Middle-East Journal of Scientific Research 24 (S2): 254-262, 2016
ISSN 1990-9233

DOI: 10.5829/idosi.mejsr.2016.24.S2.160

Analysis of Low Voltage Ride Through on Permanent Magnet Synchronous Generator Based Wind Energy Conversion System

[1]A. Gold Priya, [1]P.S. Mayurappriyan, [2]Deepa Kurup and [3]S. Maga

[1]Department of EEE, KCG College of Technology
[2]Deputy Director-Technical National Institute of Wind Energy,
[3]Department of EEE, Dhanalakshmi Srinivasan College of Technology, Chennai, India

Abstract—Nowadays the growth of wind energy system isincreasing due to the decay of fossil fuels. The variable speed wind turbine with doubly fed induction generator (DFIG) has a wide scope in the world market share with some drawbacks. The performance of wind energy conversion (WEC) system is enhanced by using low speed permanent magnet synchronous generator (PMSG) without gearbox. This paper proposes an improved control strategy for an efficient and reliable grid interface system for a direct drive operation of permanent magnet synchronous generator. The speed and torque control is achieved through the controlling techniques. In the rectifier side of the frequency converter, the zero d-axis current (ZDC) control method is implemented for generating controlled gate signal to the converter. In the grid side inverter, voltage oriented control (VOC) method is implemented to obtain constant control over the DC link voltage. So that the power flows between DC link and inverter, which is maintained constant throughout all the operating conditions. The analysis and modeling of direct driven PMSG with wind energy conversion system is achieved during low voltage ride through (LVRT) with the help of the method energy storage. The surplus active power is stored in the turbine generator mechanical system inertia during LVRT. The simulation is performed using MATLAB/SIMULINK Software.

Key words: Zero d-axis current (ZDC) control · Voltageoriented control (VOC) · Wind energy conversion (WEC) · Grid side converter (GSC) · Rectifier side converter (RSC) · Lowvoltage ride through (LVRT)

INTRODUCTION

The source of energy can vary but it is well known that the validity of Newton's law cannot be disputed, which states that the energy cannot be created nor be destroyed. We know that wind is air in motion. Wind is one of the major and abundantly available sources of green energy. Wind energy can be converted to electrical energy in two modes, (i) the standalone rooftop (ii) Grid connected electric power. India ranks fifth in the installed capacity of grid connected electricity in the world and second largest in Asia. Globally installed capacities of WTGs have crossed 290 GW. Indian Energy Industries have atotal installed capacity of 223 GW of electricity generation, of which about 28GW is from all Renewable Energy Sources in which about 19 GW is from wind energy. According to Ministry of New and Renewable Energy (MNRE) total capacity of 301 GW power has been established in India by renewable energy up to 14 Dec, 2015.

The performance of the wind energy system can be greatly enhanced with the use of a full-capacity power converter. The generator is connected to the grid via a full-capacity converter system. Squirrel cage induction generators, wound rotor synchronous generators and permanent magnet synchronous generators (PMSG) have all found applications in this type of configuration with a power rating up to several megawatts. The problems associated with induction generator based wind turbines are reactive power consumption, mechanical stress and poor power quality. Moreover, the gearbox requires regular maintenance as it suffers from faults and malfunctions. Therefore, it is important to adopt technologies that can enhance efficiency, reliability and

Corresponding Author: A. Gold Priya, Department of EEE, KCG College of Technology, India.

reduce system cost of wind based power generation system. The main features of PMSG based wind turbines are; gearless operation, higher efficiency, enhanced reliability, smaller size, reduced cost and low losses. Hence PMSG is more preferable than DFIG.

Wind machine starts generating power when wind speed exceeds cut-in (3m/s) and continue to produce power till cut-out (25m/s). It will stop rotation when the wind speed goes higher than cut-out, 25m/s under such conditions the drag force on the rotor dominates acting like a wind brake on the rotating blades. Apart from rotor controls, upwind wind turbine generators would require a yawing system with controls which would make the rotor seek the wind as it changes directions. The power rating of the converter is normally the same as that of the generator. With the use of the power converter, the generator is fully decoupled from the grid and can operate in full speed range. This also enables the system to perform reactive power compensation and smooth the grid connection. The control scheme for back-to-back (B2B) neutral point clamped (NPC) converter was discussed in [1], but in theproposed paper voltage source converter (VSC) is used instead of NPC converter. The energy storage in turbine-generator mechanical inertia is also discussed.

