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Wind Turbine Control Based DFIG with Reduced Switches AC/AC Converter

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***Abstract* –This paper presents a control strategy for a doubly fed induction generator (DFIG) using a novel rectifier-inverter topology, which consists of only nine IGBT power electronics switches for ac/ac conversion through a dc link. As compare to conventional back-to-back ac/ac converters, the numbers of power semiconductor switches are reduced in the suggested converter. The proposed topology results in reduction of installation area and cost. The operating principle, control strategy and characteristics of wind turbine based proposed ac/ac converter is described in this paper. The performance of proposed DFIG is validated with simulation results using MATLAB/SIMULINK software.**

***Keywords*-- Wind energy, Reduced switch converter, Dfig.**

I. INTRODUCTION

Growing environmental concerns and attempts to reduce dependency on fossil fuel resources are bringing renewable energy resources to the mainstream of the electrical power sector [1]. Wind power is one of the renewable energies that received more attention due to its clean and economical characteristics, and it is predicted that by 2020 up to 12% of the words electricity will be supplied by wind power [2].

Wind turbines are classified in to two categories: fixed speed and variable speed wind turbines. For the fixed speed wind turbines, the induction generator is directly connected to the electrical grid and rotor speed remains essentially constant, or varies very slightly with the speed of the wind [3]. Today variable speed wind turbines have become more common than traditional fixed speed turbines because of the more efficient energy production, improved power quality and improved dynamic performance during grid disturbances [4, 5]. In addition, they can reduce mechanical stresses respect to fixed speed wind turbines [6]. Variable speed wind turbines include alternative structures such as: DFIG and full power converters [4]. From a power system point of view, these configurations are interesting because power electronic interface isolates the generator characteristics from the rest of power system and only the controlled converter characteristics is seen by the grid [4].

Among the different structures to obtain variable speed wind turbines, the DFIG is the most used [7, 8]. Fig. 1 shows a conventional configuration of a wind turbine based on a DFIG.

As shown in Fig. 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 rotor voltage permits the adjustment of the rotor speed to match the optimum operating point at any practical wind speed [8, 9]. The variable frequency converter consists of a rotor side converter (RSC) and a grid side converter (GSC) and only handles rotor power. Consequently the control of the machine can be carried out with a converter that is sized for a power around 25%-30% of the rated power of the turbine [7, 9]. As compared to variable speed turbines that use full power converter connected to the stator, the converter of the DFIG is lower cost and lower sized [7]. The main objective of the RSC is to control the DFIG stator active power, speed and reactive power. While the GSC keeps the voltage of DC link constant [10].

Recently matrix converter has been applied in the DFIG structure [11-12]. Matrix converter consists of nine bidirectional switches enables the connection of any input phase to output phase instant without DC link capacitor. However matrix converter has a sensitive commutation due to its topological characteristics. The conventional PWM based switching strategies can not be used for a matrix converter.

The novel nine-switch converter has been reported recently as a competitive alternative to existing PWM back-to-back converters in [13], [14] and [15] as shown in Fig. 2. Compared with PWM back-to-back converter that employs twelve power electronic switches, the proposed converter uses only nine switches, which reduces the manufacturing cost and increases system efficiency. Unlike matrix converter, the nine-switch converter can be modulated by PWM strategy and has not the commutation sensitivity. This paper proposes a DFIG with a novel nine-switch converter as shown in Fig. 3.

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This paper is organized as follows. Section II introduces a new nine-switch inverter and describes the carrier based PWM switching alghorithm for mentioned inverter. Cordinated control of the DFIG is explained in section III. Simulation results on a 2MW DFIG system based a new ac/ac converter are provided in section IV and finally section V draws the conclusions.

