Performance enhancement of a DFIG wind energy conversion system using phase advanced network

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Abstract. This paper presents the development of a phase advance network to enhance the performance of a variable-speed doubly-fed induction generator (DFIG) driven by a wind turbine under various operating conditions at Zafarana wind farm, Egypt. Firstly a fairly detailed simulation of a real DFIG-based wind energy conversion system is built using Matlab/SimPower environment. The simulation output is verified by comparing the simulation output with similar practical results and also with that published by Gamesa G5x standard test results. A phase advance network is designed and implemented to enhance the DFIG-based Gamesa G5x wind energy conversion unit. The FRT characteristics is examined when the system is subjected to a three phase short circuit test and the results obtained using the various enhancement techniques have presented in a comparative form with similar results using the implementation of the phase advance network. The results illustrate significant improvement in overall system performance and superior operation of the wind conversion unit using the phase network.

1. Introduction

With the continuous increasing in the demand of electrical energy and the depletion of conventional energy sources besides the emissions of carbon dioxide, all of that have been attracted dire needs to find another source of energy. Renewable energy sources offer an alternative solution because they are continuous, environmentally clean and available worldwide. Among renewable energy sources, wind energy attracted a lot of researchers due to its competitive cost. Various techniques have been implemented in wind energy conversion systems (WECS) and it is expected that wind power generation capacity will reach 2,000 GW by 2030 and increased to 25-30% of worldwide electricity supply by 2050 [1]. Recently variable speed doubly fed induction generators DFIGs wind energy conversion systems have become widely implemented due to its flexible control, low cost, high efficiency and many others salient features[2]. However, many challenges face wind energy such as supplying power at point of common connection (PCC) with fast response through a wide range of wind speeds, fluctuation in generated power that produce undesirable effects on voltage and frequency levels and consequently performance enhancement during fault conditions as well as changes in wind speed is of prime importance in the operation of WECS.

Various techniques have been developed and implemented for the enhancement of the performance of wind energy conversion systems [3-9]. These include the use of proportional plus integral (PI) control, conventional flywheel, super capacitor and superconducting magnetic energy
storage (SMES). Probably the most widely used is the PI control as it offers the fast recovery response due to the proportional gain and elimination of the steady state error due to the integral action. However, this technique does not effectively cope during fault conditions due to difficulties in tuning the PI gains. Super capacitor and superconducting magnetic energy storage (SMES) are also used as a short term storage systems which enhance wind turbines transient characteristics. However, super capacitors suffer from low energy density while the use of SMES is not well established due to its high implementation cost. Regular flywheel acts as the energy storage system and achieves a smooth power output during wind speeds variation but very poor performance during short circuit characteristics. Moreover, wind turbine generators is required to feed reactive power during disturbances to support the voltage at the point of common coupling (PCC) and resume active power generation after fault clearing. Grid codes in countries with high penetration of wind power generation require that all new installed wind turbines should have the capability of low voltage ride through (LVRT) [3]. This capability requires an increase in the stability margin and low voltage conditions must be kept within certain limits.

This paper presents the design and implementation of a phase advance network to enhance the performance of a DFIG-based wind energy conversion system. A MatLab simulation is built for a DFIG-based wind energy conversion system and then verified by comparing the simulation output with that of Gamesa Turbine standard test and also with that obtained experimentally at Zafarana site. Various performance enhancement techniques have been discussed, implemented and their response is compared with that obtained using the proposed phase advance network when the system is subjected to a step change in wind speed and a three phase short circuit. The results illustrated superior enhanced of the performance of the WECS using the phase advance in comparison over previous techniques.

2. System Description
The largest wind farm in the Middle East is located at Zafarana, Egypt with total power 545MW. The most important wind turbine in Zafarana wind farm is Gamesa G5X with 850KW total power, it also the newest wind turbine in Zafarana wind farm and the only one that contains the advance technology equipped with a double fed Induction Generator (DFIG). A layout of the WECS is shown in Fig. 1. The DFIGs rotor and stator are both connected to electrical sources. The rotor is connected to grid through AC/DC/AC converter that consists of two components: the rotor side converter RSC (C rotor) and Grid side converter RSG (C grid)[10,11] Fig.1.

![Figure 1. Typical DFIG Wind Energy Conversion System](image)

A coupling inductor L is used to connect the grid converter to the grid. The three phase rotor winding is connected to the Crotor by slip rings and brushes. The basic principle used in DFIG is to control a frequency converter amongst the changeable frequency induction generator (it is mainly for injecting the current in the rotor circuit towards frequency compensation) as well as permanent frequency grid.
Converter works equally in both super and sub synchronous speed ranges. The slip power flow in both directions to the rotor from supply and from supply to the rotor side. DFIG is able to deal with wide variation of wind speeds with two modes of operation (sub and super synchronous speed). In the sub synchronous mode, the slip power flows from grid to the rotor, when rotor speeds less than the synchronous speed. However, when the rotor speed exceeds the synchronous speed, (super synchronous mode), the slip power flows from rotor to the grid.

