Novel Voltage Controller for Stand-alone Induction Generator using PWM-VSI

G. V. Jayaramaiah
Research Scholar, Energy Systems Engineering, Indian Institute of Technology Bombay, Powai, Mumbai - 400 076, INDIA

B. G. Fernandes
Department of Electrical Engineering, Indian Institute of Technology Bombay, Powai, Mumbai - 400 076, INDIA
Phone: +91 - 022 - 25767428, Email: bgf@ee.iitb.ac.in

Abstract—This paper presents a DSP-based constant voltage controller for stand alone wind energy conversion system using an induction generator. The system uses a pulse-width modulated voltage source inverter (PWM-VSI) with a start-up battery. The limitation of having stand alone wind energy conversion system with self-excited induction generator (SEIG) is poor voltage regulation which occurs with change in speed and load condition. To overcome this problem, a DSP-based voltage controller is developed. It regulates the voltage when SEIG is subjected to a sudden application/removal of load. It is now possible to operate the induction generator (IG) at constant voltage from no load to full load. The amplitude of the terminal voltage of the IG is regulated by varying the modulation index of the PWM inverter. The system has an inherent current limiting feature and it requires only sensing of dc link voltage. To predict the performance of the proposed system, a MATLAB/SIMULINK-based simulation study is carried out. The control algorithm is implemented on a TMS320F243 DSP platform at the assembly language level for optimum performance of the voltage controller. Viability of the compensation process is ascertained through experimental results obtained from the laboratory prototype.

I. INTRODUCTION

Among the different renewable energy systems, wind energy appears as the most promising one, due to both technical and economic factors. Important progress in wind energy conversion technologies has been achieved and more efficient and more powerful wind generators are now available. The selection of the generator depends upon many factors such as type of application, machine characteristics, maintenance, cost etc. Currently induction machines are more popular compared to other machines. However its major disadvantage is the requirement of excitation power. This reactive power can be supplied by a variety of methods [1]–[3], ranging from using simple capacitors to that of a VSI inverter with complex power conversion techniques. Another limitation of the SEIG in stand-alone systems is its inability to control the terminal voltage and frequency under change in load and wind speed. To overcome this problem, several methods are proposed in [2]–[4]. The capacitor excitation [3], [4] is suitable only when there is a constant load at the IG terminal and is driven at constant mechanical speed. However any change in load and rotor speed may result in a loss of excitation. To overcome this problem, discrete blocks of capacitors can be added or removed at the IG terminals either using contactors or power electronic switches in series with the capacitors, depending upon change in speed and load. Another method of providing excitation involves using a saturable reactor [5] connected in each phase of IG. This inductor with stepped air gap gradually saturates with stator current. As a result, its inductance decreases with load. However the overall system is bulky and expensive.

In order to improve the performance of the system, use of modern control techniques such as vector control and sliding mode control have been suggested [6 & 7]. Though the use of vector control technique improves the performance of the system, the overall system becomes complex. It should be noted that one of the key issues in standalone system is reliability and simplicity in control structure. The use of these techniques defeats this purpose.

The excitation schemes proposed in [6]–[10] involve power electronic converters to source the required reactive power to excite the IG. Though the voltage build-up process has been discussed and the results have been presented in these papers, the dynamic behaviour of SEIG is not discussed. Moreover, the overall control structure is complex in nature. Therefore the main objective of this paper is to develop a simple control strategy to overcome the limitations of the existing schemes. The proposed controller is also capable of handling reactive loads and does not require the mechanical speed sensors, ac voltage or current sensors, thereby reducing the overall cost and hardware complexity. This also improves the overall reliability of the system. The controller maintains a constant voltage at the IG terminal during the change in load by adjusting the inverter frequency. The amplitude of the terminal voltage of IG is controlled by the modulation index of the VSI. Unlike in most of the systems reported in literature, the proposed system does not require a dump load. Detailed Matlab/Simulink-based simulation studies are carried out to demonstrate the effectiveness of the scheme. Viability of the scheme is confirmed through experimental results using a scaled down laboratory prototype. The control algorithm is implemented on a TMS320F243 DSP.
II. MATHEMATICAL MODELLING OF 3-Φ SELF-EXCITED INDUCTION GENERATOR

