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Wind Energy Conversion System for Rural Application

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This paper presents the use of induction generator with suitable control strategy for use as stand-alone wind energy conversion system. This may find application in remote rural areas where extension of 11 kV feeder may not be feasible due to physical terrain and where drawing of line may not be economically viable if loads are dispersed over wide area. This Induction machine is driven from a prim em over which is usually a wind turbine. The stator terminals of the induction machine is connected to a voltage source converter. The voltage source converter (VSC) is a three level diode clamped VSC. The terminals of the converter are connected to a capacitor and a battery. The battery is initially charged to 12 V and provides initial magnetisation for the Induction Generator. The terminals of the stator are also connected to an induction motor represented by RL load. Control strategy has been developed to keep the DC voltage constant irrespective of variation of load and rotor speeds. The total harmonic distortion in the line voltage of the induction machine is ensured to be within limits by employing three level converter. The proposed system is mathematically modelled using SIMULINK/MATLAB. The simulated results validate the theory studied.

Keywords: *Induction generator (IG), Voltage source converter (VSC), Sine Pulse width modulation (SPWM), Wind Energy Conversion systems (WECS).*

1.0 INTRODUCTION

As the government is keen on providing "electricity for all" and taken up Rajeev Gandhi Grameena Vidyutikaran (RGGVY) Project, many of the villages are yet to be electrified. The allotted capacity of wind energy in Karnataka state is 12752 MW whereas commissioned capacity is 2358 MW.

This shows that wind energy hold saprominent role in power generation. In the extreme corners of rural India, electricity lines are still dream. Even where these lines exist, lengthy 11 kV feeder results in very low voltage at the load points. Usually these feeders are low priority and duration of power supply may not be more than 8 hours. However abundant solar and wind energy is not being utilized due to various problems.

The conversion of energy forms is complicated. New methods and solutions to find better means of energy conversion and utilization must continue to overcome energy crisisinthe present days. Therefore the research is now inclined towards harnessing energy from renewable energy sources.

Induction Machines and Synchronous machines are widely use delectrical machines for wind energy conversion systems. Induction machines aresimple, robust, small size per kilowatt of output power and maintenance free machines. They have ability of self protection against overloads and faults. They are available in lower ratings and on to

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require additional DC supply unlike synchronous machines. Hence induction machine is best suited for rural small wind source of electrical energy. Induction machines can be either grid connected or stand alone. Stand-alone systems are used where the load has no access to grid (remote areas). Stand-alone induction generators are also called as self-excited induction generators. In grid connected mode the voltage and frequency is fixed and decided by grid. However in stand-alone systems, the voltage and frequency depend on load and speed. [1].

A major disadvantage of induction machine is that it needs a source of excitation. A vast literature is available on the methods of excitation. Excitation can be as simple as connecting capacitor banks across stator terminals to using a complex voltage source converters [2]-[4]. Simple capacitor banks can only be used when the load and the prime mover speed is constant. Therefore usage of power electronic converter becomes inevitable. In [5] a current controlled VSC is used as a source of excitation. In [6] the author proposes a control scheme using a hysteresis control and the behaviour of the system is analysed for sudden application and removal of load. [7] presents a PWM converter with vector control scheme to control DC bus voltage scheme. However, with the usage of complex control strategies, the reliability of the system gets affected [8]. Hence it is important to choose a new methodology which provides smoother capacitance control using power electronic converters along with simple control schemes.

With the advancement of power electronics technology, multi-level converters are gaining prominent roles. Multi-level converters are used to lower the total harmonic distortion levels. Multi-level converters are used as grid side converters in grid connected solar powered plants and in wind energy conversion systems [9-10]. However it is observed that multi-level converters are very less used in self-excited systems. Application of multi-level inverters [12-13] in self-excited systems not only provide better dynamic performance but also reduces THD level in stator voltages and currents. In this paper, a three level diode clamped VSC is used and the dynamics of the system is analysed on sudden application and removal of loads. It is observed from the results that the system performance is better to usage than two level inverter. Harmonic analysis is also carried out to check reduced THD levels in stator output.

2.0 DESCRIPTION OF THE SYSTEM

The system block diagram is shown in Figure 1.

