ISSN 2229-5518

An Efficient Z-Source Inverter based Solar Power Generation System Fed IM Drive

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Abstract— The increasing importance of fuel saving has been responsible for the revival of interest in alternative source of energy. Thus, the decentralization of power generation and increasing use of non-conventional energy sources has become essential to adopt a low cost generating system for operating in remote areas. With the renewed interest in solar power generation as an alternative energy source, the conventional Voltage Source Inverter (VSI) based Solar Power Generation System has not as much efficiency and reliability. Hence, in this paper, a most recent Z-Source Inverter (ZSI) based Solar Power Generation System for feeding static as well as dynamic load (induction motor drive) is proposed and implemented for remote and rural areas. In this topology, the conventional VSI is replaced by latest ZSI. The Z-Source inverter employs a unique impedance network coupled with inverter circuit. The ZSI have recently been proposed as an alternative power conversion concept as it has both voltage buck and boost capabilities. The developed system can provide ride through capabilities during voltage sags, reduces the line harmonics, improves power factor, increases reliability and extends output voltage range. Compared to conventional Voltage Source inverter (VSI) based Solar Power Generation System, the proposed system needs less PV cells and gives the superior performance. Simulation results are given to compare the behaviour of conventional and proposed topology and also demonstrate the new features of the improved topology.

Index Terms— Solar Power Generation Systems, PV Panel, Z-Source Inverter, Harmonic Analysis.

1 Introduction

The increasing concern for the environment and resources has motivated the world towards rationalizing the use of conventional energy sources and exploring the non-conventional energy sources to meet the ever-increasing energy demand. A number of renewable energy sources like solar, hydro, wind, industrial waste, geothermal, etc. are in trend for electric power generation. Since solar energy source is available in plenty, its utilization is felt quiet promising to accomplish the future energy requirements. Harnessing solar energy for electric power generation is an area of research interest and at present, the emphasis is being given to the cost-effective utilization of these energy sources for quality and reliable power supply. The Solar power is environment friendly, noiseless, has longer life with little maintenance, highly mobile and portable because of light weight. The output voltage of Solar Energy sources can be increased by connecting a number of Solar Panels in series and using a conventional voltage source inverter. For analyzing the performance of conventional Solar System with increased number of PV cell, a MATLAB Simulink Model has been developed. However, this configuration has some drawback, such as low reliability, efficiency and accuracy at low irradiation [1]. The accuracy of the system can be improved at low irradiation with a two diode model. This model has more accurate prediction of PV system performance. The requirement of the additional iteration method for the calculation of series and parallel resistance is the major problem [2]. A simple PV array modeling has also been presented with parallel resistance [3]. In order to find out the solutions to these technical challenges, several power electronic circuit topologies have been presented in the literature. These topologies presents switching losses, EMI generation, requires an output filter, causes additional power loss and control complexity [4-5]. The Z-source inverter has overcame the problem associated with the conventional voltage source inverter for implementing DC-AC, AC-DC, AC-AC and DC-DC power conversion. It employs a unique impedance network (circuit) to couple the converter main circuit to the power source, thus providing unique features that cannot be obtainable in conventional voltage source inverter. The Z-source inverter reduces harmonics, electromagnetic interference noise and low common made noise [6-7]. The Z-source inverter can be used to feed the adjustable induction motor drive system and it has better performance and results as compared to the conventional VSI [8-11]. This new approach has been implemented to fuel cell system for boosting and inverting the DC voltage into AC voltage [12-13]. The Z-source inverter is also implementable to grid connected PV system, which is transformer less and has low cost [14-15].

In this paper, a simulation model is developed in which the Z-source inverter is implemented to boost the DC voltage generated by PV Panel for feeding the Induction Motor Drive. The induction motor is used widely now a day's such as in fans, most machinery tools, centrifugal pumps, wood working tool, crusher, compressor, reciprocating pump, punching presses, shears, hoists and elevator etc. Hence in this paper, performance analysis of ZSI with IM drives has been done. The conventional scheme is also analyzed using the simulation model fed to the Induction Motor Drive. A comparison study

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and harmonic analysis has been done to examine the better performance of Z-Source inverter.