3. Modelling of Zafarana Wind ECS

3.1. Modelling of wind turbine

The power in the moving air (P) can be written as follows [12]:

\[ P = \frac{1}{2} \rho A V^3 \]

Where:  
- \( A \) = the area swept by the rotor blades.
- \( \rho \) = the air density = 1.225 kg/m\(^3\) is the air density
- \( V \) = the wind speed in (m/sec).

The actual Power mechanical (\( P_w \)) extracted by blade can be written as follows:

\[ P_w = \frac{1}{2} \rho A V^3 C_p \]

\( C_p \) is the fraction of wind power captured by the rotor blades.

The power coefficient varies according to the turbines manufacture. Also, it varies according to the Tip Speed Ratio (TSR), of the wind turbine which can be expressed as:

\[ C_p(\lambda, \beta) = C_1 \left\{ \left( C_2 \frac{1}{\lambda_i} \right) - (C_3 \beta) - C_4 \right\} e^{-C_5 \lambda_i} + C_6 \lambda \]

Where the coefficients C1 to C6 for the Gamesa G5x Turbine are: C1= 0.5176, C2= 116, C3= 0.4, C4= 5, C5= 21, C6=0.0068, \( \beta \) is the pitch angle of the blade in degrees and \( \lambda \) is the tip speed ratio.

3.2. Modeling of doubly fed induction generator

Figure 2 shows the DFIG representation in a synchronously rotating [4], where the machine equations can be written in stator and rotor reference frame as follows:

\[ V_{qs} = R_s I_{qs} + \frac{d}{dx} \varphi_{qs} + \omega_s \varphi_{ds} \]
\[ V_{ds} = R_s I_{ds} + \frac{d}{dx} \varphi_{ds} + \omega_s \varphi_{qs} \]
\[ V_{qr} = R_r I_{qr} + \frac{d}{dx} \varphi_{qr} + \omega_r \varphi_{dr} \]
\[ V_{dr} = R_r I_{dr} + \frac{d}{dx} \varphi_{dr} + \omega_r \varphi_{qr} \]

The flux linkage expressions in terms of current can be written as follows:
\[ \phi_{qs} = L_s I_{qs} + M I_{qr} \]
\[ \phi_{ds} = L_s I_{ds} + M I_{dr} \]
\[ \phi_{qr} = L_r I_q + M I_{qs} \]
\[ \phi_{dr} = L_r I_{dr} + M I_{ds} \]

The mechanical equation is given by:
\[ J \frac{d\Omega}{dt} + f \Omega = T_e - T_d \]
\[ T_e = N_p \frac{M}{L_s} (\phi_{qs} I_{dr} - \phi_{ds} I_{qr}) \]

Figure 2. D-Q equivalent circuit of DFIG

Where:
\( V_{sdq}, I_{sdq}, \phi_{sdq} \) refer to stator voltages, currents and flux in direct and quadrature axis; \( V_{rdq}, I_{rdq}, \phi_{rdq} \) are referring respectively the rotor voltages, currents and flux in direct and in quadrature; \( R_s, R_r \) Refer respectively to the resistance of stator and rotor windings; \( L_s, L_r, M \) Refer respectively to the inductance of stator and rotor windings and mutual inductance; \( \omega_s, \omega_r \) Refer respectively to the stator electrical speed and rotor electrical angular velocity; \( T_e, T_d \) Refer respectively to electromagnetic torque and driving torque; \( J \) refers to total inertia; \( \Omega \) refers to rotor angular velocity; \( N_p \) is pole pair number and \( f \) is the friction coefficient.

4. Simulation of Gamesa G5x based WEC system

Nominal power of the WEC units at at Zafarana wind farm in Egypt is Gamesa G5x 850KW. A comprehensive simulation is built using Matlab includes the Gamesa G5x turbine interior system, DFIG circuit, crowbar and control system as shown in Fig.3. The unit output voltage is 690V which
stepped up to a 23KV bus and is then connected to the 220KV point of common connection (PCC) at the Egyptian grid via a transfers power via a 10 km underground cable as shown in Figure 4.

Figure 3. Simulation of the Gamesa G5x based WECS

Figure 4. Connections with the Unified Egyptian Grid
5. Simulation Verification

Before dealing with detailed performance analysis, the simulation is assessed by comparing the simulation output with similar results obtained experimentally. Initially, the simulation is verified by comparing the simulation results of the wind turbine output obtained at air density equals 1.225 kg/m$^3$ with that obtained experimentally using the standard test conditions as listed in the Gamesa G5x Turbine data sheet as shown in Figure 5. Moreover, the simulation output power and current at various speeds are compared with similar experimental results using field tests as shown in Figure 6 ignoring changes in wind air density. Examining these results illustrate that the simulation results are in good agreement with similar experimental results which gives confidence with other simulation results which intended to evaluate output using various performance enhancement techniques.
6. Performance Enhancement Methods

6.1. Crowbar

Crowbar is an electronic circuit consists of thyristors, diodes, and resistors in order to protect rotor circuit in the case of overvoltage, which is 1325V in Gamesa G5x. Simply when the wind turbine sense an overvoltage in the rotor circuit, it activates crowbar which provides an alternative path with low resistor to absorb high current.

