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Self-Excitation and Voltage Control of an Induction Generator in an Independent Wind Energy Conversion System

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Abstract

This paper proposes an excitation system and voltage control for a Squirrel Cage Induction Generator in an independent wind energy conversion system. Energy is considered to be very promising alternative for power generation because of its tremendous environment, social, and economic benefits. Of all wind power technologies, the variable speed systems employing the Squirrel Cage Induction Generator are the cheapest and simplest. A voltage source converter directly interfaces the Squirrel Cage Induction Generator through dc load network and also be the DC link of an inverter. The Squirrel Cage Induction Generator which is excited using voltage source converter connected to a single capacitor and battery on the DC side. In this paper, Space vector pulse width modulation technique is used because of their easier digital realization, efficient use of supply voltage and better dc bus utilization. A controller is specifically designed that keeps the DC bus voltage at a constant value under wind speed and electrical load variations. The proposed system with its controller is modeled and simulated using MATLAB/SIMULINK software.

Keywords: Squirrel Cage Induction Generator (SCIG), Space Vector Pulse Width Modulation (SVPWM), Voltage Source Converter (VSC), Wind Energy Conversion System (WECS).

1. Introduction

The development and utilization of wind energy to satisfy the electrical demand has received considerable attention in recent years, owing to the concerns regarding the dwindling energy resources and enhanced public awareness of the potential impact of the conventional energy systems on the environment. Improvements in wind generation technologies will continue to encourage the use of wind energy in both grid connected and stand-alone systems. Owing to the random nature of the wind, the wind generators behave quite differently from the power system planners and engineers to carefully consider the reliability issues [1] associated with the wind energy sources.

Squirrel-cage induction machines (SCIM) still have an edge over these approaches in terms of cost and ruggedness [2-3]. These advantages are significant and far outweigh the somewhat inferior power density and efficiency of the SCIM, especially for remote WECS installations connected to an isolated power grid. In isolated systems [4], no external ac power supply is available for setting up the magnetic field in the machine and in this mode it is called self-excited induction generator (SEIG). In these schemes, excitation power is supplied by a battery which is connected at the IG terminals. The performance of the machine is strongly influenced by the value of the terminal capacitor. It has been suggested that the terminal voltage of such machines can be controlled by the excitation capacitor. A switched capacitor approach allows the terminal voltage to be controlled in steps, whereas with a voltage source converter (VSC) connected to the SCIG terminals, smooth voltage control is possible [5]. SCIG control schemes using VSC with battery support have been discussed in [6]. The system is further simplified by optimizing the battery bank. A battery is connected across the dc bus and by switching on the power converter, initial excitation is provided. As the terminal voltage starts building up its charge the dc bus capacitors and both voltages increase in tandem. After the dc bus voltage increases beyond battery voltage, the battery is disconnected. However, the use of ac capacitor banks makes the systems costlier and less reliable, which detract from the inherent robustness of the SCIM.

In this paper, induction motor fed by voltage source converter (VSC) with a space vector modulation (SVM) is proposed [7]. Space vector PWM (SVPWM) technique is one of the most popular techniques gained interest recently (Trzynadlowski, 1994). This technique results in higher magnitude of fundamental output voltage, increases the overall system efficiency, minimizes the THD as well as switching loss, it is feasible to implement compared to sinusoidal PWM.