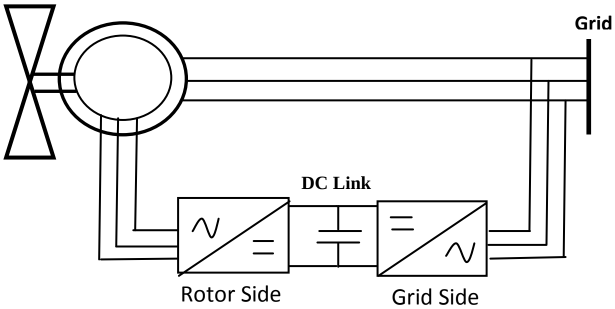

Fig.1. Conventional wind turbine based on a DFIG

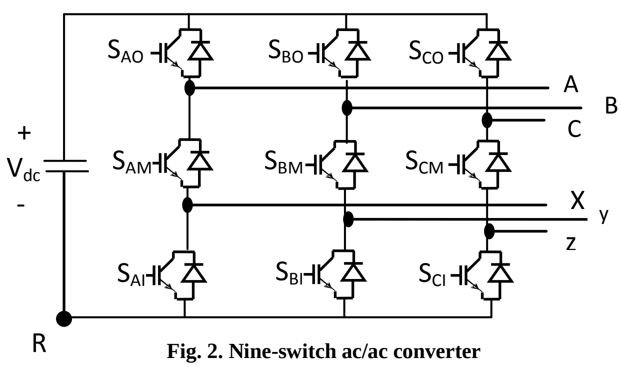

Fig. 2. Nine-switch ac/ac converter

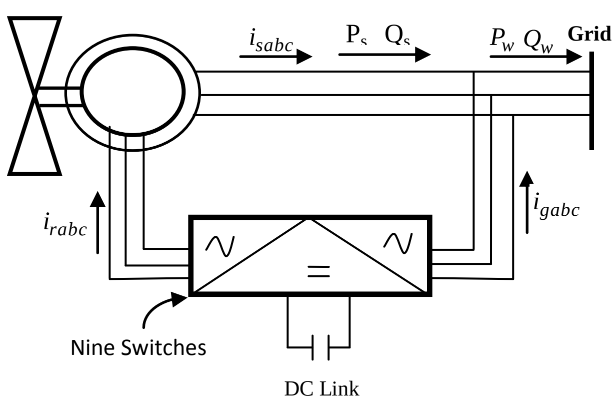

Fig. 3. Proposed DFIG with nine-switch ac/ac converter

II. Nine-Switch Converter

As shown in Fig. 2, 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. This configuration is also used as an ac/ac converter [13].

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 I indicates the switching states. As shown in Table I, this 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.

Table I
Switches States And Converter Output Voltages

Mode	ON switches	Input and output nodes voltage
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}	$V_{AR}=V_{dc}$, $V_{XR}=0$

For the convenience of discussion 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 are shown in Fig. 4, switching algorithm is the carrier based PWM control method for a nine-switch converter [13]-[15]. There are two reference signals for every phase. The principle of switching algorithm for upper and lower switches is obtained as conditions, i.e.,

Condition 1: $Se1>C$ then S_{AO} is on
Condition 2: $Se2<C$ then S_{AI} is on
Se1and Se2 can be expressed as:

$$S_{e1}= m_{out}\, sin(2*\pi* f_{out}) + of_{out} \qquad (1)$$

$$S_{e2}= m_{in}\, sin(2*\pi* f_{in}) + of_{in} \qquad (2)$$

Where f_{out}, f_{in} are 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. The mid switch is generated by the logical NAND of gate signals for the upper and lower switches as shown in Fig. 5. In the nine switch converter, peak inverse voltage (PIV) of all switches is presented by:

$$PIV = \sum_{i=1}^{9} V_{sw,i} = 9V_{dc} \qquad (3)$$

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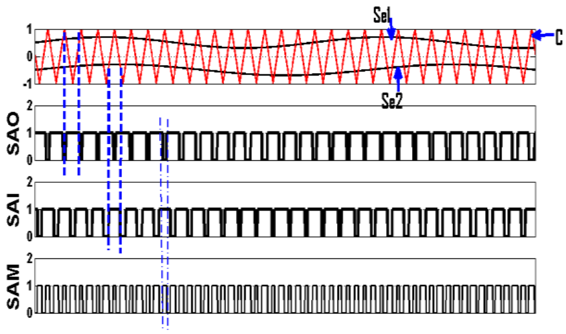

