Hybrid Renewable Energy System Using DFIG and Multilevel Inverter

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Abstract—The rotor of a doubly fed induction generator (DFIG) driven by a wind turbine needs rotor excitation so the stator can supply a load or feed the grid. In a variable-speed wind energy conversion system (WECS), the mechanical frequency of the generator varies, and in order to keep the stator voltage and frequency constant, the rotor voltage and its frequency have to be varied. Thus the system requires a power conversion unit to supply the rotor with a variable frequency voltage that keeps the stator frequency constant irrespective of the wind speed. In the scheme proposed, the rotor of the DFIG draws power either from three-phase ac mains or from a set of photo voltaic (PV) panels depending on the availability of the solar power. Maximum power point tracking techniques have been used for power extraction from both the wind turbine and solar panels. A multilevel inverter is used to convert the rectified voltage from ac mains and dc voltage from PV panels to a variable-frequency voltage to supply the rotor.

Keywords—doubly fed induction generator; maximum power point tracking; multilevel inverter; photovoltaic panel; wind turbine

I. INTRODUCTION

Since the amount of energy available from conventional sources is limited, non-conventional energy sources are considered for power generation. Among these sources, wind and solar power are the most abundant and attractive. For wind energy conversion, fixed speed systems using squirrel cage induction generator were implemented earlier [1]. At present, variable speed systems are being used for system operation with higher efficiency, absence of speed control, and reduced flicker [2]. Generally doubly fed induction generators (DFIGs) are used for variable speed wind energy conversion systems (WECSs). Permanent magnet machines which do not need gear box can also be used, but not for high capacity installations. The power converter, in the case of DFIG, needs to provide only 20%-30% of the output power [3], so the system can use converters as well as filters with lower ratings.

The increasing use of power from renewable sources has made it necessary for the sources to behave, as much as possible, like conventional power plants in terms of supporting the network voltage and frequency with good power quality. Several schemes have been proposed to solve these problems. In most DFIG-based WECSs, the load or grid is directly connected to the stator of the DFIG, and the rotor injection is controlled using an ac-dc-ac converter [4], [5]. Instead of two back-to-back converters, a diode rectifier followed by an inverter can also be used [6]. For systems with only rotor-side converter, pulse width modulation (PWM) converters are used where the grid side PWM rectifier is controlled to provide a constant dc link voltage and the rotor side PWM inverter controls the generator to provide required real and reactive power. In these schemes, the mechanical and electrical frequencies are decoupled making variable speed operation possible [5]. Back to back multilevel inverters were also tried by some researchers for higher capacity installation [2], [6].

In this paper, a new power conditioning scheme is proposed for DFIG-based WECS that uses a 3-phase diode rectifier followed by a boost regulator as grid side converter and a multilevel neutral point clamped (NPC) inverter to supply variable frequency voltage to the rotor. The system also includes photo voltaic (PV) panels which can supply the boost regulator and reduce the power drawn from the utility. The proposed system includes voltage feedback to regulate the output voltage from the DFIG.

II. PROPOSED POWER CONVERSION SYSTEM

Fig. 1 shows the complete block diagram of the proposed system designed using the software PSIM [7]. PSIM has a wind turbine model with variable wind speed and blade pitch angle input, and a wound rotor induction machine model that can be used as a DFIG. The boost regulator provides a constant dc-link voltage for the inverter from the variable voltage dc input from the rectifier. Using a diode rectifier instead of a PWM rectifier not only reduces the complexity of the system but eliminates the need for additional control. The reason for using a multilevel inverter is its ability to provide a better output power quality and lower switch ratings [8]. The present scheme uses a three-level inverter with neutral point clamping whose output voltage is controlled by controlling the amplitude modulation index. The control voltage needed for this purpose is generated by the inverter controller based on vector control scheme that uses the d-q axis current control [9]. Using maximum power point tracking (MPPT) technique, the torque reference ($T_{ref}$) is calculated for a given generator speed. The q axis current reference ($I_{qref}$) is then generated by minimizing the difference between the reference and actual torques. On the other hand, the stator side voltage is controlled to generate d axis current reference ($I_{dref}$). The d-q axis reference rotor currents provide the control voltage ($V_{ctrl}$) which is used to generate the gate pulses for the 12 switches of

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the inverter. The inverter voltage is then fed to the rotor of the DFIG.

