An AC-AC Converter for Doubly Fed Induction Generator Driven By Wind Turbine

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Abstract- This paper deals with a DFIG model employing nine switches AC/AC converter. As compared to the conventional DFIG employing Back to Back power converter the nine switch converter requires fewer switches and gate drive circuits. Therefore proposed topology results in reduction of installation area and cost. The nine switch converter DFIG is applied to the wind turbine and integrated with the grid. The results reveal that even though change in wind speed occurred, the generator terminal voltage and frequency remain same. The generator output power follows the wind speed and delivers the more power to the grid.

Index Terms- DFIG (Doubly Fed Induction Generator), RSC (Rotor Side Converter), GSC (Grid Side Converter), PWM (Pulse Width Modulator), Nine Switch Converter

I. INTRODUCTION

As conventional energy sources are going to be depleted very soon, wind power is the most reliable and developed renewable energy source over past decades. The WECS utilizing variable speed variable pitch wind turbine with DFIG is the most popular in the wind power industry especially for multi megawatt size. The power converters being utilized in the DFIG play very important role in maintaining the constant voltage and frequency. Harmonics will be certainly produced whenever converter parts are being used. However presence of this harmonic level can be reduced by reducing the size of the converter. Hence there is need to reduce the size of the power converters in the Doubly Fed Induction Generators system in order to reduce the harmonics produced. Usually in the conventional DFIG system totally 12 number of switches are being utilized i.e. six number of switches for rectification and another six number of switches for invertification. Hence there is need to minimize the number of switches by developing a new model which must consist of less number of switches as compared to conventional Back to Back converter. So by developing new less number of switches being utilized converter the cost and space requirement of power converters can be reduced.

The main reason for the popularity of the doubly fed induction generators connected to the national networks is their ability to supply power at constant voltage and frequency while the rotor speed varies [2]. And the power converters being used in the DFIG system are not required to convert the full rated generation power as in the singly fed induction generator power converters requiring conversion of full generated power. It handles only 25-30 % of rated generation power i.e. the slip power in the rotor circuit and remaining power is directly fed to the grid from the stator part [1].

Fig.1 shows,[1] the DFIG wind turbines use wound rotor induction generators, where the rotor winding is fed through a back-to-back variable frequency and amplitude PWM converter. The variable frequency converter consists of a rotor side converter (RSC) and a grid side converter (GSC) and only handles rotor power. The rotor side converter (RSC) usually provides active and reactive power control of the machine while the grid-side converter (GSC) keeps the voltage of the DC-link constant [6].

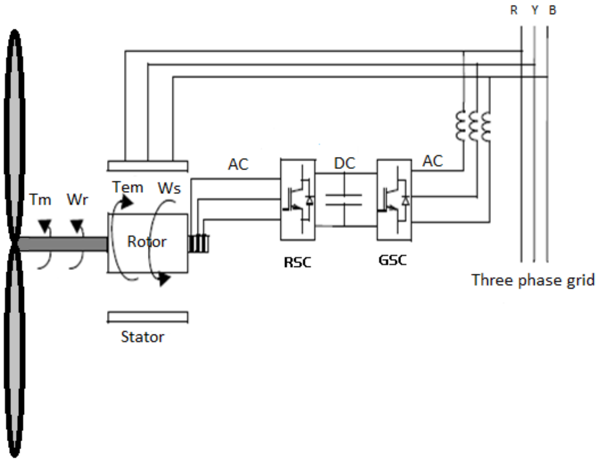

Fig.1: Conventional wind turbine based on a DFIG

In the conventional DFIG system totally twelve number of switches are being utilized i.e. six number of switches for rectification and another six number of switches for invertification. Harmonics will be certainly produced whenever converter parts are being used. Hence there is need to minimize the number of switches by developing a new model which must consist of less number of switches as compared to conventional Back to Back converter[1]. So by developing less number of switches, therefore converter cost and space requirement of power converters can be reduced [1].