Fig. 4. Modulation waveform to nine-switch converter

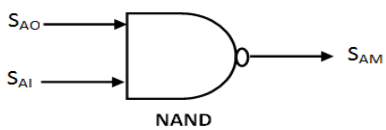

Fig. 5. Mid switches gate signal generator circuit

$V_{sw,i}$ is the peak inverse voltage of the i_{th} switch. $V_{sw,i}$ is the peak inverse voltage of the i_{th} switch. The PIV of all switches is $12V_{dc}$ in the conventional back-to-back converter therefore PIV of all switches in the nine switch converter is lees than conventional back-to-back converter.

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

III. Modeling and Control of DFIG

A. DFIG Modeling

The dynamic equations of a DFIG can be expressed in a synchronously rotating *d-q* reference frame. The DFIG was represented by the following equations [3], [5]:

$$V_{ds} = r_s i_{ds} - \omega_s \lambda_{qs} + \frac{d\lambda_{ds}}{dt} \qquad (4)$$

$$V_{qs} = r_s i_{qs} + \omega_s \lambda_{ds} + \frac{d\lambda_{qs}}{dt} \qquad (5)$$

$$V_{dr} = r_r i_{dr} - s\omega_s \lambda_{qr} + \frac{d\lambda_{dr}}{dt} \qquad (6)$$

$$V_{qr} = r_r i_{qr} + s\omega_s \lambda_{dr} + \frac{d\lambda_{qr}}{dt} \qquad (7)$$

Where ω_S is the rotational speed of the synchronous reference frame and $s\omega_S$ is the sleep frequency. The flux linkages are given by:

$$\lambda_{ds} = L_s i_{ds} + L_m i_{dr} \qquad (8)$$

$$\lambda_{qs} = L_s i_{qs} + L_m i_{qr} \qquad (9)$$

$$\lambda_{dr} = L_m i_{ds} + L_r i_{dr} \qquad (10)$$

$$\lambda_{qr} = L_m i_{qs} + L_r i_{qr} \qquad (11)$$

Where L_s, L_r and L_m are the stator leakage, rotor leakage and mutual inductances, respectively. Neglecting the stator resistances power losses, the per-unit electrical torque, active and reactive power delivered by the stator are given by:

$$T_e = L_m (i_{qs} i_{dr} - i_{ds} i_{qr}) \qquad (12)$$

$$P_s = \frac{3}{2}(V_{ds} i_{ds} + V_{qs} i_{qs}) \qquad (13)$$

$$Q_s = \frac{3}{2}(V_{qs} i_{ds} - V_{ds} i_{qs}) \qquad (14)$$

B. Control of the Nine-Switch Converter

Control of the DFIG is achieved by control of the nine-switch converter which includes control of the RSC and control of the GSC. The objectives of the RSC control are as follows: 1) regulating the DFIG rotor speed for maximum wind capture 2) maintaining a constant frequency of the DFIG stator voltages 3) controlling the DFIG reactive power. In the DFIG based wind turbines, these objectives are achieved by 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, $\lambda_S = \lambda_{ds}$ and λ . This results following relationships [5]:

$$i_{qs} = -\frac{L_m i_{qr}}{L_s} \qquad (15)$$

$$i_{ds} = \frac{L_m (i_{ms} - i_{dr})}{L_s} \qquad (16)$$

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$$T_e = -\frac{L_m i_{ms} i_{qr}}{L_s} \quad (17)$$

$$Q_s = \frac{3}{2}\frac{\omega_s L_m^2 i_{ms}(i_{ms} - i_{dr})}{L_s} \quad (18)$$

$$V_{dr} = r_r i_{dr} + \sigma L_r \frac{di_{dr}}{dt} - s\omega_s \sigma L_r i_{qr} \quad (19)$$

$$V_{qr} = r_r i_{qr} + \sigma L_r \frac{di_{qr}}{dt} + s\omega_s (\frac{\sigma L_r i_{dr} + L_m^2 i_{ms}}{L_s}) \quad (20)$$

Where

$$i_{ms} = \frac{V_{qs} - r_s i_{qs}}{\omega_s L_m} \quad (21)$$

$$\sigma = 1 - \frac{L_m^2}{L_r L_s} \quad (22)$$

Equation (17) 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 (18) 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. 6 shows the overall vector control scheme of the RSC.