The control scheme of the GSC is supported with a voltage loop to reduce the flicker emission in [2]. The vector control of GSC is discussed in [3] for PMSG fed WEC system. In [4], the reactive power control of a variable speed PMSG wind generator with a matrix converter is improved. The new trends in power electronics for the integration of wind and photovoltaic (PV) power generators are presented in [5]. In [6], different ways for emulating inertia response in full-rated power converter-based wind turbines equipped with permanent magnet synchronous generators are considered. A comparative study on grid connected WECS having two different Wind Turbine Generator Systems (WTGS) using DFIG and PMSG is presented in [7]. An open-winding permanent-magnet synchronous generator (PMSG) system with the integration of fully controlled and uncontrolled converter is investigated in [8]. The performance and the power electronic techniques are discussed inthe grid integration is discussed for PMSG in a review of some methods of LVRT is discussed in detail.

Wind Energy Conversion System: In this configuration, the turbine rotor and generator shafts may be coupled directly, that is without gearbox. The generator is excited through a permanent magnet which is coupled through a full scale power converter, consisting of grid side and generator side converters connected back-to-back through a DC link. The GSC and RSC are Voltage Source Pulse Width Modulated (PWM) Converters. The rotor side PWM-VSC converter controls the generator. The GSC maintains the DC link voltage by controlling the flow of power (active & reactive) to the grid. The performance of the PMSG in the direct-driven WEC system is analyzed with the modeling.From Fig. 1, the PMSG is fed from the wind turbine. The wind turbine converts the wind energy into mechanical energy, which then runs a generator to create electrical energy. The mechanical power developed by the turbine depends upon the power coefficient of turbine, air density and wind speed voltage as constant. So that, the power flow to the AC grid is controlled.

Wind Turbine and Pitch Control: The wind turbine is one of the most important elements in wind energy conversion systems. Two main types of wind turbines are Horizontal Axis Wind Turbine (HAWT) and Vertical Axis Wind Turbine (VAWT). The most popular wind turbine is HAWT. Wind power is harnessed by converting the kinetic energy in the wind to mechanical energy and then to electrical energy. The standard three bladed upwind configurations seem to be the basic configuration most designers are following.

A wind turbine extracts kinetic energy from the swept area of the blades. The power contained in the wind is given by the kinetic energy of the flowing air mass per unit time. That is,

Wind power,

$$P_{windturbinw} = \frac{1}{2} C_p \rho A v^3$$

where is the power contained in wind (in watts), ñ is the air density (1.225 kg/m3 at 15°C and normal pressure), A is the swept area in (square meter) and is the wind velocity without rotor interference, i.e., ideally at infinite distance from the rotor (in meter per second).

Although the above equation gives the power available in the wind, the power transferred to the wind turbine rotor is reduced by the power coefficient, Cp,

$$c_p = \frac{P_{windturbinw}}{P_{air}}$$

$$\mathrm{P_{air}} = \frac{1}{2} \rho A v^3$$

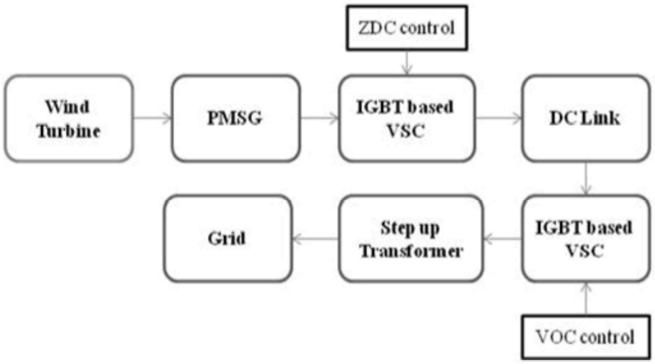

Fig 2.1: Block Diagram of WEC system

Maximum value of Cp is defined by the Betz limit, which states that a turbine can never extract more than 59.3% of the power from an air stream. In reality, wind turbine rotors have maximum Cp values in the range 25-45%. The power coefficient in this numerical approximation is given by,

As the speed increase the magnitude of output voltage and frequency of PMSG is also increase. In order to maintain the constant output voltage and frequency the PMSG is connected with the IGBT based B2B VSCs. By properly operating the switches in the VSCs, can achieve control on the magnitude of output voltage, frequency and phase angle. The RSC controls the speed and torque and the GSC maintains the DC link

$$C_p = 0.73[\frac{151}{Ai} - 058\theta - 0.002\theta^{2.4} - 13.2]e^{\frac{-18.4}{Ai}}$$

where,

$$Ai = \frac{1}{\frac{1}{A - 0.2\theta} - \frac{0.003}{\theta^3 + 1}}$$

Pitch Control: Similar to the active-stall control, pitch-controlled wind turbines have adjustable blades on the rotor hub. When the wind speed exceeds the rated value, the pitch controller will reduce the angle of attack, turning the blades (pitching) gradually out of the wind. The pressure difference in front and on the back of the blade is reduced, leading to a reduction in the lifting force on the blade. The operating principle of the pitch control is when the wind is below or at the rated speed; the blade angle of attack is kept at its rated (optimal) value. With higher than the rated wind, the angle of attack of the blade is reduced, causing a reduction in lift force. When the blade is fully pitched, the blade angle of attack is aligned with the wind and no lift force will be produced. The turbine will stop rotating and then be locked by the mechanical brake for protection.

