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Static VAR Compensator Based Voltage Control of Stand Alone Self Excited Induction Generator

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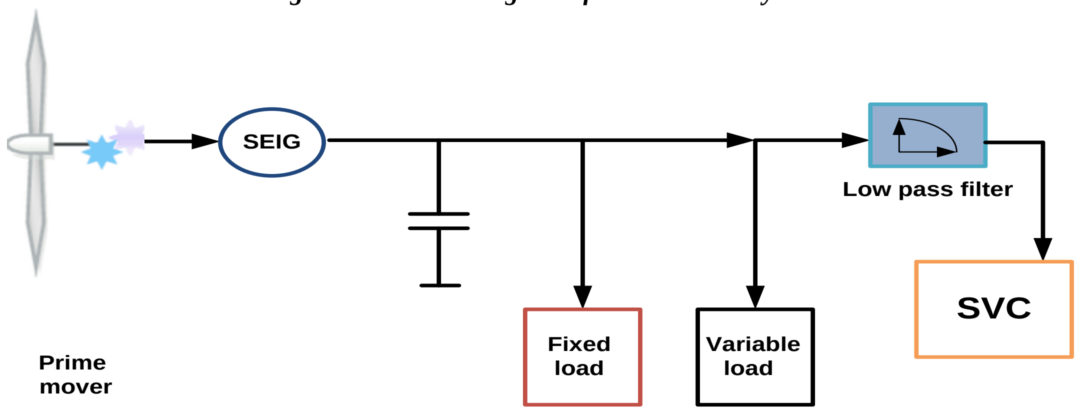
ABSTRACT
This paper presents a voltage control of a stand-alone self-excited induction generator. The voltage control is performed using a static VAR compensator (SVC). A low pass filter is used with SVC to reduce the harmonic content in voltage waveforms. This is validated by simulating a system consisting of a stand-alone induction generator, fixed load, variable load, and SVC using MATLAB SIMULINK. A proportional integral (PI) controller with fixed gains is used with the control system with using a low pass filter and without the filter. The results are obtained in the both cases. Finally, the use of low pass filter with SVC gives an improved performance as compared to the system without the filter.
KEYWORDS*: FACTS, SVC, SEIG*

I. INTRODUCTION

Squirrel cage induction generator has several advantages as compared to other generator types. These advantages are the brushless construction, robustness, low maintenance requirements, lower weight to power ratio and lower cost. These advantages make the squirrel cage induction generator to be popular for use with wind turbines [1]-[5]. Squirrel cage induction generator is used with wind turbines to provide the energy conversion of wind power to electrical power. It is used as a stand - alone generator to supply isolated loads [1], [6]-[8] as well as grid connected to supply electrical power to grid [9], [10]. For the use as a stand-alone generator, magnetic field required for energy conversion is self - generated using external capacitors at the generator terminals. Therefore, for a stand-alone operation mode, the generator is called self-excited induction generator (SEIG).

Although, SEIG has several advantages as aforementioned above, it suffers from severe voltage drop when it is loaded [10]-[14]. This voltage drop comes due to the increased need for reactive power with the increase in load. Also, at critical load, the terminal voltage can be collapsed [15]. To obtain a constant voltage to loads connected with SEIG, several voltage control techniques are used [12], [16]-[18]. Among these methods is the use of switched capacitors at the SEIG terminals [20], [21]. These switched capacitors are connected automatically according to load power. Using this method, voltage is not constant at the whole operating range [19], [22], [23]. Using series capacitors in addition to excitation capacitors is another method that is used to increase the power at which terminal voltage is collapsed [12],[14]. But, the use of series capacitor is not popular to avoid the occurrence of ferro-resonance. Using static var compensators (SVC), flexible AC transmission systems (FACTS), and static compensators (STATCOM) are used to control the voltage of SEIG [19], [24]-[26]. The use of such compensators provides a better performance as compared to switched capacitor method. In fact, FACTS and STATCOM are used as an alternative to SVC to reduce the harmonic content in terminal voltage of SEIG [25]-[26]. But, SVC is constructed using thyristors that is considered to be more robust than IGBTs which used in FACTS and STATCOM. So, this paper presents the use of SVC to control terminal voltage of SEIG with reduced harmonic content.

