Performance analysis of a new configuration of three-phase self-excited induction generator feeding a single-phase load

Yaser N. Anagreh*

Electrical Power Engineering Department,
Hijjawi Faculty for Engineering Technology,
Yarmouk University,
Irbid, Jordan
E-mail: anagrehy@yu.edu.jo
*Corresponding author

Nassim Ahmad Iqteit

Electrical and Computer Engineering Department,
Palestinian Polytechnic University (PPU),
P.O. Box 198, Hebron, Palestine
E-mail: nasm_eng83@yahoo.com

Sameer F. Mohammad

Electrical Engineering Department,
Faculty of Engineering,
United Arab Emirates University,
P.O. Box 15551, Al-Ain, UAE
E-mail: Sameer.fayz@uaeu.ac.ae

Abstract: This paper presents a steady-state performance analysis for a new configuration of self-regulated self-excited three-phase squirrel cage induction generator feeding single phase loads. The proposed scheme provides the required reactive power for excitation, small voltage regulation, acceptable phase balance and large output power. Using an equivalent circuit model incorporated with the method of symmetrical components, the total impedance equation of the generator's model is derived. This non-linear equation is minimised to obtain the operating frequency and magnetising reactance. Based on the derived circuit model, the performance of the generator under different operating conditions is predicted. To confirm the validity of the proposed scheme, simulation results are compared with their corresponding test results.

Keywords: induction generator; self-excitation; single phase; self-regulation.

Reference to this paper should be made as follows: Anagreh, Y.N., Iqteit, N.A. and Mohammad, S.F. (2013) 'Performance analysis of a new configuration of three-phase self-excited induction generator feeding a single-phase load', *Int. J. Power and Energy Conversion*, Vol. 4, No. 2, pp.167–181.

Biographical notes: Yaser N. Anagreh graduated in electrical engineering from University of Technology, Baghdad, Iraq, in 1984 and received his MPhil and PhD from University of Wales Swansea, Swansea, UK, in 1995 and 1998, respectively. He is an Associate Professor in Electrical Power Engineering Department at Yarmouk University, Jordan, where he has been since 1998. Currently, he is in a sabbatical leave for one academic year at University of Hail, Saudi Arabia. His research interests are induction generators, wind/solar renewable energy systems and motor drives.

Nassim Ahmad Iqteit graduated in electrical engineering from Palestine Polytechnic University (PPU), Hebron in 2006, and he just received his MSc in Electrical Power Engineering from Yarmouk University in 2010. Currently, he is a Lecturer in Electrical and Computer Engineering Department at Palestine Polytechnic University, Hebron. His research interests are induction generators and electric drives.

Sameer F. Mohammad received his BSc and MSc in Electrical Power Engineering from Yarmouk University, Jordan in 1994 and 2010. He is currently an Instructor in the Electrical Engineering Department at the Faculty of Engineering, United Arab Emirates University (UAEU), Al-Ain, UAE. His areas of research interests are power system operation and optimisation, power system restructuring, reactive power pricing and electrical machines.

1 Introduction

Currently, the implementation of stand-alone power systems to supply electrical loads in rural remote areas has acquired a great attention due to the depletion of conventional energy resources combined with environmental restrictions imposed. Since most of the loads fed by an autonomous power system are of single-phase type, a single phase source is preferred. This is because of its advantageous over three-phase source, such as reduced cost, less maintenance and simple protection (Canale et al., 2009; Dimitris et al., 2008; Abdullah et al., 2010; Pilla and Baneerjee, 2009; Omer, 2010). Squirrel cage induction machines are usually implemented to generate electricity from renewable energy resources, such as wind and biomass, due to its merits over other generator types (Murthy et al., 1982; Raina and Malik, 1983; Alghuwainem, 1999).

However, a single-phase induction machine can be operated as a generator to feed single phase loads (Singh et al., 1988), a three-phase induction generator is cheaper, has better efficiency and moreover it is available at higher power rating; greater than 3 kW (Chan and Lai, 2004). The operation of three-phase self-excited induction generator (SEIG) to supply single phase load may leads to undesirable performance, such as poor generation efficiency, high voltage regulation, increased winding temperature and severe vibrations. These undesirable effects can be minimised to a large extent by connecting the generator's stator winding with excitation capacitors in a certain configuration (Chan and Lai, 2001).

