Improving the Performance of DFIG Based Wind Energy Conversion System Using Vector Oriented Control Scheme: A Case Study of 49.5MW General Electric Wind Power Plant Jhimpir

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Abstract

Doubly fed induction generator (DFIG) is widely used in wind energy extraction process. The machine is generally deployed due to its better control competency and higher power size. This paper covers, a case study of single unit of 49.5mw, wind power plant located at Jhimpir, is carried out to achieve required power output, steady state operation and flexible control of active and reactive power by means of torque, speed, and converter control. The stator of DFIG is directly linked to the electrical grid and the ac/dc/ac bidirectional power converter is connected between the rotor and the grid. The modification of both converters and control of DFIG is done by considering vector-oriented control scheme in synchronously rotating reference frame. The model of the system is created in MATLAB/simulation software using data of GE 1.6-82.5-50hz operating at speed 10m/sec. The system yields closest outcomes and individual control of active and reactive power and hence the results are compared with a real time-based system operating at 13m/s wind speed that is installed at Jhimpir.

Keywords: *Environmental degradation; Green Energy; DFIG; Vector Oriented Scheme; Power Control; MATLAB*.

1. Introduction

The globe is suffering from environmental degradation issues owing to the increased use of conventional resources. As a matter of fact, the products obtained from such resources are being considered as very toxic to environment, human beings and other living creatures, their increased usage is ultimately raising CO2 emissions, greenhouse gases (GHGs) and causing climatic changes [1]. Undoubtedly, Pakistan is blessed with rich reserves of conventional resources, and the country is utilizing them on large scale in industrial, commercial, transport, and power generation sectors. Over the past decades, energy planners are planning to consider other alternatives to replace conventional resources by other reliable and feasible resources of generation. As a result, renewable resources viz solar, wind, hydropower and geothermal are considered as the best fit over the long living primary fossil fuels electricity generation [2]. On the other hand, owing to population explosion and high reliance on fossil fuels giving rise to supply and demand gap which extremely affects socio-economic growth of the country. The country may achieve reduction in greenhouse gases, may also overcome electricity shortage and attain sustainability by the optimal harness and utilization of green energy resources, such riches will alleviate energy shortage and helps in controlling and diminishing adverse effects [3]. Among all carbon free energy resources, the green energy is assumed as dominant, spotless, endless, and inexpensive basic root of generation [4]. Pakistan possesses tremendous potential of wind energy along the corridor of approximately 1050Km in south-eastern areas of Sindh, North-western areas of KPK and south-western area of Baluchistan. The coastal belt of Sindh province has sufficient wind density to produce almost 20GW of electricity with the average wind speed of about 5-12m/s [5]. Since 2009, the country has taken initiatives to harness energy from the coastal belt of Sindh province. For wind energy extraction, generally wind turbines are deployed where the use of DFIG is the worth mentioning device. The specifications of the DFIG control mechanism greatly control active and reactive power flow to or from the power grid [6]. This paper presents the case study of single unit of 49.5MW wind power plant i.e., 82.5m tall located at specific application of Jhimpir operating on variable wind speeds to yield 1.6MW output power at 50Hz frequency. Generally, the turbines are rated at 13m/s [7]. The variation in wind flow may cause fluctuations at grid and causes grid discontinuity. The Dc voltage overshoots, and voltage dips causes severe fluctuation at grid, to mitigate such issues a bidirectional converter and properly designed control schemes are implemented on converter [8]. The proper control of converters provides high power quality and controls reactive and active power injection to the grid to improve performance of overall wind energy conversion system. The wind energy extraction is dependent on various factors like

