MODIFIED DIRECT STATOR POWER CONTROL OF THE DFIG-WIND TURBINE

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Abstract: *The doubly fed induction generator (DFIG) is the most commonly used type of generator for variable speed wind turbine (WT). The advantage of the DFIG-WT is the use of the partial rated converter at its rotor. The partial rated converters can be of either the back-to-back converter or the matrix converter. This paper proposes a modified stator power control technique for the DFIG–WT with the matrix converter as the partial rated converter. The main contribution of the paper is the implementation of direct space vector modulation for the matrix converter and the modified active power and reactive power control using the FPGA, Spartan – 3E controller board. The system is modeled and simulated in Matlab/Simulink as well as in Xilinx System Generator platform and the results are verified. The decoupled power control of the stator at the sub-synchronous and super-synchronous speed is achieved with the modified control technique.*

Key words: *Matrix Converter, doubly fed induction generator, Modified direct power control, FPGA – Spartan 3E Kit.*

1. Introduction

Variable-speed wind turbines are gaining prominence due to their ability to generate power for a wide range of wind speeds. This class of turbines requires a fraction of the power to be drawn from the grid in order to compensate for the deficiency in the wind speed below synchronous speed. Fig. 1 shows a conventional DFIG with a bidirectional converter (AC-DC-AC) in the rotor side [1]. The back-to-back converter controls the flow of power from the machine to the grid, and the power drawn by the rotor in order to maintain the power generation [2]. The converter connected to the grid is called the grid side converter (GSC) while the converter connected to the rotor is called the rotor side converter (RSC). The RSC and GSC have different control parameters. The DC-link capacitor employed is of the electrolytic type. The operation of these converters can be divided into two stages (stage-1: converter) and (stage-2: inverter) and are controlled independently since they are decoupled by the DC-link capacitor. At high temperatures, the DC-link capacitor performs poorly, which may lead to failure [3]. Therefore, the use of a storage capacitor not only increases the weight and volume, but also reduces the reliability of the system [4].

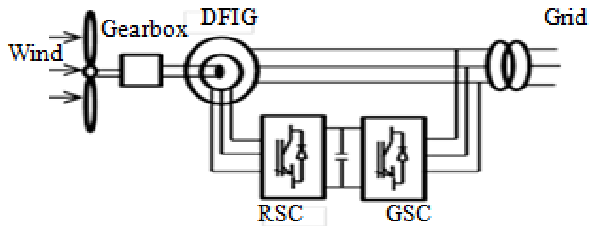

Fig.1. DFIG-WT with the Back to Back Converter

In this paper, the conventional back-to-back converter is replaced by a matrix converter (MC), thereby eliminating the energy storage element (DC-link) as shown in Fig. 2. The MC is highly versatile and there are no limits on its output frequency and amplitude. It has significant advantages such as adjustable power factor, inherent four-quadrant operation, high quality sinusoidal input/output waveforms, and high power density [4].

