A Control Methodology of Doubly Fed Induction Generator for Wind Energy Generation

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Abstract. This paper presents the Direct Power Control (DPC) strategy for a Doubly-Fed Induction Generator (DFIG) using Matrix Converter (MC). Wind turbines are subjected to irregular wind speeds and thus the power generated is varying in nature. The Active and Reactive power flow to the grid from the DFIG connected to the wind turbines can be controlled by connecting a Power Electronic converter at its rotor terminals. By this method, the Induction Machine can be operated in generating mode even at sub-synchronous speed, by controlling the slip power, fed-to or absorbed-from the grid. The DPC Scheme is a high performance, dynamic power control method for DFIG. In DPC, at every instant of switching, the vectors for the power converter are selected based on the instantaneous active and reactive power error command from a hysteresis band, rather than a predetermined pattern as in conventional PWM drives. This work presents the Matrix converter based DPC for DFIG where the conventional AC to DC to AC converter at the rotor terminal has been replaced by a three phase MC.

1. Introduction
Wind energy is a popular renewable energy source. Doubly-fed induction generator (DFIG) wind turbines are widely used in the Wind Energy Conversion Systems (WECS). DFIGs are variable speed generators with more advantages compared to other solutions. They are used more and more in wind turbine applications due to easy controllability, high energy efficiency and improved power quality. Fixed speed generators and induction generators had the disadvantage of having low power efficiencies at most speeds [1-5]. To improve the efficiency, power electronic converters driven by control algorithms are commonly connected to the generators. Voltage Source Inverter (VSI) is used to convert the voltage magnitude and frequency to synchronize with the grid values. Power converters in a DFIG system only deal with rotor power control. Due to this factor the electronics’ costs are kept low, about approximately 20-25% of the total generator power making the system economically efficient. This is due to the fact that the rotor voltage is lower than the stator voltage. This implies that the converter is designed to suit the rotor parameter and making the system more economical than using a full power rated converter in a series configuration [6-10].

To observe the system and the flow of active and reactive power, a dynamic model of the machine is needed and has been developed [11-16]. For a normal generation regime, the energy obtained by processing the wind speed as an input is fed into the network by both the stator and the rotor. This work presents a modified WECS with the AC to DC to AC converter replaced by a three phase Matrix
Converter. The control of the corresponding active and reactive power supply to the grid can be
controlled by various control techniques of the Induction Machine such as V/Hz control or Vector
control or Direct Power Control (DPC) [17-25]. This work presents a novel DPC scheme which
replaces the conventional AC-DC-AC Converter with a three phase Matrix Converter. The complete
schematic of the WECS has been given in figure 1.

![Figure 1. Complete schematic of the WECS.](image)

2. System Design
The DFIG is grid connected and draws or supplies active and reactive
power based on the availability
of energy in the wind.

![Figure 2. Block Diagram of Direct Power Control of DFIG.](image)

Direct Real and Reactive Power control strategy for a Doubly Fed Induction Generator driven by a
Wind turbine, using Matrix Converter at the rotor side for the supplying the slip power as shown in
Fig 2.
3. Concept of Direct Torque / Power Control
The evolution of the variable speed AC drive technology is driven by the desire to achieve characteristics as that of the DC motor, such as fast torque response, easier speed control to accuracy, while using inexpensive, robust and maintenance-free Induction machine drives. Direct Torque Control (DTC) has found broad industrial applications. It is an optimised vector control strategy of Induction Machine, where the machine variable (torque and speed) are controlled using a power converter according to the dynamic loading conditions [26-30]. DTC eliminates complex frame transformations thus making it faster and involving selection of appropriate switching vector of the power converter according to the loading condition. In spite of its high dynamic response, sensor-less, transformation-less operations and robustness, the DTC has some disadvantages: Control of torque and flux at low speeds are difficult; higher current and torque ripples result in higher machine losses and noise. To retain the advantages of DC drives and eliminate the problems of DTC, a hybrid Space Vector Modulation (SVM) based DTC method was proposed. Introduction of an AC to AC converter called Matrix Converter (MC) as shown in Fig 2 with n x m switches arranged in a matrix form, paved way for easier control of input current and consequently the input power factor. This DTC scheme has been the basis for the Direct Power Control (DPC) of DFIG used in WECS. The technique involves direct control of rotor active and reactive power of DFIG by selection of appropriate switching vectors of the Power Converter (Matrix Converter). The control of the Power in rotor side in-turn controls the Active and Reactive Power that the DFIG supplies to the Grid. The change in input voltage immediately changes the stator flux. This stator flux change can be brought about using a power converter, with which the input voltage vector can be determined by the space vector position, value of reference Active and Reactive Power values.

The errors in active and reactive power are fed to 3-level hysteresis band comparators. The output of the active power hysteresis band in figure 3 is CP = -1 || 0 || +1, which represents the action to be taken in the power converter for the change desired to occur. The other hysteresis band as in figure 4 gives a signal CQ = -1 || 0 || +1, which indicates the error in flux and the switching change to be done in the power converter for bringing about the change in stator flux and torque.