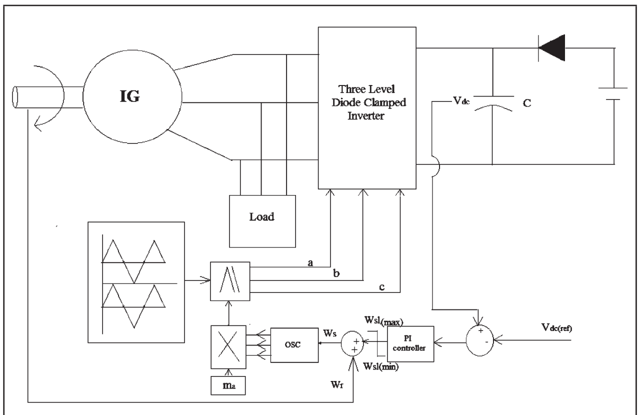

FIG. 1 BLOCK DIAGRAM OF THE SYSTEM

Induction machine is driven from a wind turbine. The stator terminal of the induction machine is connected to a three phase three level diode clamped voltage source converters. The battery is charged with an initial voltage of 12 V. This battery provides initial excitation for the IG. A three phase balanced load is applied across the stator terminals of the machine. Control strategy for maintaining a constant DC link voltage is developed. The actual value of the DC link voltage is continuously monitored with the reference value; the error is passed through a PI controller. A limiter sets proper slip frequency value. This slip frequency is added to the rotor frequency to get stator frequency. The harmonic oscillator generates sinusoidal signals whose frequency is that of the stator frequency and these are multiplied with suitable modulation index and compared with two 1.05 kHz sawtooth waves, and the pulse width modulated signal are given to the inverter switches.

When the machine starts running as a generator, the machine feeds power to the load and as well as to the capacitor andthus the capacitor voltage starts building up. DC link voltage reaches the steady state value as set by reference command. Upon sudden application of the heavy load across the terminals of the generator, the generated power becomes lesser than required load power. Thus the capacitor starts discharging to meet the load demand. This creates error between reference value and actual value and the control scheme sets suitable stator frequency such that the IG starts generating additional power as required by the load. Once the generator output power increases, the capacitor voltage is set back to the previous value.

In case of sudden removal of load across the stator terminals, the generated power exceeds the load demand and this creates mismatch between reference value and actual value across capacitor. The control scheme again sets the stator frequency so as to decrease the power generation in accordance with the decreased load demand. Whenever there is a change in wind speed, the rotor speed also changes. Due to change in input power capacitor voltage also tend to change. This creates error between actual capacitor voltage and reference value, the control strategy sets a suitable stator frequency such that the slip frequency remains constant (for a given reference DC link voltage reference). This constant slip frequency restores the capacitor value back to the reference.

3.0 INDUCTION MACHINE

Induction machine is modelled in a stationary reference frame. The set of differential equations from (1)-(5) describe the induction machine.

$$\begin{bmatrix}\dot{\psi}_{ds}\\ \dot{\psi}_{qs}\end{bmatrix} = \begin{bmatrix}v_{ds}\\ v_{qs}\end{bmatrix} - R_s\begin{bmatrix}i_{ds}\\ i_{qs}\end{bmatrix} \quad ....(1)$$

$$\begin{bmatrix}\dot{\psi}_{dr}\\ \dot{\psi}_{qr}\end{bmatrix} = -R_r\begin{bmatrix}i_{dr}\\ i_{qr}\end{bmatrix} - \omega_r\begin{bmatrix}0 & 1\\ -1 & 0\end{bmatrix}\begin{bmatrix}\psi_{dr}\\ \psi_{qr}\end{bmatrix} \quad ....(2)$$

$$\begin{bmatrix}\psi_{ds}\\ \psi_{dr}\\ \psi_{qs}\\ \psi_{qr}\end{bmatrix} = \begin{bmatrix}L_s & 0 & L_m & 0\\ 0 & L_s & 0 & L_m\\ L_m & 0 & L_r & 0\\ 0 & L_m & 0 & L_r\end{bmatrix}\begin{bmatrix}i_{ds}\\ i_{dr}\\ i_{qs}\\ i_{qr}\end{bmatrix} \quad ....(3)$$

$$t_e = \frac{3}{2}\frac{P}{2}(\psi_{ds}i_{qs} - \psi_{qs}i_{ds}) \quad ....(4)$$

$$\dot{\omega}_r = \frac{P}{2J}(t_e - t_m) \quad ....(5)$$

4.0 VOLTAGE SOURCE CONVERTER

In this section mathematical modelling of three level voltage source converter is discussed. Sine pulse width modulation technique is employed to generate pulses to three level converters.vao,vbo and vco are the inverter pole voltages in equation 6. In equation 7, van,vbn,vcn are the line to neutral voltages.