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speed of wind, direction of wind, density of wind and wind distribution. Wind energy extraction can be achieved by using different types of wind energy conversion machines such as DFIG. The modern WECS relay on DFIG to meet the energy outrage, it has various benefits such as variable speed operation, better control, improved performance, low inverter and maintenance cost and high-power size as compared to traditional technology of squirrel cage induction generator (SCIG) and Permanent magnet synchronous generator (PMSG) [9]. The DFIG technology gives maximum power output for low wind speed ranges by governing the turbine speed and decreased motional pressures on a turbine during the blusters of wind. The DFIG possess versatile control over wind turbine and the generator, and its power generation features not only depend on wind speed but also on the coordinated mechanical, electrical and electronic converter topology under variable winds [10]. While grid integration grid continuity is major concern because during a large fault high electro motive force takes place in rotor circuit of a machine and that highly affects its performance of a machine. The performance of system can be improved by either modifying generator and bidirectional converter or designing a control scheme to control the excitation of stator circuit and active power flow into the grid. The control of power flow is achieved by controlling the rotor current components through PI regulators obtained from vector-oriented control (VOC) scheme. This paper will use the vector-oriented control scheme to suppress the DC link harmonics and overcurrent in faulty conditions along with the control of stator side and rotor side converter. The contribution of proposed work are Torque and speed control of turbine to extract rated power output and to avoid damage in gusty winds. By using real time data of wind power plant located at Jhampir, system performance is analyzed at wind speed of 10m/s.

2. Wind Energy Conversion System

The wind takes place owing to the irregular heating of the earth's surface. By installing the assembly of various equipment as wind turbine, generator, and converters huge amount of wind energy extraction is possible. A nacelle is set down over the topmost position of the turbine's elected tower that holds gearbox, generator and rotor shaft linked to turbine blades. When high-speed winds strike to the turbine blades, the kinetic energy of wind is converted into rotation of turbine blades. When the speed of wind is not sufficient to generate power the low speed of rotor shaft is converted to high speed by gearbox connected to the turbine blades and the generator where energy conversion process takes place. The below is the given organized layout of wind energy extraction system as depicted shown in Fig. 1.

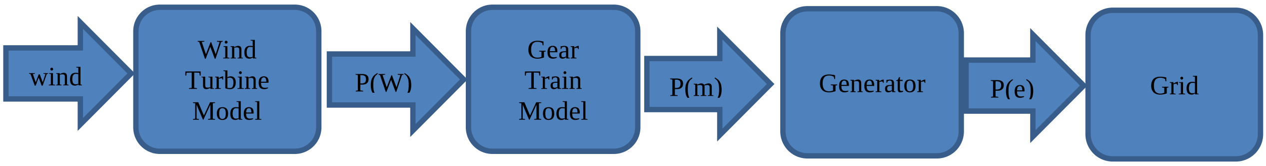

Fig.1: Block view of integrated System

2.1. DFIG based wind turbine/ Mechanical system

The wind turbine is an electromechanical device, that is responsible of mechanical power development at the rotor shaft. The DFIG based wind turbine consist of aerodynamic, pitch, mechanical, electrical, and power converter control system. The mechanical power developed to rotate the shaft is function of wind speed, shaft speed, blade pitch angle and air density, that is calculated by following formula.

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

While designing wind turbines, their rotational speed is fixed at which there will be maximum power coefficient to yield maximum mechanical power at the rotor shaft. If the wind speed is lower than rated speed, the wind turbine will function in variable speed mode. Therefore, speed control mode will adjust generator speed to keep power coefficient at maximum value. Maximum power point tracking (MPPT) control is activated during operation of wind turbine for maximum power capture at winds lower than rated speed and a part of mechanical power is wasted at higher winds by activating pitch angle control to avoid mechanical damage to the turbine [11]. The power captured through DFIG is divided into four regions. At the start, the generator output power is zero, as the required driving torque is not available. After the start, the wind turbine operates under speed control mode to control the DFIG for maximum power capture at lower winds. After the rated speed, the wind turbine is activated in power control mode to control the power generated by machine to yield constant magnitude of output power by reducing the pitch angle of turbine blades. After the cut-out speed about 25m/s the wind turbine is shut downed. (Cp vs lambda Fig .2. Power vs speed Fig.3)

2.2. DFIG Electrical System

DFIG is primarily a traditional wound rotor induction machine whose stator is mainly assembled with power grid whereas rotor is connected to the power grid via a bidirectional power converter. The converter is made up of PWM converters with in between DC link capacitor. The DC link capacitor connecting both converters store the power from a machine for more generation and the control of grid current parameter is achieved by boosting capacitor voltage to an upper level that is higher than magnitude of grid line to line voltage [12]. The slip power can flow in both directions as the voltage can be fed to either terminal of DFIG. At the start, grid supplies slip power to excite the rotor of the machine. The revolving magnetic field produced in stator generates revolving magnetic flux that produces current in the rotor of generator but as the wind turbine rotates the overall speed increases from synchronous speed. The increased speed will cause strong back emf interacting with the stator field. Thus, the current is generated in stator winding and power is supplied back to the power grid. once it starts producing power it does not require further power from grid. The DFIG system has ability to operate under variable speeds of wind slightly above or below synchronous speed over a large but limited speed [13]. The bidirectional AC/DC/AC power converter is utilized to provide flow of power in both directions to retain DFIG in generator mode over a wide range of sub-synchronous to super synchronous speed. The stator continues power supply to grid at both speeds.

