Analysis of voltage control for a self-excited induction generator using a three-phase four-wire electronic converter

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Abstract. This paper shows the effect of magnetic saturation during self-excitation process in an isolated three-phase induction generator, for a given capacitance and rotor speed value. After the steady state condition of a self-excited induction generator (SEIG) is attained, an increase of load causes a decrease in the magnitude of generated voltage and its frequency. Moreover, when a three-phase four-wire generator work under unbalanced and/or nonlinear loading conditions, the voltage and stator currents are also unbalanced, flows a current in the neutral conductor and appears harmonics.

Therefore, a three-phase four-wire active filter is used to compensate the harmonics and asymmetries in the stator currents caused by the previous type of loads. The control strategy of this electronic converter is based in a fundamental positive-sequence detector. Finally, for small hydro plants applications, the converter incorporate too a dc chopper to keeps the load constant on the SEIG, so the generator maintain the rated voltage and frequency.

The simulation results show a good performance of the SEIG and the electronic converter under different loading conditions.

Key words

Self-excited induction generator, static compensator, shunt active filter, electronic load controller.

1. Introduction

An externally driven induction machine with an appropriate value of capacitor bank can be used as a generator [1]. This system is called self-excited induction generator (SEIG). The SEIG has many advantages over the synchronous generator: brushless (squirrel cage rotor), reduced size, rugged and low cost. But the induction generator offers poor voltage regulation and its value depends on the prime mover speed, capacitor bank and load.

The cage-type induction generators have emerged in these recent years as a suitable candidate in remote areas where this machine can be driven using a wind turbine, a diesel engine or small hydro plants. Normally, in this last application, the SEIG generates constant voltage and frequency because it is operating at constant load power.

When an isolated SEIG feeds unbalanced and/or non-linear loads, the three-phase terminal voltage and stator currents are also unbalanced and may appear harmonics. These increase the power losses, create unequal heating and cause torque pulsation on the shaft of the generator. Also, the unbalanced three-phase currents yield a current in the neutral conductor that involves more power losses and heating.

2. System configuration

The proposed system consists of a SEIG driven by an unregulated hydraulic turbine. The generator supplies an isolated three-phase four-wire load. The voltage and frequency control of the system is achieved by an electronic converter connected to the generator terminals (Fig. 1). This converter is made up of a shunt active filter and an electronic load controller.

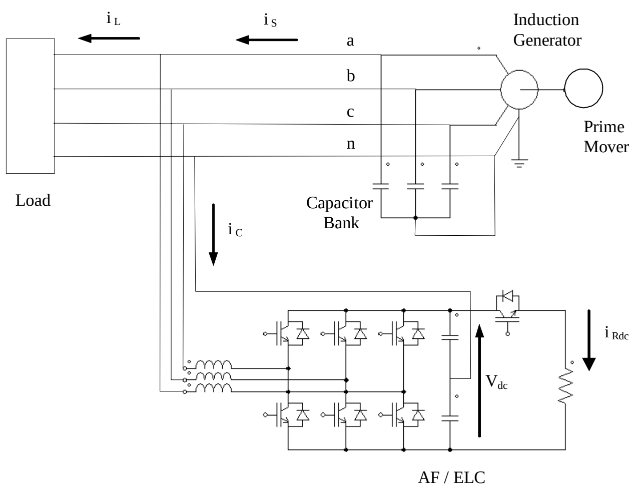

Fig. 1. Schematic diagram of proposed system

The SEIG is a three-phase induction machine with a wye-connected stator winding. Its middle point is connected to the neutral conductor. The capacitor bank is connected to the other three external terminals. Finally, a prime mover rotates the squirrel cage rotor at a speed higher than the synchronous speed.

The electronic converter is a static compensator (STATCOM). It consists of a four-wire shunt active filter (AF) made up of a three-leg split-capacitor boost converter [2] and an electronic load controller (ELC) made up of a chopper connected to a resistor [3,4].