6.2. Proportional Integral control

Proportional plus Integral (PI) controller used in WECS is a feedback control loop mechanism which consists of a proportional gain connected in parallel with an integrator gain, where the proportional gain improves the response and stability of the system, the integral gain when added to proportional gain speed up the movement towards set point and reduces the steady state error.

6.3. Superconducting magnetic energy storage (SMES)

Superconducting magnetic energy storage (SMES) is a superconducting coil stores electric energy into magnetic field with the basic configuration shown in Figure 7. However, this technique suffers from the high cost of SMES initial investment, and maintenance required, required low cooling system for the superconducting coil[9].

![Figure 7. Superconducting magnetic energy storage (SMES)](image)

6.4. Flywheel

Flywheel is a rotating mass that can be used to store and restore energy and consequently exchange the power with wind turbine during variable wind speeds. Regular FESS [10] enhances dynamic performance of wind turbine by minimizing the dynamic stress on wind turbine and smoothing the output power. However, FESS technique results in a steady state error in the DC-link and hunting oscillations following short circuit conditions. It minimizes the dynamic stress on wind turbine, besides the long live and the low overall cost of flywheel. Despite of the advantages the FESS it suffers from short discharge time, high mechanical stress, selecting the tensile strength of flywheel material, possible hazard situations and bad short circuit performance.

6.5. Super capacitor

Super capacitor is a double layer capacitor with very high capacitance [8]. It does not have a conventional dielectric and instead it has plates that are filled with two layers of an identical substance, that give the chance to super capacitor plates to pack with a larger surface area, thus
resulting in very high capacitance. Super capacitors are used in wind turbine as a storage energy devices as enhance wind turbines performance by reducing the fluctuation of wind speed and also can be used to support DC-link voltage during transient operation which enhances wind turbines low voltage ride through (LVRT) capability, as shown in Figure 8.

6.6. Proposed performance enhancement technique

Alternative, the paper suggested the phase advance network as technique to improve the performance of the WECS during both variations in wind speed and also during short circuit faults. The phase advance is a lead lag compensator whose transfer function can be written as follows:

\[ G(s) = K \frac{T_s}{T_s + \frac{1}{4}} \]

This advance network is used to replace the DC-Link PI controller as shown in Fig 10.

7. Simulation Results

The simulation model of grid connected Gamesa G5x wind turbine with DFIG that is shown in Figures 5 and 6. The different enhancement techniques are implemented by computer simulation to evaluate their performance in comparison with the proposed method. The system response with
various enhancement techniques is described subsequently in comparison with the proposed technique under step changes in wind speed and also during three phase short circuit.

7.1. Operation Under step change in wind speed

The system is subjected to about 20% increase in wind speed. The system response with various enhancement techniques are shown in comparison with the system response with the proposed technique is shown in Figure 10. Examining these results illustrate excellent performance enhancement of the system performance with the proposed technique in comparison with all previous methods. This is clear with the very small fluctuation in rotor speed, grid voltage, DC-link voltage, active power and reactive power. Moreover, it’s enhance wind turbine tracking to wind speeds change, that means the wind turbine will reach to the maximum power of wind turbine at currently wind speed faster and that lead to produce more power during same wind speed variations. Also, Phase advance enhance DC-Link performance by increasing the stability and response of DC-Link voltage in the start of wind turbine and also during wind speed changes.
7.2. Operation Under Transient Fault Condition

The system is subjected to a three phase short circuit in the middle of the 10 km underground cable that connects the unit to the point of common connect (PCC). The fault sustained for 5 cycles and the system response with various enhancement methods is shown in Figure 11. These results also show the performance at starting as well as during fault conditions. Examining these results illustrate superior performance with the proposed technique under both starting and during fault conditions. The results also show significant increase in system stability with the proposed technique.

Figure 10. System responses to about 20% step increase in wind speed.
Figure 11. System response during fault
8. Conclusion

The paper proposed phase advance network as an alternative technique to enhance the performance of a DFIG wind energy conversion system. A fairly detailed simulation model is built to simulate the Gamesa G5x DFIG based wind energy at Zafarana wind farm, Egypt. The simulation is verified by comparing simulation results with experimental measurements and good agreements are obtained. The system performance is presented with the proposed technique under step increase in wind speed as well as under three phase short circuit fault conditions in comparison with previous enhancement techniques. The results illustrate superior performance with the proposed method and form a useful guide to improve the performance of WECS under wide range of disturbances.

9. Reference

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