Fig.1 A schematic diagram of the simulated system



In this paper, a voltage control of a stand-alone self-excited induction generator is presented. The voltage control is carried out using a static VAR compensator (SVC). A low pass filter is used with SVC to reduce the harmonic content in voltage waveforms. This is validated by simulating a system consisting of a stand-alone induction generator, fixed load, variable load, and SVC using MATLAB SIMULINK. A proportional integral (PI) controller with fixed gains is used with the control system with using a low pass filter and without the filter. The results are obtained in the both cases. Finally, the use of low pass filter with SVC gives an improved performance as compared to the system without the filter.

II. SYSTEM MODELLING

A system consists of a 275 kVA, 380 V, 50 Hz SEIG, 75 kVAR fixed excitation capacitor, SVC, 50 kW fixed resistive load, and a variable load is simulated using MATLAB SIMULINK. The simulated SEIG is driven at constant speed to obtain a frequency of 50 Hz. Fig. 1 shows a schematic diagram of the simulated system. In fact, the system of Fig. 1 is simulated two times. The first time, simulation is carried out without the use of low-pass filter at SVC terminals. The second time, the system is simulated using an LC low-pass filter having an inductance of 0.1 µH and a capacitance of 100 µF at the terminals of SVC. For the two cases a PI controller is used with proportional gain (Kp) of 0.2 and an integral gain (Ki) of 0.003.

2.1. Equations

SEIG is simulated by applying the Park transformation. Park transformation uses a two-phase primitive machine with fixed stator windings and rotating rotor windings to represent fixed stator windings (direct axis) and pseudo-stationary rotor windings (quadrature axis). In d-q synchronous rotating reference frame, stator and rotor circuit equations can be written as :

A. Induction machine dynamic model

The dynamic d-q model of the induction machine derived in this paper is based on some assumptions: cylinder type rotor, constant air gap, three-phase symmetrical stator and rotor windings (on the cage type rotors, the squirrel cage equivalent to a three phase symmetrical coil), sinusoidal distribution of the air gap magnetic field (space harmonics are neglected). Rotor variables and parameters are referred to the stator winding, and core losses are neglected. In d-q synchronously rotating frame, the stator and rotor circuit equations expressed in terms of space phasors are the following[27]:

$$u_s = R_s i_s + \frac{d\psi_s}{dt} + j\omega_\lambda \psi_s, \quad (1)$$

$$u_r = R_r i_r + \frac{d\psi_r}{dt} + j(\omega_\lambda - \omega)\psi_r, \quad (2)$$

Where all the variables and parameters are referred to the stator windings. The model includes the equation of rotational motion

$$j\frac{d\omega_r}{dt} + B\omega_r + T_L = T_{em} \quad (3)$$

In (3), $\omega r = \omega / z_p$ is the mechanical angular speed of the rotor, z_p number of machine pole pairs, j is the rotor inertia, T_L is the load torque (negative value for generating operation), and T_{em} the electromagnetic torque. Other symbols used are explained in the List of Symbols. In this paper, the dynamic model of induction machine is derived by choosing computation quantities expressed in terms of stator and rotor flux d-q axis components, as state variables. The state variables expressed in terms of d-q axis flux linkages are defined as [28], [29]:

$$x_1 = \omega_b \psi_{sd}; \qquad x_2 = \omega_b \psi_{sq};$$
$$x_3 = \omega_b \psi_{rd}; \qquad x_4 = \omega_b \psi_{rq}; \tag{4}$$

where ω_b is the base angular frequency of the machine. The d-q axis voltage equations can be expressed by expanding the space phasors, in (1) and (2), in their components [27], and taking into account (4), as follows:

$$u_{sd} = R_s i_{sd} + \frac{1}{\omega_b}\frac{dx_1}{dt} - \frac{\omega_\lambda}{\omega_b} x_2, \tag{5}$$

$$u_{sq} = R_s i_{sq} + \frac{1}{\omega_b}\frac{dx_2}{dt} + \frac{\omega_\lambda}{\omega_b} x_1, \tag{6}$$

$$u_{rd} = R_r i_{rd} + \frac{1}{\omega_b}\frac{dx_3}{dt} - \frac{(\omega_\lambda - \omega)}{\omega_b} x_4, \tag{7}$$

$$u_{rq} = R_r i_{rq} + \frac{1}{\omega_b}\frac{dx_4}{dt} + \frac{(\omega_\lambda - \omega)}{\omega_b} x_3, \tag{8}$$