A. Rectifier and boost regulator

Fig. 2 shows the schematic of a boost regulator whose output is constant irrespective of the fluctuations in the input voltage and load (Fig. 3). It is done by varying the duty cycle (D) for the switch so that the output given by the equation, \( V_{out} = \frac{V_{in}}{1-D} \), is always constant. Using a triangular wave and a comparator, a gate pulse with a duty cycle proportional to the PI controller output is generated. For fast simulation, the average model of the boost regulator has been used. The average model (Fig. 4) basically uses two dependent sources to realize the following equations derived from boost regulator operation:

\[
V_{sw} = \frac{(1 - D)}{D} \times V_d, \quad (1)
\]
\[
I_d = \frac{(1 - D)}{D} \times I_{sw}. \quad (2)
\]

B. NPC inverter

In order to get a higher fundamental output voltage and power level, the dc-link voltage (\( V_{dc} \)) for the conventional bridge inverter has to be increased which means one has to use a series-connected pair in place of each device. The connection of matched devices in series, considering dynamic voltage sharing during switching, is difficult [10]. So this scheme uses a 3-level neutral point clamped (NPC) inverter which consists of 4 switches with anti-parallel diodes and 2 diodes per phase. The switches \( Q_{a1} \) and \( Q_{a4} \) are the main switches that work together like a conventional 2-level bridge inverter. The auxiliary switches
Qa2 and Qa3 clamp the output potential to the neutral point with the help of the clamping diodes. Thus they insert a new potential level in the output voltage, resulting in reduced harmonics. The simulation results show that, without any filter, the THD for the NPC inverter is about 11.2% compared to 25% for the bridge inverter. Fig. 5 shows one leg of the NPC inverter and Fig. 6 the waveforms of gate pulses. Fig. 7 shows the output voltages and the harmonic spectra of both the NPC and bridge inverters. The harmonic spectra shows that not only the THD is lower for NPC inverter but also the individual harmonics have been reduced with the lowest order harmonic (LOH) = mf – 4 as seen from Fig. 7 where mf is the ratio between the triangular frequency and reference sine frequency.

C. Inverter controller

The Inverter controller shown in Fig. 8 is designed using vector control scheme. The inner control loop, that controls the d-q axis current, is designed for a faster response. The main part of the controller is the maximum power point tracking (MPPT) block. Fig. 9 shows a set of graphs for a particular wind turbine showing the relationship between its output power and turbine speed for various wind speeds.

The mechanical power from a wind turbine is given by

\[ P_m = \frac{1}{2} C_p \rho \pi R^2 \omega_w^3, \]  

(3)

where \( C_p \) is the power coefficient, \( \rho \) is the air density (kg/m\(^3\)), \( \omega_w \) is the wind velocity (m/s) and \( R \) is the radius of the area swept by blades (m).

The MPPT equation derived from the power equation (3) is given by

\[ P_m = K_{\text{opt}} \omega_m^3, \]  

(4)

where \( K_{\text{opt}} \) is the optimum power coefficient (W/(rad/s)\(^3\)), \( \omega_m \) is the generator shaft speed (rad/s).
The equation for torque is given by

\[ T_{\text{opt}} = K_{\text{Topt}} \cdot \omega^2, \]

where \( K_{\text{Topt}} \) is the optimum torque coefficient in W/(rad/s)^2. Using the rated values, \( K_{\text{Topt}} \) for the machine is obtained as 3.097 W/(rad/s)^2. Using this coefficient and slip frequency [11], the optimum torque is calculated. Controlling the shaft torque according to the reference gives the q axis rotor current reference which controls the q axis current and provides q axis control voltage for the inverter. The d axis control voltage is obtained by controlling the d axis current based on a stator voltage feedback loop. This loop maintains a constant stator voltage (phase) amplitude at 170 volts.