The instantaneous three-phase rotor current i_{rabc} are 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_{dr} and V_{qr}.

They are then used by the carrier based PWM method to generate IGBT 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. Fig. 7 shows the overall vector control scheme of the GSC. The control of DC link voltage, V_{dc} and DFIG stator terminals voltage, V_s, are achieved by current regulation on a synchronously rotating reference frame. The output voltage signals, V_{dg} and V_{qg} from the current controllers are used by the carrier based PWM algorithm to switch the grid side of nine-switch converter [5].

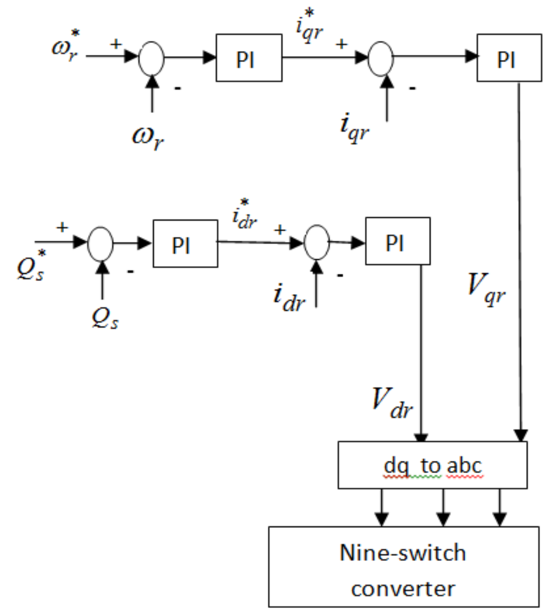

Fig. 6. Overall vector control scheme of the RSC

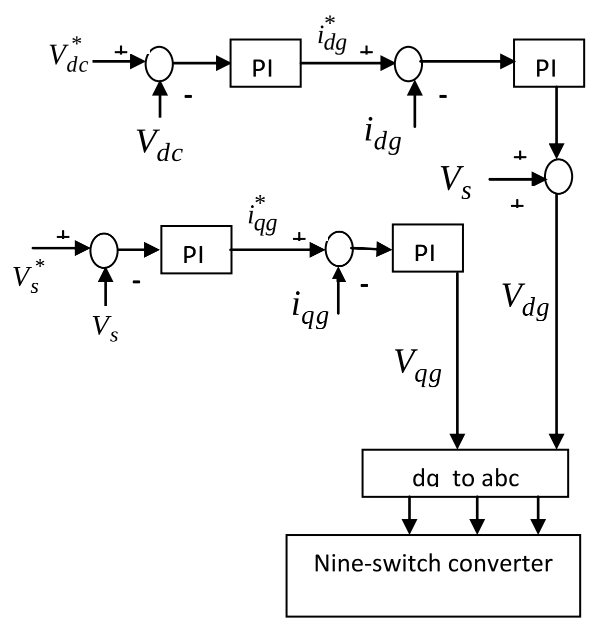

Fig. 7. Overall vector control scheme of the GSC

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IV. Simulation Results

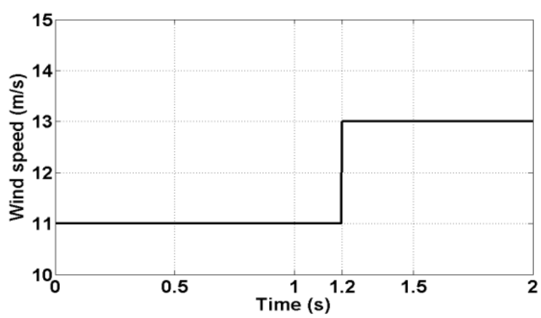
Proposed DFIG has been modeled by MATLAB/SIMULINK to verify the performance of novel converter. The simulated DFIG parameters are listed in Table II.