For a cage type induction machine it is assumed that $u_{rd} = u_{rq}$. Because the machine parameters are frequently given in ohms, or per unit of base impedance [29], it is often convenient to express then flux linkage equations in terms of reactances rather then inductances. Therefore, the expressions of state variables are given with

$$x_1 = X_{ls} i_{sd} + x_6, \tag{9}$$

$$x_2 = X_{ls} i_{sq} + x_7, \tag{10}$$

$$x_3 = X_{lr} i_{rd} + x_6, \tag{11}$$

$$x_4 = X_{lr} i_{rq} + x_7, \tag{12}$$

Where

$$X_{ls} = \omega_b L_{ls}; \qquad X_{lr} = \omega_b L_{lr}; \qquad X_m = \omega_b L_m$$

And

$$x_6 = X_m (i_{sd} + i_{rd}), \tag{13}$$

$$x_7 = X_m (i_{sq} + i_{rq}), \tag{14}$$

The currents can be expressed in terms of the state variables as:

$$i_{sd} = \frac{x_1 - x_6}{X_{ls}}; i_{sq} = \frac{x_2 - x_7}{X_{ls}} \tag{15}$$

$$i_{rd}=\frac{x_3-x_6}{X_{lr}};i_{rq}=\frac{x_4-x_7}{X_{lr}} \tag{16}$$

The expressions of x_6 and x_7 have to be written in terms of chosen state variables, and therefore are derived, by substituting (15)-(16), in (13)-(14), as

$$x_6=\frac{X_{m1}}{X_{ls}}x_1+\frac{X_{m1}}{X_{lr}}x_3, \tag{17}$$

$$x_7=\frac{X_{m1}}{X_{ls}}x_2+\frac{X_{m1}}{X_{lr}}x_4, \tag{18}$$

Where the following notation is used [4]:

$$X_{m1}=\left(\frac{1}{X_m}+\frac{1}{X_{ls}}+\frac{1}{X_{lr}}\right)^{-1}$$

The *d-q* axis voltage equations of the induction machine are derived in state-space form, by substituting the current equations (15), (16) into the voltage equations (5) – (8), as

$$\frac{dx_1}{dt}=\omega_b\left[-\frac{R_s}{X_{ls}}x_1+\frac{\omega_\lambda}{\omega_b}x_2+\frac{R_s}{X_{ls}}x_6+u_{sd}\right], \tag{19}$$

$$\frac{dx_2}{dt}=\omega_b\left[-\frac{\omega_\lambda}{\omega_b}x_1-\frac{R_s}{X_{ls}}x_2+\frac{R_s}{X_{ls}}x_7+u_{sq}\right], \tag{20}$$

$$\frac{dx_3}{dt}=\omega_b\left[-\frac{R_r}{X_{lr}}x_3+\frac{(\omega_\lambda-\omega)}{\omega_b}x_4+\frac{R_r}{X_{lr}}x_6\right], \tag{21}$$

$$\frac{dx_4}{dt}=\omega_b\left[-\frac{(\omega_\lambda-\omega)}{\omega_b}x_3-\frac{R_r}{X_{lr}}x_4+\frac{R_r}{X_{lr}}x_7\right] \tag{22}$$

The expressions of u_{sd} and u_{sq} are presented in the load model (25), (26), as additional state variables. The electromagnetic torque expression [30], is given, taking into account Eqs. (4), as follows

$$T_{em}=\frac{3}{2}z_p\frac{L_m}{L_r}\frac{1}{\omega_b}(i_{sq}x_3-i_{sd}x_4) \tag{23}$$

Thus, the equation governing the rotational motion can be expressed by (24), in which the viscous frictional torque was neglected, the fifth state variable x_5 represents the electrical rotor angular speed ω , and the current expressions are given in (15).

$$\frac{dx_5}{dt}=\frac{3}{2}\frac{z_p^2}{J}\frac{X_m}{(X_{lr}+X_m)}\frac{1}{\omega_b}(i_{sq}x_3-i_{sd}x_4)-\frac{z_p}{J}T_L \tag{24}$$

The fifth order dynamic model of the induction machine, having the state variables defined in (4) and written in terms of reactances, is formed by (19) – (22), and (24).

