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A simple model based control of self excited induction generators over a wide speed range*

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Abstract. Self excited induction generators (SEIG) are widely used to harness energy from wind power. However, maintaining constant voltage output from SEIG with varying loads and wind speeds is still a major challenge. This paper proposes a control scheme which provides stable voltage output with changing loads and widely varying wind speeds. A capacitor is employed to provide the bulk excitation for the induction generator. An inverter with a photovoltaic (PV) module supplies the variable reactive current needed to regulate the generator output voltage under variable wind speeds and variable loads. Appropriate simulations and experiments with a laboratory prototype validate the proposed model.

Keywords: self excited induction generators, speed control, reactive power, magnetization curve

1 Introduction

Induction machines with cage rotors are invariably used for generation of electricity from wind. Usually a capacitor bank is connected to the stator terminals for such schemes when used in standalone mode [1, 2, 6, 9, 10]. The prime shortcoming of using capacitor for the supply of reactive power for self-excitation of an induction generator is poor voltage regulation and is consequently not suitable for operation in wider speed ranges. Thyristor controlled capacitors were engaged but they introduce voltage harmonics at the output. Some schemes use sensorless field-orientation control to excite and control the induction generator [1, 6, 9, 10, 13] which initiate severe voltage harmonics. There are some other schemes which projected shuntCconnected PWM voltage source inverter supplying constant frequency voltage[11] and some schemes exist on supplying reactive current to the SEIG by using a static reactive power compensator[12]. An analogous approach proposes instantaneous reactive power theory for SEIG control purpose[8]. Computer model based magnetizing curve identification is also available in literature[7]. All these schemes assume a constant magnetizing inductance of the machine. This causes insensitivity of the controller towards the variation of the mutual inductance at different operating points. This causes the system to become overall unstable or uncontrollable at some conditions of operation. Due to these problems, often a compromise is made between SEIG performances or operated with these limitations to obtain optimum output[4]. In contrast, fast control strategy can be implemented for a similar fixed speed SEIG[14]. In [5], direct voltage control strategy is proposed to improve the performance of SEIGs.

In this paper, a model based strategy of providing variable excitation by an inverter fed from a battery and fixed excitation using capacitances are considered for voltage stabilization of the induction generator system over a widely varying wind speed range and varying operating loads. The existing control schemes do not consider the variations in magnetizing inductances during the generator operation which simplifies the

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control but introduces errors in various estimated quantities during the control of the generating system. The proposed technique enables assuming a nonlinear magnetization curve within its functioning region in a bid to improve the accuracy of inverter control. Fig. 1 shows the proposed induction generator scheme. The PV module along with the inverter is used to supply the variable reactive power required during varying wind speeds or fluctuating loads. The PV module acts as a dc bus to the inverter system. The energy from the PV bus can be stored in the storage battery provided during night time or during low insolation periods. The PV module is also advantageous in making the generator operate in isolation from grid providing the required reactive power through the inverter during fluctuating loads. The control technique is explained in Section 3.

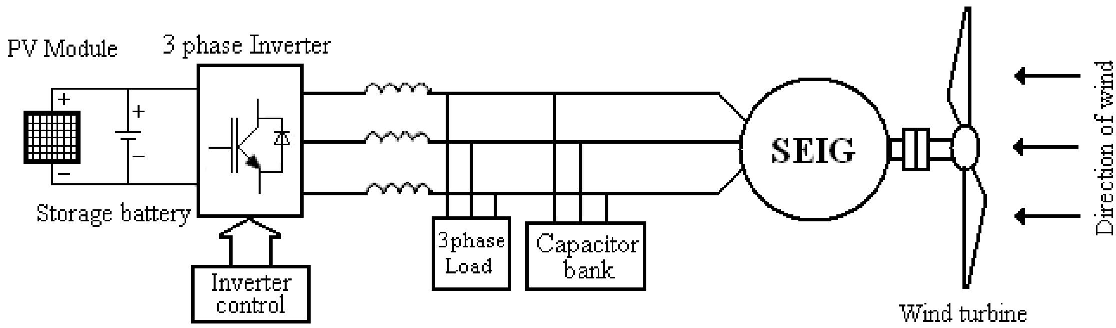

Fig. 1. Proposed generation scheme model

2 Capacitor calculation technique

The voltage and current equations for the induction generator in synchronous $d-q$ reference frame are