$$\begin{bmatrix}v_{ao}\\ v_{bo}\\ v_{co}\end{bmatrix} = \frac{v_{dc}}{2}\begin{bmatrix}S_{ao} + S_{a1} - 1\\ S_{bo} + S_{b1} - 1\\ S_{co} + S_{c1} - 1\end{bmatrix} \quad ....(6)$$

$$\begin{bmatrix}v_{an}\\ v_{bn}\\ v_{cn}\end{bmatrix} = \frac{1}{3}\begin{bmatrix}2 & -1 & -1\\ -1 & 2 & -1\\ -1 & -1 & 2\end{bmatrix}\begin{bmatrix}v_{ao}\\ v_{bo}\\ v_{co}\end{bmatrix} \quad ....(7)$$

(Sao,Sa1), (Sb0,Sb1) and (Sc0,Sc1) are the switching functions (upper two switches of a leg) of a,b and c phases respectively.

Inverter current is given by

$$i_{inv} = S_a i_a + S_b i_b + S_c i_c \quad ....(8)$$

$$S_a = S_{ao} + S_{a1}; S_b = S_{bo} + S_{b1} \text{ and } S_c = S_{co} + S_{c1}$$

$$v_{dc} = -\frac{1}{C}\int i_{inv} \quad ....(9)$$

Equation 9 describes the voltage build up process across the capacitor.

5.0 RESULTS AND DISCUSSION

The simulation results for no load, on load, step decrease in load, step increase in load rotor speed variations, simultaneous variation in speed and reference voltage are discussed.

5.1 No Load

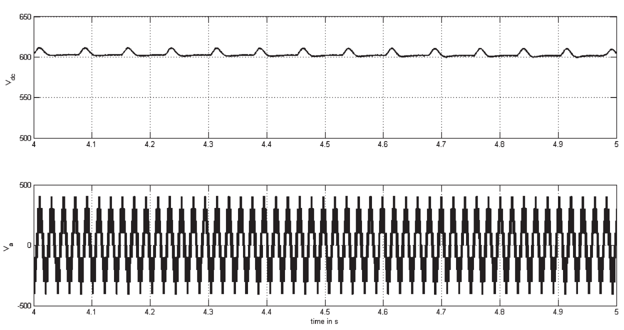

FIG. 2 RESULTS FOR NO LOAD CONDITIONS

The machine is run at no load at the speed of 314 rad/s. The DC link reference is set to a reference value of 600V. From Figure 2, it can be seen that DC link voltage is maintained at 600V as given by the reference command. V_a is the L-N voltage of the stator. It is clearly seen from the results that the output voltage is almost sine wave and hence harmonic content is controlled.

5.2 On load

Figure 3 shows the performance of the system for loaded condition. The reference value was set to 600V.

Va andIa are the phase voltage and current value of the stator terminal of induction generator.