3. DFIG Modeling and Designed Control Scheme

The dynamic performance of DFIG is analyzed and simulated using synchronously rotating $d-q$ reference frame (SRF) using Clark and Park conversion in form of space vectors. The SRF provides better DFIG control by regulating PI controllers and Power Electronic Converter [14]. The DFIG model in SRF can be presented by following equations.

$$\begin{gathered}v_{ds}=R_s i_{ds}+\frac{d\psi_{ds}}{dt}-\omega_s\\ v_{qs}=R_s i_{qs}+\frac{d\psi_{qs}}{dt}+\omega_s\psi_{ds}\\ v_{dr}=R_r i_{dr}+\frac{d\psi_{dr}}{dt}-\omega_{sl}\psi_{qr}\\ \psi_{qr}=L_r i_{qr}+L_m i_{qs}\\ v_{qr}=R_r i_{qr}+\frac{d\psi_{qr}}{dt}+\omega_{sl}\\ \therefore\ \omega_{sl}=\omega_s-\omega_r\end{gathered}\tag{3}$$

The stator and rotor flux can be represented in SRF as follows

$$\begin{gathered}\psi_{ds}=L_s i_{ds}+L_m i_{dr}\\ \psi_{qs}=L_s i_{qs}+L_m i_{qr}\\ \psi_{dr}=L_r i_{dr}+L_m\end{gathered}$$

Electromagnetic Torque developed in system can be represented as

$$T_e=1.5P\frac{L_m}{L_s}\left(?_{qs}\,i_{dr}-?_{ds}\,i_{qr}\right)\tag{4}$$

Eliminating the electrical losses in DFIG, both the stator and rotor power in SRF can be shown as

$$P_s=1.5\left(v_{ds}i_{ds}+v_{qs}i_{qs}\right)\tag{5}$$

$$Q_s=1.5\left(v_{qs}i_{ds}-v_{ds}i_{qs}\right)\tag{6}$$

$$P_r=1.5\left(v_{dr}i_{dr}+v_{qr}i_{qr}\right)\tag{7}$$

$$Q_r=1.5\left(v_{qr}i_{dr}-v_{dr}i_{qr}\right)\tag{8}$$

3.1. Design of Control System

There are three levels through which we can achieve control of the DFIG system in wind power plant i.e., Generator, wind turbine and centralized wind farm [15]. The control of generator is executed by controlling the bidirectional converter through decoupled $d - q$ vector control approach that is implemented in this paper. The rotor converter grips over the DFIG for independent control of power, maximum wind energy extraction and effective grid integration while grid controller puts the DC-link voltage in constant mode irrespective of wind speed, and rotor power. It also controls the reactive power sharing with the power grid and maintains power factor near unity. The control mechanism of wind turbine includes speed controller, Torque controller and mechanical power limitation controller to produce rated power output. The mainstream wind farm examines the power needed by grid and disperses power outwards to a reference signal for each individual turbine to meet the grid requirement while some local wind turbines control ensure the power requirement according to central control unit has been reached.