$$V_{ds} = R_s i_{ds} + \frac{d\lambda_{ds}}{dt} - \omega_s \lambda_{qs}, \tag{1}$$

$$V_{qs} = R_s i_{qs} + \frac{d\lambda_{qs}}{dt} - \omega_s \lambda_{ds}, \tag{2}$$

$$0 = R_r i_{dr} + \frac{d\lambda_{dr}}{dt} - (\omega_s - \omega_r)\lambda_{qr}, \tag{3}$$

$$0 = R_r i_{qr} + \frac{d\lambda_{qr}}{dt} - (\omega_s - \omega_r)\lambda_{dr}, \tag{4}$$

where, λ is the flux linkage, subscripts d and q denotes the d axis and q axis components respectively and subscripts s and r denotes the stator and rotor quantities respectively, ω_s is the speed of the synchronous reference frame and ω_r is the speed of the rotor reference frame. The flux linkage equations can be further simplified as:

$$\lambda_{ds} = L_s i_{ds} + L_m i_{dr}, \tag{5}$$

$$\lambda_{qs} = L_s i_{qs} + L_m i_{qr}, \tag{6}$$

$$\lambda_{dr} = L_r i_{dr} + L_m i_{ds}, \tag{7}$$

$$\lambda_{qr} = L_r i_{qr} + L_m i_{qs}. \tag{8}$$

Where, L_s, L_r and L_m indicate the stator leakage, rotor leakage and magnetizing inductances respectively.

The steady state model of the induction machine is considered for calculating the bulk excitation capacitance required for the machine. The derivative terms of Eq. (1)-(4) becomes zero for constant flux operation. Also, neglecting the leakage inductances, the stator and rotor voltage Eqs. from (1)-(4) in steady state can be given as:

$$v_{ds} = R_s i_{ds} - \omega_s \lambda_{qm}, \tag{9}$$
$$v_{qs} = R_s i_{qs} + \omega_s \lambda_{dm}, \tag{10}$$
$$0 = R_r i_{dr} - (\omega_s - \omega_r)\lambda_{qm}, \tag{11}$$
$$0 = R_r i_{qr} - (\omega_s - \omega_r)\lambda_{dm}. \tag{12}$$

Where, $\lambda_{dm} = L_m i_{dm}$, $\lambda_{qm} = L_m i_{qm}$, $i_{dm} = i_{dr} + i_{ds}$ and, $i_{qm} = i_{qr} + i_{qs}$.
The stator resistance drop at rated voltage can also be neglected in [8] and [7] giving,

$$v_{ds} = -\omega_s \lambda_{qm}, \tag{13}$$
$$v_{qs} = \omega_s \lambda_{dm}. \tag{14}$$

Assuming air-gap flux orientation of d-axis, $\lambda_{dm} = \lambda_m$ and $\lambda_{qm} = 0$.
Therefore, $i_{qm} = 0$.
Thus from rotor voltage Eq. (11),

$$R_r i_{dr} = 0. \tag{15}$$

As the rotor resistance is a non-zero quantity, $i_{dr} = 0$(from Eq. (15). Therefore, $i_{ds} = i_{dm}$. Thus the air-gap flux can be given as:

$$\lambda_m = L_m i_{ds}. \tag{16}$$

Where, i_{ds} is the stator magnetizing current. The capacitor bank is utilized as a bulk uncontrolled source of reactive power which supplies the base requirement of the machine at no-load conditions. The basic design principle for the capacitor is such that it has to supply the whole reactive current needed to generate the initial voltage under nominal speeds and no load conditions. The current i_{ds} will be provided by the capacitor alone. Based on Eqs. (13)-(16), the d-axis equivalent circuit for the generator can be developed, which is shown in Fig. 2. Therefore, from Fig. 2 it can be shown:

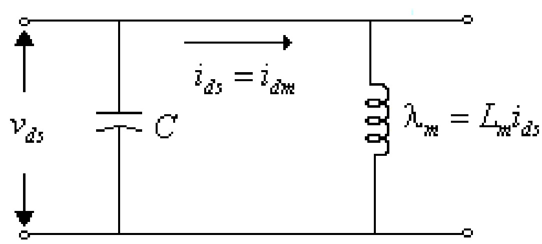

Fig. 2. D-axis equivalent circuit of the proposed induction generator

$$i_{ds} = j v_{ds} \omega_r C, \tag{17}$$
$$\text{Or, } i_{ds} = v_{qs} \omega_r C. \tag{18}$$

The open circuit characteristics (OCC) of the induction machine used was found out experimentally, as given in Fig. 3. The excitation voltage and magnetizing current as depicted in the OCC are the q-axis stator voltage v_{qs} and d-axis stator current i_{ds} respectively. As seen from Fig. 3 , the OCC shows highly nonlinear variations of v_{qs} with i_{ds}. Presumption of a linear magnetization curve provides a capacitor value which will be inaccurate, error prone and thus, cannot provide a stable output voltage with wider variation of rotor speeds. Hence, taking into account of this nonlinearity, λ_m can be obtained as a non-linear function of i_{ds}. The mixed model equations from [3], for λ_m takes the form:

$$\lambda_m = k + k_1 i_{ds} + k_2 i_{ds}^2. \tag{19}$$

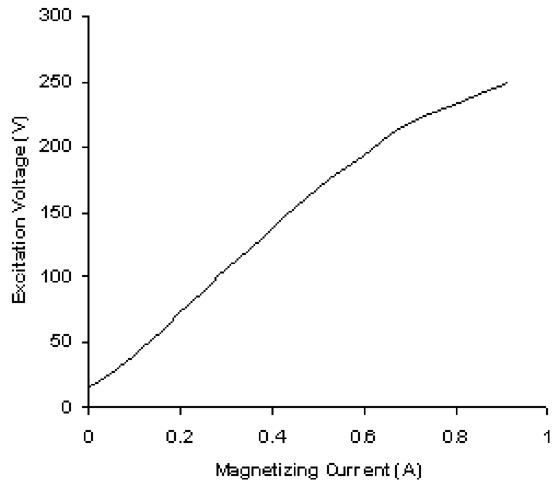

Fig. 3. Open Circuit Characteristics of the experimental induction machine (OCC)

Where,k , k_1 and k_2 are constants and can be obtained from the magnetization curve for the induction machine. Putting the value of λ_m from Eq. (19) into Eq. (14) and also using value of i_{ds} from Eq. (17), a quadratic equation involving capacitance term C can be obtained as:

$$(\omega_r^3 k_2 v_{qs}^2)C^2 + (\omega_r^2 k_1 v_{qs})C + (\omega_r k - vqs) = 0. \tag{20}$$

Examining the valid roots for Eq. (20), the capacitance can be calculated as:

$$C = \frac{-k_1 - \sqrt{k_1^2 - 4k_2\left(\frac{\omega_r k - v_{qs}}{\omega_r}\right)}}{2k_2\omega_r v_{qs}} \text{ Farads.} \tag{21}$$

The above equation can be used to calculate the initial bulk capacitance C required for the machine to start generation initially at no-load condition. The values of k, k_1 and k_2 can be found with the help of any of the already known standard curve fitting techniques. Least square method is used in the present work for the same. The co-efficients k_2, k_1 and k are obtained as -97.0, 359.3 and 7.95 respectively.