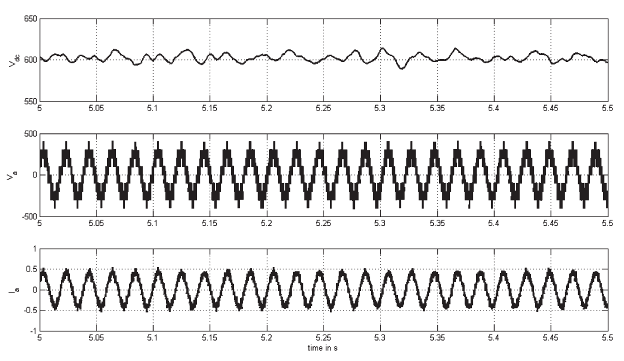

FIG. 3 RESULTS FOR ON LOAD CONDITION

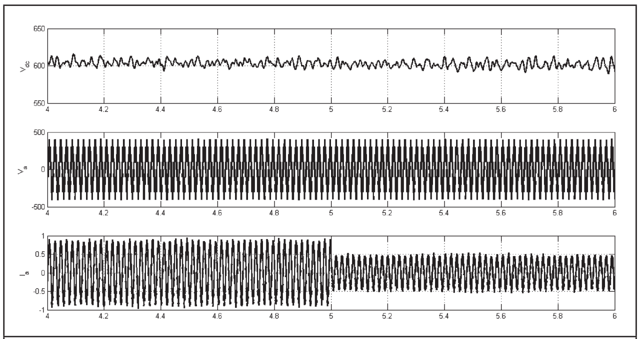

FIG. 4 RESULTS FOR SUDDEN DECREASE IN LOAD

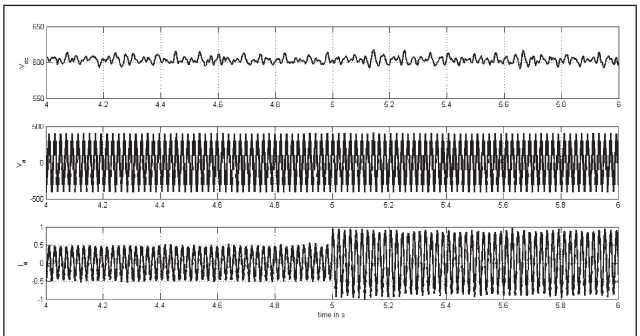

FIG. 5 RESULTSFORSUDDENINCREASEINLOAD

5.3 Decrease in load

Figure 4 illustrates the system performance for sudden decrease in load. At t = 5 s, the load is decreased, as seen from Ia amplitude decreasing at t = 5 s. However the dc link voltage is still maintained constant by the controller and hence the terminal voltages (L-L and L-N) are also maintained constant.

5.4 Increase in load

Figure 5 illustrates the system performance for sudden increase in load. At t=5 s load was applied, this can been from Ia amplitude increasing at t=5 s. However the dc link voltage is still maintained constant by the controller in this case lso and hence the terminal voltages are also maintained constant.

5.5 Variation in rotor speed

The rotor speed was varied at different time instants and the variation of stator frequency, slip frequency and DC link voltages are studied. In Fig

6, at t=18s, the rotor speed was increased to 320 rad/s, the controller increases stator frequency to value of 305rad/s so as to maintain a constant slip speed of 15rad/s. The slip is maintained constant in order to maintain a constant DC link voltage and hence constant power. At t=25s, when the rotor speed was decreased to 305 rad/s, the stator frequency is also found to be decreasing to a value of 290 rad/s so that the slip is maintained at 15 rad/s. The constant slip maintains a constant DC link voltage and hence constant power. This is obtained by changing stator frequency in accordance with rotor frequency.

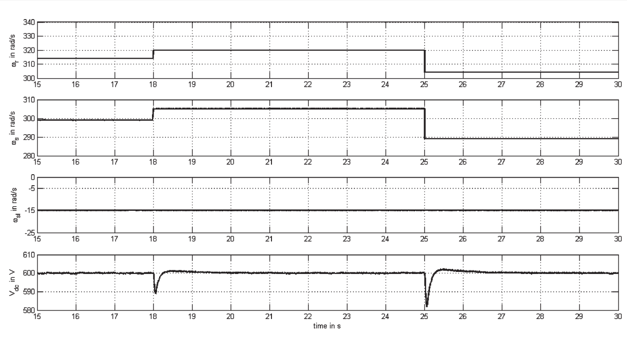

FIG. 6 RESULTS FOR VARIATION IN ROTOR SPEED

5.6 Simultaneous Variation of rotor speed and DC Link reference

Figure 7 a shows the variation of rotor speeds at two different instants. At 18s the speed was increased to a value of 320 rad/s. The DC reference voltage was 600V. From Figure 7b, it can be seen that the controller maintains the DC link voltage constant even though there is a step change in rotor speed.

At t=25 s, there is a dip in rotor speed to 305rad/s and also simultaneously there was a decrease in DC reference value. The DC reference command was decreased to 300V.

It can be seen from Figure 7b that, controller is able to maintain, the DC voltage value to the new reference value, though there is a variation in rotor speed and DC reference command at the same instant. Since the reference command has changed, voltage value at terminals also decreases and can be seen from Figure 7c.