2. System Description

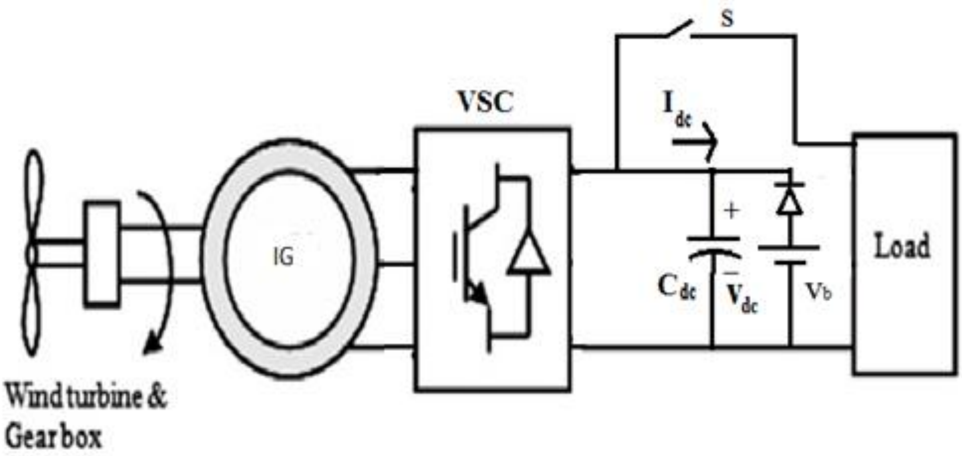

Fig.1 schematic representation of the system

The overall system configuration is shown in Fig. 1. Induction generator is driven by the wind turbine and that is connected to the DC load by means of the Voltage Source Converter (VSC). The proposed system starts its excitation process from an external battery V_b. The external battery V_b helps to charge the capacitor and also start the build up of flux in core. When the generated voltage rises to value higher than V_b then the diode blocks the flow of current to the battery and then the diode is replaced by a switch.

Initial voltage in the dc bus is supplied to the terminal voltages of unexcited machine in turn there is voltage buildup because of the residual magnetism of the magnetic core, and therefore rectified by the anti-parallel diodes of the VSC. Voltage build-up is achieved by controlling the machine slip speed. The rotor flux is maintained at its rated value to ensure increased terminal voltage, hence higher output power, at higher turbine speed. The proposed scheme is verified through simulation on MATLAB-SIMULINK platform. All simulation results are validated using a 2.2KW SCIG coupled with wind turbine. DC voltage and speed are sensed and fed back for control which is based on the space vector modulation technique.

3. System modeling

The main components of the proposed system are shown in Fig.1. The components are IG, WT, and VSC those modeling are explained below.

3.1 Mathematical model of induction machine

The dynamic model [8] of induction machine using rotating d-q reference frame, whose stator and rotor voltage equation is given by

$$V_{sd} = R_s i_{sd} + \frac{d}{dt}\lambda_{sd} - \omega_d \lambda_{sq} \qquad (1)$$

$$V_{sq} = R_s i_{sq} + \frac{d}{dt}\lambda_{sq} - \omega_d \lambda_{sd} \qquad (2)$$

$$V_{rd} = R_r i_{rd} + \frac{d}{dt}\lambda_{rd} - \omega_{dA} \lambda_{rq} \qquad (3)$$

$$V_{rq} = R_r i_{rq} + \frac{d}{dt}\lambda_{rq} - \omega_{dA} \lambda_{rd} \qquad (4)$$

Where $V_{sd}, V_{sq}, V_{rd}, V_{rq}$ are the direct and quadrature axes stator and rotor voltage.
R_s, R_r are the stator and rotor resistance
$i_{sd}, i_{sq}, i_{rd}, i_{rq}$ are the direct and quadrature axes stator and rotor current

$\lambda_{sd}, \lambda_{sq}, \lambda_{rd}, \lambda_{rq}$ are flux linkages

ω_d is the angular velocity.
Electromagnetic torque is expressed as

$$T = {}^{P}\!/_{2}\, L_m \left(i_{sq} i_{rd} - i_{sd} i_{rq}\right) \qquad (5)$$

Where L_m is the mutual inductance .

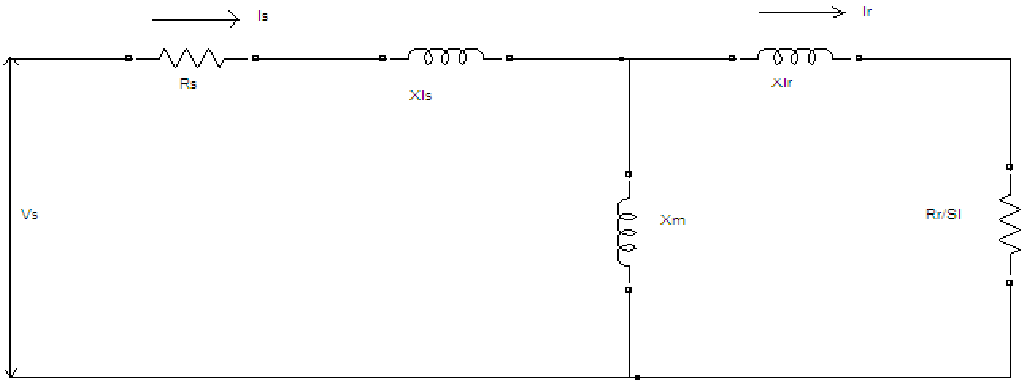

Fig.2 Per phase steady-state circuit of induction machine

3.2. Modeling of Wind Turbine (WT)

Wind turbines are used to generate electricity from the kinetic power of the wind. Historical they were more frequently used as a mechanical device to turn machinery. The output power of wind turbine is given by