3. Modeling of the system

A. Induction generator model

The dynamic model of the squirrel cage induction generator in the stationary dq0 reference frame is described by the following equations [5]:

Flux linkages per second with saturation effect

$$\psi_{qs} = \omega_b \int \left[v_{qs} + \frac{r_s}{x_{ls}} \left(\psi_{mq}^{sat} - \psi_{qs} \right) \right] dt \qquad (1)$$

$$\psi_{ds} = \omega_b \int \left[v_{ds} + \frac{r_s}{x_{ls}} \left(\psi_{md}^{sat} - \psi_{ds} \right) \right] dt \qquad (2)$$

$$\psi'_{qr} = \omega_b \int \left[\frac{\omega_r}{\omega_b} \psi'_{dr} + \frac{r'_r}{x'_{lr}} \left(\psi_{mq}^{sat} - \psi'_{qr} \right) \right] dt \qquad (3)$$

$$\psi'_{dr} = \omega_b \int \left[-\frac{\omega_r}{\omega_b} \psi'_{qr} + \frac{r'_r}{x'_{lr}} \left(\psi_{md}^{sat} - \psi'_{dr} \right) \right] dt \qquad (4)$$

The stator qd0 currents can be calculated as

$$i_{qs} = \frac{\psi_{qs} - \psi_{mq}^{sat}}{x_{ls}} \qquad (5)$$

$$i_{ds} = \frac{\psi_{ds} - \psi_{md}^{sat}}{x_{ls}} \qquad (6)$$

$$i_{0s} = \frac{\psi_{0s}}{x_{ls}} = \frac{\omega_b}{x_{ls}} \int \left(v_{0s} - r_s i_{0s} \right) dt \qquad (7)$$

The electromagnetic torque equation is

$$T_{em} = \frac{3}{2} \frac{P}{2\omega_b} \left(\psi_{ds} i_{qs} - \psi_{qs} i_{ds} \right) \qquad (8)$$

The motion of the rotor is given by

$$T_{em} = J \frac{2}{P} \frac{d\omega_r}{dt} + T_{damp} - T_{mec} \qquad (9)$$

The magnetic saturation is the main factor for voltage buildup and its stabilization on SEIG. For machines with uniform air gap, the saturated value of the mutual flux linkage per second in qd-axes is given by

$$\psi_{mq}^{sat} = x_M \left(\frac{\psi_{qs}}{x_{ls}} + \frac{\psi'_{qr}}{x'_{lr}} - \frac{\Delta\psi_{mq}}{x_m} \right) \qquad (10)$$

$$\psi_{md}^{sat} = x_M \left(\frac{\psi_{ds}}{x_{ls}} + \frac{\psi'_{dr}}{x'_{lr}} - \frac{\Delta\psi_{md}}{x_m} \right) \qquad (11)$$

where

$$\frac{1}{x_M} = \frac{1}{x_{ls}} + \frac{1}{x'_{lr}} + \frac{1}{x_m} \qquad (12)$$

Assuming a proportional reduction in the mutual flux linkages of the qd-axes (Fig. 2), the value of $\Delta\Psi_{mq}$ and $\Delta\Psi_{md}$ is determined from the following relationships

$$\Delta\psi_{mq} = \frac{\psi_{mq}^{sat}}{\psi_m^{sat}} \Delta\psi_m \qquad (13)$$

$$\Delta\psi_{md} = \frac{\psi_{md}^{sat}}{\psi_m^{sat}} \Delta\psi_m \qquad (14)$$

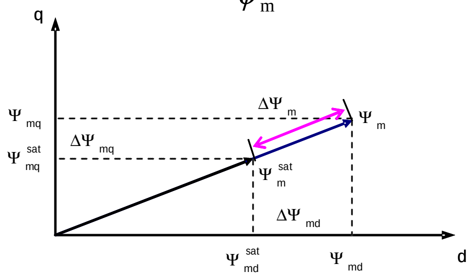

Fig. 2. Saturation in dq components

While the value of $\Delta\Psi_m$ and $\Psi_m{}^{sat}$ is obtained from the terminal voltage versus no-load stator current test (Fig.3).

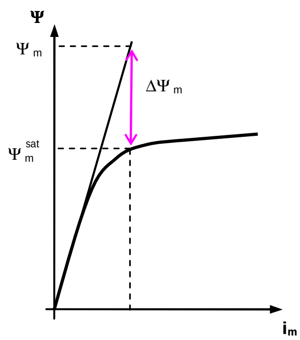

Fig. 3. Saturation curve of the induction machine

Another way of consider the effect of saturation on SEIG is trough the nonlinear relationship between magnetizing reactance and magnetizing current in the induction machine [6].

