Synchronization of DFIG output voltage to utility grid in wind power system

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Abstract

This paper presents a new synchronization algorithm for grid connection of a doubly fed induction generator (DFIG) in a variable speed wind generation system. Stator flux-oriented vector control for back-to-back PWM converters in the DFIG rotor circuit is used for synchronization process. By controlling the rotor $d$-axis current, the magnitude of the stator EMF is adjusted to be equal to the grid voltage. PLL circuit is used to compensate for the phase shift between the stator EMF and the grid voltage. By controlling the turbine pitch angle, the generator speed is determined to adjust the stator frequency to be equal to the grid. The experimental results show a smooth synchronization and fast dynamic responses. Compared to the existing DFIG synchronization algorithms, the proposed method gives fast starting and can take only 2 cycles to be performed and has satisfactory performance and better robustness than existing methods.

1. Introduction

It is well known that wind power generation using a variable speed constant frequency (VSCF) scheme produces electricity over a wide range of wind speeds, thus having a high energy capture capability. One commonly used VSCF scheme employs a doubly fed wound-rotor induction generator using an ac/dc/ac PWM converter in the rotor circuit [1,2]. The DFIG can supply power at constant voltage and constant frequency while the rotor speed varies. This makes the DFIG suitable for variable speed wind power generation. The main advantages of this system are the decoupled control of active and reactive power and the reduced rating of power converter (25–30%). The DFIG using back-to-back PWM converters for the rotor circuit has been well established in wind generation applications. When used with a wind turbine, it offers several advantages compared with fixed speed generators. These advantages, including speed control and reduced flicker, are primarily achieved by controlling the voltage-source converter, with its inherent four-quadrant active and reactive power capabilities [3–6].

As shown in Fig. 1, the stator of the DFIG is connected through SW 3 to the balanced three-phase grid and the rotor side is fed via the back-to-back IGBT voltage-source converters with a common dc bus. The ac–dc converters control the power-flow between the dc bus and the rotor side and allows the system to be operated in sub-synchronous or super synchronous speed. The active power is generated based on the wind speed value and wind turbine characteristics while the reactive power command is determined as a function of the desired reactive power converter compensation. The vector control strategy of the power converter is based on the stator flux oriented control which allows a decoupled control of generator torque and rotor excitation current. The control system makes it possible to improve dynamic behavior of the wind turbine, resulting in the reduction of the drive train stress and electrical power fluctuations, and increasing energy capture [7].

The DFIG operation and control have been intensively investigated so far [8–10]. On the other hand, only a few papers have handled the DFIG control during the synchronization process. There are two control schemes for DFIG synchronization published. One method is based on direct torque control (DTC) [7], and the other is based on the field oriented control (FOC) [11]. These methods are very simple, however, null current connection without an impact to the grid and the machine is not guaranteed. As a result, inrush current may go high depending on the degree of failure in the process of synchronization.

In this paper an induced stator voltage equal to the grid voltage is generated before the synchronization by adjusting the rotor flux. This procedure performs a null current connection with a very low impact to the grid and the machine. The paper describes soft and fast synchronization of the DFIG to the grid as well as independent control of active and reactive power of the generator using the stator flux-oriented vector control at normal operation. During the generator synchronization process, the turbine pitch angle controller adjusts the speed close to the synchronous speed to
make sure that the stator frequency is the same as that of the grid. The magnitude of stator EMF is controlled by adjusting the rotor flux and the phase shift between the stator and grid voltages is compensated by PLL circuit. The effectiveness of the proposed algorithm is verified and demonstrated by the experimental results.

2. DFIG synchronization control

2.1. Normal operation control

Fig. 2 shows the schematic of the DFIG wind turbine configuration and its control scheme. The stator of the DFIG is connected to the utility grid. The back-to-back PWM converter in the rotor side provide a bi-directional power-flow control thereby enabling the DFIG to operate either in sub-synchronous \((\omega_r < \omega_g)\) or in super synchronous modes \((\omega_r > \omega_g)\). In both modes the stator active power is generated from the DFIG and delivered to the grid. On the other hand, the rotor active power is either supplied to the machine in the sub-synchronous mode or delivered to the grid in the super synchronous mode. The stator active power is controlled directly assuming that a maximum generator developed power is known from the optimum generator speed value. The operating curve of the studied wind turbine, which is applied to most modern wind turbines [12], is illustrated in Fig. 3. This curve is characterized by four sections as follows: A \(\sim\) B for rotor speed which is less than the minimum angular speed for optimum operation, B \(\sim\) C for an optimal characteristic curve given by \(P_{opt} = K_{opt}v^3\) (where \(v\) is the wind speed) in between the cut-in speed and the rated speed, C \(\sim\) D for a constant speed characteristic up to the rated power, and D \(\sim E\) for a constant power characteristic beyond the speed limit followed by a blade pitch control action for high wind speed.