III. SIMULATION RESULTS

Figs. 2a and 3a show load voltage waveforms expressed in p.u. when the variable load of 0.4 p.u. with 0.5 lagging p.f. is switched at SEIG terminals. Fig. 2a and 3a represent the voltage waveforms without the use of passive LC filter and when using the filter at SVC terminals, respectively. From these figures, terminal voltage is constant due to the use of SVC considering the both studied cases. So, SVC can be used to control the terminal voltage of SEIG. But, after load switching, ripples in voltage started to appear at the case of no filter as demonstrated from Fig. 2b. These ripples do not appear when the filter is used as shown from Fig. 3b. The ripples comes due to the injected harmonics from SVC, so that, injected reactive power is more distorted in the system without filter (Fig. 2c) if compared to the system with filter (Fig. 3c). The increase in load current due to loading is shown as waveforms for the two systems in Figs. 2d and 3d, respectively. Also, the increase in load current is shown as RMS values by Figs. 2e and 5e for the two systems, respectively. The increase in load power due to loading for the two studied systems is demonstrated by Figs. 2f and 5f, respectively and the same discussions can be adopted.

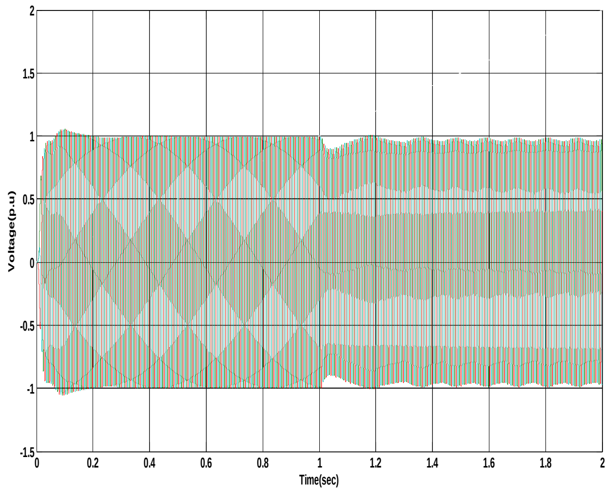
For more validation, another case is presented. In this case a sudden change of 0.2 p.u. load with unity power factor is suddenly connected at the SEIG terminals. Terminal voltage waveforms, load currents, RMS voltages, reactive power injected from SVC, load current waveforms, load RMS currents and load active power are shown in Figs. 4 and 5 for the two studied systems, respectively. From these figures, it can be also shown that the performance of SVC considering LC low pass filter at its terminals is improved as the harmonic content is reduced. So, it is recommended to use a low-pass filter at the terminals of SVC when used to control the voltage of a SEIG.

IV. CONCLUSION

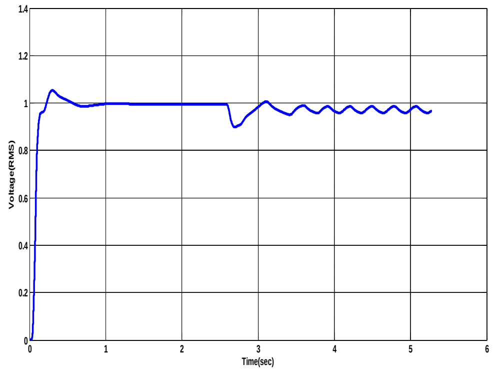
Performance of SEIG control system using SVC has been presented. The performance of the studied system has been investigated considering two cases (i.e. without and with filter at SVC terminals). The use of LC low-pass filter at SVC terminals has proven its efficacy in reducing harmonic content in terminal voltages as well as load currents. Generally, the following points can be concluded:

1- The use of SVC with SEIG can be used to control the terminal voltages at the desired level considering load variations.
2- The use of SVC without low-pass filter causes injection of harmonic content in terminal voltages.
3- To reduce the harmonic content produced by SVC, a low-pass filter can be used across its terminals.
4- Using a low-pass filter across the terminals of SVC resulting in a reduced harmonic content in terminal voltages and so, an improved performance.