2 System Description

Fig.1 shows the schematic diagram of a ZSI based Solar Power Generation System fed induction motor drive, where a unique impedance network is introduced to couple the inverter main circuit to the power source. A ZSI based Solar Power Generation System fed induction motor drive system has four major parts: a PV array- Source of DC voltage, Z-Source network containing two series inductors and two equal diagonally connected capacitors, a three-phase IGBT/Diode based inverter bridge and a three-phase induction motor drive. For feeding the required DC voltage to the Z-Source Network, a PV array is used to generate the DC voltage with proper series and parallel combination of PV cells. Reverse current flow can be prevented by connecting a diode in series with the load circuit. The L_1, L_2, C_1 and C_2 are forming the Z-Source network. The boost function of the generated DC voltage is achieved by this Z-source network. The ZSI bridge can boost the DC capacitors (C_1 and C_2) voltage to any value that is the above the average DC value of the PV array. The desired output voltage is always obtainable regardless of the line voltage with the help of Z-source bridge. Comparing the Z-source inverters with the traditional inverters, a shoot-through state that the upper and lower switches of any one phase leg are shorten and this is the added state besides the zero state and active state. This is the best advantage and feature of the Z-source inverter.

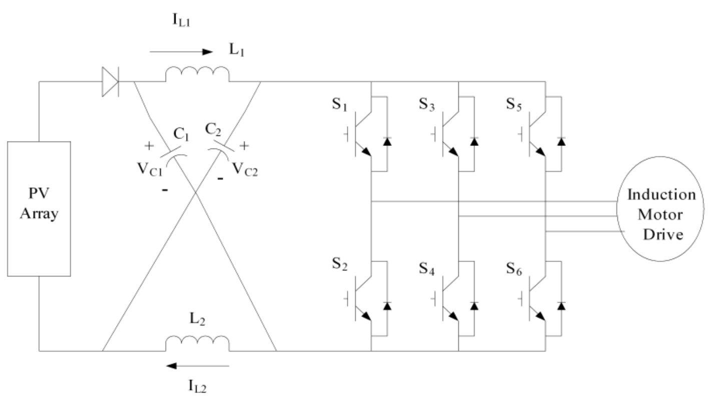

Fig. 1 System configuration of ZSI based Solar Power Generation System

The proposed system is able to feed the three-phase induction motor drive. The conventional VSI based Solar System is also capable of supplying power to the IM drive, but its performance is affected by EMI noise, has considerable amount of harmonic distortion, high power loss and low efficiency. Over these problems the proposed system has the advantages such as both buck and boost operation is possible, less affected by the EMI noise, low harmonic distortion, low power loss and higher efficiency.

3 Modeling Of The System

The mathematical modeling of Solar Power Generation System involves the modeling of PV Panel, Z-Source inverter and Induction Motor drive.

3.1 Modeling of PV Panel

The PV cells are usually represented by a simplified equivalent circuit model as shown in the fig. 2. The series resistance R_S represents internal resistance to current flow. The shunt resistance is inversely related to the leakage current to ground. In ideal $R_S = 0$ and R_{Sh} = infinite.

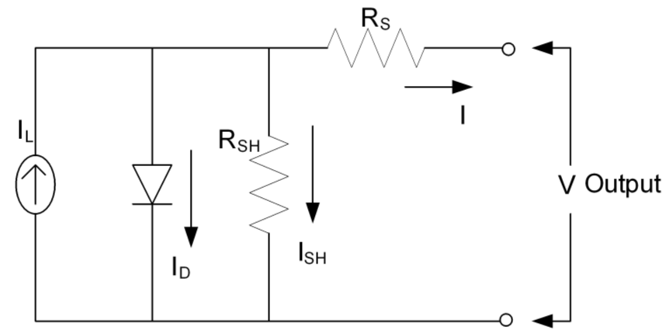

Fig. 2 Equivalent Circuit of PV Cell

The PV cell output voltage is a function of photocurrent. The photocurrent depends upon the temperature and solar irradiation level. The PV cell output voltage can be expressed as:

$$V = \frac{AkT}{e} \ln\left(\frac{I_{Ph} + I_0 - I}{I_0}\right) - R_s I \qquad (1)$$

Where, e = Electronic charge (1.602×10^{-19} C).
k = Boltzmann constant (1.38×10^{-23} J/^{0}K).
I = Cell output current, in A.
I_{Ph} = Photocurrent depends on temperature and solar irradiance (5 A).
I_0 = Reverse Saturation Current of diode (0.0002 A)
R_s =Series resistance of cell (0.001 Ω).
T = Reference cell operating temperature (20^0 C).