II. OPERATING PRINCIPLE OF DFIG

As shown in fig.2 the stator is directly connected to the AC mains, while the wound rotor is fed from the power electronics converter via slip rings to allow DIFG to operate at a variety of speeds in response to changing wind speed. Indeed, the basic concept is to interpose a frequency converter between the variable frequency induction generator and fixed frequency grid. The DC capacitor linking stator and rotor side converters allows the storage of power from induction generator for further generation. To achieve full control of grid current, the DC-link voltage must be boosted to a level higher than the amplitude of grid line-to-line voltage. The slip power can flow in both directions, i.e. to the rotor from the supply and from supply to the rotor and hence the speed of the machine can be controlled from either rotor or stator side converter in both super and sub-synchronous speed ranges. As a result, the machine can be controlled as a generator or a motor in both super and sub-synchronous operating modes realizing four operating modes. Below the synchronous speed in the motoring mode and above the synchronous speed in the generating mode, rotor-side converter operates as a rectifier and stator-side converter as an inverter, where slip power is returned to the stator. Below the synchronous speed in the generating mode and above the synchronous speed in the motoring mode, rotor-side converter operates as an inverter and stator side converter as a rectifier, where slip power is supplied to the rotor. At the synchronous speed, slip power is taken from supply to excite the rotor windings and in this case machine behaves as a synchronous machine.

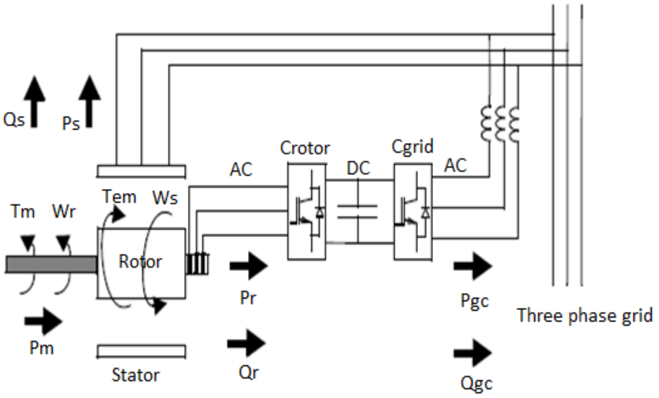

Fig.2: Power flow diagram of DFIG

This paper presents a control strategy by means of algebraic analytical relationships given by the mathematical model of the machine to the performances of doubly fed induction generators using back to back converter, thereby maximizing the efficiency of the generation system. The main problem using renewable energy sources is to make them work at full power for different operating conditions of the source. This is usually achieved by means of the implementation of control algorithms known as MPPT algorithms. For wind plants it is not so easy because wind changes rapidly and randomly. The output power of a wind turbine can be written as;

$$P = \frac{1}{2} C_p(\lambda, \beta) \varsigma \pi R^2 V_w^{\ 3} \quad \text{….. …………….} \quad (1)$$

The power co-efficient Cp is a function of the pitch angle $\boldsymbol{\beta}$ and tip speed ratio λ. The results reveal that the output power regulation of a wind turbine can be achieved in two ways; acting on the tip speed ratio and acting on the pitch angle.

This paper gives information about the controlling of DFIG wind turbines using back to back variable frequency converter.

The mechanical power and the stator electric power output are computed as follows:

$$P_r = T_m * \omega_r \quad \text{……………………………} \quad (2)$$

$$P_s = T_{em} * \omega_r \quad \text{……………………......….} \quad (3)$$

For a loss less generator the mechanical equation is:

$$\frac{d_{wr}}{J\ dt} = T_m - T_{em} \quad \text{…………………………..…….} \quad (4)$$

In steady-state at fixed speed for a loss less generator

$$T_m = T_{em} \text{ And } P_m = P_s + P_r \quad \text{……….......…….} \quad (5)$$

And it follows that:

$$P_r = P_m - P_s = T_m \omega_r - T_{em} \omega_s = -sP_s \quad \text{……….} \quad (6)$$

Where,

$S = \frac{\omega_s - \omega_r}{\omega_s}$ is defined as the slip of the generator

Generally the absolute value of slip is much lower than 1 and, consequently, P_r is only a fraction of P_s. Since T_m is positive for power generation and since ω_s is positive and constant for a constant frequency grid voltage, the sign of P_r is a function of the slip sign. P_r is positive for negative slip (speed greater than synchronous speed) and it is negative for positive slip (speed lower than synchronous speed). For super synchronous speed operation, P_r is transmitted to DC bus capacitor and tends to raise the DC voltage. For sub-synchronous speed operation, P_r is taken out of DC bus capacitor and tends to decrease the DC voltage. C_{grid} is used to generate or absorb the power P_{gc} in order to keep the DC voltage constant. In steady-state for a lossless AC/DC/AC converter P_{gc} is equal to P_r and the speed of the wind turbine is determined by the power P_r absorbed or generated by C_{rotor}. The phase - sequence of the AC voltage generated by C_{rotor} is positive for sub-synchronous speed and negative for super synchronous speed. The frequency of this voltage is equal to the product of the grid frequency and the absolute value of the slip. C_{rotor} and C_{grid} have the capability for generating or absorbing reactive power and could be used to control the reactive power or the voltage at the grid terminals.