Table II.

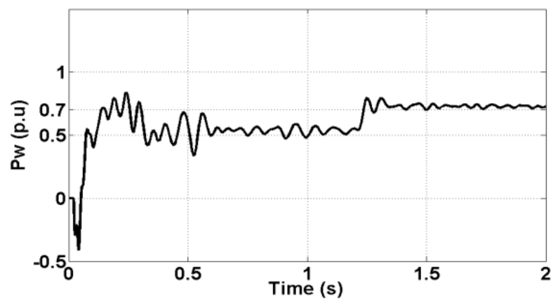
Parameters Of The DFIG Simulated

Rated power	2MW
Stator voltage	690V
R_S	0.0108pu
R_r	0.0121pu (referred to the stator)
L_m	3.362pu
L_s	0.102pu
L_r	0.11pu (referred to the stator)
Number of pole pairs	2

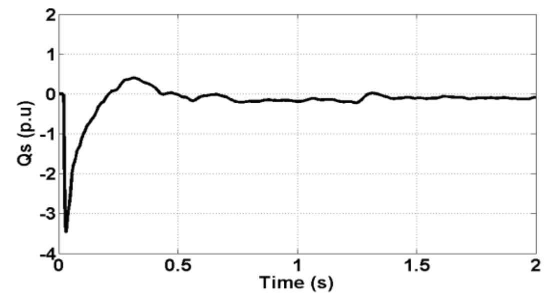
In order to evaluate the dynamic performance of the proposed DFIG, sudden variation in the wind speed is occurred. The step change as in Fig. 8(a) is applied to wind speed at t=1.2 s. In the following study case $Q^*_S = 0$ (reference value of Q_S) and $\omega^*_r = 1$ (reference value of ω_r). Fig. 8(b) shows the DFIG output electrical power that follows wind speed and deliveries more electrical power to the electrical grid by increasing the wind speed. Fig. 8(c) presents the stator output reactive power which follows Q^*_S. Fig. 8(d) shows the stator terminal voltage and current which are in phase and thus, the generator operates nearly in unity power factor. The rotor speed is shown in Fig. 8(e) that is regulated to ω^*_r.



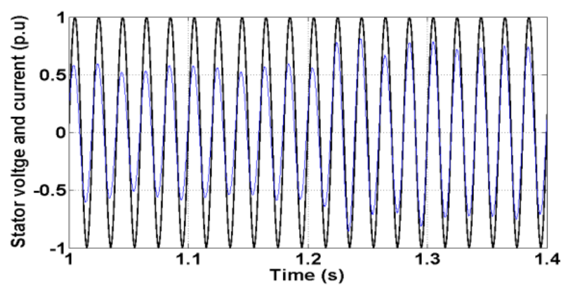
(a)



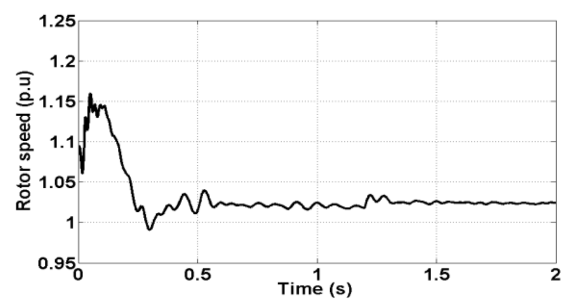
(b)



(c)



(d)



(e)

Figure. 8. Dynamic performance of proposed DFIG for step change in the wind speed, (a) wind speed, (b) generator output power, (c) stator output reactive power, (d) generator terminal voltage and current, (e) rotor speed.

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V. Conclusion

This paper proposed a DFIG employing novel nine-switch ac/ac converter. The suggested topology needs fewer switches and gate drive circuits. Therefore, the proposed topology results in reduction of installation area and cost. Also PWM based switching algorithm presented for novel converter. Besides, control strategy of DFIG based on a suggested converter was described.

The simulation results show that the proposed DFIG can operate according to control strategies aims in the wind speed sudden variations.

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