The model of induction generator, with saturated mutual flux linkage per second, is implemented with Simulink [7]. It is divided in blocks that consider the transformations: abc-qd0 of the stator voltages and qd0-abc of the stator currents and solve the previous equations (1) to (14): stator currents, flux linkages, magnetic saturation, torque and rotor speed (Fig. 4).

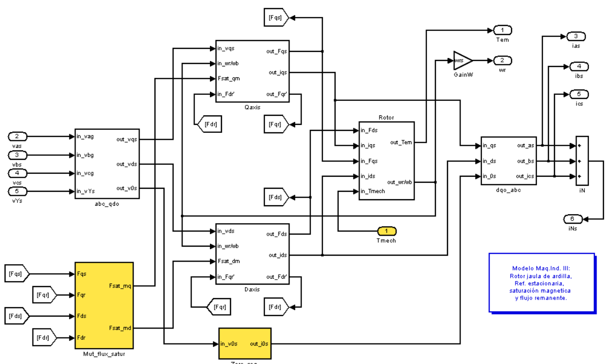

Fig. 4. Induction generator model implemented in Simulink

B. Electronic converter model

Fig. 5 shows the electrical scheme of the electronic converter. This system is made up of a three-phase four-wire current controlled voltage source inverter (CC-VSI) [8] and a chopper connected to its dc bus. The three-leg converter topology with the neutral wire connected directly to the midpoint of the capacitors (split-capacitor) is preferred due to its lower number of power semiconductor devices respected the four switch-leg topology.

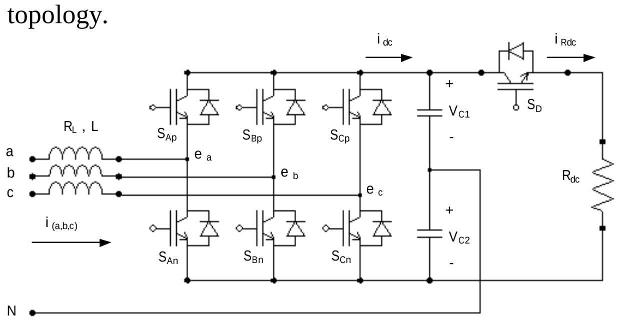

Fig. 5. Electronic converter

The CC-VSI is modeled by three switching functions (S_A, S_B, and S_C) to determinate the state of the IGBTs (S_{Ap} to S_{Cn}) in each branch of the bridge. Considering the commutation basic rules of converters, the switches of a branch must change of complementary form (Table 1). As far as the chopper is concerned, S_D is the switching function to determinate the state of its IGBT.

Table 1. Switching functions of CC-VSI

S_A	1	S_{Ap}=1	S_{An}=0
	0	S_{Ap}=0	S_{An}=1
S_B	1	S_{Bp}=1	S_{Bn}=0
	0	S_{Bp}=0	S_{Bn}=1
S_C	1	S_{Cp}=1	S_{Cn}=0
	0	S_{Cp}=0	S_{Cn}=1

The differential equations of the inverter are as follow

$$v_{aN} = R_{La} i_a + L_a \frac{di_a}{dt} + e_{aN} \tag{15}$$

$$v_{bN} = R_{Lb} i_b + L_b \frac{di_b}{dt} + e_{bN} \tag{16}$$

$$v_{cN} = R_{Lc} i_c + L_c \frac{di_c}{dt} + e_{cN} \tag{17}$$

The voltage of the dc bus can be calculated from the inductor currents at the VSI and the chopper current.

$$v_{dc} = v_{C1} + v_{C2} \tag{18}$$

$$v_{C1} = \frac{1}{C1} \int \left(S_A i_a + S_B i_b + S_C i_c - S_D \frac{v_{dc}}{R_{dc}} \right) dt \tag{19}$$

$$v_{C2} = \frac{1}{C2} \int \left(\bar{S}_A i_a + \bar{S}_B i_b + \bar{S}_C i_c - S_D \frac{v_{dc}}{R_{dc}} \right) dt \tag{20}$$

The voltages on the ac side of inverter are described by

$$e_{aN} = S_A v_{C1} - \bar{S}_A v_{C2} \tag{21}$$

$$e_{bN} = S_B v_{C1} - \bar{S}_B v_{C2} \tag{22}$$

$$e_{cN} = S_C v_{C1} - \bar{S}_C v_{C2} \tag{23}$$

The set point of V_{dc} must be greater than the peak value of ac phase voltages in order to generate the desired ac line currents.