$$P_m = C_p(\lambda,\beta)\frac{\rho A}{2}V_{wind}^3 \qquad (6)$$

Where, P_m - mechanical output power of wind turbine,

C_p – performance coefficient of wind turbine (0.48-0.5),
ρ – Air density (kg/m^3),
A – Area of the blades (m^2),
V_{wind} – wind speed (m/s),
λ – Tip speed ratio (V_{tip}/V_{wind}),
β – Blade pitch angle (deg).

The Power – Speed characteristics for wind turbine which are illustrated in Fig.4.

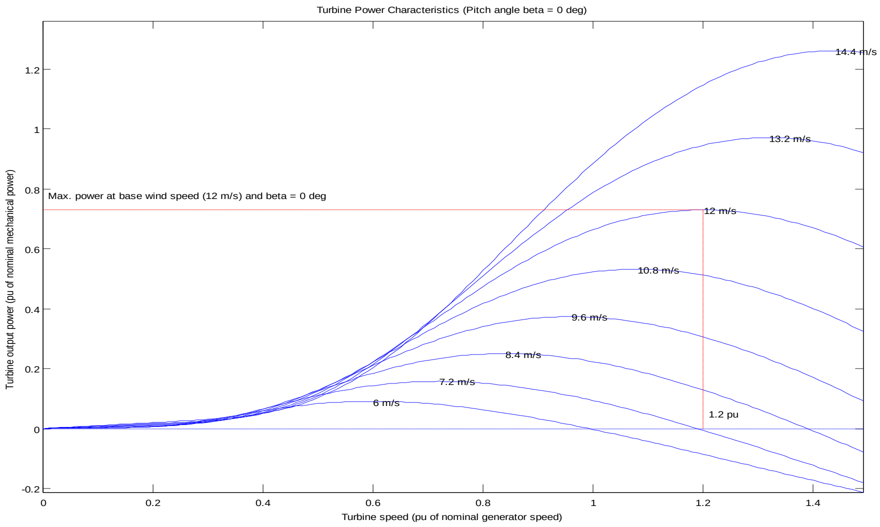

Fig.3 Power-Speed characteristics of WT

3.3. Modeling of VSC

Voltage-source converter (VSC) is connected to a single capacitor and battery on the DC side. The VSC is switched by SVM technique and the line to line voltages are given by

$$v_{ab} = v_{an} - v_{bn} \qquad (7)$$

$$v_{bc} = v_{bn} - v_{cn} \qquad (8)$$

$$v_{ca} = v_{cn} - v_{an} \qquad (9)$$

Phase voltage is given by

$$\begin{bmatrix} v_{an} \\ v_{bn} \\ v_{cn} \end{bmatrix} = v_{dc}\begin{bmatrix} 2/3 & -1/3 & -1/3 \\ -1/3 & 2/3 & -1/3 \\ -1/3 & -1/3 & 2/3 \end{bmatrix}\begin{bmatrix} a \\ b \\ c \end{bmatrix} \qquad (10)$$

Where a, b, c are switching variable vector

4. Control Scheme based on SVM

SVM treats the sinusoidal voltage as a constant amplitude vector rotating at constant frequency. This PWM technique approximates the reference voltage V_{ref} by a combination of the eight switching patterns (V_0 to V_7). The proposed control scheme based on SVM which are shown in fig. 5. The speed and load errors are directly sent through PI controllers. Controllers generate voltage reference V_d and V_q in the stator flux frames. SVM is calculated from V_d and V_q and then drives the inverter. To implement the space vector PWM, the voltage equations in the *abc* reference frame can be transformed into the stationary *dq* reference frame that consists of the horizontal (d) and vertical (q) axes as depicted in Fig.4

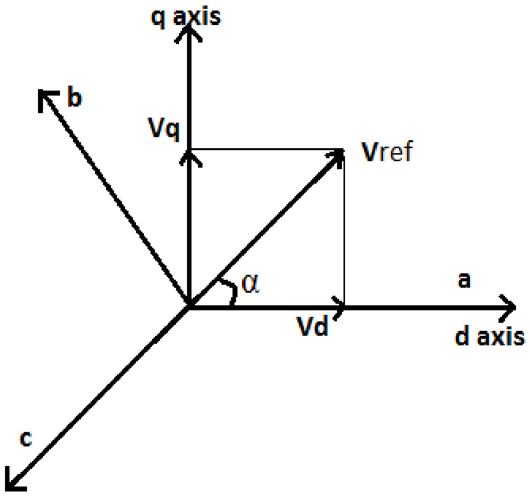

Fig. 4 The relationship of abc reference frame and stationary dq reference frame.