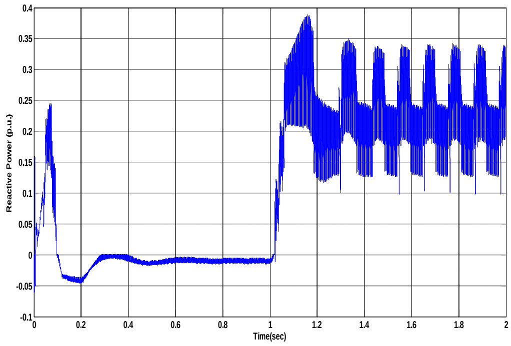
Fig. 2 load voltage, voltage RMS, reactive power, RMS Current, load Power an Current versus with time at 0.4 p.u., 0.5 lagging without filter



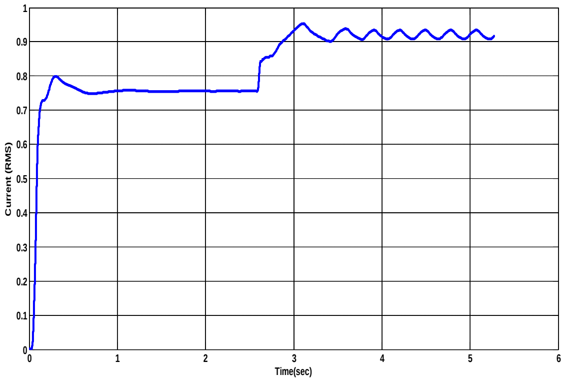
(2a) Voltage versus with time without using filter



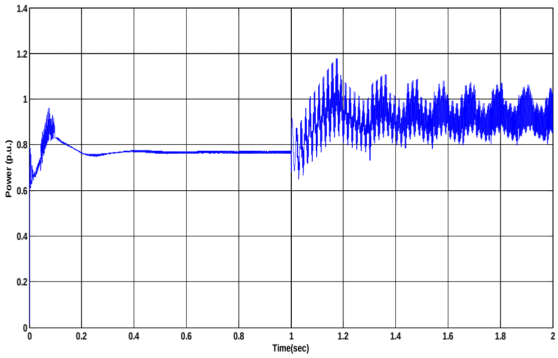
(2b) voltage RMS without using filter



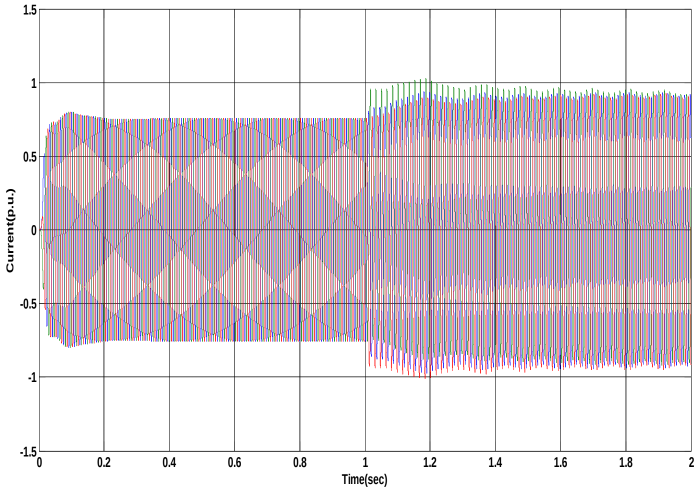
(2c) reactive power without using filter