The d-q axes equivalent circuits of an induction generator (IG) in synchronously rotating reference frame are shown in Fig. 1. The complete dynamic equations of IG, taking saturation into account, in synchronously rotating reference frame [11], [12] is represented in matrix form as follows:

\[
\frac{d}{dt} \begin{bmatrix} \lambda_{ds} \\ \lambda_{qs} \end{bmatrix} = \begin{bmatrix} V_{ds} \\ V_{qs} \end{bmatrix} - R_s \begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} - \omega \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} \lambda_{ds} \\ \lambda_{qs} \end{bmatrix}
\]

\[
\frac{d}{dt} \begin{bmatrix} \lambda_{dr} \\ \lambda_{qr} \end{bmatrix} = \begin{bmatrix} V_{dr} \\ V_{qr} \end{bmatrix} - R_r \begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} - (\omega - \omega_r) \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} \lambda_{dr} \\ \lambda_{qr} \end{bmatrix}
\]

Equations for electromagnetic torque and mechanical speed of the SEIG are expressed as follows:

\[ T_e = \frac{3P}{4} (i_{qr} \lambda_{dr} - \lambda_{qr} i_{dr}) \]

\[ \frac{d}{dt} \omega_r = \frac{P}{2J} (T_{shaft} - T_e) \]

III. MATHEMATICAL MODELING OF 3 - Φ PWM - VSI

The complete mathematical modeling of the PWM-VSI and the load are explained in the following sections.

A. Representation of the d. c. side of the inverter

The capacitor voltage equation is governed by:

\[ \frac{d}{dt} V_{dc} = - \frac{I_{dc}}{C} \]

where \( V_{dc} \) is the voltage across the capacitor and \( I_{dc} \) is the current flowing through it, as shown in Fig. 2.

The set point of \( V_{dc} \) must be greater than the peak value of the machine line voltage in order to force the desired line currents. Total d. c. current \( I_{dc} \) can be expressed in terms of inverter switching function as

\[ I_{dc} = S_a i_{ea} + S_b i_{eb} + S_c i_{ec} \]

(suffix e identifies compensator phase currents)

The three switching functions take the value of 1 if the upper switch of the inverter leg is on and it is 0 if the lower switch in the same inverter leg is on.

B. Model of the Voltage Source Inverter (VSI)

Using the switching function \( SF_{1a,b,c} \) the \( V_{ao}, V_{bo} \) and \( V_{co} \) can be obtained as:

\[ V_{ao} = \frac{V_{dc}}{2} SF_{1a} = \frac{V_{dc}}{2} \sum_{n=1}^{\infty} A_n \sin(n\omega t) \]

\[ V_{bo} = \frac{V_{dc}}{2} SF_{1b} = \frac{V_{dc}}{2} \sum_{n=1}^{\infty} A_n \sin(n\omega t - 120^\circ) \]

\[ V_{co} = \frac{V_{dc}}{2} SF_{1c} = \frac{V_{dc}}{2} \sum_{n=1}^{\infty} A_n \sin(n\omega t + 120^\circ) \]

The Line-to-Line voltages generated by the inverter can be derived as:

\[ V_{ab} = V_{ao} - V_{bo} \]

\[ V_{bc} = V_{bo} - V_{co} \]

\[ V_{ca} = V_{co} - V_{ao} \]

C. Mathematical model of the Load

Equations dealing with generator feeding a (R-L) load in d-q frame are

\[ V_{ds} = R_L i_{Lds} + L_L \frac{d}{dt} i_{Lds} - \omega_L L_i L_{Lqs} \]

\[ V_{qs} = R_L i_{Lqs} + L_L \frac{d}{dt} i_{Lqs} + \omega_L L_i L_{Lqs} \]

where \( i_{Lds} \) and \( i_{Lqs} \) are the d-axis and q-axis components of the load current