3 Proposed control technique

The self excited induction generator system consists of a conventional three phase cage induction machine which is driven by an electrical prime mover (dc motor). The initial excitation at no load is provided by the capacitor bank. The PV module acts as the dc bus to the inverter assembly and supplies the inverter during the day. The battery backup can be used during the night or cloudy conditions. The stator reactive current will be the sum of the uncontrolled capacitor reactive current and the controlled inverter reactive current when under loaded conditions. As depicted in Fig. 4 , the generator line voltages v_{abc} and currents i_{abc} are sensed to derive the inverter d-axis and q-axis current references $i_{di}*$ and $i_{qi}*$ respectively. v_s* is the reference voltage. Now the inverter side line currents i_{abc} are sensed and are used to calculate the corresponding α-axis and β-axis currents i_α and i_β. Using the derived unit vectors from the generated voltage, $i_{di}*$ and $i_{qi}*$ are converted to the corresponding α-axis and β-axis reference currents $i_{\alpha i}*$ and $i_{\beta i}*$ respectively. These currents are then compared with the inverter side α-axis and β-axis currents i_α and i_β in a hysteresis based current controller to generate the inverter switching pulses.

The unit vectors $cos\theta_e$ and $sin\theta_e$ can be calculated from α and β axis flux linkages which are functions of α and β axis stator voltages as shown in the Fig. 4. The equations are given as:

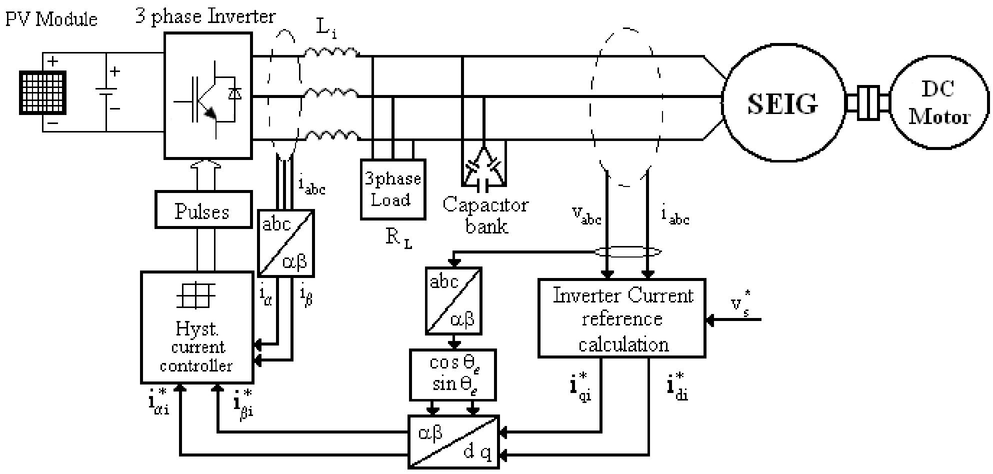

Fig. 4. Experimental block diagram.

$$\lambda_{\alpha m} = \int (v_{\alpha s} - R_s i_{\alpha s}) dt, \tag{22}$$

$$\lambda_{\beta m} = \int (v_{\beta s} - R_s i_{\beta s}) dt. \tag{23}$$

Therefore the unit vectors are,

$$cos\theta_e = \frac{\lambda_{\alpha m}}{\sqrt{(\lambda_{\alpha m})^2 + (\lambda_{\beta m})^2}}, \tag{24}$$

$$sin\theta_e = \frac{\lambda_{\beta m}}{\sqrt{(\lambda_{\alpha m})^2 + (\lambda_{\beta m})^2}}. \tag{25}$$

Fig. 5, shows the Hysteresis current controller used to produce the pulses of the inverter.