(2d) RMS Current without using filter

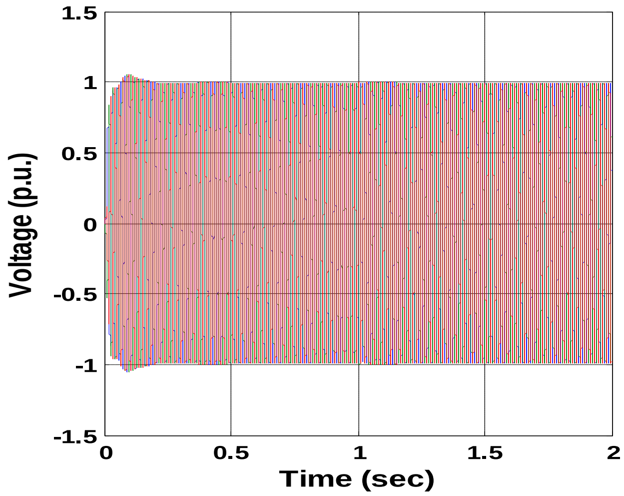


(2e) Load power without using filter

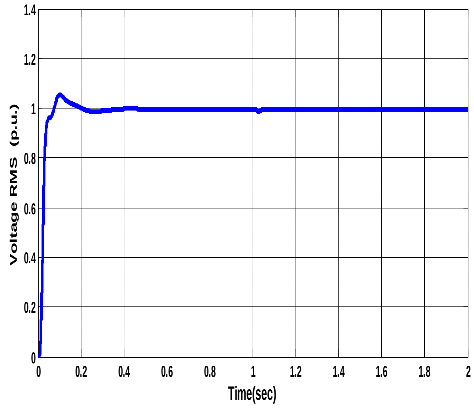


(2f) Current without using filter

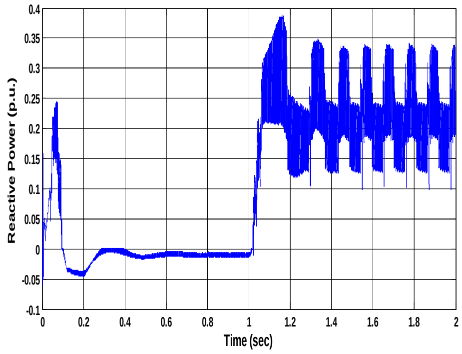
Fig. 3 load voltage, voltage RMS, reactive power, RMS Current, load Power an Current versus with time at 0.4 p.u., 0.5 lagging p.f with using filter



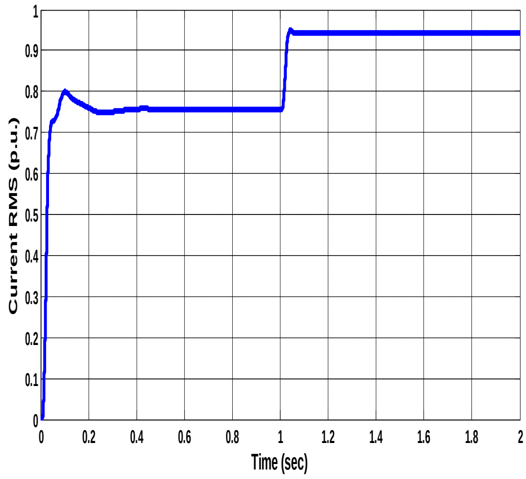
(3a) Voltage versus with time with using filter