3.1.1. Rotor-Side Converter Control

The vector-oriented control scheme is applied on the stator of the DFIG in synchronously rotating reference frame by aligning d-axis of SRF in direction of stator voltage vector and voltage fed to stator is assumed constant, then the stator q-axis voltage vector will be zero and d-axis voltage will be equal to constant supply voltage.

$$v_{ds} = v_s \ , \ v_{qs} = 0$$

$$\psi_{ds} \cong 0 \ , \quad \psi_{qs} = \psi_s = -\frac{v_{ds}}{\omega_s}$$

Substituting in stator flux equation gives

$$i_{ds} = -\frac{L_m}{L_s} i_{dr} \ , \qquad i_{qs} = -\frac{L_m}{L_s} i_{qr}$$

By putting in electromagnetic torque equation, it yields

$$T_e = -1.5P \frac{L_m}{\omega_s L_s} v_{ds} i_{dr} \qquad (9)$$

By putting stator voltage condition in stator power expression

$$P_s = 1.5 v_{ds} i_{ds} \quad , \qquad Q_s = -1.5 v_{ds} i_{qs}$$

Hence, it is proved in above stator power and torque expressions that stator active and reactive power can be controlled separately by controlling the rotor current components. By using rotor side converter control diagram, the control scheme is simulated in MATLAB/Simulink to analyze the mathematically obtained results.

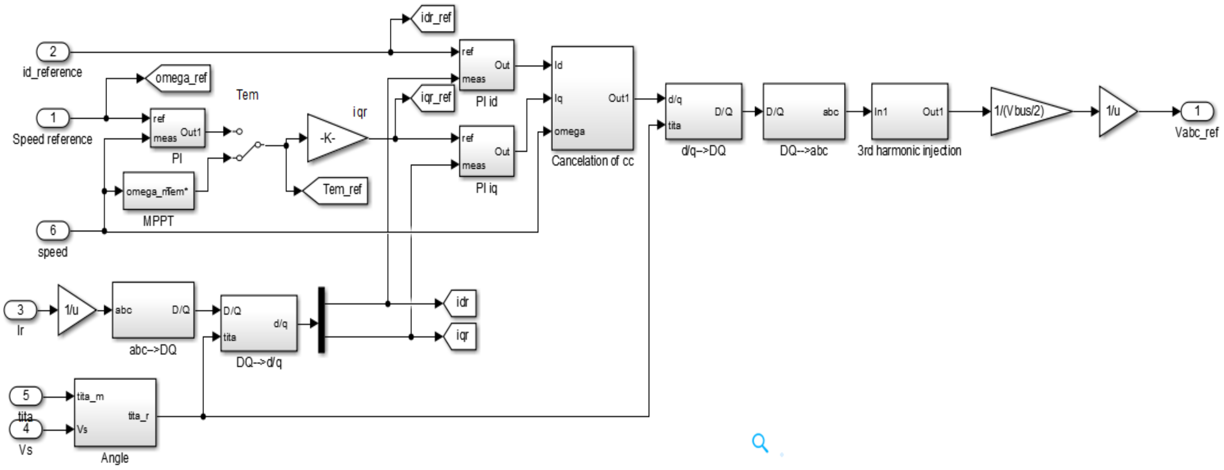

Fig. 2: Simulink Block diagram for rotor-side converter control

3.1.2. Grid-Side Converter Control

The grid side converter has two current control loops, to regulate and control DC-link voltage and reactive power accordingly. The active power can flow to or from the grid to turn upon the operational speed of the DFIG. Therefore, grid side converter (GSC) is synchronized and linked with power grid to avoid the undesirable disturbance caused by the transient currents owing to phase difference between the grid voltage and GSC. In Grid side voltage-oriented control scheme (GVOC), the SRF d-q axis is rotated along the grid voltage and the d- axis of reference frame is aligned along the grid voltage space vector.
Then the

$$V_{dg} = v_g \ , \ V_{qg} = 0$$

According to above condition power equations will be

$$P_g = -1.5(v_{dg}i_{dg} + v_{qg}i_{qg}) = -1.5v_{dg}i_{dg}$$
$$Q_g = -1.5(v_{qg}i_{dg} - v_{dg}i_{qg}) = 1.5v_{dg}i_{qg}$$

The DC link capacitor equation will be

$$C_{dc} = \frac{V_{dc}}{dt} = i_{dc} - 1.5\frac{v_{dg}}{v_{dc}}i_{dg} \quad (10)$$

Thus, the grid d and q current component regulates constant DC link voltage and the power sharing with the grid by controlling active and reactive power flow respectively. To ascertain unit level power factor, grid reference reactive power is assumed zero. By visualizing and compared side by side the pre-reference and actual counted values of DC link voltage, the grid d-axis current reference is achieved from error signal by PI regulator. The whole GVOC scheme is simulated in MATLAB/Simulink by using control diagram of designed scheme to examine the output given through mathematical modeling.

