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PV-ASSISTED WIND ENERGY SYSTEM WITH A DFIG

NIDESH GANGWAR*

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Abstract

Doubly fed induction generators used in wind energy applications require a source and power converter system to feed variable frequency ac voltage to its rotor. The paper presents a hybrid system in which the rotor power can be drawn either from three-phase ac mains or a photo voltaic (PV) panel-battery combination. While drawing power from ac mains, the ac-dc converter used has a soft switching feature and also power factor correction. One of the MOSFET switches of the ac-dc converter will be used for boosting the PV panel output. The results obtained on an experimental converter are presented.

Keywards: DFIG's, Photovoltaic (PV), power factor corrector (PFC)

I. Introduction

Renewable energy sources like wind energy and photovoltaic (PV) power are becoming popular. Doubly fed induction generators (DFIGs) are increasingly used in wind generating systems in which the rotor speed need not be maintained constant. These systems use a wound-rotor induction machine to convert the mechanical power from the wind turbine into a fixed-frequency ac output supplied to the grid. The frequency of the voltage injected into the rotor is adjusted such the sum of rotor frequency and the equivalent frequency corresponding to mechanical rotation is equal to the desired stator frequency (60Hz). In this scheme, the power required for rotor injection is a small fraction (25%) of the output power and it comes from the ac mains through a set of power converters [1,2]. Thus the system uses power converters as well as filters with correspondingly lower ratings. The inverter provides a sinusoidal

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voltage to the rotor terminals at a frequency determined by the mechanical speed of the rotor. The dc link voltage for the inverter is usually provided by a converter/rectifier. Some of the issues not addressed in the existing DFIG control schemes are: (a) the absence of power factor correction in the rectifier (b) the absence of soft switching that will improve the efficiency of the rectifier and (c) the ability to supply ac power to isolated loads using photovoltaic (PV) power. As for (c), PV panels installed along side the wind turbine can be used to aid wind generation particularly when the system uses a DFIG. The modified system can also supply isolated loads.

The paper proposes a hybrid scheme in which the injection power can be drawn from (a) ac mains at unity power factor if available or (b) a set of PV panels and a back-up battery in the absence of ac mains. The three-phase power from the ac mains is converted into a dc using a three-phase resonant-boost power factor corrector (PFC) with only two switches operating under zero voltage switching (ZVS)[3].

In the absence of an ac bus, a set of PV panels supply injection power to the rotor through a boost converter which is realized using one or more of the switches in the power factor corrector. A battery is added as (a) a buffer storing the extra energy from the PV panel when the maximum power available is more than what is required for rotor injection and (b) a dc source providing injection power in the absence of sun light. Simulation and experimental results including the PFC waveforms and harmonic distortion are presented.

II. Three Phase Power Factor Corrector

The power converter system proposed for rotor injection in a DFIG is shown in Fig. 1. The three-phase PFC is made up of the line inductors L_a, L_b, L_c, the diodes D_1-D_8, the resonant capacitors C_a, C_b, C_c, the resonant inductor L, and the MOSFETS M_x and M_y [3]. The PFC draws sinusoidal currents from the bus (V_a, V_b, V_c) and supplies a dc voltage to the three-phase inverter which in turn supplies variable-frequency sine voltage to the rotor of the DFIG. The three-phase inverter is a Sine PWM inverter and its frequency and modulation index are varied through feedback to give rated stator voltage at 60Hz.

In the PFC topology, three capacitors are used to decouple the three-phase system into three single-phase systems and to control each phase independently and this helps to obtain a low THD value for each input current while delivering a lower output dc voltage. The two switches M_x and M_y along with the inductor L constitute a high-frequency current source which is responsible for the energy transfer from the three phase ac side to the dc side. The input current is partly continuous and partly discontinuous depending upon the input voltage level which modulates the equivalent duty cycle for the inductor current.

For a balanced three-phase system, the converter can be decoupled into three single-phase PFC converters and analyzed [3]. The input capacitor C_a first transfers part of the input energy to the inductor L and the energy is then transferred to the dc filter capacitor and the load maintaining an output voltage V_{dc}. Depending on the magnitude of the instantaneous input voltage, the circuit may operate under (i) a resonant input mode or (ii) a boost input mode. The resonant input mode corresponds to a low instantaneous input voltage, and during this mode, the voltage on C_a is always less than V_{dc}. The boost input mode, on the other hand, corresponds to a high instantaneous input voltage, and during this mode the voltage on C_a approaches V_{dc}.