The dc side currents of VSI and its relationships with the ac side currents are expressed by

$$i_{dc} = i_{C1} + i_{R_{dc}} \tag{24}$$

$$i_{C2} = i_{C1} + i_N \tag{25}$$

$$i_a + i_b + i_c + i_N = 0 \tag{26}$$

The currents can flow in both directions through the switches and capacitors. But the split-capacitor inverter topology has a problem with the voltage in the capacitors C1 and C2. The total dc side voltage (V_{dc}) and the voltage difference (V_{C1} - V_{C2}) will oscillate not only at the switching frequency of power semiconductor devices, but also at the corresponding frequency of the zero sequence component current that flow by the neutral wire.

The ac side currents of CC-VSI must to follow its reference current. For this purpose the switching patterns are generated, by the current controller, according to the compared results between the measured ac side currents and the reference currents with a small hysteresis band.

4. Control scheme

The block diagram of the proposed control scheme is shown in Fig. 6. This controller forces the electronic converter to compensate the load current and to absorb a determinate value of power from induction generator. Thus the current supply from SEIG becomes sinusoidal, balanced and its active value is maintained constant. Therefore, the induction generator provides the active power of load and also other active power component to regulate the voltage in the dc capacitors. This last additional component determines a current value to cover the losses in the power converter (switching losses of IGBTs, leakage current of capacitors, etc), to supply the current of controlled dc load and to follow the new conditions imposed to the system. All this power changes cause voltage variation on dc bus [9], the slower feedback control loop of the dc voltage regulator will change the signal i_{loss} to make the active filter absorb/supply a fundamental positive-sequence current to compensate the above voltage variation.

For the purpose explained above, a PLL block is used to determine the magnitude and phase of fundamental positive-sequence of the voltage line and the load current [10]. From this two magnitudes and its phase difference, another block generates the three-phase balanced active component of the load current, i_{Ld}(a,b,c)*. The difference between this value and the measured load current, i_L(a,b,c), yields the reference current to compensate the reactive power, the unbalanced currents and load harmonics of four-wire electric system [11].

The total reference currents of electronic converter, i_C(a,b,c)*, are the sum of previous compensated current (active filter part) and other current to absorb by a controlled load (chopper part). This last component value is the result of the difference between active fundamental component of the load current, i_{Ld}(a,b,c)*, and active fundamental rated current to supplies from SEIG, i_{Sd}(a,b,c)*. Moreover, this rated current value is compensated through a regulator according to voltage value in the generator terminals.

The three-phase four-wire currents of VSI are determined by a hysteresis band current control. It compares the measured ac side currents, i_C(a,b,c), and the reference currents of the converter, i_C(a,b,c)*.

The difference between the active current value that SEIG supplies, the active fundamental current of the load with and another component from the dc voltage regulator i_{loss} are computed to generate the reference current i_{Rdc}* of PWM current controller. Finally, this reference current of PWM controller, a triangular carrier waveform and the current through R_{dc} determine the gating signal to switch the IGBT (S_D) of chopper.