If the temperature and solar irradiation levels change, the output voltage and current of the PV array will follow this change. The variable ambient temperature T_a affects the cell output voltage and cell photocurrent. These effects are represented in the model by the temperature coefficients C_{TV} and C_{TI} for the cell output voltage and cell photocurrent respectively as:

$$C_{TV} = 1 + \beta_T (T_a - T_x) \qquad (2)$$

$$C_{TI} = 1 + \frac{\alpha_T}{S_C} (T_x - T_a) \qquad (3)$$

Where, β_T = 0.004 and a_T=0.06 for the cell used. The ambient temperature (T_a) during the cell testing is equals to 20^0C. The change in the temperature is represented by T_x. This will be responsible for the change in the voltage generated by the PV Panel.

A change in solar irradiation level causes a change in the cell photocurrent and operating temperature, which affects the cell output voltage. The change in the operating temperature and in the photocurrent due to variation in the solar irradiation level can be expressed by the correction factors i.e.

ISSN 2229-5518

C_{RV} and C_{RI} for changes in cell output voltage V and photocurrent, respectively;

$$C_{RV} = 1 + \beta_T \alpha_s (S_x - S_R) \quad (4)$$

$$C_{RI} = 1 + \frac{1}{S_C}(S_x - S_R) \quad (5)$$

Where, S_R is the reference solar irradiation level during the cell testing. S_x is the new level of solar irradiation. The new values of the cell output voltage V_{CX} and photocurrent I_{Phx} for the new temperature T_x and solar irradiation S_x can be given as:

$$V_{Cx} = C_{TV} C_{RV} V_c \quad (6)$$

$$I_{Phx} = C_{TI} C_{RI} I_{Ph} \quad (7)$$

3.2 Modeling of Z-Source Inverter

The Z-Source inverter is used to overcome the problems in the traditional voltage source inverters. This Z-Source Inverter employs a unique impedance network coupled with the inverter main circuit to the power source. This inverter has unique features compared with traditional sources. The equivalent circuit arrangement is shown in the fig. 3.

The PV Panel generates DC voltage. This DC voltage is fed to the Z- Source network consisting of two equal valued inductors (L_1 and L_2) and capacitors (C_1 and C_2). The network inductors are connected in series arms and capacitors are connected in diagonal arms. The impedance network bucks or boosts the input voltage depending upon the boosting factor. This network also acts as a second order filter. This network requires less number of inductors and capacitors, hence size of components is small. The inverter main circuit consists of six switches. Gating signals are generated from the Pulse Width Modulation (PWM) operation.

Assume the inductors (L_1 and L_2) and capacitors (C_1 and C_2) have the same inductance and capacitance values respectively. From the fig. 3.

$$V_{C1} = V_{C2} = V_C \quad (8)$$

$$V_{L1} = V_{L2} = V_L \quad (9)$$

$$V_L = V_C,\ V_{pv} = 2V_C,\ V_0 = 0$$

During the switching cycle T,

$$V_L = V_{pv} - V_C \quad (10)$$

$$V_0 = V_C - V_L = V_C - (V_{pv} - V_C); \quad (11)$$

$$V_0 = 2V_C - V_{pv}$$

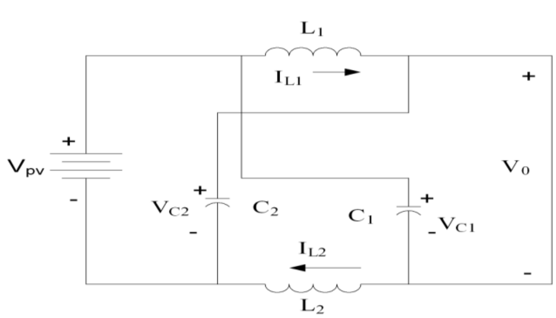

Fig. 3 Equivalent circuit of the Z-Source Inverter

Where, V_{pv} is the output DC voltage of the PV panel and $T = T_0 + T_1$. The T_0 and T_1 are the ON and OFF periods of the switching cycle respectively.