According to the relationship among abc and dq axes, we can get the following equation.

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} \tag{11}$$

$$V_{ref} = \sqrt{V_d^2 + V_q^2} \tag{12}$$

$$\theta_s = \tan^{-1}\left(\frac{V_q}{V_d}\right) = \omega t = 2\pi f t \tag{13}$$

Where f = fundamental frequency

The objective of space vector PWM technique is to approximate the reference voltage vector

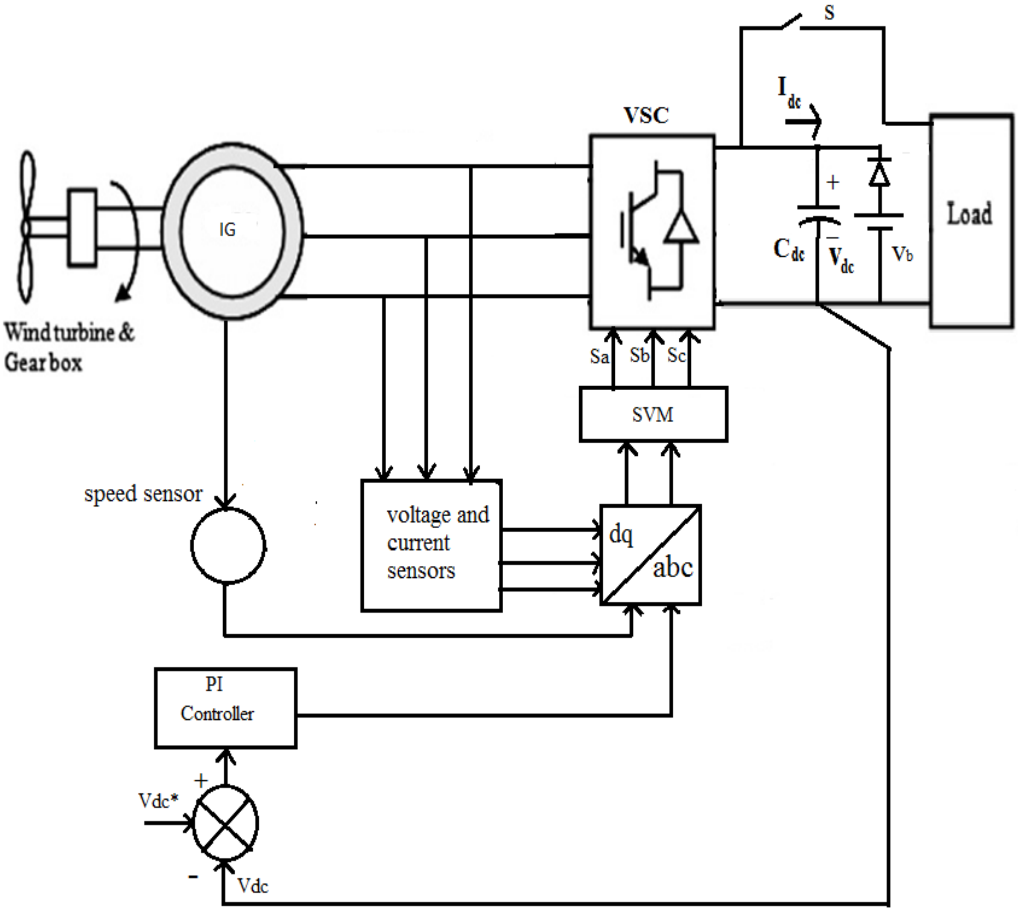

Fig. 5 Control Scheme

Vref using the eight switching patterns. One simple method of approximation is to generate the average output of the inverter in a small period, T to be the same as that of Vref in the same period. The Fig.6 shows the basic switching vector and sector which are shown below.