Both pitch and active-stall controls are based on rotating actions on the blade, but the pitch control turns the blade out of the wind, leading to a reduction in lift force, whereas the active-stall control turns the blades into the wind, causing turbulences that reduce the lift force. The passive-stall technology was mainly used in the early fixed-speed wind turbines. This technology was further developed into the active-stall technology. The pitch control reacts faster than the active-stall control and provides better controllability.

Control Methods for the Voltage Sourceconverters: The voltage source converters in the frequency converter have two major control techniques for the generation of duty cycles of the PWM switching strategies. The two controls are follows:

Zero d-axis Current Control: The zero d-axis current control can be realized by resolving the three-phase stator current in the stationary reference frame into d-axis and q-axis components in the synchronous reference frame. The d-axis component, ids, is then controlled to be zero. With the d-axis stator current kept at zero, the stator current is equal to its q-axis component IQs.

$$Is = \sqrt{Isd^2} + Isq^2$$

Is represents its magnitude, which is also the peak value of the three-phase stator current in the stationary reference frame. The electromagnetic torque of the generator,

$$Te = \frac{3p}{2}[Ar\ Isq - (Ld - Lq)Isq\ Isq]$$

It can be simplified into

$$Te = \frac{3p}{2} Ar\ Isq = \frac{3p}{2}\ Ar\ Is$$

where p is the pole pairs and ër is the rotor flux linkage produced by permanent magnets in the PMSG. The above equation indicates that with Isd = 0, the generator torque is proportional to the stator current Is. With a constant rotor flux linkage ër, the torque exhibits a linear relationship with the stator current, which is similar to torque production in a DC machine with a constant field flux, where the electromagnetic torque is proportional to the armature current.

For the ZDC scheme, Isd = 0, the stator power factor angle is given by,

$$\phi = \tan^{-1}\left(\frac{vsq}{vsd}\right) - \frac{x}{2}$$

For,

$$\mathbf{I_{sd} = 0}$$

Voltage Oriented Control of Inverter: The grid-connected inverter can be controlled with various schemes. One of the schemes is known as voltage orientedcontrol (VOC), as shown in Figure 3.3. This scheme is based on transformation between the ABC stationary reference frame and d-q synchronous frame. The control algorithm is implemented in the grid-voltage synchronous reference frame, where all the variables are of DC components in steady state. This facilitates the design and control of the inverter.

To realize the VOC, the grid voltage is measured and its angle is detected for the voltage orientation. This angle is used for the transformation of variables from the ABC stationary frame to the dq synchronous frame through the abc-dq transformation or from the synchronous frame back to the stationary frame through the dq-abc transformation. Various methods are available to detect the grid voltage angle. We use the ZDC method. In practice, the grid voltage may contain harmonics and be distorted, so digital filters or phase-locked loops (PLLs) may be used for the detection of the grid voltage angle.

There are three feedback control loops in the system: two inner current loops for the accurate control of the dq-axis currents idg and iqg and one outer DC voltage feedback loop for the control of DC voltage vdc. With the VOC scheme, the three-phase line currents in the ABC stationary frame iag, ibg and icg are transformed to the two-phase currents idg and iqg in the dq synchronous frame, which are the active and reactive components of the three-phase line currents, respectively. The independent control of these two components provides an effective means for the independent control of system active and reactive power.

To achieve the VOC control scheme, the d-axis of the synchronous frame is aligned with the grid voltage vector.