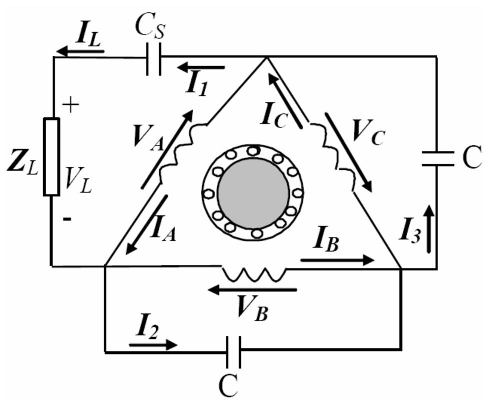
In the literature, authors have published several papers deal with different configurations of three-phase SEIGs feeding single phase loads. Some of the papers are directed to investigate the performance of the these proposed schemes, other researchers concentrated their work on computing the optimal excitation capacitors under different operating conditions. Bahrani and Malik (1990) investigated the steady-state performance characteristics of a three-phase induction generator self-excited with a single-capacitor and feeding a single-phase load. Other two configurations of a three-phase SEIG supplies a single-phase load; Steinmetz connection I and Steinmetz connection II, are analysed by Chan (1999). Fukami et al. (1999) investigated the behaviour of a Y-connected SEIG with series and parallel capacitors that feeds a single-phase load. The transient and steady-state performance of a three-phase induction generator with two excitation capacitors and feeding a single phase load is evaluated by Mahato et al. (2007). Chan and Lai (2002) investigated the configuration of Δ-connected induction generator with one series and one shunt capacitors to supply a single-phase load. Chan and Lai (2004) analysed their proposed scheme, which consists of three capacitors connected with the stator windings in a certain arrangement, to feed a single-phase load. Chan and Lai (2002) presented a method to find the minimum capacitance needed to initiate voltage build up in a three-phase induction generator self-excited with a single-capacitor and feeding a single-phase load. Determination of the optimal excitation capacitances to acquire high output power for the configuration of Y-connected SEIG with series and parallel capacitors to feed a single-phase load is presented in Mahato et al. (2008).

In the present work, a new scheme of self-excited self-regulated three-phase delta-connected squirrel cage induction generator feeding single phase loads is proposed. The main advantages of the present scheme are small voltage regulation, acceptable level of voltage unbalance, large output power and enough reactive power for excitation. One more important advantage is the simplicity to obtain the generator's performance under different conditions. This can be achieved using the equivalent circuit of the proposed configuration incorporated with the method of symmetrical components.

2 Analysis and equivalent circuit

The schematic diagram of the proposed scheme is shown in Figure 1. Based on the electrical connections presented in this figure, the inspection equations (1) to (6) are obtained.

Figure 1 Schematic diagram for the proposed configuration of SEIG feeding 1ϕ-load



$$V_A + V_B + V_C = 0 \tag{1}$$

$$V_A = I_1 Z \tag{2}$$

$$V_B = I_2 Z_C \tag{3}$$

$$V_C = I_3 Z_C \tag{4}$$

$$I_1 - I_3 = I_C - I_A \tag{5}$$

$$I_2 - I_1 = I_A - I_B \tag{6}$$

Equations (1) to (6) can be solved for the currents I_1, I_2 and I_3 in a matrix form as given in the following equation:

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} = \frac{1}{Z + 2Z_C} \begin{bmatrix} 1 & Z_C & -Z_C \\ 1 & Z_C & Z + Z_C \\ 1 & -(Z + Z_C) & -Z_C \end{bmatrix} \begin{bmatrix} 0 \\ I_C - I_A \\ I_A - I_B \end{bmatrix} \tag{7}$$

where

$$Z = Z_{CS} + Z_L \qquad Z_L = \frac{R_L}{F} + jX_L$$

$$Z_C = \frac{1}{j2\pi f_{base} C F^2} = -\frac{jX_C}{F^2} \qquad Z_{CS} = \frac{1}{j2\pi f_{base} C_S F^2} = -\frac{jX_{CS}}{F^2}$$