The input/output power can be controlled by controlling the amplitude of the high-frequency current source which is in turn controlled by the switching frequency. The following equations are used to design of the converter: the DFIG. The duty cycle of M_y is adjusted for extracting the maximum power

The voltage sensed across the resistor R1 is applied to a second sample and hold circuit which the

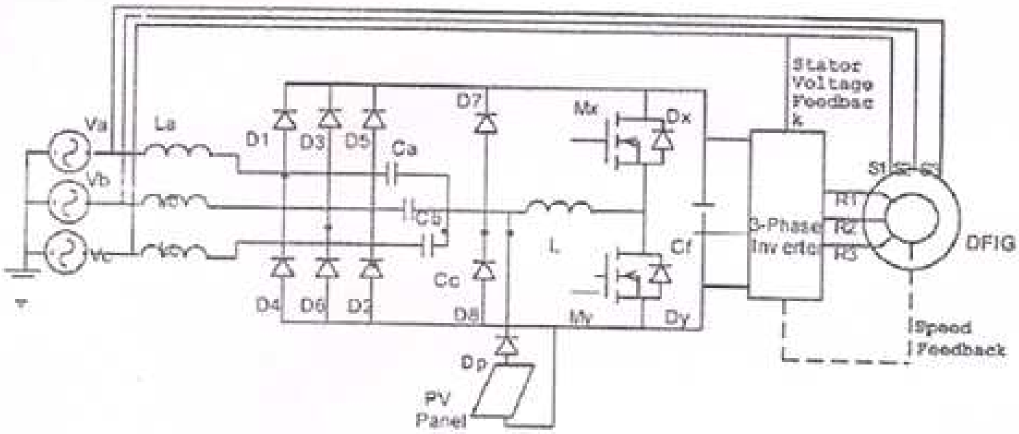


Fig. 1 Power converter arrangement for a DFIG

available from the PV panels under a given level of insolation. The converter system uses a current-based maximum power point tracking (MPPT) scheme [5,6]. The scheme senses the short circuit current under a given insolation by applying a long pulse to M_y and shorting the panel. The voltage sensed across R_S is applied to a sample and hold circuit which provides the short circuit current (I_{SC}) data to a PI.

$$\frac{1}{2f_s} \quad \sqrt{LC_a} \quad L\frac{I_m}{dc} \qquad (1)$$

$$P_{in} \quad K\sqrt{\frac{C_a}{L}} \qquad (2)$$

where f_S is the switching frequency, I_m is the amplitude of the current through the resonant inductor and K is a proportionality constant. The three-phase PFC was designed for operation for an input voltage of 120Vline to line at 60Hz and an output power of 300W at about 200Vdc. The switching frequency of the MOSFETs was selected as 155kHz. The values of the components $L_a = L_b = L_c$, $C_a = C_b = C_c$, in the PFC are calculated for the nominal power to be supplied to the rotor of the DFIG. The circuit of Fig. 1 was simulated using the software PSIM [4] and the waveforms of input current and its frequency spectrum of input current are obtained. The harmonic amplitudes in the input current and the total harmonic distortion (THD) for different input voltages were obtained to show the effectiveness of the circuit in handling a range of input voltages.

III. PV Power And Maximum Power Point Tracking

During grid-connected operation, the three-phase PFC supplies dc power to the inverter which feeds a variable frequency ac voltage to the rotor of the DFIG. For isolated loads, the injection power is drawn from the PV panel through a boost converter made up of the high-frequency inductor L, the MOSFET My, and the diode D_X which are part of the three- phase PFC. In this case, the bulk capacitor Cf is replaced by a battery which provides injection power in the absence of sunlight. During night when sunlight is not there, the battery may be charged by rectifying the 3-phase ac voltage output of controller.

The voltage sensed across the resistor R1 is applied to a second sample and hold circuit which provides the PV current (Ipv) to the PI controller [6]. The PI controller forces the PV current to be at a fraction (0.9) of the short circuit current by adjusting the duty cycle of My. The complete MPPT controller shown as MPPT controller is realized (Fig.2) using a Digital Signal Controller (dsPIC) [7]. The details of the programming are not shown for want of space.