The average voltage of the inductors over one switching period (T) should be zero in steady state.

$$V_L = T_0 . V_C + T_1 \frac{(V_{pv} - V_C)}{T}$$

$$V_L = \frac{1}{T}\left(T_0 . V_c + V_{pv} . T_1 - V_{C.} T_1\right) = 0$$

$$V_L = \frac{(T_0 - T_1)}{T} V_C + \frac{T_1 V_{pv}}{T} \quad (12)$$

$$\frac{V_C}{V_{pv}} = \frac{T_1}{(T_1 - T_0)} \quad (13)$$

Similarly the average DC link voltage across the inverter bridge can be found as follows:

$$V_0 = \frac{1}{T}\left(T_0 . 0 + T_1 (2 . V_c - V_{pv})\right) \quad (14)$$

$$= \left(\frac{2 . V_C . T_1}{T}\right) - \left(\frac{T_1 V_{pv}}{T}\right)$$

$$2V_C = V_{pv}$$

From eq.12

$$V_C = \frac{V_{pv} T_1}{(T_1 - T_0)}$$

The peak DC link voltage across the inverter bridge is

$$V_0 = V_C - V_L = 2 . V_C - V_{pv} = \frac{T}{T_1 - T_0} . V_{pv} = B . V_{pv} \quad (15)$$

Where,

$$B = \text{Boost Factor} = \frac{T}{(T_1 - T_0)} \geq 1$$

The output peak phase voltage from the inverter:

$$V_{ac} = M . \frac{V_0}{2} \quad (16)$$

Where, M is the modulation index. Substituting the value of in eq. 16, the expression of the output peak phase voltage from the inverter will be:

$$V_{ac} = M . \frac{B . V_{pv}}{2} \quad (17)$$

The output voltage can be stepped up and down by choosing an appropriate Buck-Boost factor (BB):

BB = B*M (it varies from 0 to α)

The capacitor voltage can be expressed as:

$$V_{C1} = V_{C2} = V_C = \left(1 - \frac{T_0}{T}\right) . \frac{V_{pv}}{\left(1 - 2 . \frac{T_0}{T}\right)} \quad (18)$$

The Buck-Boost Factor (BB) is determined by the modulation index (M) and the Boost Factor (B). The Boost Factor B can be controlled by the duty cycle of the shoot through zero state over the non-shoot through states of the PWM inverter. The shoot through state does not affect PWM control of the inverter, because it equivalently produces the same zero voltage to the load terminal. The available shoot through period is limited by the zero state periods that are determined by the modulation index.

3.3 Induction Motor Model

The dynamic model of three-phase squirrel cage induction generator is developed using stationary d-q reference frame. The involved equations are as:

$$[V] = [R][i] + [L]p[i] + w_r [G][i] \quad (19)$$

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Hence the current derivative can be expressed as:

$$P[i] = L^{-1}\{[V] - [R][i] - w_r[G][i]\} \quad (20)$$

Where,

$$[V] = [V_{ds}\ \ V_{qs}\ \ V_{dr}\ \ V_{qr}]^T$$

$$[i] = [i_{ds}\ \ i_{qs}\ \ i_{dr}\ \ i_{qr}]^T$$

$$[R] = \mathrm{diag}[R_s\ \ R_s\ \ R_r\ \ R_r]$$

$$[L] = \begin{bmatrix} L_{ls} + L_m & 0 & L_m & 0 \\ 0 & L_{ls} + L_m & 0 & 0 \\ L_m & 0 & L_{rr} + L_m & 0 \\ 0 & L_m & 0 & L_{ls} + L_m \end{bmatrix}$$

$$[G] = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & -L_m & 0 & -L_{rr} - L_m \\ L_m & 0 & L_{lr} + L_m & 0 \end{bmatrix}$$

The transformation of stator phase variable to stationary reference frame d-q is carried by abc to d-q transformation.

$$[V_{dq0}] = [k][V_{abc}] \quad (21)$$

Where,

$$[k] = \frac{2}{3}\begin{bmatrix} \cos\theta & \cos(\theta - \phi) & \cos(\theta + \phi) \\ \sin\theta & \sin(\theta - \phi) & \sin(\theta + \phi) \\ 1/2 & 1/2 & 1/2 \end{bmatrix}$$