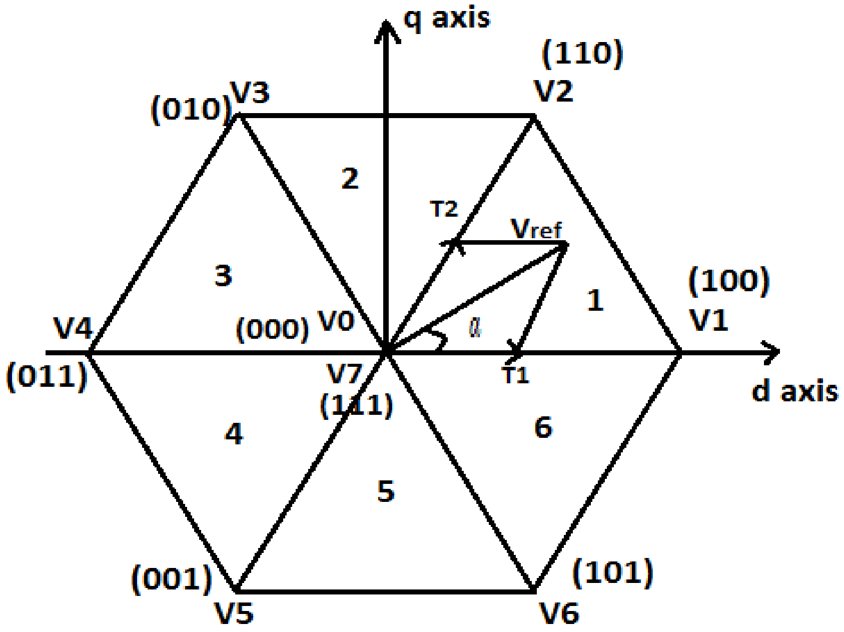

Fig. 6 Basic switching vector and sector

The vectors (V_1 to V_6) divide the plane into six sectors (each sector: 60 degrees). For each sector, the switching time duration ($T_{1,}$ T_2, T_0) are calculated by

$$T_1 = \frac{\sqrt{3}\, T_z |\overline{V_{ref}}|}{V_{dc}} \left(\sin\frac{n\pi}{3}\cos\theta_s - \cos\frac{n\pi}{3}\sin\theta_s \right) \qquad (14)$$

$$T_2 = \frac{\sqrt{3}\, T_z |\overline{V_{ref}}|}{V_{dc}} \left(-\sin\frac{(n-1)\pi}{3}\cos\theta_s - \cos\frac{(n-1)\pi}{3}\sin\theta_s \right) \qquad (15)$$

$$T_0 = T_z \quad T_1 - T_2 \qquad (16)$$

The switching time at each sector is summarized in table 1.

SECTOR	UPPER SWITCHES (S1, S3, S5)	LOWER SWITCHES (S4, S6, S2)
1	S1 = T1 + T2 + T0/2 S3 = T2 + T0/2 S5 = T0/2	S4 = T0/2 S6 = T1 + T0/2 S2 = T1 + T2 + T0/2
2	S1 = T1 + T0/2 S3 = T1 + T2 + T0/2 S5 = T0/2	S4 = T2 + T0/2 S6 = T0/2 S2 = T1 + T2 + T0/2
3	S1 = T0/2 S3 = T1 + T2 + T0/2 S5 = T2 + T0/2	S4 = T1 + T2 + T0/2 S6 = T0/2 S2 = T1 + T0/2
4	S1 = T0/2 S3 = T1 + T0/2 S5 = T1 + T2 + T0/2	S4 = T1 + T2 + T0/2 S6 = T2 + T0/2 S2 = T0/2
5	S1 = T2 + T0/2 S3 = T0/2 S5 = T1 + T2 + T0/2	S4 = T1 + T0/2 S6 = T1 + T2 + T0/2 S2 = T0/2
6	S1 = T1 + T2 + T0/2 S3 = T0/2 S5 = T1 + T0/2	S4 = T0/2 S6 = T1 + T2 + T0/2 S2 = T2 + T0/2

From the table.1, the switching times of each transistor are calculated which helps to control the VSC.

