M and the torque input should be at 25.35 NM. Also, the value of torque at that speed is calculated by the MPPT block itself. It reads the value of 26.28 NM. Hence the block as a whole is working to track the maximum power from the available wind speed. Towards increase the accuracy of the system, the value of gain constants in the rotor side controller needs to appropriately fine-tuned. Hence it can be said that the rotor side controller is indeed decided by the value of the gain constant of the PI controller present in it. Proper selection of this value would result in better effect fast response time.

5.4. Simulation Results

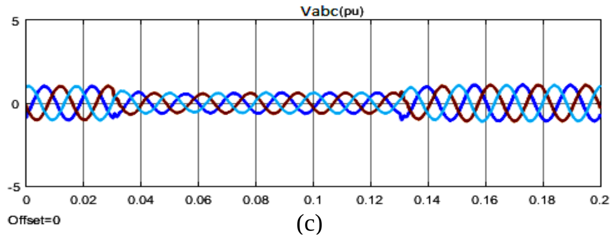
The developed MPPT based ON-OFF control for DFIG driven by variable speed wind turbine system model has been tested for various cases with the inbuilt model(conventional model) of Asynchronous machine present in the library of MATLAB. The simulation results are shown in Figs.9(a-d)-12(a-b) respectively. Fig. 10(c&d) is the reactive power. The reactive output power of each wind turbine is almost 0 Var by controlling the rotor-side converter. Whereas the Fig.11(b&c)indicates that the dc-link capacitor voltage can be well maintained at 1200 V through the voltage closed-loop control of the grid-side converter. On the other hand Fig. 12(a&b) indecates the actual electromagnetic torque. Also it can be seen that from Fig. 12(a&b), the value of electromagnetic torque is nearly constant.



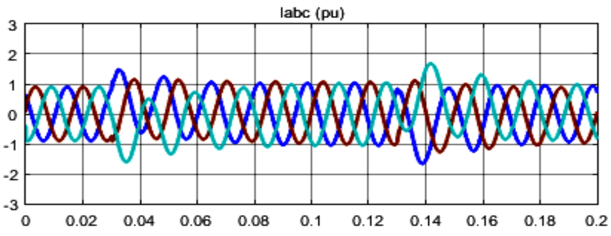
(a)



(b)

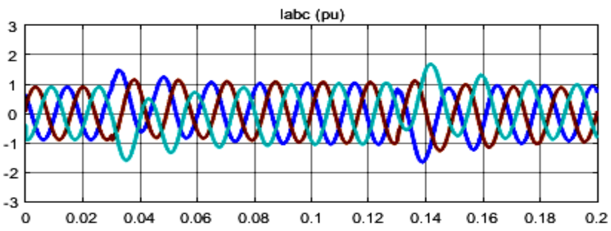


(c)

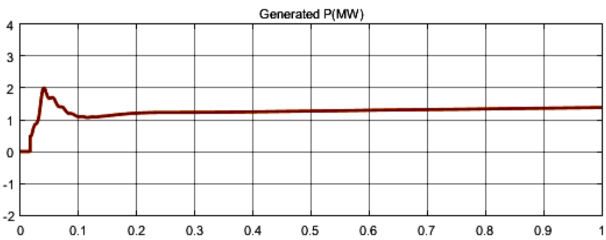


(d)

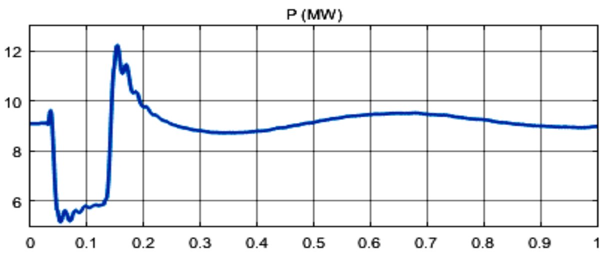
Fig.9(a) wind speed v/s time from developed model; (b)Vabc v/s time from developed model; (c)V_{abc} v/s time from conventional model; (d) I_{abc} v/s time from developed model



(a)



(b)



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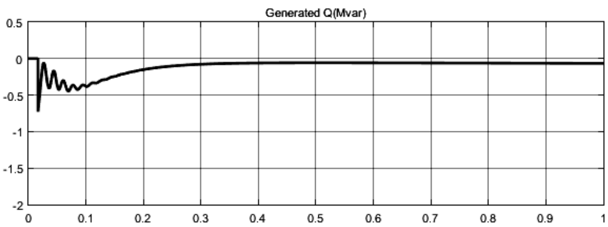
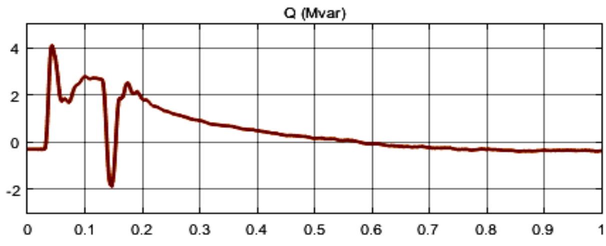
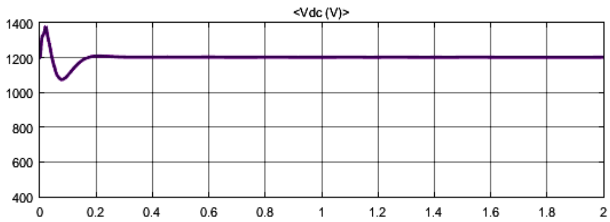


(d)

Fig. 10(a) I_{abc} v/s time from conventional model; (b) Active Power P v/s time from developed model; (c) Active Power P v/s Time from the conventional model; (d) Reactive Power Q v/s time from developed model.