Therefore, the (d-axis grid voltage is equal to its magnitude (vdg= vg)) and the resultant q-axis voltage vqgis then equal tozero $[Vqg = \sqrt{vg} - vdg = 0]$, from which the active and reactive power of the system can be calculated by,

$$\boldsymbol{Pg = \frac{3}{2} Vdg\ Idg}$$

$$\mathbf{Qg} = \frac{3}{2}\boldsymbol{Vdg\ iqg}$$

Q*g is the reference for the reactive power, which can be set to zero for unity power factor operation, a negative value for leading power factor operation, or a positive value for lagging power factor operation. The d-axis current reference idg, which represents the active power of the system, is generated by the PI controller for DC voltage control. When the inverter operates in steady state, the DC voltage vdc of the inverter is kept constant at a value set by its reference voltage vdc. The PI controller generates the reference current i*g according to the operating conditions. Neglecting the losses in the inverter, the active power on the AC side of the inverter is equal to the DC-side power, that is,

$$\mathbf{Pg} = \frac{3}{2}\boldsymbol{Vdg\ iqg} = \mathbf{v_{dc}\ i_{dc}}$$

The power flow of the inverter system is bidirectional which is shown in the Table 1 below.

Table 4.1: Power Flow in DC Link

E < Vdc	Idc > 0	Pg > 0	Power from grid to load (rectifier)
E > Vdc	Idc < 0	Pg < 0	Power from load to grid (inverter)
E = Vdc	Idc = 0	Pg = 0	No power flow between DC circuit

Modeling of PMSG: The PMSG has been considered as a system which makes possible to produce electricity from the mechanical energy obtained from the wind. Permanent Magnet Synchronous Generator provides an optimal solution for varying-speed wind turbines. The dynamic model of the PMSG is derived from the two phase synchronous reference frame, which has the q-axis is 90° ahead of the d-axis with respect to the direction of rotation. The stator windings are positioned sinusoidal along the air-gap as far as the mutual effect with the rotor is concerned; the stator slots cause no appreciable variations of the rotor inductances with rotor position; magnetic hysteresis and saturation effects are negligible; the stator winding is symmetrical; damping windings are not considered; the capacitance of all the windings can be neglected and the resistances are constant (this means that power losses are considered constant).

The d-axis and q-axis voltages of PMSG are,

$$Vsd = - RsId - Ls\frac{dIsd}{dt} + Lswe\phi$$

$$Vsq = - RsId - Ls\frac{dIsd}{dt} + LsweIsd + we$$

where,
Id, Iq are d-q axis stator currents R**s** is stator resistance
Lmd, Lmq are d-q axis inductance Lls is stator inductance
Φ is magnetic flux
ωe is electrical angular velocity of the generator

The electromagnetic torque may be expressed in terms of the stator currents as,

$$T_e = \frac{3p}{2} I_{sq}[(L_d - L_q) I_{sd} + \phi]$$

In surface mounted PMSGs, Ld = Lq = Ls. Hence, the electromagnetic torque can be rewritten as follows,

$$T_e = \frac{3p}{2} I_{sq}\phi$$

Low Voltage Ride Through: Wind turbines disconnect from the grid when voltage at the point of connection drops. Wind turbines can remain connected to the grid during a fault, only if adequate reactive power support is provided. LVRT is ability of the wind turbine to remain connected to the grid without tripping from the grid for a specified period of time during a voltage drop at the point of connection. Period of LVRT depends on, magnitude of voltage drop at the Point of Common Coupling(PCC) during the fault and the time taken by the grid system to recover to the normal state.

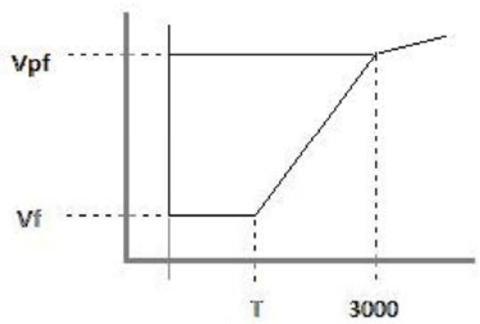

Fig. 4.1: LVRT as per IWGC

The above Fig 4.1 shows the voltage limit curve which is between the voltage in KV and the time in ms according to Indian Wind Grid Code (IWGC). Here, Vf is 15% of nominal system voltage and Vpf is minimum voltage for normal operation of wind turbine.

Storage of Turbine-generator Mechanical system: During grid faults, the active power injected to the grid is zero (*Pg*= 0). The surplus energy must be managed by the wind turbine system and power converters. Thus,

$$P_w - P_s = P_m = w_m J \frac{dw_m}{dt}$$

where,
is the power captured from the wind
is the mechanical input power to the electric generator
is the active power output of the generator *J* is the turbine–generator moment of inertiais the mechanical shaft speed