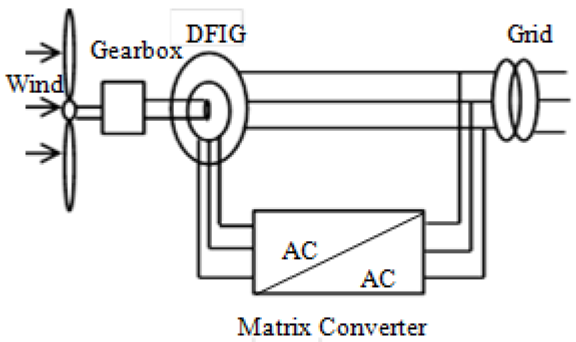

Fig.2. DFIG – WT with the MC

2. Description of the MC

The MC consists of nine bi-directional switches with 2^9 (512) possible switching states. However, only 27 switching states are used due to the limitations on the power circuit. At any instant, the voltage source should not be short-circuited and the current source should not be open circuited [5].Of the 27 allowable switching states in the MC, only 18 active switching states are used and each state specifies one switching state vector (SSV). These vectors are classified into three groups: rotating SSV, allowable SSV and zero SSV [6]. The bidirectional switches of the MC are connected in a common emitter (CE) configuration. The two IGBTs are connected with the two diodes in an anti-parallel configuration. The diodes provide the reverse-blocking capability of the IGBTs. The difficulty in commutation of the current arises due to the absence of a freewheeling path in the converter. Therefore, the four-step commutation technique is used to commutate the switches. In this technique, the load current is commutated from one phase to another in four steps. Each step involves the turning ON/OFF the incoming and outgoing switches. The four D flip-flops employed in the four-step commutation circuit introduce the required delay while the combinational logic gates decide the state of the switches depending on the current direction in that phase. Fig. 3 shows the implementation of the MC in Matlab/Simulink.

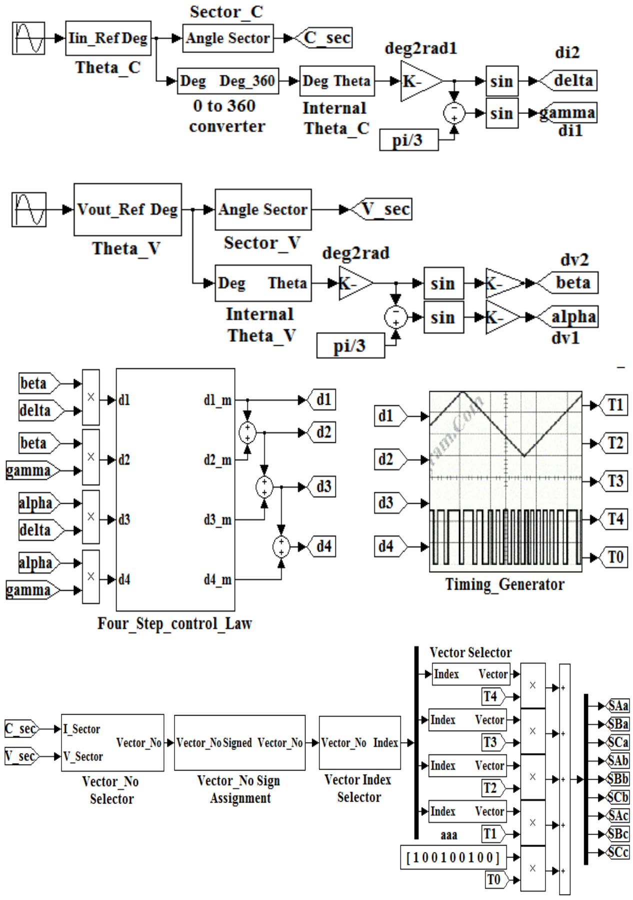

Fig.3. Implementation of MC in Matlab/Simulink

3. Description of DFIG and its Control

Equations (1) and (2) give the dynamic model of the DFIG [9].

$$\left.\begin{aligned} v_{ds} &= r_s i_{ds} + \frac{d}{dt}\lambda_{ds} - \omega_s \lambda_{qs} \\ v_{qs} &= r_s i_{qs} + \frac{d}{dt}\lambda_{qs} + \omega_s \lambda_{ds} \\ v_{dr} &= r_r i_{dr} + \frac{d}{dt}\lambda_{dr} - (\omega_s - \omega_r)\lambda_{qr} \\ v_{qr} &= r_r i_{qr} + \frac{d}{dt}\lambda_{qr} + (\omega_s - \omega_r)\lambda_{dr} \end{aligned}\right\} \quad (1)$$

$$\left.\begin{aligned} P_s &= \frac{3}{2}(v_{ds} i_{ds} + v_{qs} i_{qs}) \\ Q_s &= \frac{3}{2}(v_{qs} i_{ds} - v_{ds} i_{qs}) \end{aligned}\right\} \quad (2)$$

In this paper, the stator voltage oriented frame is chosen, where the d axis is aligned along the voltage vector, such that $v_{ds}=v_s$, and $v_{qs}=0$. Also, as the flux vector is at 90^0, $\lambda_{ds}=0$. Applying the constraints in equations (1) and (2) leads to the equation (3).