Substitution of equation (7) in the phase voltage equations (2) to (4) yields:

$$V_A = \frac{ZZ_C}{Z + 2Z_C}\left[(I_C - I_A) - (I_A - I_B)\right] \tag{8}$$

$$V_B = \frac{Z_C}{Z + 2Z_C}\left[(Z + Z_C)(I_A - I_B) + Z_C(I_C - I_A)\right] \tag{9}$$

$$V_C = \frac{Z_C}{Z + 2Z_C}\left[-(Z + Z_C)(I_C - I_A) - Z_C(I_A - I_B)\right] \tag{10}$$

Since the generator's stator windings are connected in delta, the zero sequence voltage is absent (Chan, 1999; Chan and Lai, 2002, 2004). The positive and negative sequence voltages can then be given by:

$$\begin{bmatrix} V_p \\ V_n \end{bmatrix} = \frac{1}{\sqrt{3}} \begin{bmatrix} 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} \tag{11}$$

Based on the symmetrical component theory and consider the elimination of zero sequence current, stator phase currents can be expressed by:

$$\begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} = \frac{1}{\sqrt{3}} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} 0 \\ I_p \\ I_n \end{bmatrix} \tag{12}$$

Based on equations (8) to (10), in association with equations (11) and (12), the positive and negative sequence components of the voltage could be expressed by:

$$\begin{bmatrix} V_p \\ V_n \end{bmatrix} = \begin{bmatrix} 2Z_Y + Z_{CY} & Z_Y - Z_{CY} \\ Z_Y - Z_{CY} & 2Z_Y + Z_{CY} \end{bmatrix} \begin{bmatrix} I_p \\ I_n \end{bmatrix} \tag{13}$$

where

$$Z_Y = \frac{ZZ_C}{Z + 2Z_C} \quad Z_{CY} = \frac{Z_C^2}{Z + 2Z_C}$$

Using the positive and negative sequence components of the generator's impedances, Z_{gp} and Z_{gn}, equation (13) can be rewritten in the following form:

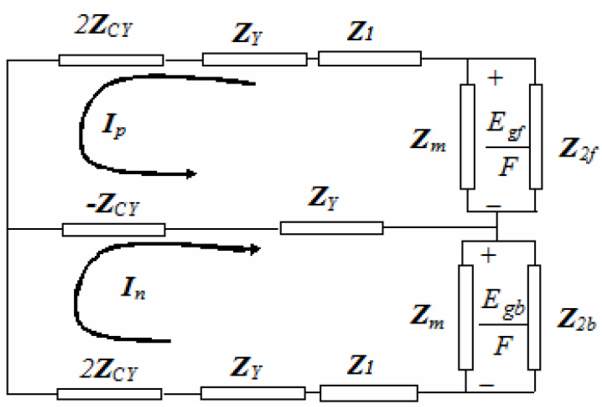
$$\begin{bmatrix} 0 \\ 0 \end{bmatrix} = \begin{bmatrix} 2Z_Y + Z_{CY} + Z_{gp} & Z_Y - Z_{CY} \\ Z_Y - Z_{CY} & 2Z_Y + Z_{CY} + Z_{gn} \end{bmatrix} \begin{bmatrix} I_p \\ I_n \end{bmatrix} \tag{14}$$

where

$$Z_{gp} = Z_1 + \frac{Z_m Z_{2f}}{Z_m + Z_{2f}}, \quad Z_{gn} = Z_1 + \frac{Z_m Z_{2b}}{Z_m + Z_{2b}}, \quad Z_1 = \frac{r_1}{F} + jX_1,$$

$$Z_m = jX_m, \quad Z_{2f} = \frac{r_2}{F - v} + jX_2, \quad Z_{2b} = \frac{r_2}{F + v} + jX_2$$