If is decreased with constant during the voltage dip, the will be increased from ω0 to ωf. Hence,

$$\int P_m dt = \frac{1}{2} J (w_f^2 - w_0^2)$$

where,
is the maximum value of the shaft speed during the grid fault
$_0$ is the rated shaft speed
Here, ***dt* = *t***, is the fault time. Then,

$$w_f = \sqrt{(\frac{2p_m t_f}{J} + w_0^2)}$$

Inertia constan

$$H = (\frac{J w_0^2}{2p_m})$$

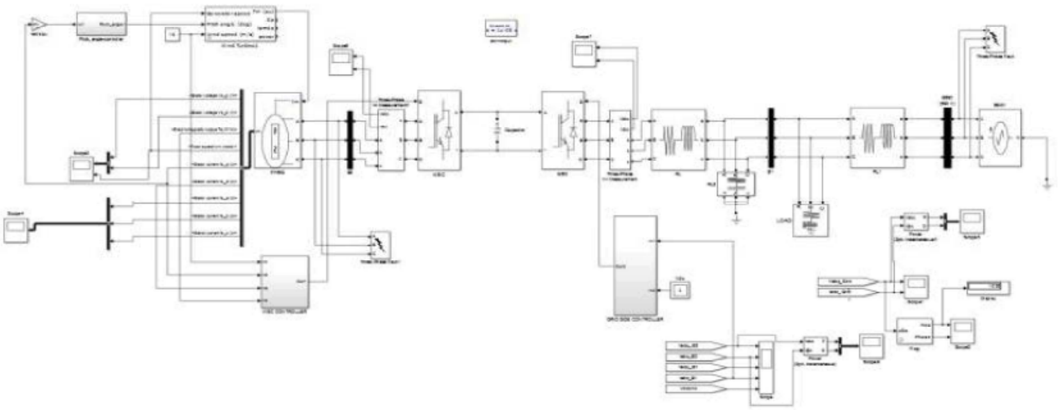

Fig. 8.1: Simulation model for PMSG based WEC system

$$W_0 = \frac{N2\pi}{60} \frac{rad}{sec}$$

$$J = \frac{H2P_m}{W_0^2}$$

The above formulas are used for the simulation calculations. The percentage increase in speed is calculated by,

The% increase of speed $= \frac{W_r - W_0}{W_0} \times 100\%$

Simulation and Results: The simulation of proposed WEC system using PMSG with LVRT is developed using MATLAB/SIMULINK software. In proposed work the ZDC and VOC control schemes are performed in both the voltage source converters. The Fig 8.1 shows the simulation model for the proposed work.

This model is designed for 20KW wind turbine system of 4 pole pairs of PMSG. The PMSG based WEC system operates with low speed and there is no need of gear box. In pitch control technique, the Cp value determines the torque of the wind turbine and the speed control takes the value to determine the torque from the pre-defined data by tracking the power curve. The RSC control is used to generate the gate signal to the.

The simulation is performed with and without three phase fault. Here, the fault period is from 0.4s to 0.6s. During this fault period the voltage at the point of common coupling will dip. But according to IWGC requirement the fault should be clarified within 3000ms. Here, the fault is cleared within 2000ms. In the GSC control, the reference components of dq-axis currents are compared and the error value is controlled through the PI controller. The controller gives the reference components of d-q-axis voltages, which are compared with the reference values and processed through some transformation to produce the gate signal to the IGBT based grid side VSC. IGBT based rotor side VSC using some transformations. Take the d-axis reference current as zero. Since, the PM is used. The reference vale and actual value of the d,q-axis currentcomponents are compared and the error values are controlled using PI controller. The resultant transformation gives the gate signal.