4 Simulation Model

Fig. 4 shows the simulation model of ZSI based Solar Power Generation System. The simulation model of the proposed system consists of PV Panel model, subsystem of Z-source inverter and the induction motor drive. The PV panel model consists of six series and one parallel connected PV cells to generate the required voltage for the 15.2387^{0}C temperature and 102.6268 W/m^2. The PV cell model is modeled using the basic circuit eq. (1-8). The voltage generated by the PV cell is 150 volt. The effect of temperature and solar irradiation can be seen by dragging the variable temperature and variable solar irradiation slider gain. Similarly, variation in voltage generation according to the series and parallel connected PV cell can be analyzed by changing the values of N_S (Number of series connected PV cells) and N_P (Number of parallel connected PV cells). The generated voltage of the PV panel is given to the Z-source inverter subsystem model for boosting and DC-AC inversion.

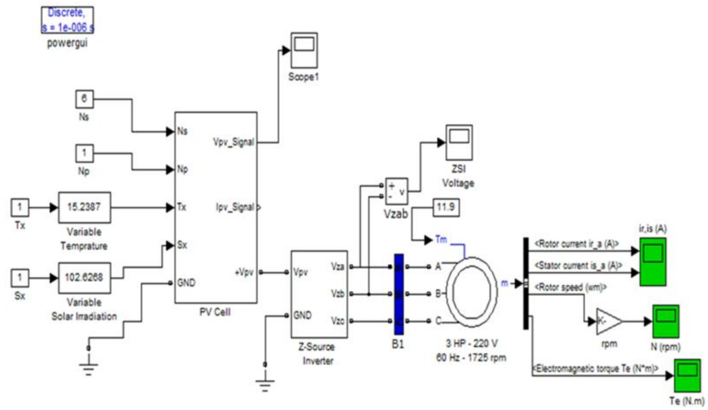


Fig. 4 Simulation Model of the Z-Source Inverter based Solar Power Generation System

Fig. 5 shows the subsystem of the Z-source inverter model. A diode is connected in series to prevent the circuit from reverse current flow. This model consists of Z-source network i.e. combination of two equal values inductor ($L_1 = L_2 = 160$ μH) and capacitor ($C_1 = C_2 = 1000$ μF). The three leg IGBT based voltage source inverter is gated by PWM operation. The PWM operation is performed by comparing the sinusoidal waveform (321sinωt) and repetitive triangular waveform having 10 kHz frequency. The upper switches are gated with the signal obtained by the PWM operation and the gating signals of the lower switches are the NOT operated signal of the signal obtained by PWM operation. The capacitor filters ($C_{f1} = C_{f2} = C_{f3} = 10$ μF) are connected in parallel before the induction motor load to maintain the stable voltage.

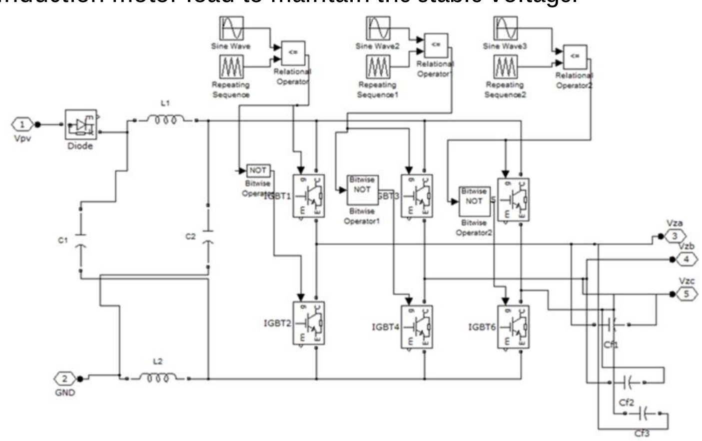


Fig. 5 Subsystem of the Z-Source Inverter

Fig. 5 shows the subsystem of the Z-source inverter model. A diode is connected in series to prevent the circuit from reverse current flow. This model consists of Z-source network i.e. combination of two equal values inductor ($L_1 = L_2 = 160$ μH) and capacitor ($C_1 = C_2 = 1000$ μF). The three leg IGBT based voltage source inverter is gated by PWM operation. The PWM operation is performed by comparing the sinusoidal waveform (321sinωt) and repetitive triangular waveform having 10 kHz frequency. The upper switches are gated with the signal obtained by the PWM operation and the gating signals of the lower switches are the NOT operated signal of