$$\left.\begin{aligned} P_s &= \frac{3}{2} v_{ds} i_{ds} \\ Q_s &= -\frac{3}{2} v_{ds} i_{qs} \end{aligned}\right\} \quad (3)$$

Equation (3) shows that the stator active power and reactive power can be controlled by controlling the stator d-q axes currents, i_{ds} and i_{qs}. The stator currents i_{ds} and i_{qs} can be controlled by regulating the rotor voltages and currents. Fig.4 shows the modified power control of the DFIG. In the modified direct stator power control technique, only the outer power control loop requires a PI controller. The inner current control loop is not employed and hence the system is simpler and found to be reliable compared to the conventional control. Also, the modified direct stator power control technique does not require the knowledge of system parameters and the estimation of the stator flux. Simulation results verify the effectiveness of this technique.

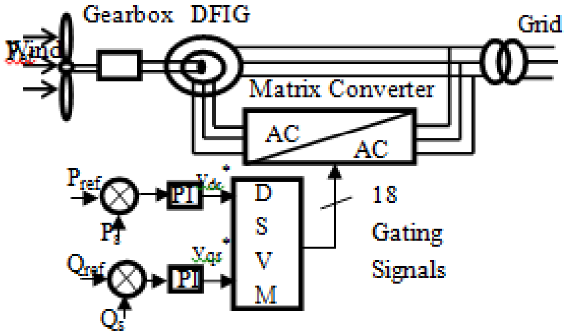

Fig.4. Block diagram of the proposed control of DFIG -WT connected to the MC

The technique employs PI controllers, one for the active power control and the other for the reactive power control. The d axis rotor voltage is directly controlled to regulate the stator active power and the q axis rotor voltage is controlled to regulate the stator reactive power. The output voltages generated from the PI controllers acts as the reference voltage to trigger the MC.

Fig. 5 shows the control of the DFIG in the synchronous reference developed in Matlab/Simulink. Figs. 6-13 illustrate the simulation results of the stator current, electromagnetic torque, stator active and reactive powers, rotor active and reactive powers, rotor currents, rotor voltages and the reference voltage for the variable wind speed (both at sub-synchronous speed and super-synchronous speed). Fig.6 shows the transition of the rotor speed from sub-synchronous speed to super-synchronous speed.

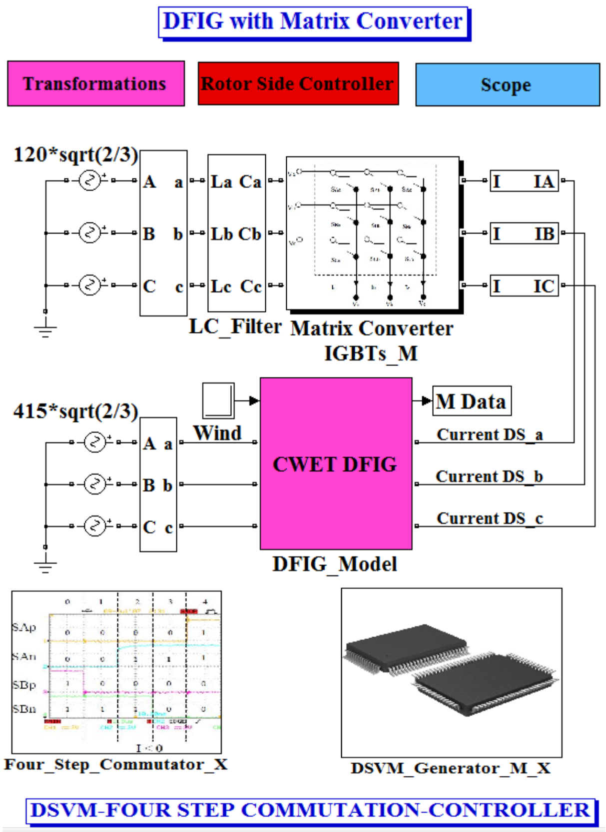

Fig.5. Matlab/Simulink implementation of the proposed control of the DFIG-WT connected to the MC

