DFIG Grid-Synchronization Control of a WECS Based on Matrix Converter

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Abstract-This paper proposes a direct voltage control scheme to synchronize doubly-fed induction generators (DFIGs)-based wind energy conversion system (WECS) to the grids. The stator of the DFIG is directly connected to the grid, the rotor is connected to the grid fed by an indirect matrix converter. The proposed scheme controls the stator terminal voltage of the DFIG, with the rotor converter operating at a constant frequency to track the grid voltage. The advantage of the proposed synchronization methodology is the minimization of possible transients that might arise when the DFIG is directly connected to the busbars without synchronization. The complete control system has been developed and analysed using MATLAB/Simulink.

Keywords-Component: DFIG; synchronization; WECS; voltage control; matrix converter.

I. Introduction

Due to the increasing demand on electrical energy, a considerable amount of effort is being made to generate electricity from new sources of energy. One of the major sources of air pollution is fossil fuel combustion in power plants for producing electricity. Preferred solutions to prevent emissions are using renewable and cleaner energy sources. Wind is one of the most abundant renewable sources of energy in nature. The economical and environmental advantages offered by wind energy are the most important reasons why electrical systems based on wind energy are receiving widespread global attention. Wind energy can be harnessed by a wind energy conversion system (WECS), composed of wind turbine blades, an electric generator, a power electronic converter and the corresponding control system[1]. Wind energy conversion system (WECS) can be divided into fixed speed type and variable speed type. In a fixed-speed wind turbine, the stator of the generator is directly connected to the grid. However, in a variable-speed wind turbine, the machine is controlled and connected to the power grid through a power electronic converter. Compared to fixed speed WECS, variable speed WECS has the advantages of maximizing the output power, reducing mechanical stresses, improving the power quality, and increasing the transient stability margin of the electrical grids [1], [2]. Variable speed WECS can further be subdivided into two types: one based on synchronous generators and the other based on doubly fed induction generators (DFIG). Compared with synchronous generators, DFIG are more suitable for high-power application, because only a portion of the generated energy needs to be processed by the power electronics converters [3]. Hence, DFIG-based WECS have dominated the high-power wind turbine market. The control of DFIG is achieved by changing the magnitude, frequency, and phase of the rotor voltages or rotor currents. In the early years, most DFIG systems employed either naturally commutated dc-link converters or matrix converters in the rotor circuits, which resulted in expensive dc-link choke, low-frequency current harmonics. Through the matrix converter, the terminal voltage and frequency of the induction generator is controlled, based on a constant V/f strategy, to adjust the turbine shaft speed and accordingly, control the active power injected into the grid to track maximum power for all wind velocities[4]. The power factor at the interface with the grid is also controlled by the matrix converter to either ensure purely active power injection into the grid for optimal utilization of the installed wind turbine capacity or assist in regulation of voltage at the point of connection. Furthermore, the reactive power requirements of the induction generator are satisfied by the matrix converter to avoid use of self-excitation capacitors[5].

II. Description of The DFIG System

The DFIG technology allows extracting maximum energy from the wind for low wind speeds by optimizing the turbine speed, while minimizing mechanical stresses on the turbine during gusts of wind. The optimum turbine speed producing maximum mechanical energy for a given wind speed is proportional to the wind speed[6]. Another advantage of the DFIG technology is the ability for power electronic converters to generate or absorb reactive power,
thus eliminating the need for installing capacitor banks as in the case of squirrel-cage induction generator. A commonly used model for induction generator converting power from the wind to serve the electric grid is shown in Fig.1. The DFIG is a wound rotor asynchronous machine mechanically coupled to a wind turbine[7]. The stator winding is connected to the grid through a three-phase contactor. The rotor winding is connected to the grid through a matrix converter. The rotor converter controls the voltage applied to the rotor winding of the DFIG. The controller of the rotor-side converter is a two-stage controller which is comprised of a real and reactive power controller. Further, the effectiveness of DFIG controller in extracting maximum energy from the wind by decoupled d-q voltage control is extremely important in analyzing its design and performance. A suitable control system has to be designed to achieve successful grid synchronization[8]-[10].