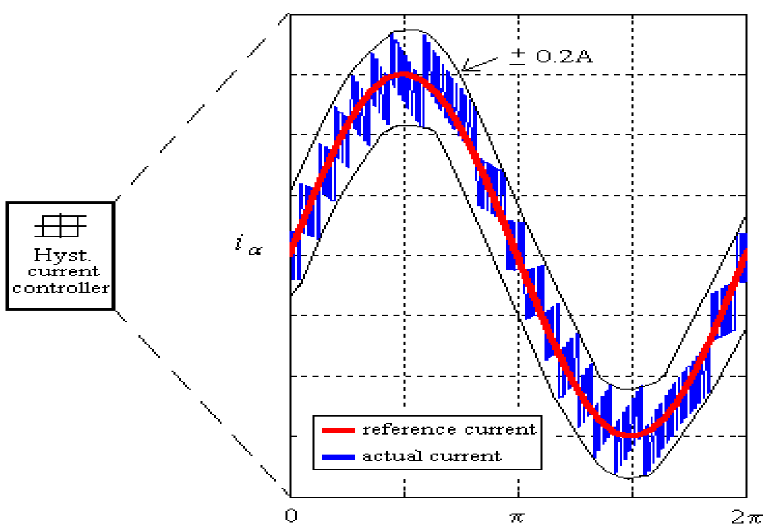

Fig. 5. Hysteresis current controller.

4 Simulation and experimental results

A cage induction machine (Tab. 1) was used for the experimental setup with a dc motor as a prime mover emulating the wind turbine. The current and voltage sensing were carried with LEM Hall-effect sensors LTS

25-NP and LV 25-P respectively. Microcontroller PIC18F452 of Microchip was used to generate the switching pulses for the inverter. A digital storage oscilloscope (Tektronix make, Model No. TDS2022B) was used for acquiring the waveforms of line voltage and current. The calculated capacitor value considering magnetizing curve nonlinearity is $13\mu F$ for generating nominal voltage at nominal speed. However, if a linear magnetizing curve is considered, the capacitor value requirement is $10\mu F$. The induction generator was made to generate using both these values of terminal capacitances separately. The plot is shown in Fig. 6. The generation was steadier using $13\mu F$ capacitor as shown.

Table 1. Induction machine specifications

Rated output	No. of Poles	Rated speed	Rated voltage	Stator winding	Rotor type
1 hp	4	1400 r/min	415 V, 50 Hz	Star connected	Cage

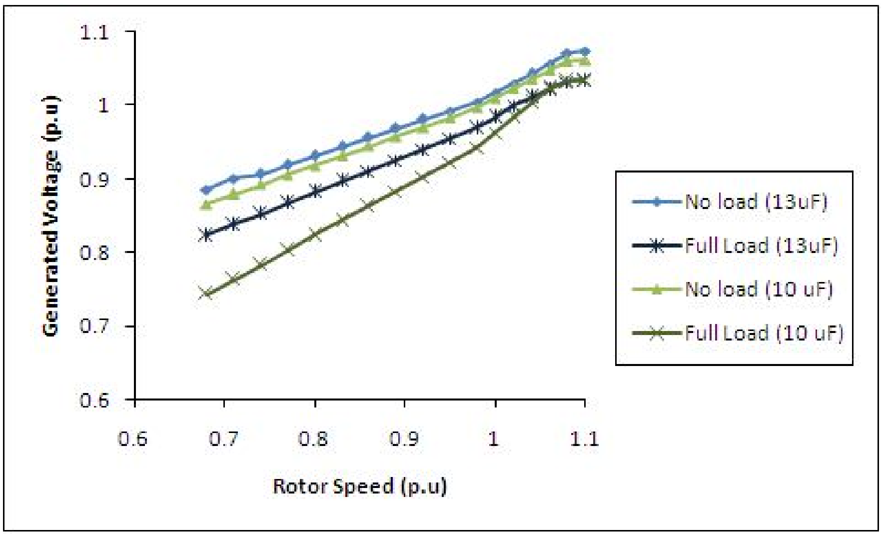

Fig. 6. Comparative experimental voltage variation against the speed of the generator for both the capacitances.

The proposed model based control technique is applied for the induction generator as shown in Fig. 4, at full load. Experimental result for voltage variation using the proposed control technique is shown in Fig. 7. The control technique shows steady output voltage across a wide range of varying rotor speed. Thus it can be concluded that this control technique can be of good realistic worth and can revolutionize power generation using induction generator where maintaining a stable voltage with varying rotor speeds is a major challenge.