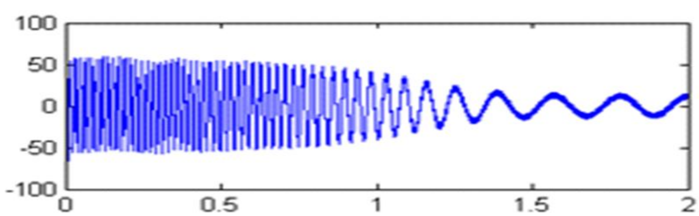
the signal obtained by PWM operation. The capacitor filters (C_{f1} = C_{f2} = C_{f3} = 10 μF) are connected in parallel before the induction motor drive to maintain the stable voltage.

An induction motor of 3 HP, 220 V, 60 Hz and 1725 rpm is connected to a constant load of nominal value (11.9 N.m). The stator current, rotor current, rotor speed and electromagnetic torque responses of the induction motor drive are observed by the bus selector block.

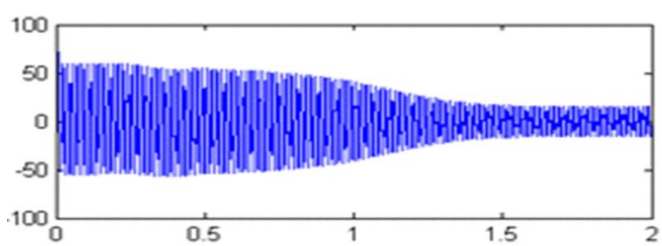
5 Results And Discussion

In order to verify the effectiveness and identify the better performance of the conventional VSI and ZSI based Solar Power Generation System and its control strategy, mathematical models are developed and compared using MATLAB/Simulink software. For feeding the DC voltage from PV Panel to the IM drive, 16 PV cells are connected in series and one PV cell is connected in parallel. The PV Panel generates 150 V for the temperature 15.2387^{0}C and solar irradiation 102.6268 W/m^2.

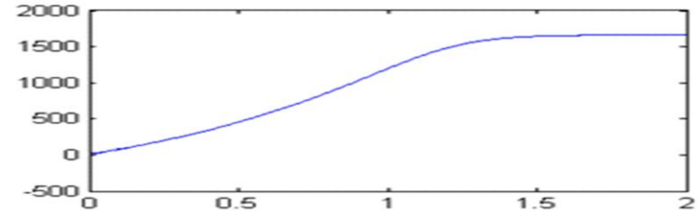
The conventional and proposed techniques have been simulated by MATLAB/Simulink software for feeding the Induction motor drive. The simulation is performed for feeding a squirrel cage induction motor rated at 3 HP (2.2 kW), 220 V, 60 Hz and 1725 rpm. Fig. 6 shows the simulation results of the rotor and stator current waveform, rotor speed response and the torque response for the conventional VSI based Solar Power Generation System. Fig. 6 (a) and fig. 6 (b) shows that the rotor and stator starting current of IM is about 50 A and current finally settles with the peak value 15.0 A. Fig. 6 (c) shows the speed response of the induction motor drive, which sets to its steady state speed 1650 rpm within 1.5 sec. As per the simulation result shows in the fig. 6 (d) the torque is having the value of 15 Nm.