Figure 2 The equivalent circuit of the proposed scheme



Based on equation (14), the generator's equivalent circuit could be obtained as shown in Figure 2. The total impedance (the equivalent impedance) of this circuit could be given in equation (15). The components of positive sequence current and negative sequence current are given in equations (16) and (17), respectively. The performance characteristics of the generator could be obtained using equations (18) to (21).

$$Z_T = Z_{gp} + \left(Z_Y + 2Z_{CY}\right) + \frac{\left(Z_{gn} + Z_Y + 2Z_{CY}\right)\left(Z_Y - Z_{CY}\right)}{Z_{gn} + 2Z_Y + Z_{CY}} \tag{15}$$

$$I_p = \frac{E_{gf}}{Z_1 + \left(Z_Y + 2Z_{CY}\right) + \dfrac{\left(Z_{gn} + Z_Y + 2Z_{CY}\right)\left(Z_Y - Z_{CY}\right)}{Z_{gn} + 2Z_Y + Z_{CY}}} \tag{16}$$

$$I_n = -I_p \frac{Z_Y - Z_{CY}}{Z_{gn} + 2Z_Y + Z_{CY}} \tag{17}$$

$$I_L = -\frac{2Z_C}{Z + 2Z_C}\left(I_P + I_n\right) \tag{18}$$

$$V_L = \left[\left(R_L + jX_L F\right)\right] I_L \tag{19}$$

$$P_{out} = \left|I_L\right|^2 R_L \tag{20}$$

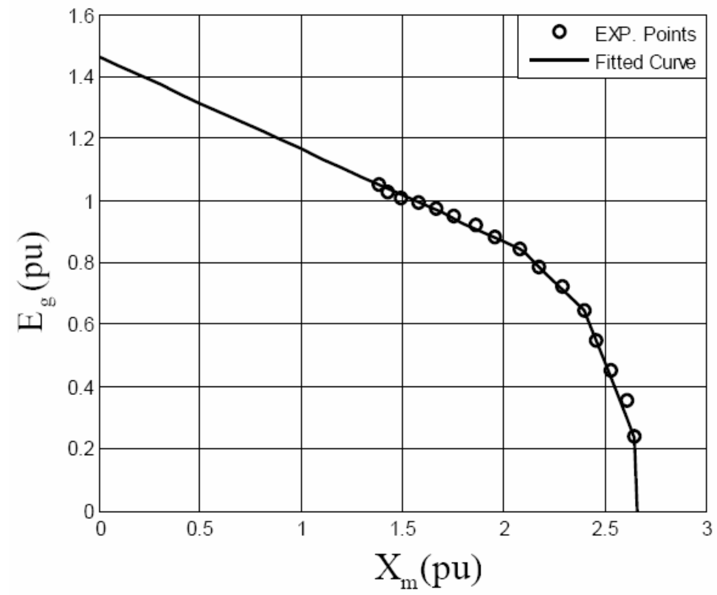
$$f = f_{base} F \tag{21}$$

3 Results and discussions

In the present work, a standard 1.5 kW, 4-pole, 220 V, 6.4 A, 1,415 rpm Δ-connected squirrel cage three-phase induction machine was used as a test generator. A 2 kW, 220 V separately excited DC motor, having a rated field current of 0.8 A, was used to drive the generator. The constant parameters of the generator which are determined experimentally from the DC and locked rotor tests (Chapman, 1985) are: r_s = 5.027 Ω, r_r = 3.51 Ω and $X_{ls} = X_{lr}$ = 5.78 Ω. The generator's magnetising characteristic (E_g vs. X_M) is obtained by synchronous speed test (Bahrani and Malik, 1990). Figure 3 shows the experimental E_g vs. X_M test points and their fitted curve when the induction machine is run at its synchronous speed; 1,500 r.p.m. The fitted curve could be mathematically expressed by:

$$E_g = -0.1314X_M^5 + 0.7269X_M^4 - 1.4118X_M^3 + 1.126X_M^2 - 0.6172X_M + 1.4779 \tag{22}$$