IV. PRINCIPLE OF OPERATION OF THE CIRCUIT

The proposed overall system block diagram is shown in Fig. 2. A 12 V battery on the dc side of inverter is provided for initial excitation. The reactive power required by the IG and load is provided by the voltage source inverter. Therefore the rating this inverter is chosen based on the excitation power of IG and reactive power requirements of the load. During startup, the controller sets the stator frequency lower than the rotor frequency so that the power produced by IG is used to charge the capacitor connected across the dc link to a set reference value. In this study this voltage is maintained at 150 V. The error between the reference and actual capacitor
voltages is processed by the PI controller. If the measured capacitor voltage is higher than the reference value, the stator frequency is increased by the controller, thereby decreasing the torque and power supplied by IG, and, if the measured capacitor voltage is lower than the reference value the stator frequency is decreased. The output of the PI regulator is fed to the harmonic oscillator to generate the sine and cosine waveforms. These waveforms are multiplied by the modulation index ($m_a$) to get $V_r, V_y$ and $V_b$ as shown in Fig. 2. These sinusoidal waveforms are compared with 1 kHz triangular carrier signal to generate the switching pulses to the IGBT inverter.

Any variation in the output power of IG is directly indicated by the variation in the terminal voltage of the generator. A decrease in capacitor voltage below the reference value indicates that the active power drawn by the load is higher than the power generated by IG. This difference in power is supplied by the VSI and hence the dc link voltage falls. Due to step change in load, the input power to the induction generator decreases as speed of the prime mover decreases. To maintain a constant voltage at the IG terminal, the controller decreases the inverter frequency.

An increase in capacitor voltage indicates that the active power required by the load is reduced due to the removal of load. Under this condition active power generated by the IG is higher than the power required by the load. In order to decrease the active power the controller increases the inverter frequency.

V. SIMULATION RESULTS

The developed models of the sub-system are integrated and the resulting system is simulated using MATLAB/SIMULINK. The machine rating and its equivalent circuit parameters used for the study are given in appendix. In order to prove the viability of the control scheme a TMS320F243 DSP based scaled down laboratory prototype is designed and developed. The simulated results showing the variation of terminal voltage of the generator and the voltage across dc link capacitor during start up are shown in Fig. 3 while, Fig. 4 shows these results obtained from the prototype developed in the laboratory.

When the IG is suddenly loaded the frequency and terminal voltage of IG, and the capacitor voltage tend to fall. The terminal voltage is restored to the reference value by adjusting the inverter frequency. The simulated and experimental results are shown in Fig. 5 and Fig. 6 respectively. Similar behaviour of SEIG is observed when
the load on IG is reduced. The terminal voltage and stator frequency tend to increase. The terminal voltage and capacitor voltage increase due to the mismatch in active power produced by the IG, which is more than the power consumed by the load. The closed loop controller adjusts the inverter frequency so that the terminal voltage is maintained at the reference value. The simulated and experimental results are shown in the Fig. 7 and Fig. 8 respectively. The variation of the stator frequency and capacitor voltage during step change in load

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Parameters of the Induction Machine at 50 Hz

Phase .......................................................... 3Φ
Connection .................................................... Δ
Rated voltage ........................................... 220 V
Rated current ......................................... 2.425 A
Speed ..................................................... 1430 RPM
Stator resistance($r_s$) ......................... 7.83 (Ω)
Rotor resistance($r_r$) ......................... 7.55 (Ω)
Stator inductance($l_s$) ..................... 0.4535 (H)
Rotor inductance($l_r$) ..................... 0.475 (H)
Magnetizing inductance(unsaturated) ........ 0.3H
Rated power ......................................... 1.1kW
Number of Poles ................................. 4
Rotor inertia(J) ................................. 0.664 (kg.m²)

REFERENCES