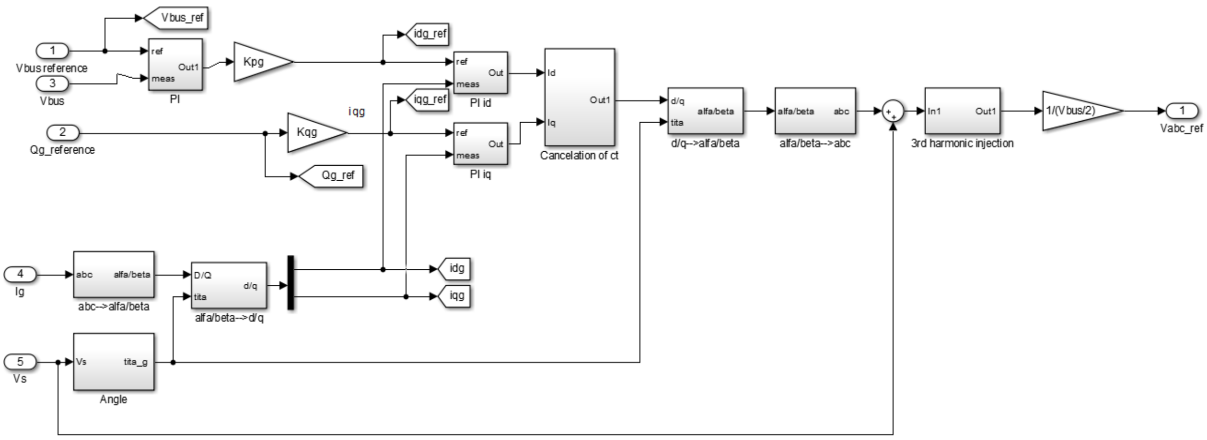

Fig. 3: Simulink Block diagram for Grid-side converter control

4. Simulation Results

In the above proposed model, a vector-oriented control scheme is used to improve the control of rotor side converter and grid side converter of GE 1.5MW DFIG-based wind turbine located at Jhimpir are analyzed and examined. In the simulated model a real time-based data has been considered where the rate of wind speed is taken 10m/s in comparison to the installed wind turbine that is operating at 12m/s, where it is observed that a wind turbine operating at 12m/s is providing constant power output of 1.5MW whereas, the performed study is providing approximately 1.2MW of power output. In the light of theoretical background and mathematical modeling of rotor side and grid side converters for improving the performance of DFIG is presented in section 3, the prolonged numerical based simulations have been simulated using MATLAB/Simulink software. The simulation model results are depicting that by implementing the designed control scheme provides satisfactory power output at the lower wind speed rates in comparison to the rated speed of GE wind turbine and independent control of both active and reactive power. The designed system also seems very effective to suppress DC-link voltage variations to feed constant frequency electrical power to the power grid.

Fig. 4, 5 and 6 shows stator voltage, stator current and rotor current in normal condition and Fig. 7 is the fixed reference d-axis current at rotor side that is an input to PI regulator with almost zero magnitude. Fig. 8 shows d and q-axis current in grid side to produce enough reactive power to control Dc link voltage. Fig 9 shows dc link voltage variation with respect to time, that are maintained constant at reference value 1150v. Fig. 10 represents reference reactive power in grid side to guarantee unity power factor in rotor circuit. Fig. 11 shows that the stator of DFIG is transmitting about 0.7MW active power to grid while 5MVAR reactive power is required at start magnetization of the stator circuit. The Fig. 12 represent the power vs time graph of rotor circuit. The grid side converter maintains unity power factor in rotor circuit owing to negligible reactive power. The converter rating of rotor that is generating about 0.5MW active power is $(\frac{0.5}{2}) \times 100 = 25\%$. The power output from DFIG is directly proportional to cube of wind speed. Generally, the wind turbines are designed at rated speed 13m/s to yield 2MW output power as shown in Fig. 13.