If the power output from the PV panel exceeds the power required for rotor injection, then the excess power goes to charge the battery. Otherwise the battery supplies the difference. The voltage rating of the PV panels and the number of panels are selected such that it is possible to boost the panel output voltage to the rated dc link voltage of the inverter with reasonable values for the duty cycle.

IV. Inverter and Frequency Control

a. Sine PWM inverter using a single DC Source

A three-phase Sine PWM inverter is used to convert the dc voltage from the thee-phase PFC/ PV boost converter as obtained in Fig. 1. The rotor speed information of the DFIG is provided using a digital speed transducer. The gate signals for the MOSFETs in the inverter are provided by the dsPIC. The injection frequency f_r is adjusted such that for a mechanical frequency (speed) f_m, $f_m + f_r = f_s$ (3), where f_s is the stator frequency (60Hz).

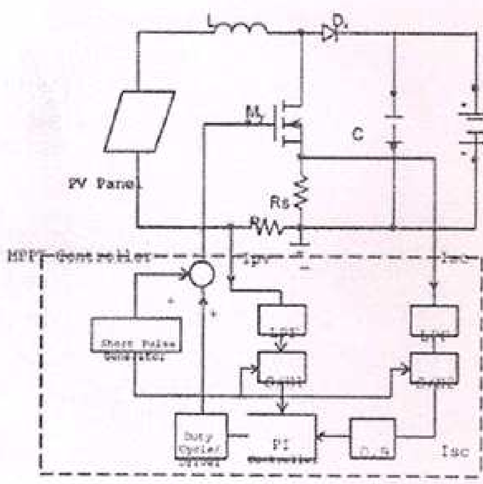


Fig. 2 Block diagram of MPPT converter

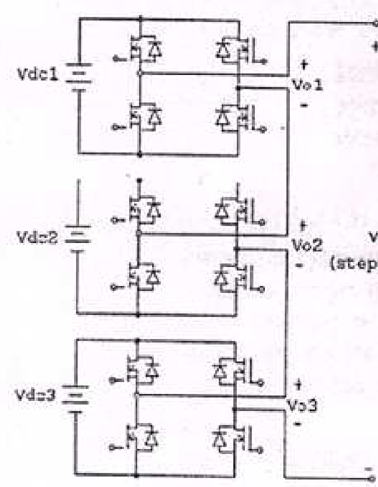


Fig. 3 Power circuit of multilevel inverter (1 phase)

The inverter uses a six-switch full bridge with IGBTs [8]. The modulation index of the inverter is adjusted such that the inverter outputs rated voltage. The stator frequency and voltage (grid frequency and voltage) information necessary is fed to the Digital Signal Controller as shown in Fig. 1. In the absence of a three-phase ac bus (isolated loads), the frequency and magnitude information have to be provided separately to the inverter. The reactive power exchanged can be controlled by varying the phase angle of the sine voltage used as reference to the inverter.

b. Multilevel cascaded inverter using several DC sources

The PV assisted wind energy system has two or more dc sources at its disposal. The output voltage of the three-phase PFC is the primary dc source and the PV panels constitute one or more dc sources. The availability of multiple dc sources makes it possible to build a multi-level inverter [8,9] which has reduced switching losses compared to a conventional Sine PWM inverter. In the multilevel inverter proposed, several dc sources are used to synthesize the desired output sine waveform. The outputs from three or more single-phase bridge inverters (Fig. 3) operating in the pulse width control (PWC) mode (Fig. 4) are added to give a net waveform which is close to a sine.

As can be seen from Fig. 4, Vdc3 supplies power almost the entire portion of the period so it is formed by the three- phase PFC. The other sources Vdc1 and Vdc2 are formed by groups of PV panels in series or parallel combination depending on the power requirement. The following are the advantages of the proposed multilevel inverter compared to a conventional Sine PWM inverter:

(i) Reduced switching losses and noise
(ii) Reduced value of the line inductor to be used for reducing the ripple in the current
(iii) Possibility of modularizing the inverter blocks making up the cascade.