D. PV panel and MPPT

PV panels are used in the system in place of the ac mains whenever possible to save energy drawn from the ac mains. It is connected in parallel with the output of the diode rectifier and is capable of supplying a dc voltage to the boost converter. Other than boosting the dc level to 200V, the boost converter can also be used as the maximum power point tracker for the PV panel. It is a simple technique using the relationship between the short circuit current and panel output current at maximum power point [12] i.e.

\[ I_{mp} = 0.9 \cdot I_{sc}. \]

Fig. 10 shows the MPPT scheme for the PV panel whose output is stepped up using a boost converter which supplies a battery. The simulation results are shown in Fig. 11. Normally the gate pulse of the switch is controlled by the output of a PI controller based on the current error. In this scheme an extended pulse repeating at a low frequency is supplied to the gate of the switch to make it a short for a longer period allowing the measurement of the short-circuit current of PV panel [12]. The gate pulse is generated from a 5kHz triangular carrier signal and the extended pulse, for \( I_{sc} \) measurement, has a frequency of 500Hz. To store the measured value of \( I_{sc} \), a sample and hold circuit block which is controlled by a signal, also of 500Hz, that gives a short pulse to the block at the end of \( I_{sc} \) measurement. All gate pulses are given in Fig. 11. The simulation results also show that the output power from the panel closely follows the maximum power curve that has a step translated from the input step in the light intensity (500 ~ 900W/m^2).
III. SIMULATION RESULTS

The parameters of the wind turbine, DFIG, and the PV panel are given in Appendix. Fig. 12 shows the simulation waveforms for a period of 4 sec with a change in wind speed from 7 m/s to 15 m/s at $t = 2$ sec. The 1st waveform shows the speed profile of the generator with a gear ratio of 50. The 2nd waveform shows the stator voltage with constant amplitude of 170 V (shown in the 3rd waveform) and a frequency exactly equal to 60 Hz. In the 4th waveform, the stator and rotor powers of the generator are given. Since a constant 3-phase load is connected to the stator, the stator power is constant $50 \text{W}$ and the power supplied to the rotor varies with the speed. The rotor injection power is higher for lower wind speeds and lower for higher wind speed since at higher speed more power can be extracted from the turbine. The output voltage has a THD of about 9% and the individual harmonics are also no more than 3% of the fundamental voltage. The figure also shows the harmonic profile of the output voltage.

Fig. 12. Simulation results – a) generator speed (rpm), b) rotor current (A), c) stator current (A), d) stator voltage (V), e) amplitude of stator voltage (V), f) stator and rotor power (W), and g) stator voltage spectrum
A simple and economical power converter system has been
designed to provide power from wind farm either to the grid or
to an isolated load. To reduce the power drawn by the rotor
from the grid, an auxiliary source for rotor injection has been
included in the system i.e. the PV panel. The source for the
converter can be selected manually or based on the availability
of solar power. MPPT technique used for the wind turbine
ensures high efficiency at all wind speeds reducing the power
rating of the converter. The surplus power output from PV
panel, if available, can be stored in the battery for future use.
The use of NPC inverter reduces the harmonics in the stator
voltage. Both the boost regulator and inverter controller have
good dynamic response with a very low overshoot and a low
settling time.

**APPENDIX**

| TABLE I. PV PANEL PARAMETERS |   |
|-----------------------------|---|
| Parameter                   | Value       |
| No. of Cells                | 36          |
| Standard Light Intensity    | 1000 W/m²  |
| Reference Temperature       | 25 °C       |
| Series Resistance           | 0.008 Ω     |
| Shunt Resistance            | 1000 Ω      |
| Short Circuit Current       | 3.87 A      |
| Saturation Current          | 21.6 nA     |
| Band Energy                 | 1.12 eV     |

| TABLE II. DFIG PARAMETERS |   |
|---------------------------|---|
| Parameter                 | Value       |
| Stator Resistance         | 0.59 Ω      |
| Stator Inductance         | 35.81 mH    |
| Rotor Resistance          | 3.39 Ω      |
| Rotor Inductance          | 19.894 mH   |
| Mutual Inductance         | 1.104 H     |
| Stator to Rotor Turns Ratio| 1           |
| No. of Poles              | 4           |
| Moment of Inertia         | 0.05 kg.m²  |

| TABLE III. WIND TURBINE PARAMETERS |   |
|------------------------------------|---|
| Parameter                          | Value       |
| Nominal Output Power               | 20 kW       |
| Base Wind Speed                    | 7 m/s       |
| Base Rotational Speed              | 10 rpm      |
| Initial Rotational Speed           | 0.8 rpm     |
| Moment of Inertia                  | 2 kg.m²     |

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