The reference stator power \(P^*\) of the DFIG is used as the reference value for the power control loop. In the inner current control loop, the stator flux vector position is used to establish a reference frame that allows q-axis components of the rotor current to be controlled. As the reference rotor current components are in stator flux-oriented coordinates, these must be transferred to the same reference frame as the DFIG rotor current vector. This is achieved by rotating the rotor reference current vector by an angular position \(\theta_g\). Due to the rotor speed variation, \(\theta_g\) is updated at every sample interval. Once the reference frame for both the reference and measured current vectors are conformed, simple proportional plus integral (PI) regulators can be used to control the \(d\)- and \(q\)-components of the rotor current.

Adjustment of the \(q\)-axis component of the rotor current controls either the generator developed-torque or the stator-side active power of the DFIG.

Fig. 1. Basic configuration of DFIG wind turbine.

Fig. 2. Active and reactive power control for synchronization mode and running mode.
\[ P_s = \frac{3}{2} (v_{qs} l_{qs} + v_{ds} l_{ds}) = \frac{3}{2} v_{qs} i_{qs} \]
\[ T_e = \frac{3}{2} \frac{P}{T_s} (\lambda_{qs} l_{dr} - \lambda_{ds} l_{qr}) \]
\[ Q_s = \frac{3}{2} (v_{qs} l_{ds} - v_{ds} l_{qs}) = \frac{3}{2} v_{qs} i_{ds} = \frac{3}{2} v_{qs} \left( \lambda_{ds} - \frac{L_m}{L_s} l_{dr} \right) \]

where \( P_s \) is the stator power, \( v_{qs}, v_{ds}, i_{qs}, \) and \( i_{ds} \) are the dq stator voltage and current components, \( L_s \) and \( L_m \) stator and magnetizing inductances, \( \lambda_{qs} \) is the stator flux \( d \)-axis component and \( i_{qr} \) is the rotor \( q \)-axis component.

Regulating the \( d \)-axis component controls directly the stator-side reactive power-flow as shown in Fig. 2.

\[ Q_s = \frac{3}{2} v_{qs} \left( \frac{v_{qs}}{L_{ms}} - i_{dr} \right) = \frac{3}{2} \frac{L_m}{L_s} v_{qs} (i_{ms} - i_{dr}) \]

2.2. Synchronization process control

The process of connecting the DFIG to the grid consists of two stages, that is, synchronization stage and running stage. At standstill, rotor blades are in a feathering position and the generator is disconnected from the grid. From a complete stop, the first step is to charge the dc-link voltage by closing SW1 as shown in Fig. 1. The anemometer measures the wind speed and if the wind speed is higher than the cut-in value, the switch SW2 is closed and the pitch controller changes the blade pitch angle so that the turbine begins to rotate. The controller of the generator rotor side is activated so an excitation current is sent through the rotor. The excitation current generates the generator flux and build-up the stator EMF. The turbine accelerates until it reaches near the rated speed. At this point the frequency of the stator EMF is about the same as that of the grid voltage. The amplitude of the stator EMF is about the same as that of the grid. Even slightly different frequencies may cause the phase difference between the two voltages. To compensate for the phase difference between the stator EMF and grid voltage, the phase difference compensation component \( \delta \theta_d \) is added to the calculated slip angle as shown in Fig. 4. The compensation component \( \delta \theta_d \) is calculated by controlling the stator \( d \)-axis voltage component to be zero, equally to the grid \( d \)-axis voltage. The synchronization process is summarized in the flow chart shown in Fig. 5. After the synchronization conditions are achieved, the stator-side contactor is closed, and the generator is connected to the grid. The pitch angle controller sets the blade pitch at the optimum point if the blades are not yet at this point.