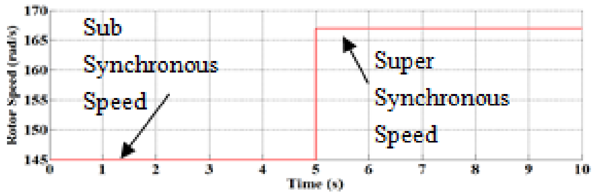

Fig. 6. Variable speed operation of the rotor

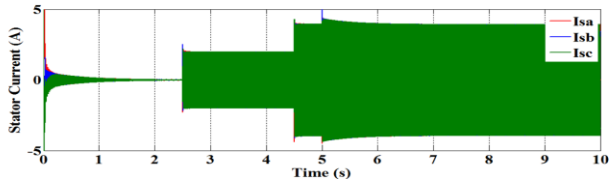

Fig. 7. Stator current during the variable speed operation

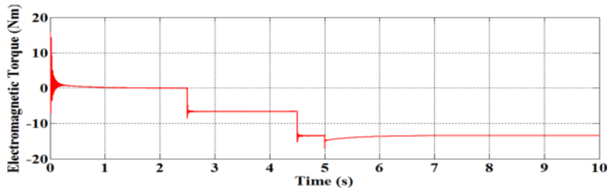

Fig.8. Electromagnetic torque during variable speed

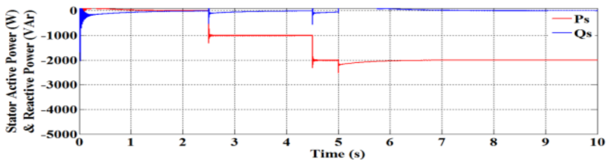

Fig. 9. Stator active power and reactive power during variable speed operation

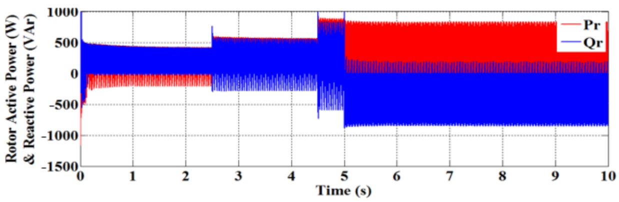

Fig. 10. Rotor active power and reactive power during variable speed operation

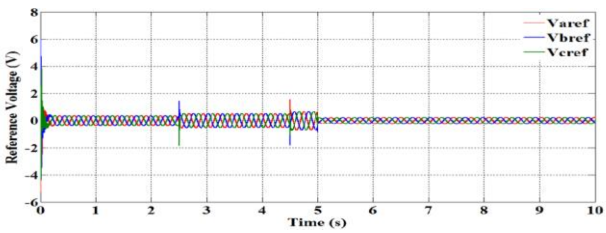

Fig. 11. Reference voltages for the MC

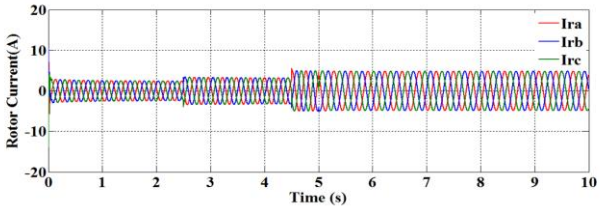

Fig. 12. Rotor current under variable speed operation

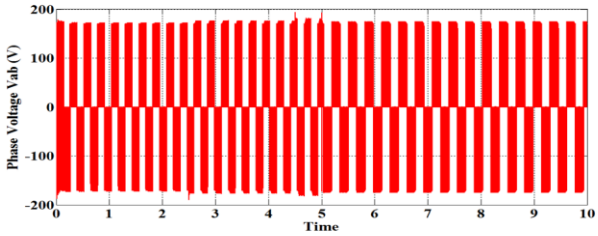

Fig. 13. Rotor phase voltage V_{ab} under variable speed

Fig. 14 shows the hardware implementation. The laboratory model 3 HP DFIG is driven by a squirrel cage induction motor fed by a YASKAWA variable frequency drive (VFD). The rotor of the DFIG is connected to the MC. The modified stator power control technique is developed in FPGA-SPARTAN 3E – 500 K (Nexys 2) controller. Fig. 15 shows the switching pulses generated for the MC.