A. Steady State Characteristics

The steady state equivalent circuit of DFIG is shown in below fig.2.A

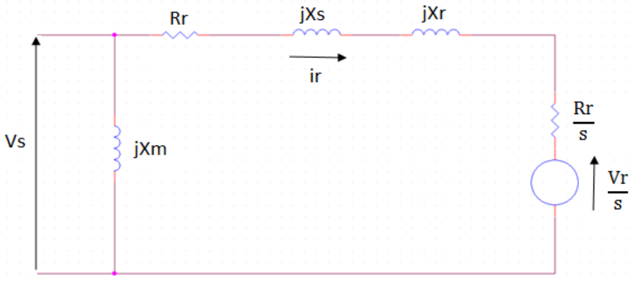

Fig.2.A: Steady state equivalent circuit of DFIG

To obtain the torque equation from the equivalent circuit, we can simplify the steady state induction motor circuit by moving X_m to the stator terminal .The rotor current I_r is expressed as;

$$I_r = \frac{V_s - (\frac{V_r}{s})}{(r_s + \frac{r_r}{s}) + j(X_s + X_r)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

The electrical torque Te, from the power balance across the stator to rotor gap, can be calculated from;

$$T_e = \left(I_r^2 \frac{r_r}{s}\right) + \frac{P_r}{s} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

Where the power supplied or absorbed by the controllable source injecting voltage into the rotor circuit, that is the rotor active power, P_r can be calculated from

$$P_r = \frac{V_r}{s} I_r \cos\theta \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

$$P_r = R_e(\frac{V_r}{s} I_r^*) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

III. OPERATION OF NINE SWITCH CONVERTER

As shown in Fig.1.2 [5], the proposed converter has three legs with three switches per leg. The middle switch in each of phase legs is shared by rectifier and inverter, therefore count of switches reduces. In this topology, the converter input and output voltages can be independently controlled although the middle switch in each leg is shared by the rectifier and inverter. Table.1 indicates the switching states. Here the converter has only three valid switching states per phase and V_{AR}, V_{XR} are the voltage at nodes A and X with respect to the negative dc link R respectively.

For the convenience it is considered that x, y, z are the input nodes of the converter and A, B, C are the output nodes. Modulation waveform to switching algorithm is the carrier based PWM control method for a nine-switch converter [3]-[8]. There are two reference signals for every phase. The principle of switching algorithm for upper and lower switches is obtained for the conditions given below:

Condition 1: Se1>C then S_{AO} is on

Condition 2: Se2<C then S_{AI} is on

Table.1: Switching states and converter output voltages

Mode	**ON Switches**	**Input and Output node voltages**
1	S_{AO}, S_{AM}	$V_{AR}=V_{dc}$, $V_{XR}=V_{dc}$
2	S_{AM}, S_{AI}	$V_{AR}=0$, $V_{XR}=0$
3	S_{AO}, S_{AI}	$V_{AR}=V_{dc}$, $V_{XR}=0$

Se1 and Se2 can be expressed as:

Se1= $m_{out} \sin(2 * \pi * f_{out}) + of_{out}$ …………. (11)

Se2= $m_{in} \sin(2 * \pi * f_{in}) + of_{in}$ ……………... (12)

Where,

f_{out}, f_{in} is the output and input frequency respectively. m_{out}, m_{in} are the modulation index and of_{out}, of_{in} are the offset of output and input references signals respectively.

In this topology x, y, z are connected to the grid and lower switches (S_{AI}, S_{BI}, S_{CI}) operate as a rectifier or Grid Side Converter. A, B, C are connected to the rotor, therefore upper switches (S_{AO}, S_{BO}, S_{CO}) operate as an inverter or Rotor Side Converter.