Fig. 8 shows the reactive current variation of inverter with the rotor speed of the generator keeping the load fixed at 1 $p.u$. The experimental waveforms for inverter voltage, load current and load voltages are shown in Fig. 9, Fig. 10 and Fig. 11 respectively. As seen from Fig. 10, as the load is increased from 0.5 $p.u$ to 1 $p.u$, the load voltage remains almost constant as depicted in Fig. 11. This shows that the proposed induction generator with its control provides good voltage regulation with change in load.

5 Conclusions

A simple model based control of self excited induction generator is proposed in this paper. A technique for calculation of the bulk capacitance considering magnetic nonlinearity for three-phase SEIG is proposed using the model. The induction generator with the proposed control chiefly aims at wide ranges of speed and load variation control for this type of generation. The induction generator shows stable voltage generation with the proposed control and is supported by the simulated and experimental findings. The PV module backs

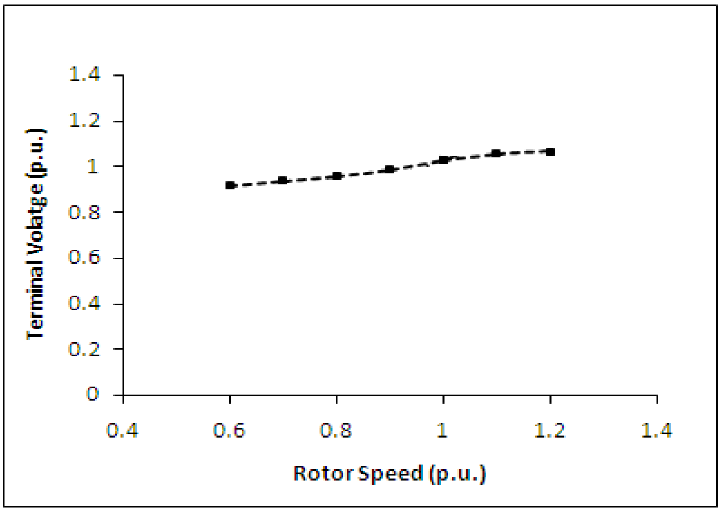

Fig. 7. Terminal voltage variation with proposed control at full load with $13F$ capacitor.

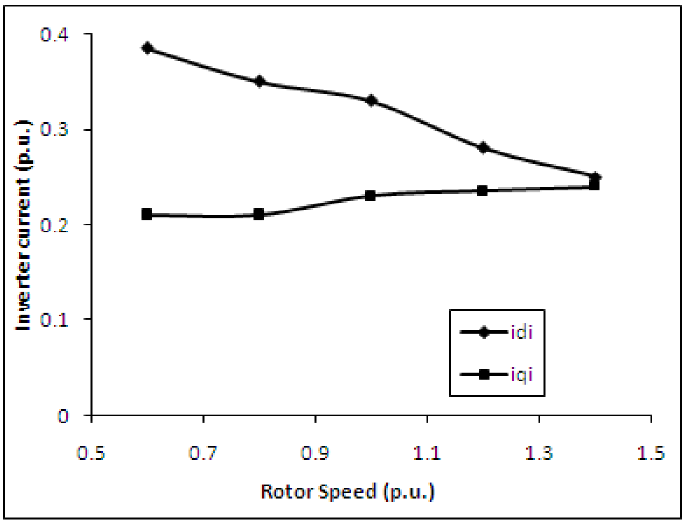

Fig. 8. Inverter reactive current variation with rotor speed at fixed load of 1 $p.u.$

the inverter dc bus which also makes the scheme suitable for its use in grid isolated modes. The proposed model based induction generator is thus a suitable generation scheme for wide speed range applications.