Figure 1. DFIG-based WECS.

III. Mathematical Modeling of DFIG

Park’s model is the most commonly used model for the DFIG. Using standard motor principles, the mathematical representation of stator voltage, rotor voltage and the flux equations as per space vector theory can be described by the equations below [11]-[13]:

\[ \frac{d \lambda_{sd}}{dt} = v_{sd} i_{sd} + \omega \lambda_{sq} \]  
(1)

\[ \frac{d \lambda_{sq}}{dt} = v_{sq} i_{sq} + \omega \lambda_{sd} \]  
(2)

\[ \frac{d \lambda_{rd}}{dt} = v_{rd} i_{rd} - \omega \lambda_{rq} \]  
(3)

\[ \frac{d \lambda_{rq}}{dt} = v_{rq} i_{rq} + \omega \lambda_{rd} \]  
(4)

\[ \lambda_{sd} = (L_{LS} + L_{m}) i_{sd} + L_{m} i_{rd} \]  
(5)

\[ \lambda_{sq} = (L_{LS} + L_{m}) i_{sq} + L_{m} i_{rq} \]  
(6)
\[ \lambda_{rd} = (L_{ls} + L_{m}) i_{rd} + L_{m} i_{sd} \]  
(7)

\[ \lambda_{rq} = (L_{lr} + L_{m}) i_{rq} + L_{m} i_{sq} \]  
(8)

Where \( R_s, R_r, L_{ls}, L_{lr} \) are the resistances and leakage inductances of the DFIG stator and rotor windings. \( L_m \) is the mutual inductance. \( v_{sd}, v_{sq}, v_{rd}, v_{rq}, i_{sd}, i_{sq}, i_{rd}, i_{rq}, \lambda_{sd}, \lambda_{sq}, \lambda_{rd}, \lambda_{rq} \) are the d and q components of the space vectors of stator and rotor voltages, currents and fluxes and \( \omega_s \) and \( \omega_r \) are the angular frequencies of stator and rotor currents.

IV. Grid Synchronization Control Method

The main goal of successful synchronization is to reduce stresses on the electrical and mechanical components of the wind turbine. Also it helps in preventing power system disturbance due to stator-grid connection. The mechanical stress is caused by heavy transient torque at the start-up and electrical stress is due to huge heavy start-up currents which are transient in nature and take some to settle[14]. The mechanical stress can damage the gearbox, shaft and the rotor of the machine while electrical stress can damage the insulation, and winding of the stator and the rotor over a period of time. To synchronize the generated voltage vector with the grid voltage vector, at the start-up stage before connecting to the grid, d-axis and q-axis rotor currents are applied as obtained in the stator-voltage orientation frame. Then we connect stator induced voltage to the grid through three-phase circuit breaker. The rotor-side current controller controls the magnitude, phase angle and frequency of the stator induced voltage. Since we expect the DFIG stator induced voltage to be same as the grid system voltage in terms of magnitude, phase angle and frequency, the grid system voltage is considered to be the reference signal for the rotor-side controller instead of stator voltage as shown in Fig. 2.

The angle estimated for the grid voltage would also be the angle for the stator-induced voltage. This implies that, the stator-voltage space vector position would be the same as grid-voltage space vector position and is computed directly in the \( \alpha-\beta \) reference frame.

V. Synchronization Method

The start-up and synchronization process irrespective of the type of orientation frame used can be achieved in steps mentioned below:

A. Turbine acceleration

The first step is to start the DFIG system. The aerodynamic drive torque exerted by wind on the wind turbine blades rotates the system and accelerates the generator shaft. The pitch angle \( \beta \) is maintained at the lowest point in order to obtain maximum torque and to keep the acceleration time very short. Due to inertia of heavy masses of the wind turbine mechanical system, this step can take the longest time[17].