IV. CONTROL OF NINE SWITCH CONVERTER

In the DFIG based wind turbines rotor current regulation on the stator flux oriented reference frame. Therefore the d axis is aligned with the stator flux linkage vector λ*s* , namely, λs=λds and λqs=0. This results in following relationships [6]:

$$i_{qs} = -\frac{L_m i_{qr}}{L_s} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (13)$$

$$i_{ds} = \frac{L_m(i_{ms} - i_{dr})}{L_s} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (14)$$

$$T_e = -\frac{L_m i_{ms} i_{qr}}{L_s} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (15)$$

$$Q_s = \frac{3}{2}\frac{w_s L_m^2 i_{ms}(i_{ms} - i_{dr})}{L_s} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (16)$$

$$V_{dr} = r_r i_{dr} + \sigma L_r \frac{di_{dr}}{dt} - sw_s \sigma L_r i_{qr} \ldots\ldots\ldots\ldots (17)$$

$$V_{qr} = r_r i_{qr} + \sigma L_r \frac{di_{qr}}{dt} + sw_s (\frac{\sigma L_r i_{dr} + L_m^2 i_{ms}}{L_s}) \ldots.. (18)$$

Where,

$$i_{ms} = \frac{V_{qs} - r_s i_{qs}}{w_s L_m} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (19)$$

$$\sigma = 1 - \frac{L_m^2}{L_r L_s} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (20)$$

Equation (14) shows that the DFIG electrical torque can depends on I_{qr}, as a result the rotor speed ω_r, can be controlled by regulating I_{qr}. Equation (15) indicates that the Q_s can be controlled by regulating the I_{dr}, therefore, the reference values of I_{dr} and I_{qr} can be determined from Q_s and ω_r regulation. Fig.4 shows the overall vector control scheme of the Rotor Side Converter (RSC).

The instantaneous three-phase rotor current i_{rabc} is transformed to d-q components I_{dr} and I_{qr} in the stator – flux oriented reference frame. Then I_{dr} and I_{qr} are compared with their reference signals ($i_{dr}^* and i_{qr}^*$) to generate the error signals, which are passed through two PI controllers to form the voltage signals V_{dr1} and V_{qr1} . These two voltage signals are compensated by the corresponding cross coupling terms (V_{dr2}

and V_{qr2}) to form the d-q voltage signals V_{dr} and V_{qr}. Where V_{dr2} and V_{qr2} are assumed as:

$$V_{dr2} = -s\omega_s \sigma L_r i_{qr} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (21)$$

$$V_{qr2} = s\omega_s(\sigma L_r i_{dr} + L_m^2 \frac{i_{ms}}{L_s}) \qquad \ldots\ldots\ldots\ldots\ (22)$$

They are then used by the carrier based PWM method to generate MOSFET gate control signals of the RSC.

The objective of the GSC is to keep the DC link voltage constant regardless of the magnitude and direction of the rotor power. The control of DC link voltage, V_{dc} and DFIG stator terminals voltage, Vs, are achieved by current regulation on a synchronously rotating reference frame. The output voltage signals V_{dg} and V_{gq} from the current controllers are used by the carrier based PWM algorithm to switch the grid side of nine-switch converter. Figure 4.1 shows the overall vector control scheme of the Grid Side Converter [6].