5. Simulation Results

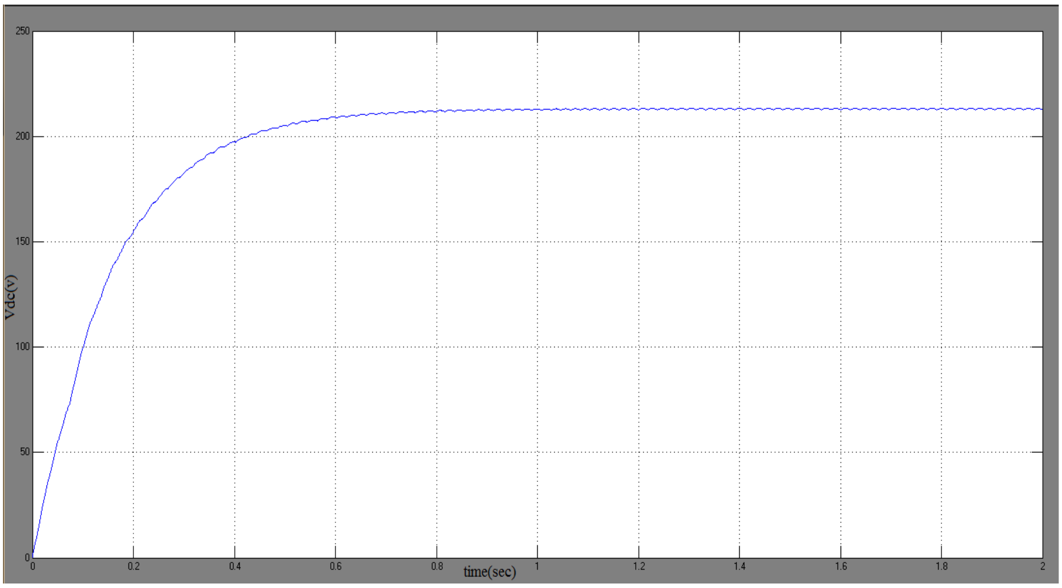

Fig.7 DC Bus voltage

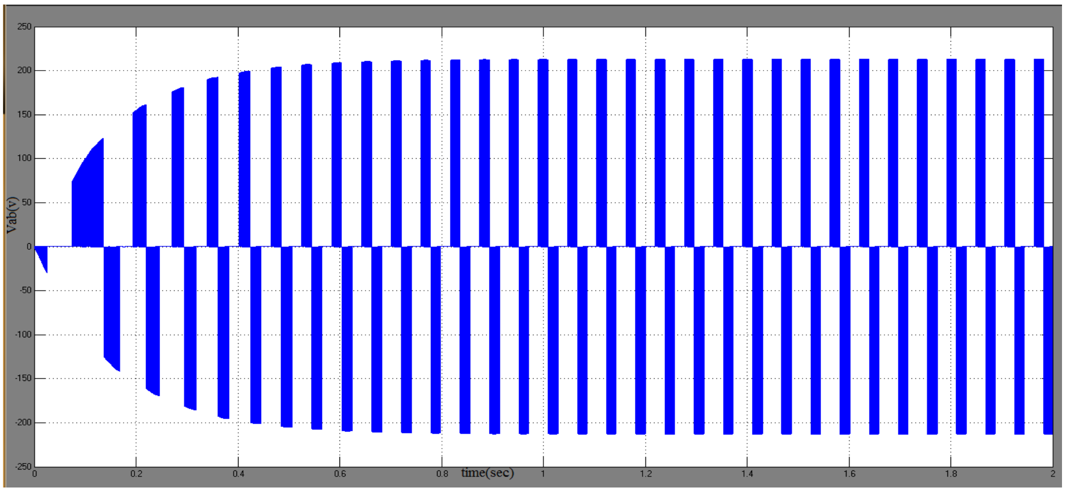

Fig. 8 Line to Line voltage of Induction Generator

he DC bus voltage build up process for variable wind speed and load for a capacitance value of 1500µF is shown in the fig.7. When the capacitance is large it takes longer time to reach its steady state value. If the capacitance is too small, there will not be enough exciting current and as a result there will not be voltage build up. For variable rotor speed the voltage build up process starts with the low frequency and then rises until it reaches its steady state value. For low valve battery, the voltage is maintained at 220v.

The Fig. 7 shows the DC Bus voltage and Fig.8 shows the line to line voltage of induction generator. It is observed that the value of the DC bus voltage is maintained at constant value even if the rotor speed changes at 1.5 sec. This is achieved by the SVM controller.

6. Conclusion

This proposed system has an effective method of power generation in WECS using SCIG. A novel scheme for dc bus voltage build up is presented which requires no capacitor bank at IG terminals. This ensures good dynamic control of dc bus voltage with very small changes in speed and load. A scheme of enhancement of power extraction by maintaining constant voltage has been proposed, thereby resulting in better utilization of IG and WT. The proposed method provides the achievement of better utilization and reliable solution for large wind form installations.

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