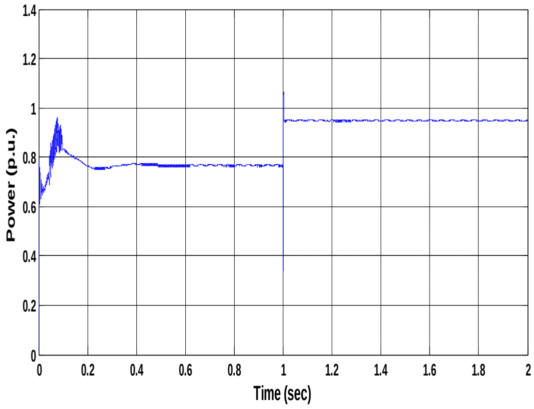
(3b) voltage RMS with using filter



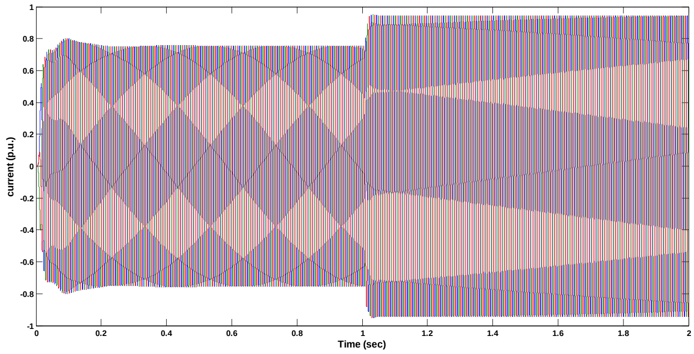
(3c) reactive power with using filter



(3d) RMS Current with using filter

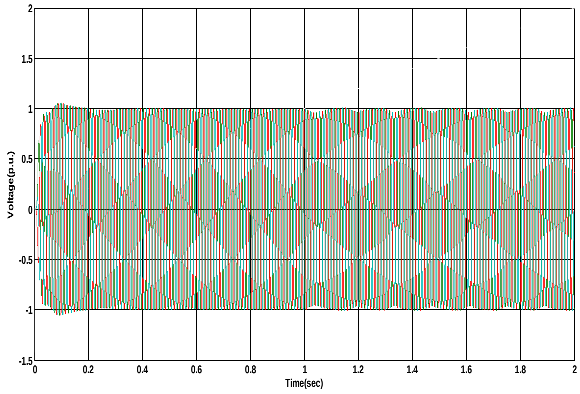


(3e) Load power with using filter

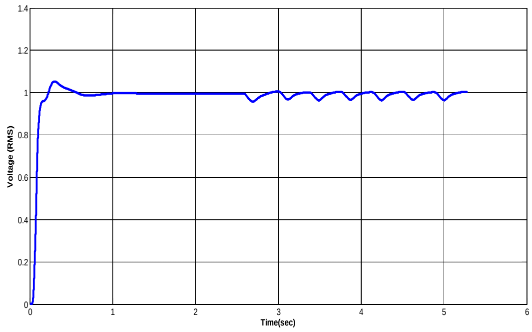


(3f) Current with using filter

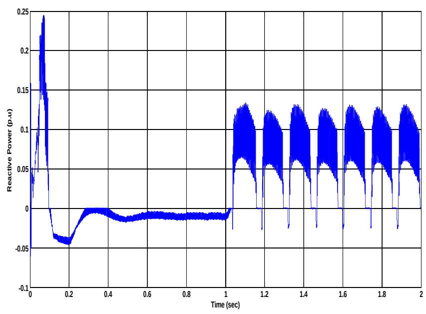
Fig. 4 load voltage, voltage RMS, reactive power, RMS Current, load Power an Current versus with time at 0.2 p.u., and unity p.f without filter



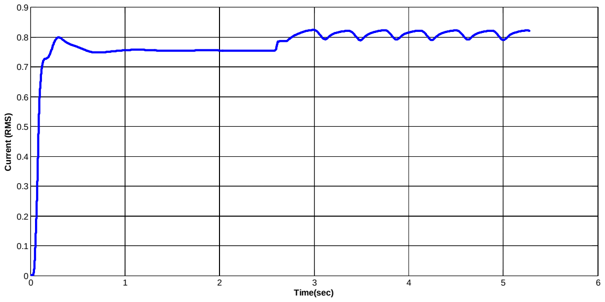
(4a) Voltage versus with time without using filter



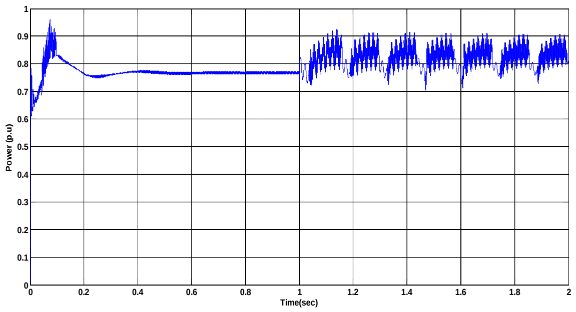
(4b) voltage RMS without using filter



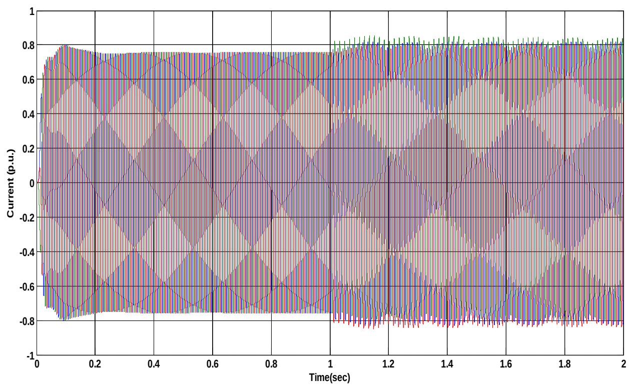
(4c) reactive power without using filter