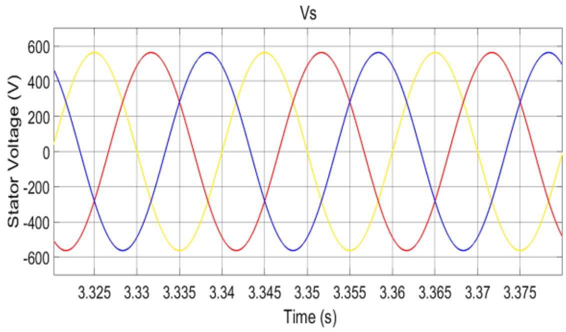

Fig. 4: Stator Voltage

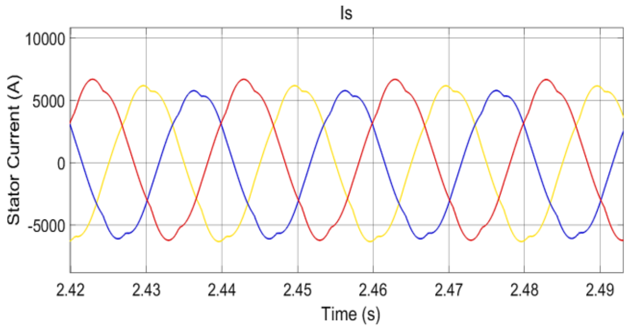

Fig. 5: Stator Current

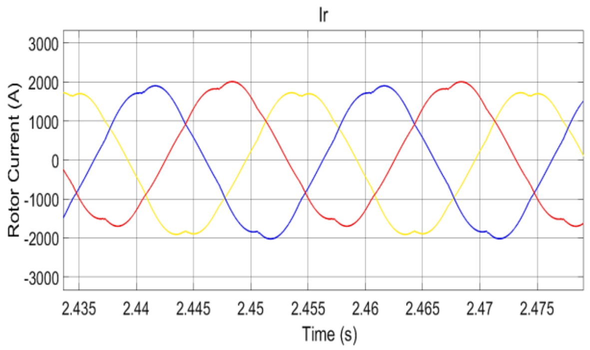

Fig. 6: Rotor Current

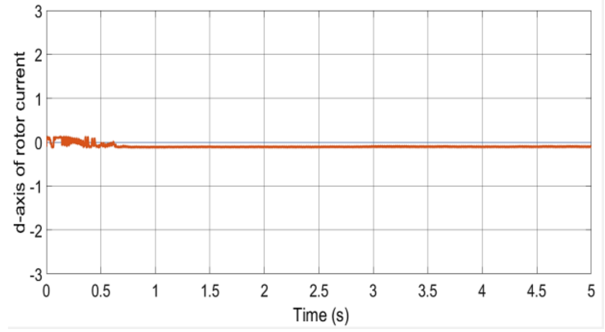

Fig. 7: d-axis of rotor current

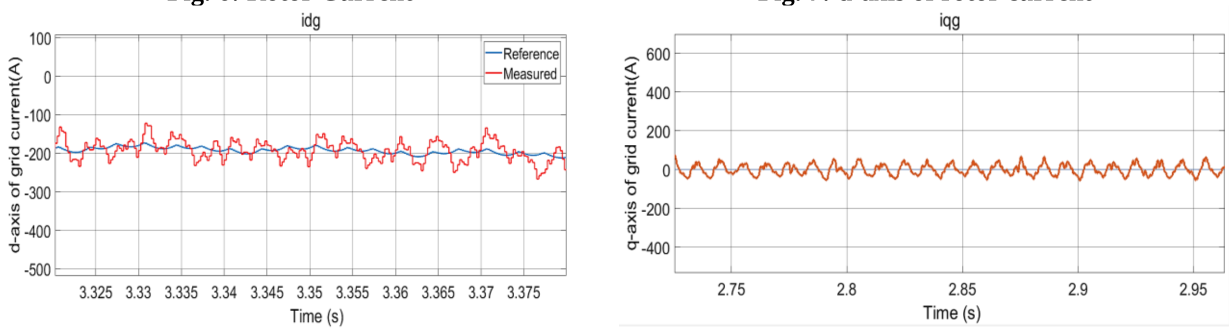

Fig. 8: d-q axis of Grid Current

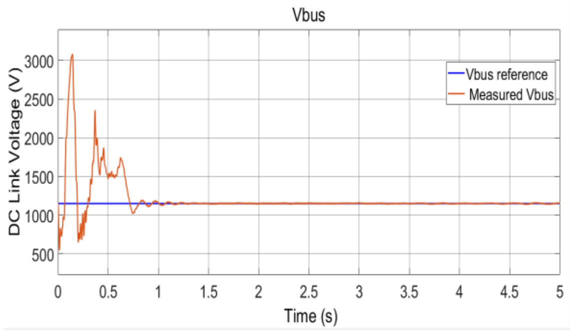

Fig. 9: DC-link voltage

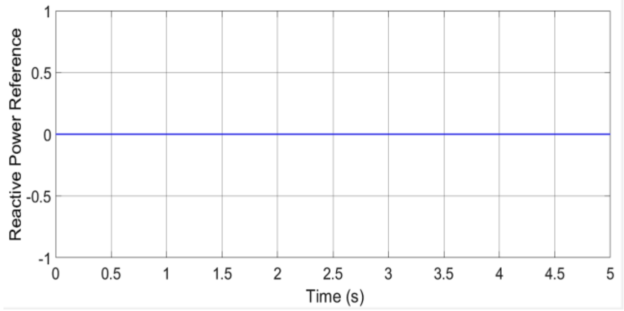

Fig. 10: Reactive Reference Power

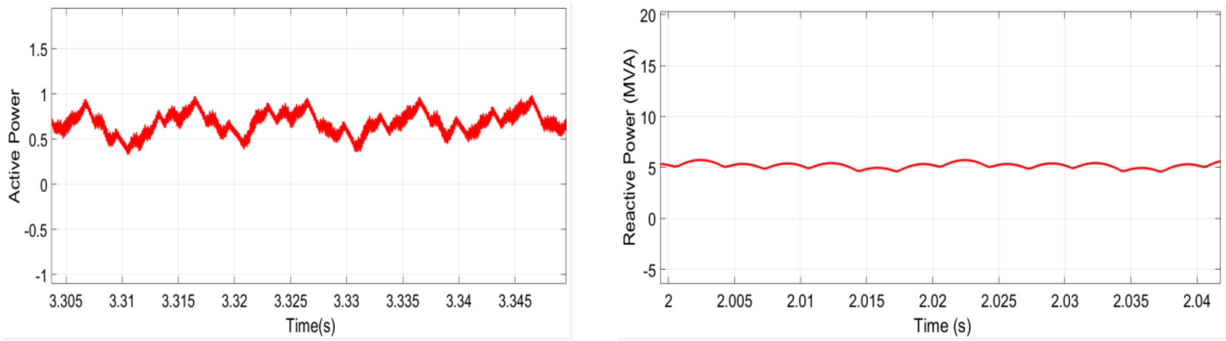

Fig. 11: Stator Side Active and Reactive Power

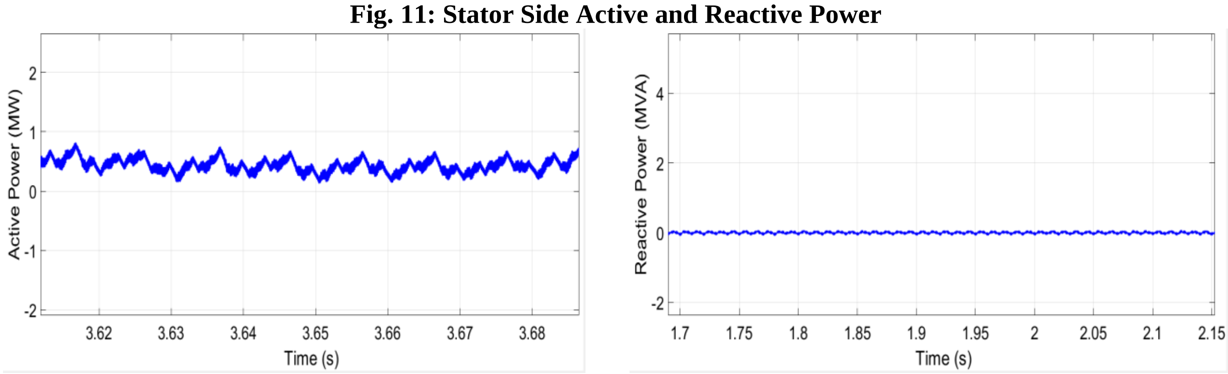

Fig. 12: Rotor Side Active and Reactive Power Curves

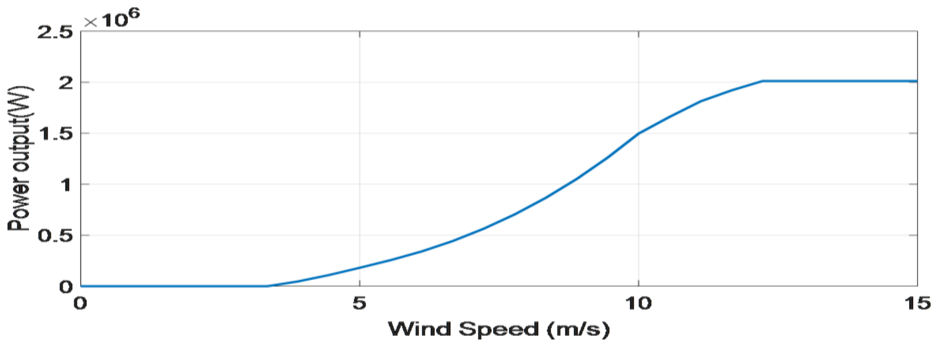

Fig. 13: Power vs Wind speed Curve

The GE wind turbines are operating at 12m/s to give expected power output of $2 \times (12 \div 13)^3 = 1.57 \approx 1.6$ MW. While we have performed simulation at 10 m/s w.r.t GE wind turbine, the