4. Direct Power Control of DFIG
The basic concept of direct control of active and reactive powers can be appreciated from the phasor diagrams based on the equivalent circuit of the doubly-fed machine as shown in figure 5. From the phasor diagram in figure 6, it is noted that the stator current Is has to be controlled to control the stator active power Ps and the stator reactive power Qs. This is achieved in turn by controlling the rotor currents Ir in conventional field oriented control strategy. The effect of injection of these rotor currents on the air-gap and rotor fluxes can be derived by subtracting and adding the respective leakage fluxes. The reactive power drawn from the grid by the stator can be reduced by increasing the magnitude of the rotor flux and vice-versa.

It can be concluded that

i. The stator active power can be controlled by controlling the angular position of the rotor flux vector.
ii. The stator reactive power can be controlled by controlling the magnitude of the rotor flux vector. 

DPC is a technique in which, at every instant of switching, the vectors are selected on the basis of the instantaneous active and reactive power hysteresis command, rather than a predetermined pattern as in conventional PWM flux vector drives. The actual control of power by directly changing the input voltage can be expressed as below using equation (1) to (17), representing the behavior of Induction Machine. Neglecting the copper loss in stator of the IM, the Stator voltage of an induction machine is given by.

\[ V_s = \frac{d\psi_s}{dt} \]  

Where \( \psi_s \) is the stator flux,
Assuming flux changes in a considerable amount of time, the voltage is given by,

\[ V_s = \frac{\Delta \psi_s}{\Delta t} \]  

Thus, the stator flux can be directly controlled changing the input voltage of the motor for a given amount of time \( t \), as in equation (3)

\[ V_s \Delta t = \Delta \psi_s \]  

\[ \psi_s = \psi_{qs} - \psi_{ds} \]  

The stator current, \( I_s \), is given by,

\[ I_s = i_{qs} - i_{ds} \]  

Expressing Stator flux and the Rotor flux in complex form,

\[ \psi_s = L_s I_s \]  

\[ \psi_r = L_r I_r \]  

Equations (6) and (7) can be equated and reframed as follows. In Equation (6), eliminating the term \( I_r \),

\[ \psi_s = L_m \psi_r - L_a I_s \]  

Where \( L_a = \frac{(L_s L_r - L_m^2)}{L_r} \).

The corresponding stator current is given by equation (9)

\[ I_s = \frac{1}{L_a} \psi_s + \frac{1}{L_m L_a} \psi_r \]  

\[ P_s = \frac{3}{2} V_s I_s \]  

\[ Q_s = -\frac{3}{2} V_s I_s \]  

Neglecting copper losses in equation (12) and substituting equation (12) and (9) in equation (10) and (11),

\[ P_s = \frac{3}{2} \frac{L_m}{L_a} \omega_1 * |\psi_s|^1 \cos \theta \]  

\[ Q_s = \frac{3}{2} \frac{\omega_1}{L_a} |\psi_s|^1 \sin \theta \]
\[
\frac{dp_s}{dt} = \frac{3}{2} \frac{L_m}{L_r L_a} \omega_1^* \left| \psi_s^r \right| dt \sin \theta \tag{15}
\]
\[
\frac{dQ_s}{dt} = \frac{3}{2} \frac{L_m}{L_r L_a} \omega_1^* \left| \psi_s^r \right| dt \cos \theta \tag{16}
\]

According to equation 15 and 16, it can be seen that fast reactive and active power changes can be achieved by changing \( \left| \psi_s^r \right| \cos \theta \) and \( \left| \psi_s^r \right| \sin \theta \) respectively. From figure 5 & 6, \( \left| \psi_s^r \right| \sin \theta \) and \( \left| \psi_s^r \right| \cos \theta \) represent the components of the rotor flux \( \psi_r^r \) at the perpendicular and the same direction of the stator flux respectively. This indicates that, if the change of the rotor flux is at the stator flux direction, i.e., \( \left| \psi_s^r \right| \cos \theta \), reactive power \( Q_s \) is changed. Alternatively, if the change of the rotor flux is at 90\(^\circ\) to the stator flux direction, i.e., \( \left| \psi_s^r \right| \sin \theta \), active power \( P_s \) is changed.

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**Figure 5.** Equivalent Circuit of DFIG.

**Figure 6.** Stator and Rotor Flux Components.

The initial position of the rotor flux and its amplitude do not directly affect the active and reactive power changes

\[
V_f^r = \frac{d\psi_f^r}{dt} + R_r I_f^r \tag{17}
\]

Neglecting the effect of rotor resistance \( R_r \), equation (17) indicates that the variation of rotor flux is determined by the applied rotor voltage. The rotor flux moves at the direction of applied rotor voltage vector and its speed is proportional to the amplitude of the voltage vector applied. Therefore, by selecting appropriate voltage vectors, the movement of the rotor flux can be controlled. The selection of the voltage vector also depends on the location of the flux linkage and the \( \alpha_r - \beta_r \) plane is divided into six regions (I–VI) as shown in figure 7.