![Fig. 3. Wind turbine characteristics.](image1)

![Fig. 4. Phase difference compensation for synchronization.](image2)

![Fig. 5. Sequence of DFIG synchronization.](image3)
The generator power reference is set to the maximum value which is determined by the wind speed and the pitch angle. The overall control system for both synchronization mode and running mode is shown in Fig. 2.

2.3. Grid-side control

The function of the grid-side converter is to keep the dc-link voltage constant regardless of the magnitude and direction of the rotor power [13]. If a vector control method is applied, with a reference frame oriented along the grid voltage vector position, an independent control of the active and reactive power for the grid-side is guaranteed. Fig. 6 shows a block diagram of the grid-side converter control. The PWM converter is current-regulated, with the $q$-axis current used to regulate the dc-link voltage and the $d$-axis current component control of grid-side PWM converter used to regulate the reactive power.

3. Experimental results

The proposed control system has been verified its validity for the smooth and fast synchronization. Fig. 7 shows the proposed configuration of the control system with the laboratory 3 kW system. The characteristics of the wind turbine are simulated using a torque-controlled induction motor drive. Torque reference is calculated using torque equations by a control program running in a DSP TMS320C33 control board. Reference torque is passed to the gate-drivers as a voltage signal by using one of the D/A outputs of the control board and one of the A/D inputs of the gate-driver. In order to calculate the reference torque, the control program reads wind velocity from an input file and shaft speed from an encoder. The wind data file can be generated in different ways, depending on the desired test conditions, or even being real data from an anemometer. The motor is fed by a PWM controlled IGBT converter. Experiments were carried out using the setup Tables 1–3.

Fig. 6. Control block diagram of grid-side converter.

Fig. 7. System configuration.
The synchronization process is depicted in Fig. 8, where the stator voltage is synchronized with the grid one. From zero stator voltage, the rotor d-axis current is controlled in order to build-up the stator voltage in a short time. Meanwhile, the phase shift between the two voltages is compensated using the proposed PLL algorithm. The synchronization process takes place in an almost couple cycles as shown in the figure; hence, the proposed synchronization scheme is faster than the existing synchronization methods [11,12]. It is well known that the back-to-back PWM converters provide a bi-directional power-flow control thereby enabling the DFIG to operate either in sub-synchronous or in super synchronous modes. Fig. 9(a) shows that the converter input current flows in phase with the converter input voltage in the sub-synchronous mode which means the current is supplied by the grid to the rotor. If the generator speed increases to the super synchronous, the phase shift changes to 180 which means the current is supplied by rotor to the grid as shown in Fig. 9(b).

Fig. 10 shows the transition through synchronous speed. As a result of increasing rotor speed, the rotor power decreases up to zero and the increase in the reverse direction. Theoretically, the zero crossing point occurs at synchronous speed. However, in Figs. 11 and 12 the zero crossing occurs at 1875 rpm due to the different sources of loss such as rotor and converter losses.

On the other hand, the stator power is optimized to extract the maximum power for different wind speed. Region AB in Fig. 13 shows the power optimization during the wind speed increasing.

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Fig. 8. Stator and grid voltages.

Fig. 9. Voltage and current of grid-side converter in super synchronuous and sub-synchronuous speed.

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Fig. 10. Rotor current variation due to speed transition.

Fig. 11. Rotor power variation due to speed transition.
If the rotor speed reaches the maximum value, the rotor speed is controlled to this value while the stator power increase as the region BC depicts in Fig. 13.

4. Conclusions

In this paper, a synchronization scheme for stator flux-oriented DFIG control systems to the utility grid has been proposed. The pitch angle controller adjusts the turbine speed at the required value for equal frequency. The stator voltage is generated to be equal to the grid voltage by adjusting the rotor d-axis current. The voltage phase shift is compensated using the d-axis voltage component of both sides. The proposed synchronization algorithm gives smooth and fast synchronization, which enables the system to be reclosed quickly after grid fault clearing. Experimental results have verified that the proposed synchronization algorithm is effective, gives fast starting and has satisfactory performance and better robustness than existing methods.

Appendix

The parameters of the wind turbine used are shown in Table 1. The specification of the induction motor used for test is three-phase, four poles, 230 [V], 60 [Hz], 3 [kW], and 1435 [rpm], of which parameters are listed in Table 2. The specification of the DFIG used for test is three-phase, four poles, 230 [V], 60 [Hz], 3 [kW], of which parameters are listed in Table 3.

References