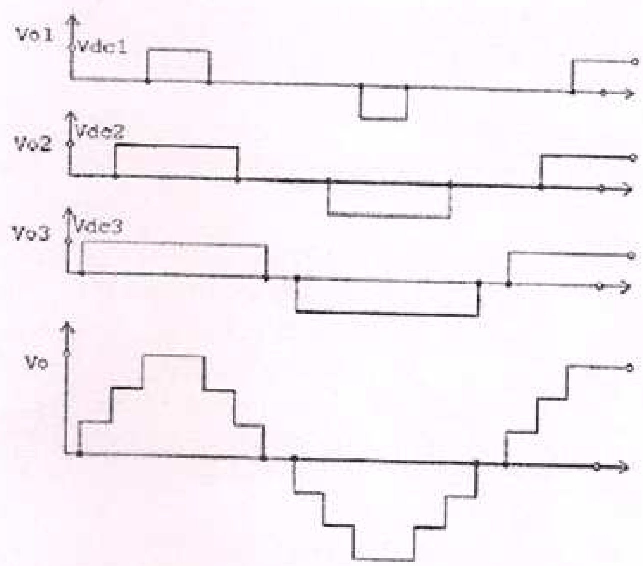


Fig. 4 Output waveforms of the converter of Fig. 3

V. Simulation and Experimental Results

A 5HP, 4-pole wound rotor induction motor is used as the DFIG. A separately excited dc motor is used as the prime mover substituting the wind turbine.

Four 120W PV panels (Solarex SX-120) connected in series give a maximum output 400W at a voltage of 120V under medium sunlight conditions. With this, it is possible to step up to 200V matching the output from the 3-phase PFC. The total wind generation scheme can output as high as 1500W.

The waveform of one of the line currents and its frequency spectrum obtained from simulation[7] of the PFC circuit are given in Fig. 3. It is seen that the THD is less than 10%. Table 1 gives the output dc voltage and THD for a range of input voltages and it is seen that the three-phase PFC has a consistently low distortion over a range of input voltages. Other parameters are: Ca = 5.1nF, La = 0.4mH, L = 65uH.

The three-phase PFC was built and tested and the experimental waveform of one of the line currents and its frequency spectrum (obtained using a waveform processing software) are shown in Fig. 4. The THD is found to be 8.1% which is very close to the result obtained from simulation. The output dc voltage is 169.8V for an input voltage of 120V line.

Vin, Volts	52	104	166	208
Vdc, Volts	74.4	148.8	237.5	297.6
THD, %	9.25	9.25	9.25	9.25

Table 1 Variation of Output voltage and THD with input voltage (f_S = 155kHz, R_L = 300Ω)

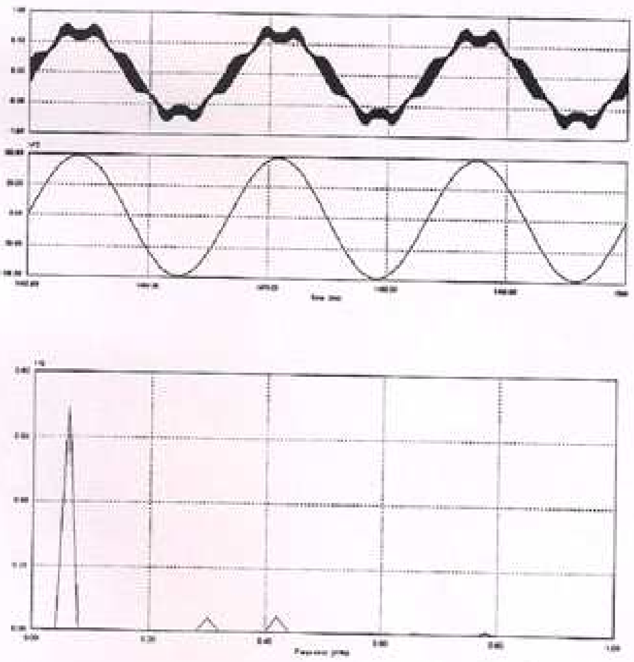
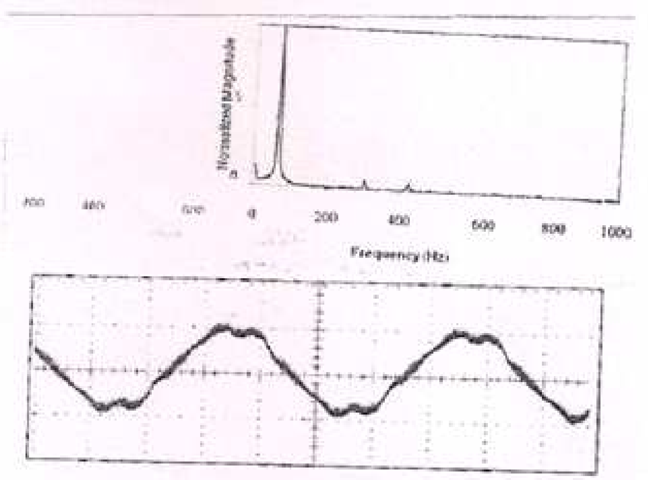