**Figure 7.** Space Vectors and their Locus.
5. Implementation
The selection of switching vectors for triggering the MC for DPC can be directly done but selected from the switching table of VSI in table 2. The active power error CP and the reactive power error CQ are obtained from the active power hysteresis and reactive power hysteresis bands respectively.

Table 1. Matrix Converter Switching Vectors.

| Vector | Switches On | Output Voltage | Vector Position |
|--------|-------------|----------------|-----------------|
| abb(+1) SbA SbB SbC 2/3Vab 0 |
| baa(-1) SaA SaB SaC -2/3Vab 0 |
| bce(+2) SaB ScB ScC 2/3Vbc 0 |
| cbb(-2) Sca SaB SbC -2/3Vbc 0 |
| caa(+3) Sca SaB ScC 2/3Vca 0 |
| acc(-3) SaA ScB ScC -2/3Vca 0 |
| bab(+4) SaA SaB SbC 2/3Vab 120 |
| aba(-4) SaA SbB ScC -2/3Vab 120 |
| cbe(+5) Sca SaB ScC 2/3Vbc 120 |
| beb(-5) SaA ScB SbC -2/3Vbc 120 |
| aca(+6) SaA ScB SaC 2/3Vca 120 |
| cac(-6) Sca SaB ScC -2/3Vca 240 |
| bba(+7) SaA SbB SaC 2/3Vab 240 |
| aab(-7) SaA SaB SbC -2/3Vab 240 |
| ccb(+8) Sca ScB SbC 2/3Vbc 240 |
| bbc(-8) SaA SbB ScC -2/3Vbc 240 |
| aac(+9) SaA SaB ScC 2/3Vca 240 |
| cca(-9) Sca ScB SaC -2/3Vab 240 |
| aaa(10) SaA SaB ScC 0 0 |
| bbb(11) SaA SbB SbC 0 0 |
| ccc(12) Sca ScB ScC 0 0 |

The switching table 2 for the inverter based DPC has been formed based on the flux Sector(S), CP and CQ. The input voltage sector (Vs) is calculated and is utilized for the MC-DPC vector selection. Also, the input power factor control is performed in this method and a separate hysteresis band is used for the same. A two-level hysteresis band fed by the error of the power factor and giving output variable namely CPF with values -1 || +1 for increasing or decreasing the power factor has been used to an appropriate switching vector for the MC for the PF control.

The MC switching table is selected from this VSI based DPC, CPF, and the input voltage sector number and has been selected from table 1 and has been tabulated in table 3. The simulation results are shown in figure 8 to figure 15.
Table 2. Optimal Switching Table.

| Sector(S) | 1 | 2 | 3 | 4 | 5 | 6 |
|-----------|---|---|---|---|---|---|
| $C_F$     | 2 | 3 | 4 | 5 | 6 | 1 |
| $C_T$     | 0 | 9 | 7 | 8 | 9 | 7 |
| -1        | 1 | 6 | 1 | 2 | 3 | 4 |
| -1        | 3 | 4 | 5 | 6 | 1 | 2 |
| 1         | 0 | 9 | 7 | 8 | 9 | 7 |
| 1         | 5 | 6 | 1 | 2 | 3 | 4 |

Table 3. Matrix Converter Based DTC.

| Input Voltage Sector (Vs) | 1 | 2 | 3 | 4 | 5 | 6 |
|---------------------------|---|---|---|---|---|---|
| $C_{PF}$                  |   |   |   |   |   |   |
| V1                        | 1 | -3 | 2 | -1 | 3 | 2 |
| V2                        | -7 | 9 | -8 | 7 | -9 | -8 |
| V3                        | 4 | -6 | 5 | -4 | 6 | 5 |
| V4                        | -1 | 3 | -2 | 1 | -3 | -2 |
| V5                        | 7 | -9 | 8 | -7 | 9 | 8 |
| V6                        | 4 | 6 | -5 | 4 | 6 | -5 |
| V1                        | -3 | 2 | -1 | 3 | 2 | 1 |
| V2                        | 9 | -8 | 7 | -9 | -8 | -7 |
| V3                        | -6 | 5 | -4 | 6 | 5 | 4 |
| V4                        | 3 | -2 | 1 | -3 | -2 | -1 |
| V5                        | -9 | 8 | -7 | 9 | 8 | 7 |
| V6                        | 6 | -5 | 4 | 6 | -5 | -4 |

Figure 8. Torque and Speed of a Doubly Fed Induction Machine.

Figure 9. Active Power of a Doubly Fed Induction Machine.
6. Conclusion
Matrix Converter provides a very handy solution for compact applications eliminating the use of bulky capacitors as there is no DC link between the AC-DC-AC converters. The major drawbacks associated with the Matrix Converters are Common Mode Voltage; High frequency switching harmonics; complexity of switching algorithm; complexity of commutation circuit. MCs are normally triggered using standing vectors- those that are pulsating in magnitude at a particular position in space. The MC’s output voltage, synthesized from the standing space vectors, produces a high frequency Common Mode Voltage (CMV). The CMV produces bearing current causing the discharge of the stored energy in the parasitic capacitance through the low impedance path provided by the bearing leading to its failure and the subsequent failure of the machine shaft.

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