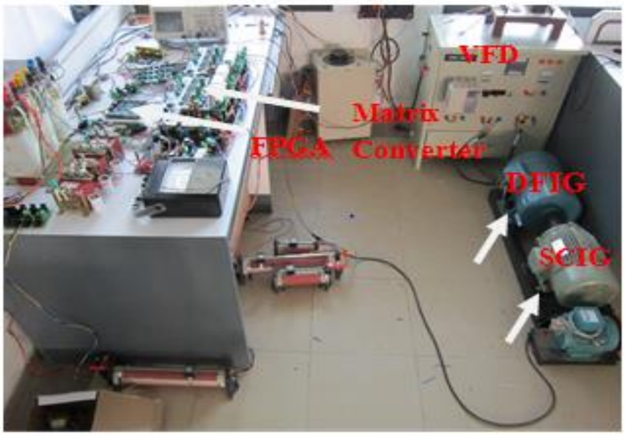

Fig. 14 Laboratory setup for the stator power control of the DFIG-WT connected to the MC at the rotor using FPGA-SPARTAN 3E Controller

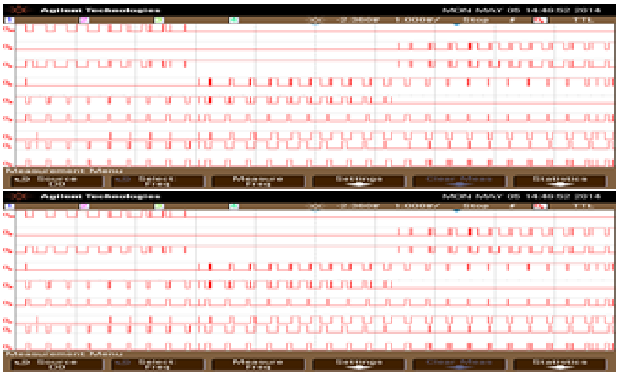

Fig 15 Switching pulses of the MC

Figs. 16-22 show the output line voltage, output current and input current respectively of the MC connected to the rotor of the DFIG. The active power reference is set to 1kW and the reactive power reference is set to 0 kVAr. The proposed power controll dynamically controls the stator power to its reference value.