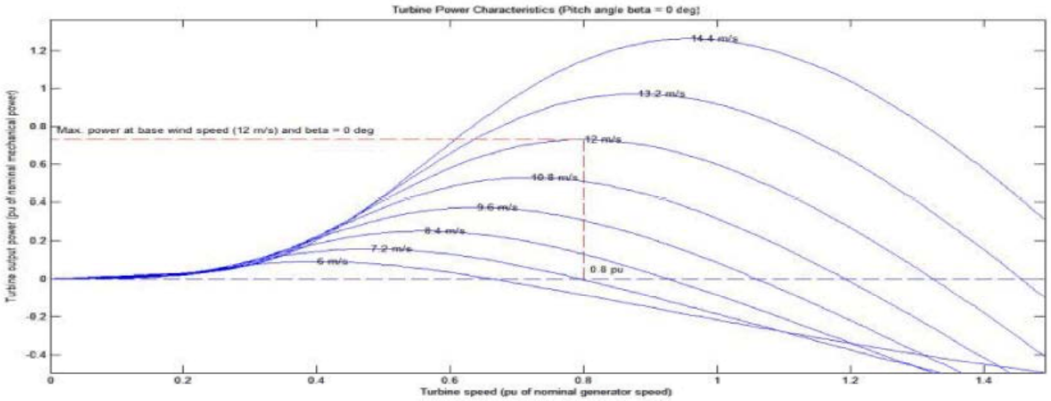

Fig. 8.2: Wind turbine characteristics

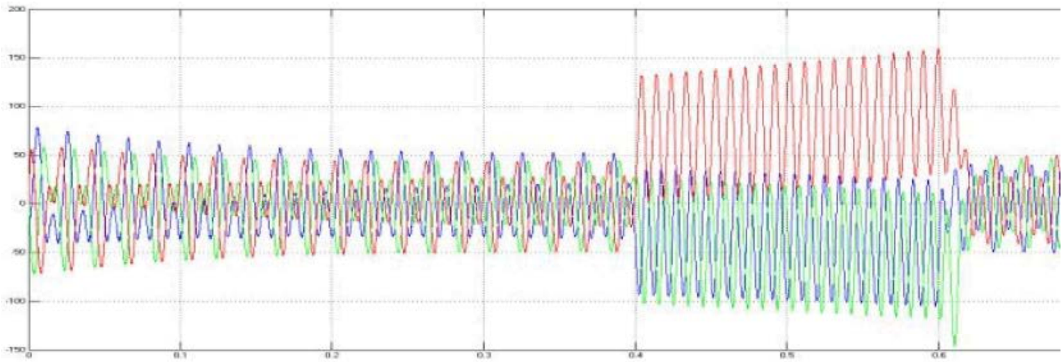

Fig. 8.3: PMSG voltage during the fault

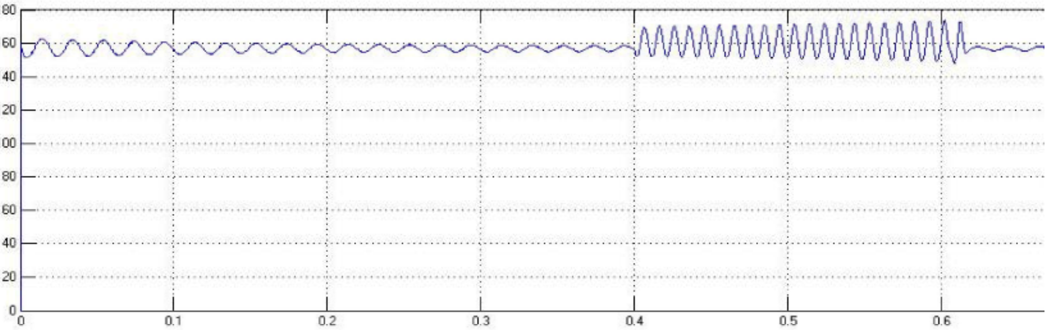

Fig. 8.4: Rotor speed in rad/s

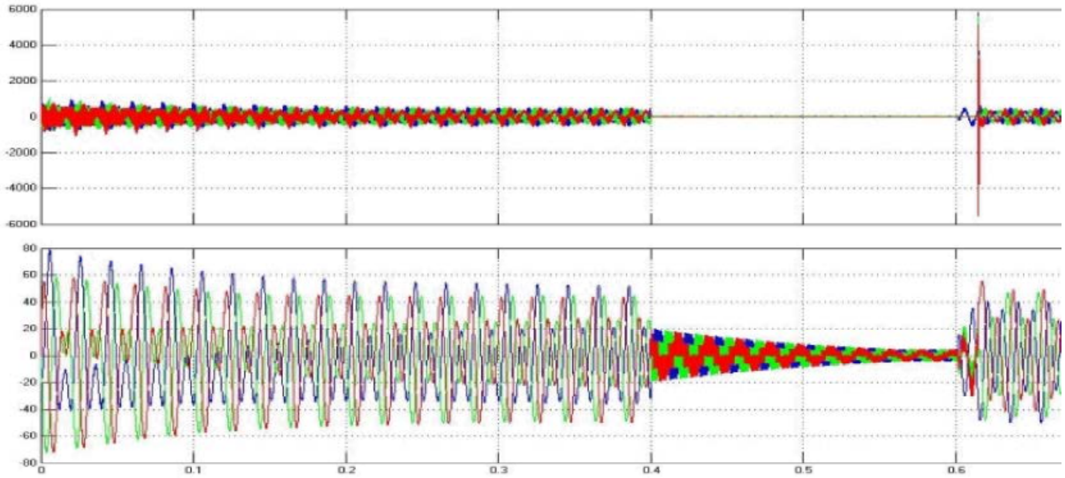

Fig. 8.5: Rectifier input voltage and current

The Fig 8.2 shows the wind turbine characteristics which is in between the turbine output power in pu and the turbine speed in pu. The maximum power 0.73 pu is achieved at the .8 pu of turbine speed with 12m/s and the zero beta value.