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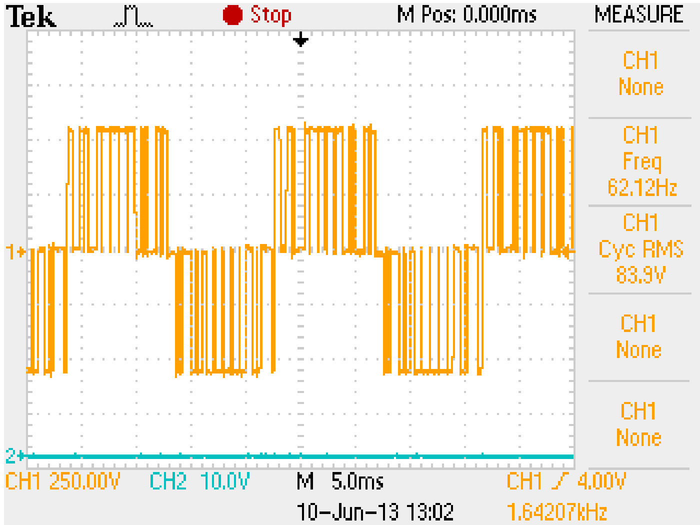

Fig. 9. Inverter voltage at 1 $p.u.$ load and 1 $p.u.$ speed.

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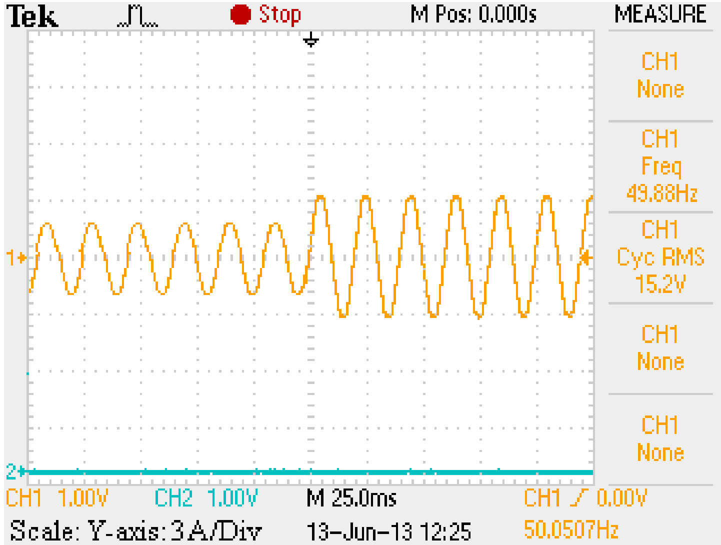

Fig. 10. Experimental waveforms for Load current at when load is changed from 0.5 $p.u$ to1 $p.u$.

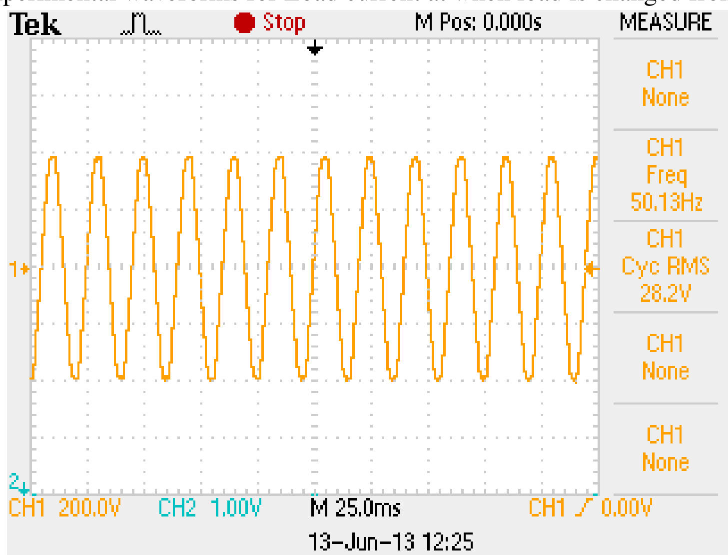

Fig. 11. Experimental waveforms for Corresponding load voltage.