(a)



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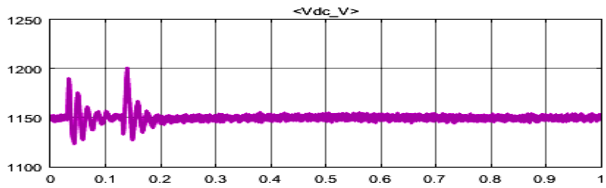
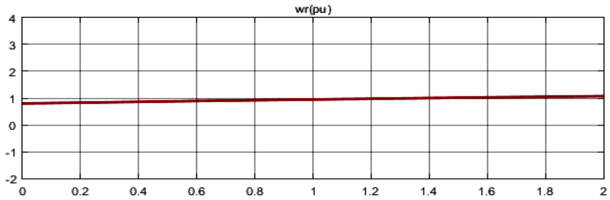
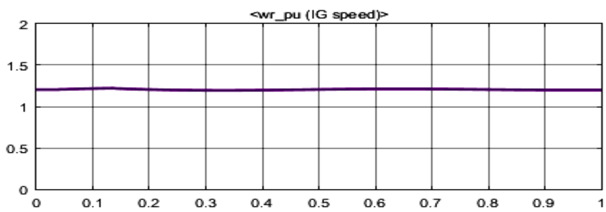


(c)

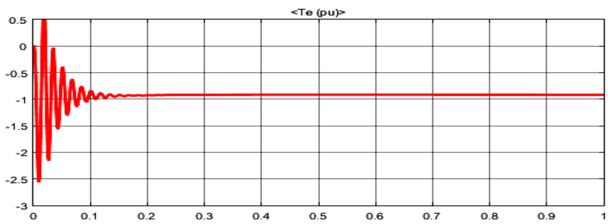


(d)

Fig. 11(a) Reactive Power Q v/s time from conventional model; (b) DC bus voltage v/s time from developed model; (c) DC bus voltage v/s time from conventional; (d) Rotor speed v/s time from developed model.



(a)



(b)

Fig. 12(a) Rotor speed v/s time from conventional model; (b) Electromagnetic torque v/s time from developed model.

Comparing the different set of characteristics of the established and traditional model, Fig. 9(a-d) to Fig.12(a-b).We can see that the developed MPPT based ON-OFF control for DFIG driven by variable speed wind turbine system model has better characteristics as that of the conventional model. Hence the performance analysis of the DFIG driven by WT model along with MPPT based ON-OFF control is assessed with the conventional model, demonstrate the enhanced performance output as compared to the traditional model.Therefore it can be insured that the standard Matlab/Simulink model at different wind velocities has excellent achievement at average wind speeds than that at lower and higher wind speeds.

6. CONCLUSION

Wind Energy market is rocketing high at present. A lot of research and developmental works have been going on in the field of wind energy to find the optimal ways to harness the available power. A conception of MPPT has been proposed to achieve the goal of tracking maximum power at a given wind velocity. To perform the MPPT from the wind system, the MPPT block in coordination with the rotor control block acts to maintain the torque to the value that is optimum for extracting the maximum power output from it. The energy conversion device which is used in wind turbine systems is Doubly Fed Induction Generator. Therefore, a doubly fed induction generator is modeled as an energy conversion device. The modeling included the verification of developed model with that of the generator present in the library of the MATLAB/ Simulink. The results are better than the model in the MATLAB library. Further to achieve a double-fed induction generator the modeled generator has incorporated with rotor side converters and controllers. Thus the performance of the DFIG has driven WT model along with ON-OFF control based MPPT demonstrate the enhance performance output. The results obtained showed that the system could perform well at average wind speeds while the results are inconsistent with that of expected values at lower and higher wind speeds. Hence at average wind speed, the rotor side controller changes such that to alter the torque to the optimal value generated by the MPPT controller.

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NOMENCLATURE

P_T : Mechanical power extracted from turbine rotor,
ρ :Air density [kg/m3],
A_r : Area covered by the turbine blade,
C_p : Power coefficient or performance coefficient,
B : Pitch angle,
λ : Tip speed ratio,
V_ω : Wind velocity,
ω_t : Turbine rotation speed,
P_{max} : Maximum Power,
P_r : Rotor Power,
P_s : Stator Power,
S : Slip,
P_θ : Park's Transform,
V_{ds}, V_{qs} : d-axis and q-axis stator voltages,
V_{dr}, V_{qr} : d-axis and q-axis rotor voltages,
p : Derivative,
R_s, R_r : Stator and Rotor Resistance per phase,
ψ_{ds}, ψ_{qs} : d-axis and q-axis stator flux linkages,
ψ_{dr}, ψ_{qr} : d-axis and q-axis rotor flux linkages,
i_{ds}, i_{qs} : d-axis and q-axis stator currents,
i_{dr}, i_{qr} : d-axis and q-axis rotor currents,
ω_s, ω_e : Synchronous speed,
ω, ω_r : Rotor speed,
ω_b : Base frequency,
X_{ls} : Stator leakage reactance,
X_{lr} : Rotor leakage reactance,
ψ_{md}, ψ_{mq} : d-axis and q-axis magnetizing flux linkages,
p : Number of poles,
T_e : ElectromagneticTorque,
T_m : Input Mechanical Torque,
J : Moment of Inertia,
D : Frictional Coefficient,
σ : LeakageFactor,
i_{ms} : Magnetizing stator current,
ω_{slip} : Slip speed

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