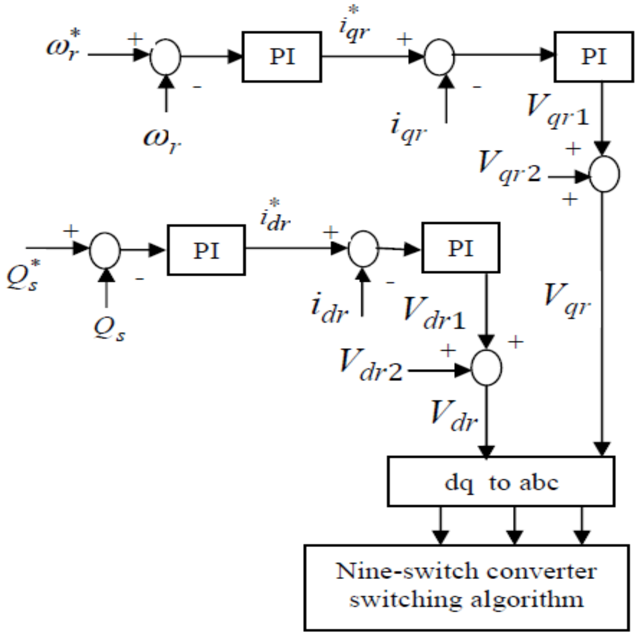

Fig.4: Overall vector control of RSC

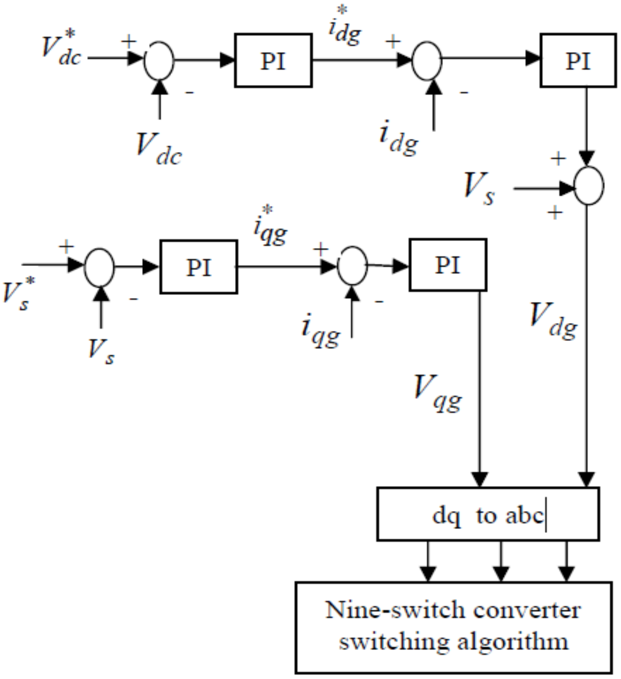

Fig.4.1: Overall vector control of GSC

V. SIMULATION MODELS

A. Simulation of overall pulse generation

Fig.16 shows the overall pulse generation model for nine switch converter. As mentioned earlier the nine switch converter model consists of three legs and each consisting of three switches. Fig.16 shows how the pulses have been generated for all the three leg MOSFET switches. For all the nine switches, voltage signals generated from the Rotor Side Converter and Grid Side Converter are compared with the carrier wave signal and an appropriate gate pulse is generated.

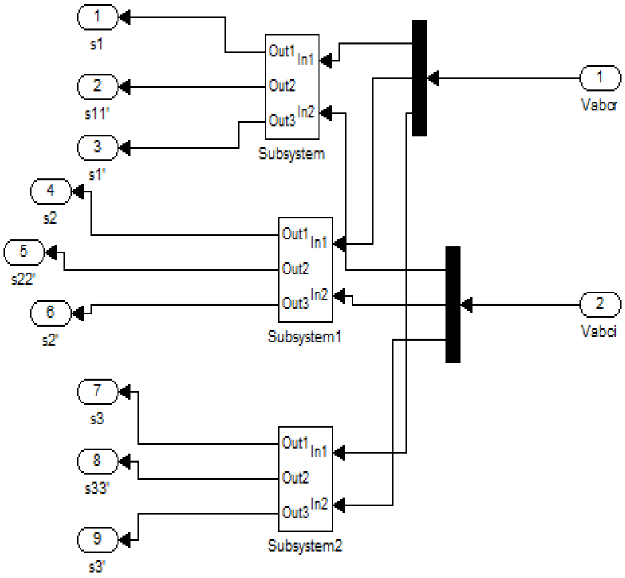

Fig.5.A: Simulation model of overall pulse generation

B. Simulation of nine switch converter

Fig.17 shows the simulation model of nine switch converter. It consists of totally three legs, each leg consisting of three switches. Then total number of switches is nine. The above six switches act as Rectifier i.e. the conversion of AC/DC and the below six switches act as Inverter i.e. the conversion of DC/AC. The pulses for all the MOSFET gates are generated using the voltage signals generated from RSC and GSC comparing with the carrier wave signal.

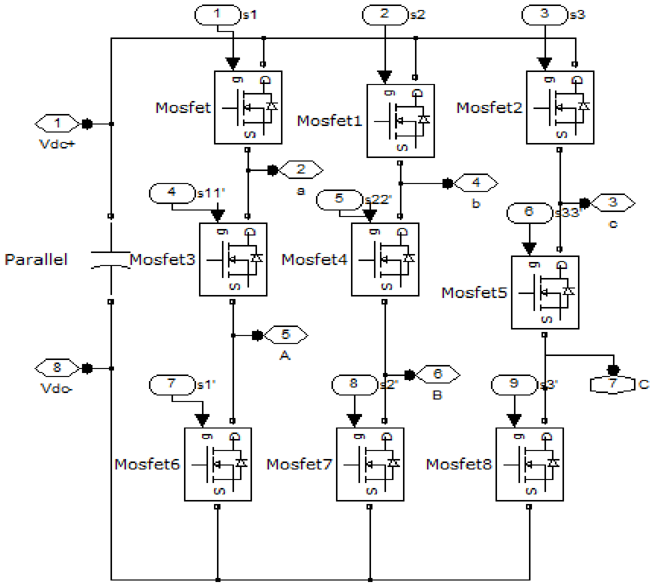

Fig.5.B: Simulation model of nine switch converter

VI. SIMULATION RESULTS

The DFIG parameters are given in Table 2.