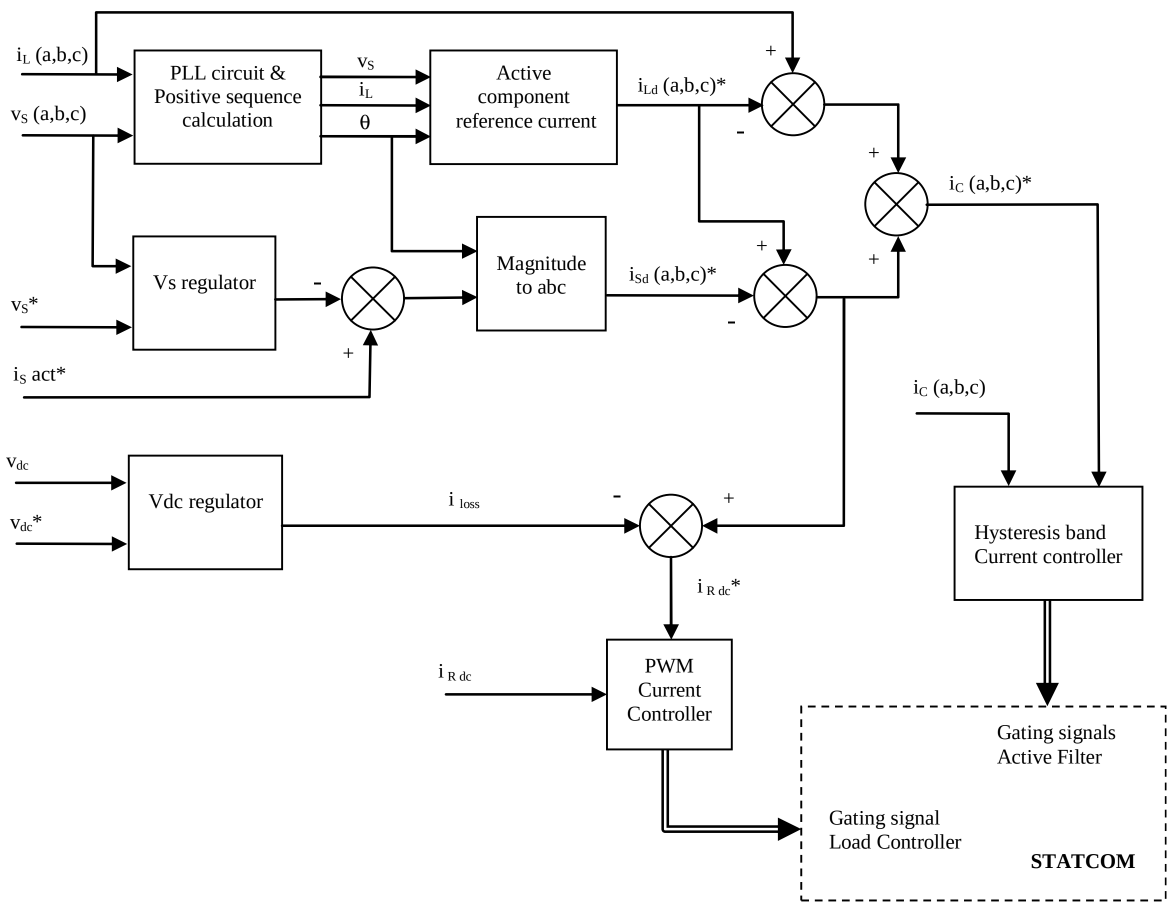

Fig.6. Block diagram of the electronic converter control

5. Simulation results

The SEIG starts its operation with constant rotor speed, the capacitor bank connected to its terminals, without load and the STATCOM disabled. Fig. 7 represents the transient self-excitation process of the induction generator.

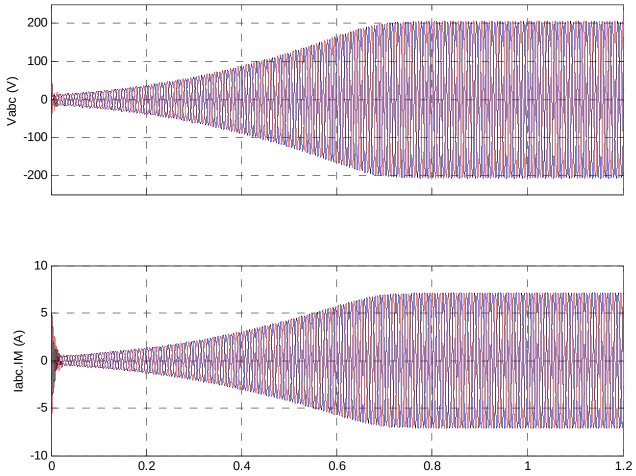

Fig. 7. Growth and stabilization of generated voltage and stator current of the induction machine.