Fig. 5 Simulated waveforms of line current, voltage, frequency spectrum



(a) Waveform of line current
(b) Frequency spectrum of line current
Fig. 6 Experimental waveforms of three-phase PFC

The waveforms of the gate signal and the drain-source voltage of My are shown in Fig. 5 and it is seen that the drain- source voltage goes to zero before its gate pulse is applied showing zero voltage switching condition.

The PV panels used have an open circuit voltage of 39.2V, a short circuit current of 2.89A, and maximum power voltage 37.15V. The nominal duty cycle of the boost converter was found to be 0.62. The complete system with the PFC and the inverter is built and tested. The wind turbine is simulated (replaced) using a dc generator. The speed of the DFIG is varied and the system provides rotor injection with suitable frequency and magnitude such that the output voltage has a constant magnitude (120V, line-line) and frequency (60Hz). Fig. 6 shows the waveforms of the rotor current waveform and stator output voltage at a rotor speed of 1230 rpm and a dc link voltage of 44V.

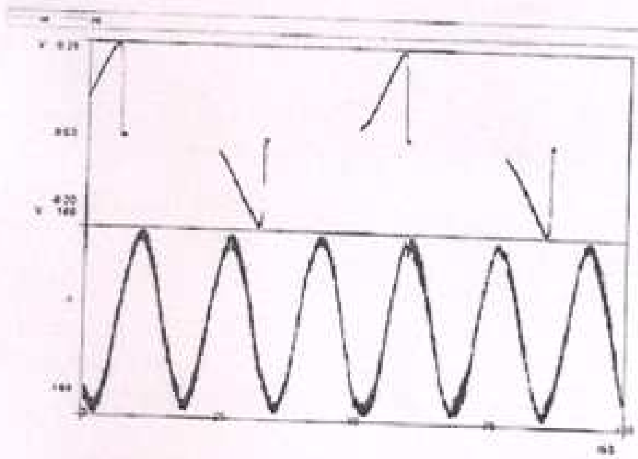


Fig. 6 Waveforms of rotor current and stator voltage

VI. Conclusions

The paper presents a hybrid renewable energy system with an efficient rotor injection scheme for a DFIG with the possibility of feeding from either three-phase ac mains or a PV panel-battery combination. The ac-dc converter used during ac mains operation has features like power factor correction and soft switching. The boost converter used to feed PV power to the rotor does not use any additional switches thereby resulting in a simpler power circuit.

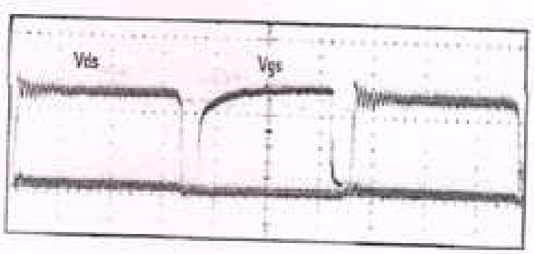


Fig. 5 Experimental waveforms of drain and gate voltages showing ZVS condition

The power converter system proposed in the paper is useful in combining wind energy and solar energy such that the wind energy constitutes the bulk of the power produced while the solar energy is used to provide the rotor excitation.

However, when there is no sunlight, the system in the present form will have problem in that the battery can supply power only for a limited amount of time. This can be overcome by adding an auxiliary charging circuit from the three-phase ac mains.

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