Table.2: Parameters of the DFIG simulated

Rated Power	2MW
Stator Voltage	690V
Rs	0.0108pu
Rr	0.0121pu (referred to the stator)
Lm	3.362pu
Ls	0.102pu
Lr	0.11pu (referred to the stator)
Number of pole pairs	2

In order to evaluate the dynamic performance of the proposed DFIG, sudden variation in the wind speed is made.

A. Generator output power

Fig.6.A shows the generator output power. It is observed that when the wind speed is increased at 12 sec, the power output of the generator also slightly increased. In means the generator output power follows the wind speed and delivers more power to the grid whenever wind speed increases

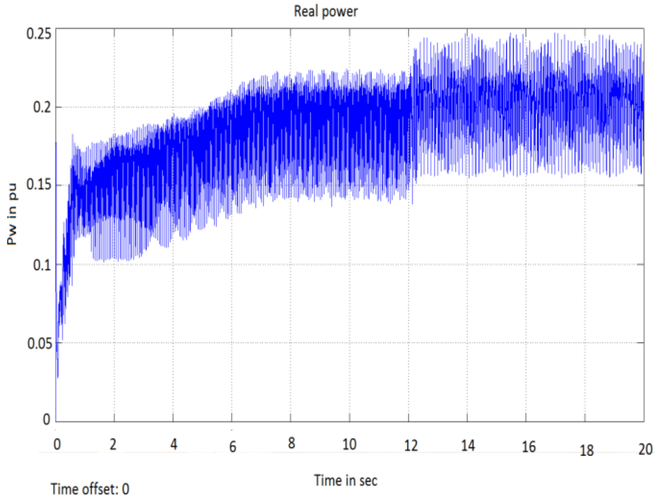

Fig.6.A: Generator output power

B. Stator output reactive power

Fig.6.B shows the stator output reactive power. At 12 sec there is sudden variation in the wind speed i.e. initially wind blowing at 12m/s increased to 15m/s at 12 sec. The reference value of reactive power is set to zero and stator reactive power produced by generator is tried to keep around zero. In the above figure it is observed that at the time of wind speed change the reactive power generated by stator is maintained constant around zero.

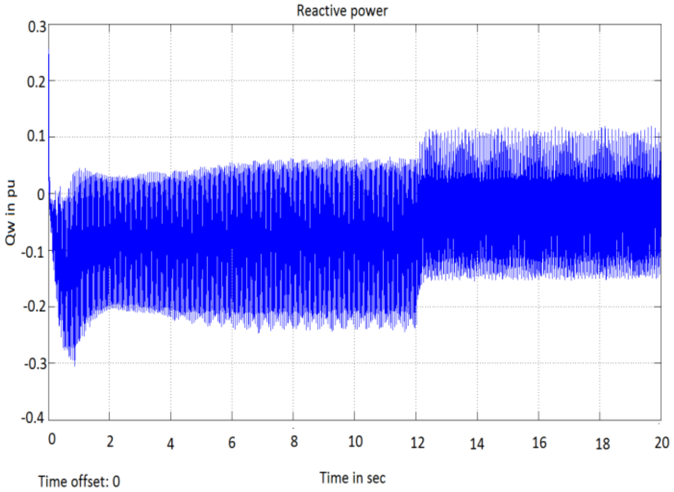

Fig.6.B: Stator output reactive power

C. Generator terminal voltage

Fig.6.C shows the stator each phase output voltage. It is observed that, initially when the wind is blowing at 12 m/s stator terminal each phase voltage is around 690 volts. Then at 12 sec, when wind speed changes to 15m/s the magnitude of stator output each phase voltage is not affected and is maintained almost constant i.e. around 690 volts. It means irrespective of the wind speed changes and rotor speed variation the stator output each voltage remains almost constant in order to make it possible to integrate the wind turbine generated power with the grid. This

is one of the very essential controlling aspects in doubly fed induction generators achieved through nine switch converter.