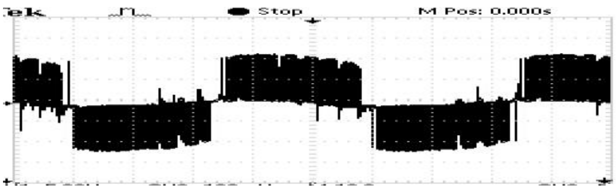

Fig.16. Output line voltage of the MC

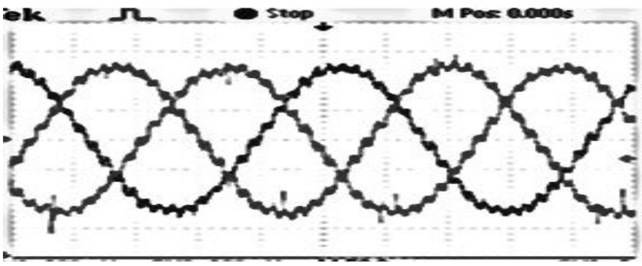

Fig.17. Output currents of the MC

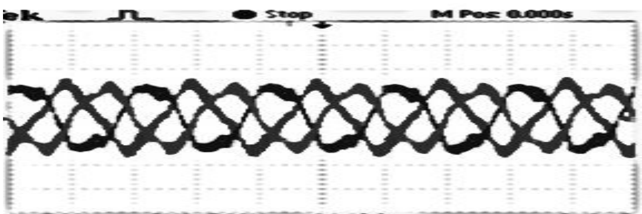

Fig.18. Input currents of the MC

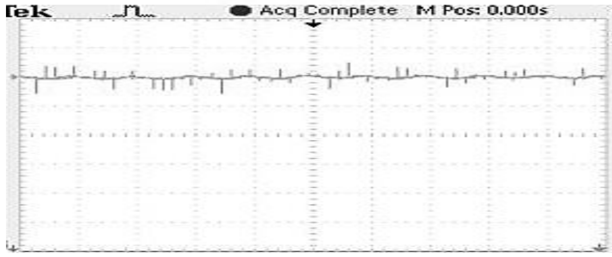

Fig.19. Stator active power at super-synchronous speed

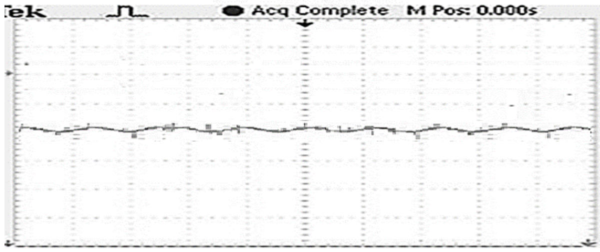

Fig.20. Stator reactive power at super-synchronous speed

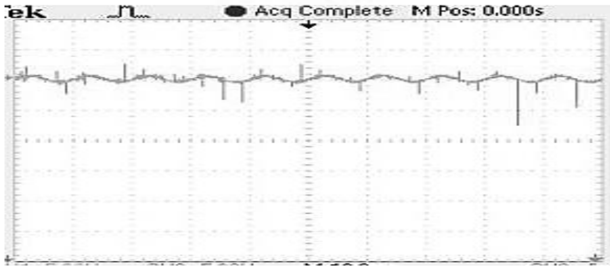

Fig.21. Stator active power at sub-synchronous speed

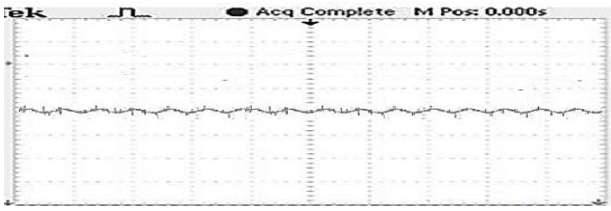

Fig.22. Stator reactive power at sub-synchronous speed

The MC connected to the rotor of the DFIG provides good decoupled control of stator the active power and reactive power. The stator active power delivered is 1 kW (reference stator power) and the reactive power delivered is 0 kVAr (reference reactive power) at the super-synchronous as well as the sub-synchronous speeds.

5. Conclusions

The DFIG–WT fed by rotor side MC is tested for the decoupled stator power control. The proposed control is developed in Matlab/Simulink as well as in Matlab/Xilinx platforms. The FPGA-SPARTAN 3E controller is used to implement the control technique without the aid of any other digital signal processor/microcontroller. The hardware implementation of the proposed controller shows the good dynamic performance for the decoupled control of the stator active power and reactive power for the variable speed operation of the rotor. The advantages of the proposed method are (i) the implementation of simple PI controller, independent of system parameters and stator flux estimation; and (ii) the hardware implementation using the FPGA-SPARTAN 3E controller is found to be easy than the conventional controllers/processors. The proposed technique gives good stator power control for the laboratory model DFIG-WT and the results are found to be promising.

Appendix

I) Parameters of the wind turbine

R (m)	ρ (kg/m³)	C_1	C_2	C_3	C_4	C_5	C_6
1.4	1.225	0.5	116	0.4	0	5	21

II) Parameters of the DFIG

Voltage (V) (line –line)	415
Frequency (Hz), f	50
Stator resistance (Ω), R_s	4.608
Stator inductance (H), L_s	0.0210
Rotor resistance (Ω), R_r	6.578
Rotor inductance (H), L_r	0.0210
Mutual Inductance (H), L_m	0.4580
Pole pairs, p	2
Turns Ratio, K	0.5

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