B. Controller Initialization

As the wind turbine speeds up to the cut-in wind speed, the rotor-side current controller is initialized. The d-q rotor control voltage generated by the controller is injected to the rotor of the DFIG through the matrix converter to induce voltage in the stator.

C. Stator connection
This is the most critical stage of the synchronization process. The time at which the three-phase circuit breaker needs to be closed for connecting the stator is very important. Care has to be taken that the breaker is closed at a point of time when the stator induced voltage is exactly equal in magnitude to the grid voltage. The stator induced voltage would be in phase with grid voltage and so would be the frequency, but the magnitude needs to be monitored\[18\]-\[20\]. If the circuit breaker is closed with a stator induced voltage less than the grid voltage, heavy transient stator and rotor currents would be observed which indicates unsuccessful synchronization.

VI. Transient simulation study and results

This paper describes the technique and control system designed to achieve successful grid synchronization of the DFIG. The simulation model has been described primarily in the stator-voltage orientation frame. A comparative analysis has been carried out between direct synchronization method and the method proposed here to demonstrate the effect of proper grid synchronization. The magnitude of the stator induced voltage was observed at about 50 different test points after the start-up to determine the point at which this voltage was equal to the grid voltage. It was found that at $t = 0.1s$, the magnitude of the stator induced voltage is equal to the grid voltage. It was at this point the circuit breaker was closed and the connection was established between the stator and the power grid. Fig. 3 shows the stator connection for one of the three phase voltages. The fundamental component of the induced voltage over the grid voltage shows no deviation in magnitude, phase angle and frequency. A high frequency noise is observed in the induced voltage before the synchronization which can be attributed to ripples in the rotor current.

A successful synchronization at $t = 0.1s$ reflects in almost no or very low impact on the grid. Fig.4 below shows that stator-grid current has very low oscillations. The stator current reaches a peak transient value of 2200A which is just a little over the peak value of the rated current which is 1950A. Rotor current also has very small oscillations.

![Figure 3. Stator-Grid Synchronization](image3)

![Figure 4. Synchronization impact on stator current and rotor current](image4)

Stator power and electromagnetic torque also have very small oscillations as shown in the figures below(see Fig.5).

![Figure 5. Synchronization impact on DFIG stator power and torque](image5)
VII. Transient simulation results in direct Synchronization

A comparative analysis of the parameters such as stator current, rotor current, stator power and electromagnetic torque can be done with the help of results obtained for direct connection through various figures presented below (see Fig.6).

From Fig.6 it is clear that in case of direct connection, improper stator to grid connection causes heavy oscillation in the currents which has an adverse affect on the machine and power system. The proposed synchronization algorithm gives smooth and fast synchronization, which enables the system to be reclosed quickly after grid fault clearing.
The results of stator power and torque in Fig.7 show oscillations of very high magnitude. The huge swings in the stator power can cause power system instability and serious grid disturbance. The start-up transient torque of high magnitude can impart enormous stress to the mechanical assembly of the wind turbine damaging the gearbox and shafts.

VIII. Conclusion

This paper presents a new synchronization process for grid connection of a doubly fed induction generator (DFIG) in a variable speed wind generation system. Also DFIG grid-synchronization control technique has been proposed and performance of the control system under two approaches has been compared. The proposed synchronization algorithm gives smooth and fast synchronization, which enables the system to be reclosed quickly after grid fault clearing. Simulation results is carried out using Matlab software. The results show that proposed control scheme has better robustness.

Appendix

Machine Parameters
Stator rated voltage: 380 V
Stator rated current: 4.5 A
Rotor rated voltage: 120 V
Rotor rated current: 10 A
Operating frequency: 50 Hz
Synchronous speed: 1500 rpm
Magnetizing inductance: 0.2987 H
Rotor leakage inductance: 0.0186H
Stator leakage inductance: 0.0186 H
Rotor winding resistance: 5.8985 Ω
Stator winding resistance: 2.6596 Ω
REFERENCES