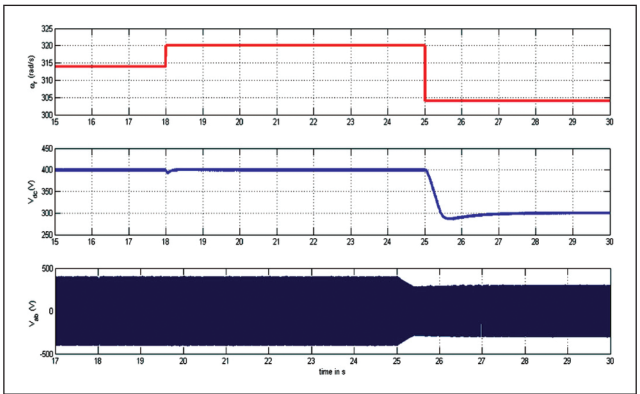

FIG. 7 RESULTS FOR VARIATION IN ROTOR SPEED AND DC REFERENCE VOLTAGE

5.7 Harmonic Spectrum

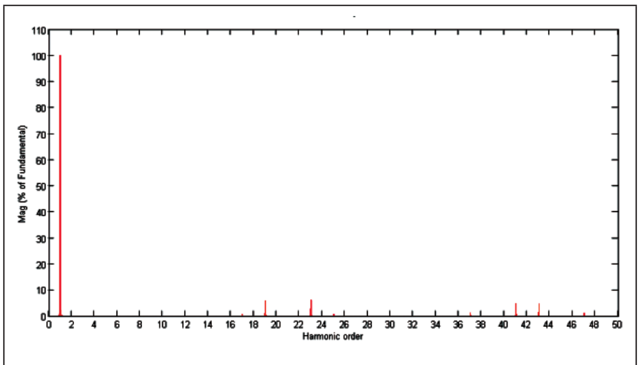

FIG. 8 HARMONIC SPECTRUM

Figure 8 shows the line voltage spectrum of three level inverter. Triplen harmonics areabsent. Dominant harmonics are seen at harmonic number 19(850 Hz) and 23(1150 Hz). Higher order harmonics are easily filtered by the system reactance and is in accordance with the theory studied in [11]. The variation of THD against modulation index is shown in Figure 9. It can be seen that as the modulation index increases, the value of THD comes down and the variation becomes non linear. For ma<1, there exists a linear relationship between Va and Vdc. However, in this case the THD is high. If ma is set for a value greater than 1, though THD reduces, the linear relationship between vdc and ma will no longer be valid and the output saturates. Hence, the system's modulation index is maintained at 0.8.

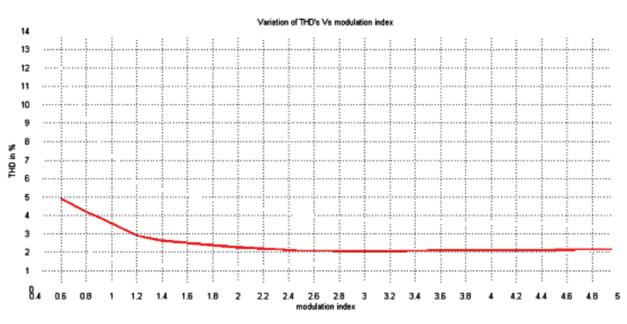

FIG. 9 THD VS. MODULATION INDEX

6.0 CONCLUSION

In this paper a voltage control scheme for stand-alone system employing a three level diode clamped inverter is studied. The system is tested for different conditions like no load, on load, sudden increase/decrease in load and rotor speed variations. The control strategy developed, maintains a constant DC link voltage in spite of variations in rotor speed and change inloads. Harmonic analysis is also carried out to make the study complete. The proposed scheme is mathematically modelled and simulated using MATLAB/SIMULINK. The simulated results validate the studied theoretical concepts.

APPENDIX I

IM machine specifications

IM Parameters	Values
Phase	3
Poles	4
Rated Power	5 HP
Rated Speed	1460 rpm
Rated Voltage	240 V
Frequency	50 Hz
Stator Resistance	2 Ω
Rotor Resistance	2.4 Ω
X ls	4.12 Ω
X lr	4.12 Ω
Moment of inertia of rotor J	0.1384 kg-m^2

Voltage Source Converter Specifications

Modulation index ma = 0.8

Carrier frequency fc = 1.05KHz

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