The Fig 8.3 shows the stator voltage of PMSG during the three phase fault condition. The voltage value is increased during the fault from 50 volts to 120 volts.

The Fig 8.4 shows the rotor speed which is increased from 150 rad/s to 170 rad/s during the fault period. Thus the energy stored in the turbine-generator mechanical system. So that the speed is increased and during fault clearing the speed is gradually decreased and reached the normal speed range.

The Fig 8.5 shows the input voltage and current of the rectifier from PMSG. Due to the three phase fault in the generator side transmission

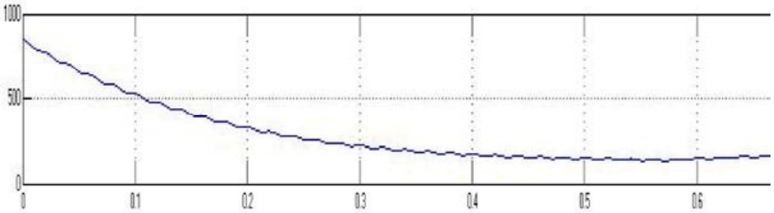

Fig. 8.6: DC link voltage

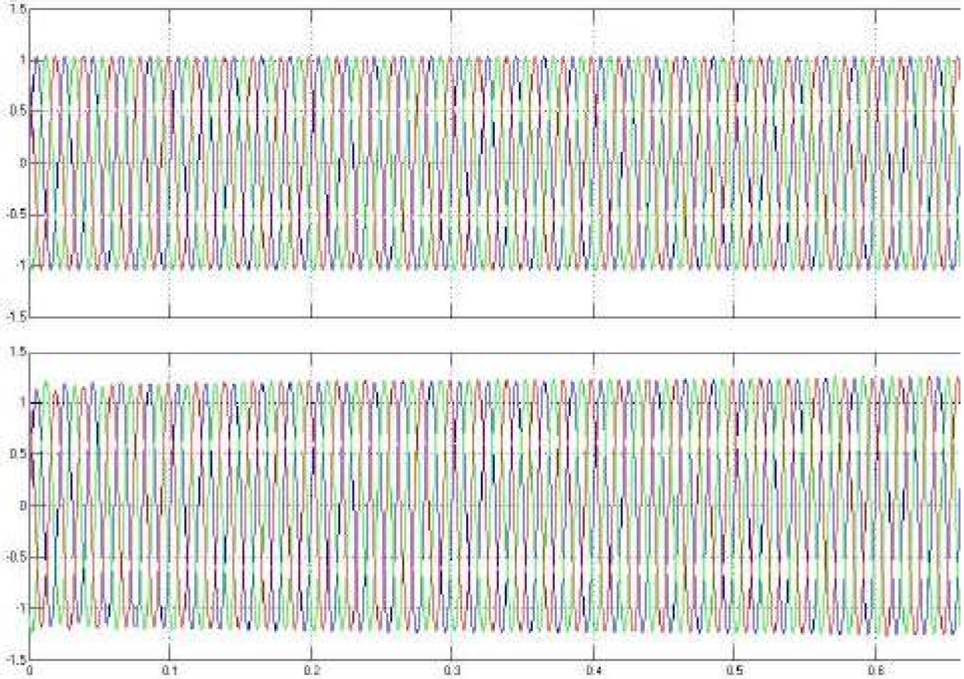

Fig. 8.7: Grid voltage and current during the fault in wind side

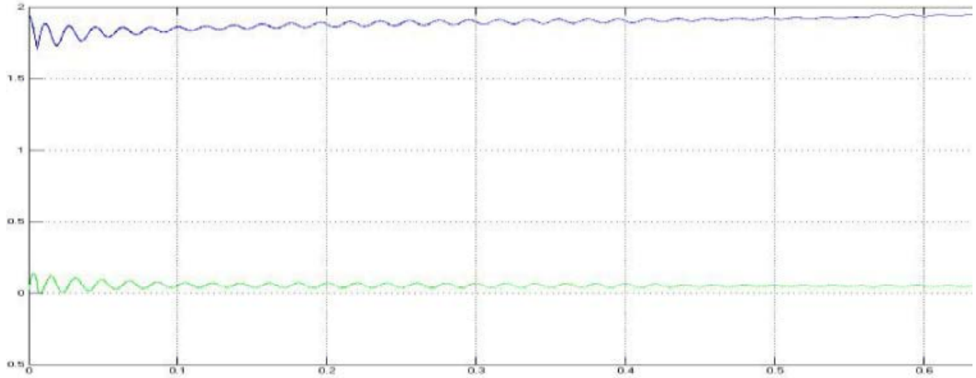

Fig. 8.8: Grid real and reactive power during the fault in wind side

line the voltage and current startsdecreasing and after fault clearance it reaches the normal ranges of 500V and 50A.