Whereas Fig. 8 shows de behavior of SEIG under a sudden unbalanced load switched at 1.5 seconds and electronic converter disabled. In this case, the generated voltage and its frequency decrease. Moreover, the three-phase terminal voltage and stator currents are also unbalanced. As a result of this unbalanced currents yield a current that flow by the neutral conductor.

When the system reaches the steady state, the electronic converter begins its operation before the connection of the load to the system terminals. In this way the electronic converter, together with its control loops, is able to react to the disturbing characteristics of the load keeping the right average value, the frequency and the shape of the voltage on SEIG terminals.

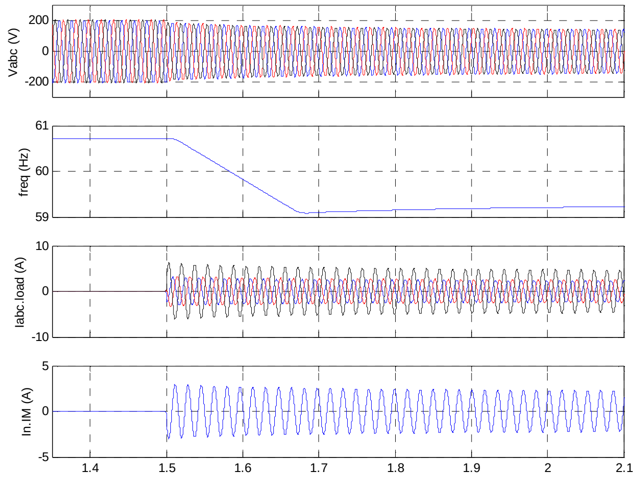

Fig. 8. Transient responses of SEIG supplying an unbalanced load

Fig. 9 shows the response of the system under various loading conditions through the plot of next transient waveforms: induction generator currents, load currents, terminal voltage on SEIG, three-phase currents of electronic converter, neutral current of electronic converter and average current of chopper.

First SEIG supplies its rated power, but it works without load, so the converter consumes all this generated power. The left side of Fig. 9 depicts the respective values of three-phase four-wire currents in electronic converter and average current of chopper.

At 0.27 seconds, a three-phase balanced inductive load is connected to generator. This involves a decrease of ac

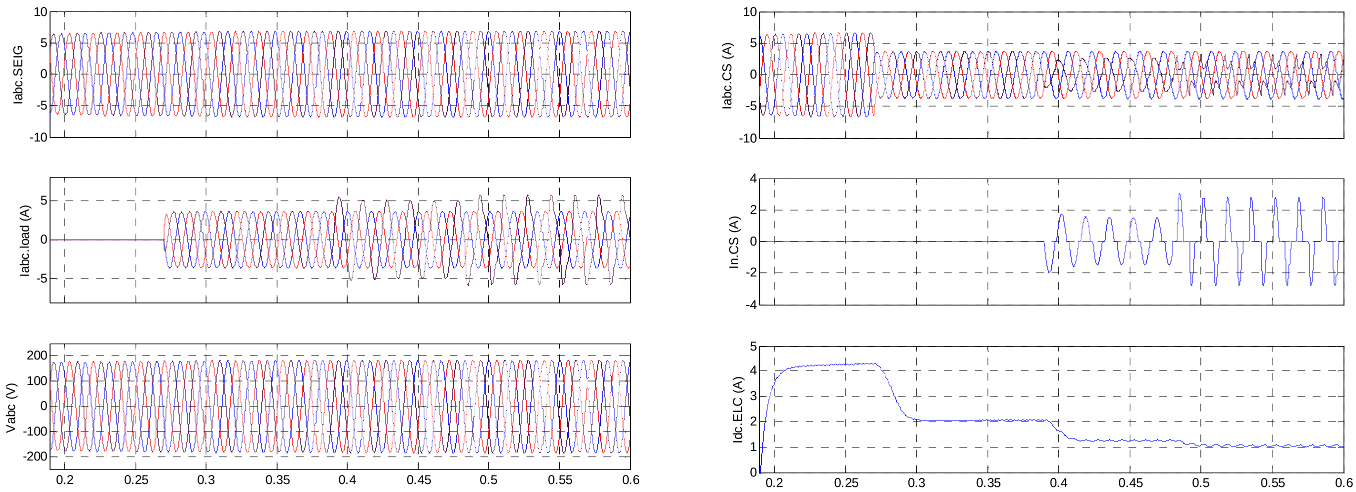

Fig. 9. Transient responses of SEIG and electronic converter under different loading condition

and dc currents on electronic converter. But de voltages and currents on SEIG are the same.