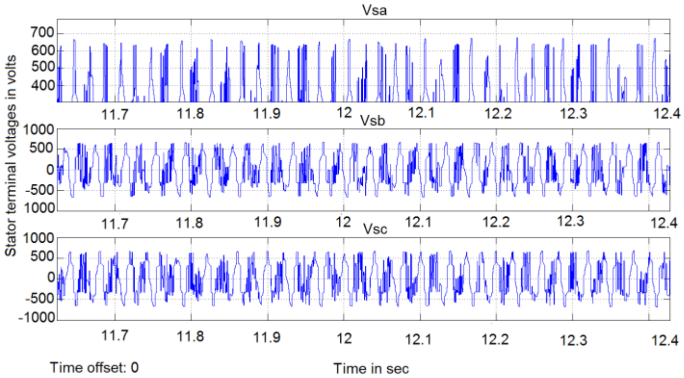

Fig.6.C: Generator terminal voltages

D. Generator terminal current

Fig.6.D shows the each phase generator terminal current. We know that when wind speed increases the power delivered to the grid also increases. As stator terminal voltage is going to remain constant during wind changes, the current drawn by the grid increases in order to increase the power delivered to the grid. It can be observed in Fig.22 that when there is sudden change in the wind speed at 12 sec the magnitude of each phase stator output current increases slightly. Stator output terminal each phase voltage and current are in phase. It means that the generator is operating approximately at its unity power factor.

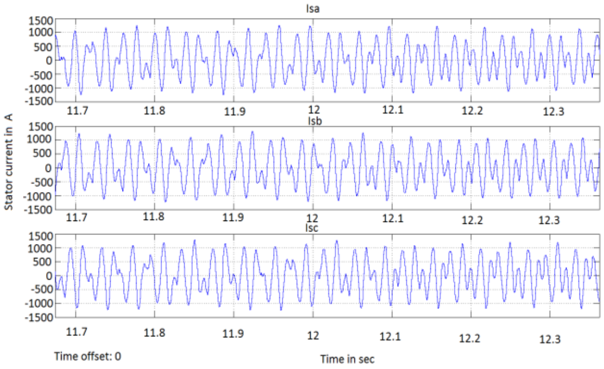

Fig.6.D: Generator terminal current

E. Generator rotor speed

Fig.6.E shows the generator rotor speed. It is observed that before the step change in wind speed occurred i.e. wind blowing at 12m/s, the rotor is rotating at 0.55pu but when the wind speed increases to 15m/s the rotor speed also increases. After a fraction of second the rotor speed again gains its steady state at 0.67pu. From Fig.21 and 23 it can be clearly observed that even though there is change in rotor speed in course of time period because of change in wind speed the stator terminal each phase output voltages remains almost constant. From Fig.19 and 23 it is clear that the power delivered to the grid from the generator increases with increase in rotor speed because of change in wind speed.

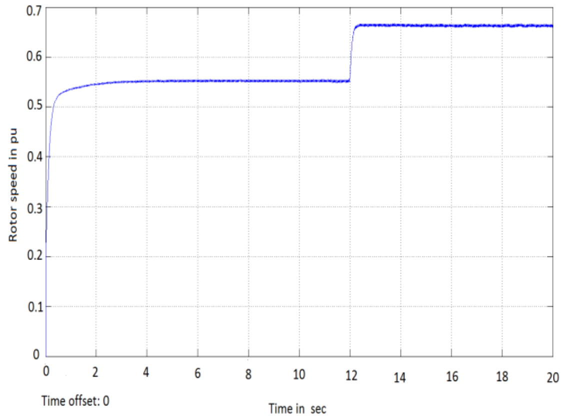

Fig.6.E: Generator rotor speed

VII. CONCLUSION

This thesis presented a DFIG model employing new nine switches AC/AC converter. As compared to the conventional DFIG employing Back to Back power converter the new nine switch converter requires fewer switches and gate drive circuits. Therefore proposed topology results in reduction of installation area and cost. The new nine switch converter DFIG is applied to the wind turbine and integrated with the grid. The results reveal that even though change in wind speed occurred, the generator terminal voltage and frequency remain same. The generator output power follows the wind speed and delivers the more power to the grid. It means proposed DFIG will operate according to control strategies aims in the wind speed sudden variations

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