The Fig 8.6 shows the DC link voltage of the WEC system. The voltage of DC link should be maintained as constant to achieve the LVRT. Thus the DC link voltage is maintained as constant (250V) even during the fault. The Fig 8.7 shows the grid voltage and grid current during the fault. The grid voltage and current are not affected due to the fault in the wind side and their values are 1 pu each (415V and 50A).Salvador Alepuz, Alejandro Calle, Sergio Busquets-Monge, Samir Kouro and Bin Wu, "Use of Stored Energy in PMSG Rotor Inertia for Low-Voltage Ride-Through in Back-to-Back NPC Converter-Based Wind Power Systems," *IEEE Trans. Ind. Electron*., vol. 60, no.5, May. 2013.

The Fig 8.8 shows the real and reactive power of the grid. The WEC system supplies 20KW real power and zero reactive power even during the fault. Thus the LVRT technique solves the low voltage problem.

CONCLUSION

In the proposed system, PMSG is connected to the wind turbine through the WEC the power electronics system. The PMSG is fully controlled through AC-DC-AC system. The ZDC method is used in the rotor side and the VOC method is used in the grid side to produce the gate signals for the IGBT switches in the VSCs. Use of stored energy in PMSG rotor inertia for LVRT in back-to-back VSC is studied. The speed is increased 13% during the fault to store the energy in mechanical inertia. Thus the analysis of LVRT on direct drive PMSG based WEC system is performed using MATLAB/SIMULINK software.

REFERENCES

1. Ali H. Kasem Alaboudy, Ahmed A. Daoud, Sobhy S. Desouky and Ahmed A. Salem, 2013. Converter controls and flicker study of PMSG-based grid connected wind turbines, Elsevier, Ain Shams Engineering Journal (2013) 4: 75-91. Monica Chinchilla, Santiago Arnaltes and Juan Carlos Burgos, Control of Permanent-Magnet Generators Applied to Variable-Speed Wind-Energy Systems Connected to the Grid, IEEE Trans. Energy Conversion, 21(1).
2. Hossein Hojabri and hossein Mokhtati, 2008. Permanent Magnet Synchronous Generator Wind Turbine Application, IEEE Trans.Power. Electrons. 23(3).
3. Juan Manuel Carrasco, Leopoldo Garcia Franquelo, Jan T. Bialasiewicz, 2006. IEEE, Eduardo Galván, Ramón C. Portillo Guisado, IEEE, Ma. ÁngelesMartín Prats, José Ignacio León and Narciso Moreno-Alfonso, 2006. Power-Electronic Systems for the Grid Integration of Renewable EnergySources: A Survey, IEEE Trans. Ind. Elec., 53(4).
4. John Licari, Janaka Ekanayake and Ian Moore, 2013. Inertia response from full-power converter-based permanent magnet wind generators, J. Mod. Power Syst. Clean Energy (2013) 1(1):26–33, DOI 10.1007/s40565-013-0002-6.
   Lata Gidwani, 2015. A Comparative Power Quality Study of DFIG and PMSG Based Wind Energy Conversion System, Wseas Transactions on Systems and Control, E-ISSN: 2224-2856, Vol. 10, 2015.
5. Heng Nian and Yijie Zhou, 2015. Investigation of Open-Winding PMSG System with the Integration of Fully Controlled and UncontrolledConverter, IEEE Trans. Indus. Applications, 51(1), January/February 2015.
6. Suji Muhammed and V. Krishna kumari, XXXX. Performance
7. Analysis of a PMSG Based Wind Energy Conversion System, 2014. International Journal ofEngineering Research & Technology (IJERT), Vol. 3 Issue 8 and ISSN:2278-0181, August 2014.
8. Rajveer Mittal, K.S. Sandhu and D.K. Jain, 2009. Low voltage ride through(LVRT) of grid interfaced wind driven PMSG, ARPN Journal ofEngineering and Applied Sciences, VOL. 4, NO. 5, JULY 2009.A.Bala Alagu Raja, S. Ajin, R. Suja and A.Subanth Williams, "Review of low voltage ride through methods in PMSG, InternationalJournal of Research in Science and Technology, ISSN: 2349-0845, Vol. 2, January2015.