(4d) RMS Current without using filter

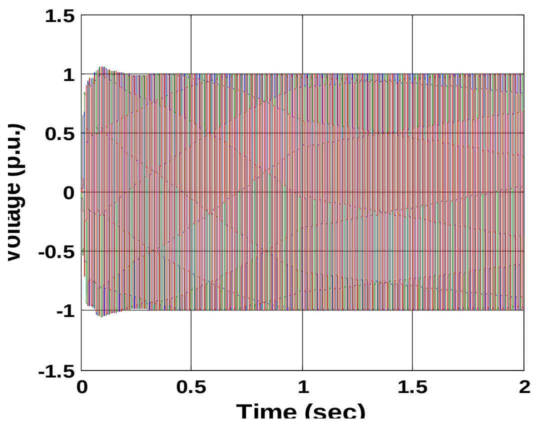


(4e) Load power without using filter

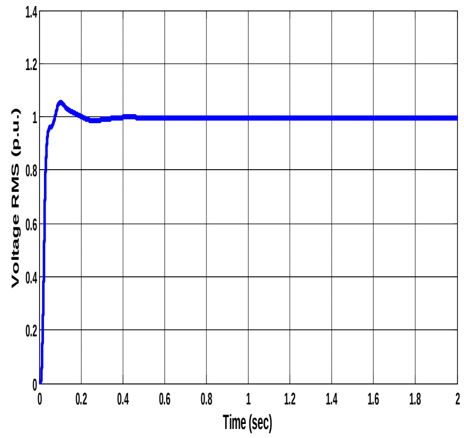


(4f) Current without using filter

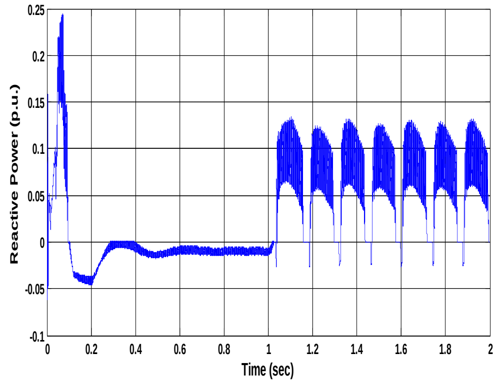
Fig. 5 load voltage, voltage RMS, reactive power, RMS Current, load Power an Current versus with time at 0.2 p.u., unity p.f. and with using filter



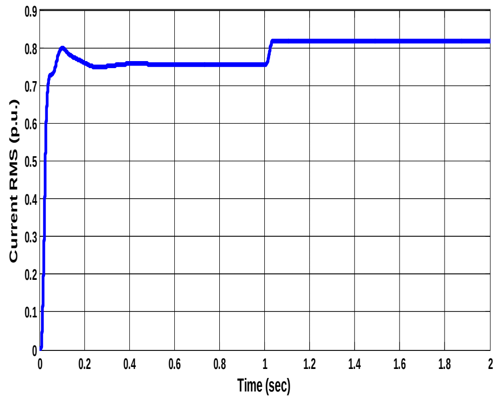
(5a) Voltage versus with time with using filter



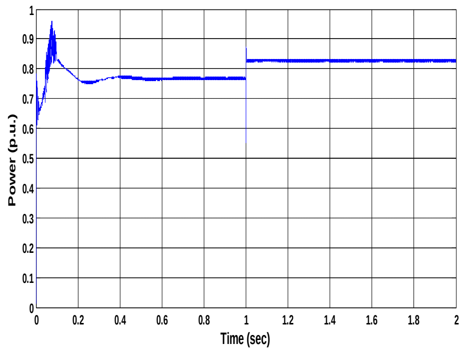
(5b) voltage RMS with using filter



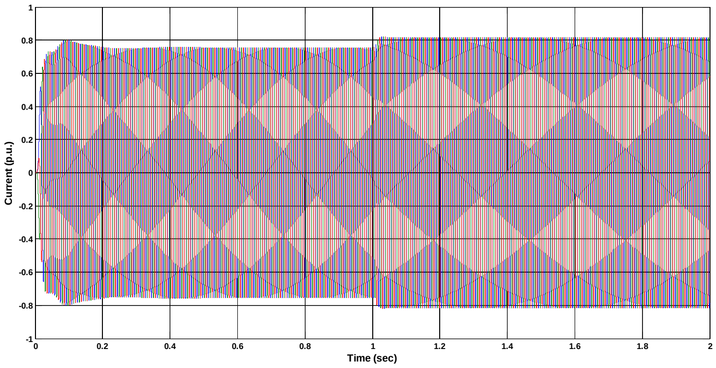
(5c) reactive power with using filter



(3d) RMS Current with using filter



(5e) Load power with using filter



(5f) Current with using filter

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