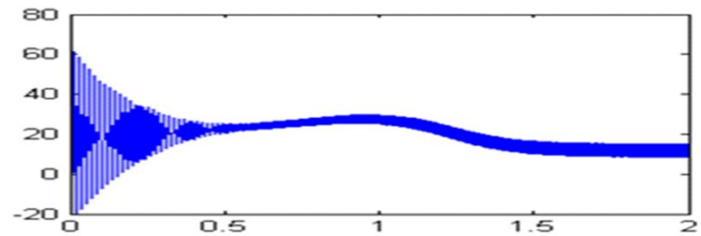
(a) Rotor Current



(b) Stator Current



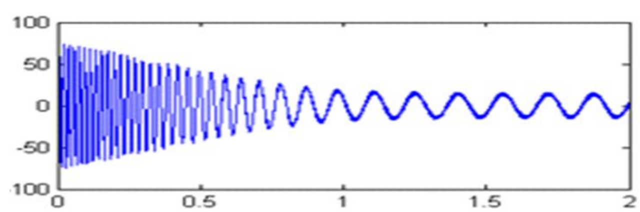
(c) Rotor Speed



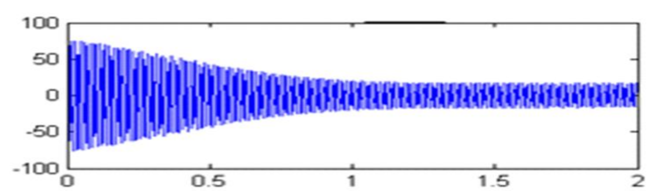
(d) Torque

Fig. 6 Simulation Results of VSI based Solar Power Generation System fed IM Drive

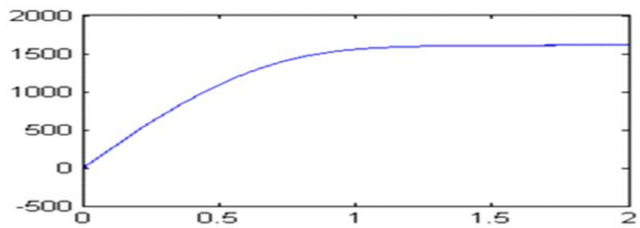
The Z-Source Inverter based Solar Power Generation System has also simulated to feed the induction motor drive and analyze the performance of the system. For feeding the DC voltage from PV Panel to the IM drive, 6 PV cells are connected in series and one PV cell is connected in parallel. The PV Panel generates 150 V for the temperature 15.2387^{0}C and solar irradiation 102.6268 W/m^2. Fig. 7 shows the simulation results of the rotor and stator current waveform, rotor speed response and torque response. As shown in the fig. 7 (a) the induction motor takes starting current of about 70 A and the steady state peak value is 16 A. Fig. 7 (b) shows that the stator current settles with the peak value 17.5 A. The simulation speed response shown in the fig. 7 (c) certifies that the speed settles with 1650 within 0.8 sec. The torque response shown in the fig. 7 (d) has the value of about 15 Nm.



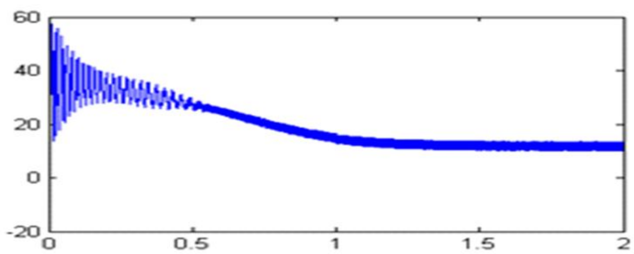
(a) Rotor Current



(b) Stator Current



(c) Rotor Speed



(d) Torque

Fig. 7 Simulation Results of VSI based Solar Power Generation System fed IM Drive

The effectiveness of the proposed system is proven by no overshoot, no undershoot, less harmonic distortion and zero steady-state error of speed response. It is also seen in fig. 6 and fig. 7 that the speed response of the proposed and conventional solar power generation system fed to induction motor drive is also comparable. The analysis and simulation result shows that this proposed technique can drastically reduce the complexity of the control and cost.

6 Conclusion

This paper has presented the simulation model of VSI and Z-Source Inverter (ZSI) based Solar Power Generation System fed induction motor drive. The conventional scheme requires 16 series connected PV cells for feeding three-phase induction motor drive and the new scheme can perform the same task with 6 PV cells. Hence, as compared to conventional system the new proposed technique requires very less number of PV cells. The speed and torque of the induction motor drive fed through the ZSI and conventional VSI based Solar Power Generation System settles with in 1.0 sec. and 1.5 sec. respectively. Assessment of both the system concludes that the performance of the proposed system is better than the conventional system with a less amount of cost. The simulation results verified the operation and demonstrated the promising features. The induction motor drive system has several unique advantages that are very desirable for many drive application such as it can produce any desired output AC voltage, even greater than the line voltage, provides ride through during voltage sags without any additional circuits and energy storage, minimizes the motor ratings to deliver a required power, reduces inrush current and harmonic current, unique drive features include buck-boost inversion by single power conversion stage, improved reliability, strong EMI immunity and low EMI.

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