Finally, at 0.39 seconds, a variable single-phase nonlinear load is connected to the SEIG that is feeding the previous three-phase balanced load. The ac line currents of converter are unbalanced, so a current flows by its neutral conductor. However, the SEIG currents are balanced and the line-to-neutral terminal voltages have the same value for the three phases.

The results of the simulation are obtained with the following parameter values of system:

- Induction machine
  $P = 3$ HP, $V_s = 127/220$ V (Δ/Y), $f = 60$ Hz, 4 poles, $R_s = 0.435\ \Omega$, $R'_r = 0.816\ \Omega$, $X_{ls} = X'_{lr} = 0.829\ \Omega$, $X_m = 26.729\ \Omega$.

- Electronic converter
  $R = 0.06\ \Omega$, $L = 1.2$ mH, $C_1 = C_2 = 4000\ \mu$F.

- Three-phase inductive balanced load
  $V_{ac} = 220$ V, $P = 900$ W, $Q = 300$ var

6. Conclusions

This paper proposed a controller of a static compensator to regulate and to balance the generated voltage of a stand-alone SEIG with hydraulic turbine. The converter is made up of an active filter and a controlled load. It compensates harmonics, reactive power and eliminates neutral current. The tested model of three-phase four-wire SEIG-STATCOM is a powerful tool for study the transient and steady state responses of this system at different types of loads. The simulated results show a good performance and efficiency of the whole system under different loading conditions.

References

[1] E.D. Bassett and F.M. Potter, “Capacitive excitation for induction generators”, AIEE Transactions on Electrical Engineering, Vol. 54, pp. 540-545, May 1935.

[2] C.A. Quinn and N. Mohan, “Active filtering of harmonic currents in tree-phase four-wire systems with three-phase and single-phase non-linear loads”, Applied Power Electronics Conference, pp. 829-836, 1992.

[3] R. Bonert and G. Hoops, “Stand alone induction generator with terminal impedance controller and no turbine controls”, IEEE Trans. Energy Conversion, Vol. 5, Issue 1, pp. 28-31, March 1990.

[4] B. Singh, S.S. Murthy and S. Gupta, “An improved electronic load controller for self-excited induction generator in micro-hydel applications”, IEEE Annual Conference of the Industrial Electronic Society, Vol. 3, pp. 2741-2746, 2-6 November 2003.

[5] P.C. Krause, "Analysis of electric machinery", New York: McGraw-Hill, 1986. ISBN: 0-7803-1101-9.

[6] D. Seyoum, C. Grantham and M.F. Rahman, “The dynamic characteristics of an isolated self-excited induction generator driven by a wind turbine”, IEEE Transactions on Industry Applications, Vol. 39, Issue 4, pp. 936-944, July-August 2003.

[7] Chee-Mun Ong, “Dynamic simulation of electric machinery using MATLAB/Simulink”, New Jersey: Prentice Hall PTR, 1997. ISBN: 0-13-723785-5.

[8] A. Cavini, F. Ronchi and A. Tilli, “Four-wires shunt active filters: optimized design methodology”, IEEE Annual Conference of the Industrial Electronic Society, Vol. 3, pp. 2288-2293, 2-6 November 2003.

[9] R. Rodríguez, R. Pindado and J. Pou, “Energy control of three-phase four-wire shunt active power filter”, IEEE Annual Conference of the Industrial Electronic Society, Vol. 2, pp. 1061-1066, 2-6 November 2003.

[10] M. Aredes and L.F.C. Monteiro, “A control strategy for shunt active filter”, International Conference on Harmonics and Quality of Power, Vol. 2, pp. 472-477, 6-9 October 2002.

[11] B. Singh, K. Al-Haddad and A. Chandra, "Harmonic elimination, reactive power compensation and load balancing in three-phase four-wire electric distribution systems supplying non-linear loads", Electric Power Systems Research, Vol. 44, pp. 93-100, 1998.