expected power output will be $2 \times (10 \div 12)^3 = 1.157$MW. Thus the Fig. 11 and 12 show that total generated active power is (0.7+0.5) = 1.2MW that matches with theoretically calculated output power. The Fig. 14 represents the Speed and Torque control of DFIG-based wind Turbine at reference input speed of 1800 rpm/ 188 rad/s.

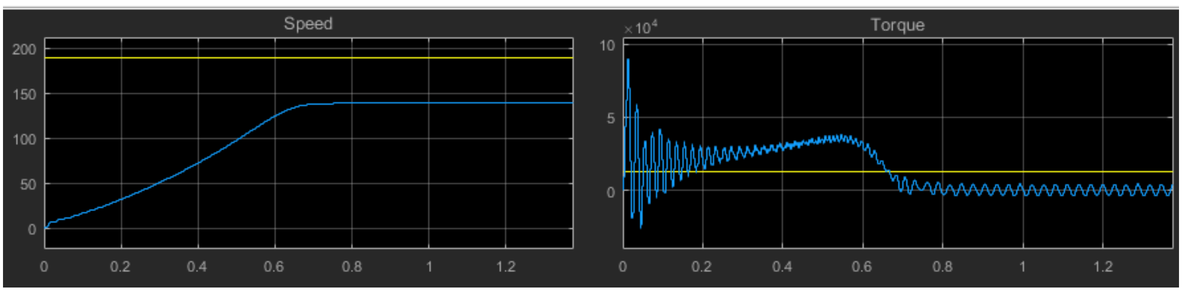

Fig. 14: Speed and Torque Control Curves

5. Conclusion

It is evident from above study that by deploying DFIG in WECS, a bulk amount of electric power can be harnessed over the variating range of wind speed as such lower to higher. This study focuses, the simulation of DFIG and its power output behavior is observed over the two speeds, one is the 12m/s that is the existing case study of Jhimpir corridor, and its output parameters compared with DFIG operating at 10m/. The wind profile of Pakistan and its availability is also discussed and found that average wind speed is 5.6 throughout year and it reaches above 18m/s during high winds, therefore the power input to the grid varies from season to season and suitable control is required. For turbine speed control torque control is provided that rotates wind turbine at fixed speed without any damage to turbine. The proposed research work considers a case study of 1.5MW GE wind turbine installed at the specific location of Jhimpir is carried out by implementing the vector-oriented control scheme on bidirectional AC/DC/AC converter to improve the control of rotor side and grid side converter parameters. The study results compare the power obtained from a DFIG based wind turbine operating at 12m/s to another simulated model operating at 10m/s and the simulated system generates almost exact power output that were mathematically evaluated and ultimately provides decoupling between active and reactive power.

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