Figure 3 Air-gap voltage versus the magnetising reactance



The per unit values of the system parameters are computed based on the rated values of the generator parameters as base quantities which are given in Table 1. Figure 4 shows the variation of the load voltage with load current for three different values of series capacitor (C_S). During this test the generator is run at a speed of 1,430 rpm to feed a variable single-phase resistive load. The two equal excitation capacitors, connected across the generator's phases b and c, are maintained fixed at 50 µF. The variation of the output power with load current for the same operating conditions is presented in Figure 5. As expected, the output voltage decreases with load but the output power increases as the load increase. The voltage regulation is greatly improved when the series capacitance C_S is increased from 70 µF to 120 µF, but it is slightly improved when C_S was increased from 120 to 150 µF. Concerning with the output power characteristics, it can be noticed that the increase in C_S from 70 µF to 120 µF resulted in a great increase in the output power for each load. However, a small increase on the output power is obtained when C_S is increased from 120 to 170 µF. As can be observed the proposed scheme can provide high output power with good voltage regulation if a suitable series capacitor is used.

Table 1 The base quantities used to obtain the per-unit system's parameters

Quantity	*Base value*
Base voltage (V_{base})	220 V
Base current (I_{base})	3.7 A
Base impedance (Z_{base})	$Z_{base} = V_{base} / I_{base}$ = 59.3 W
Base frequency (F_{base})	50 Hz
Base power (P_{base})	$P_{base} = V_{base} I_{base}$ = 814 W

Figure 4 The variation of the load voltage with load current for different C_S values

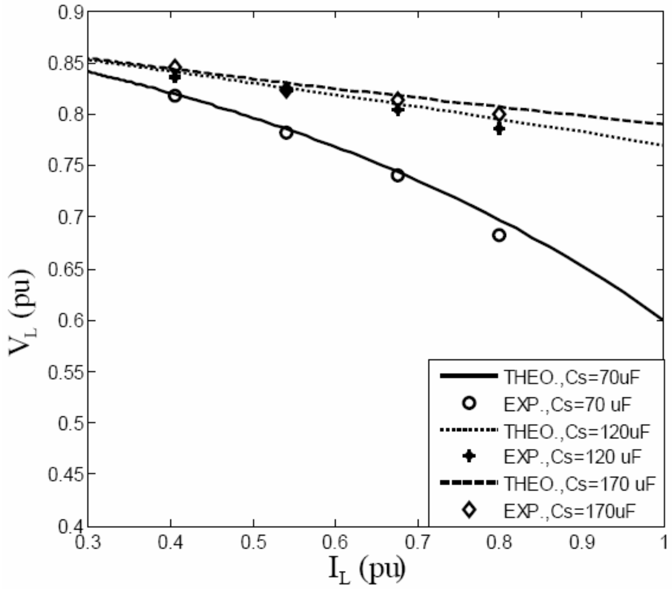


Figure 5 The variation of the output power with load current for different C_S values

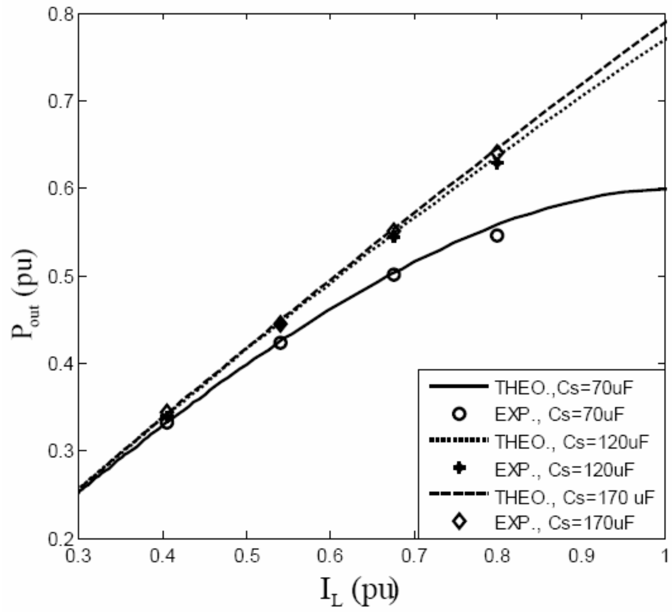


Figure 6 The variation of the load voltage and output power with C_S

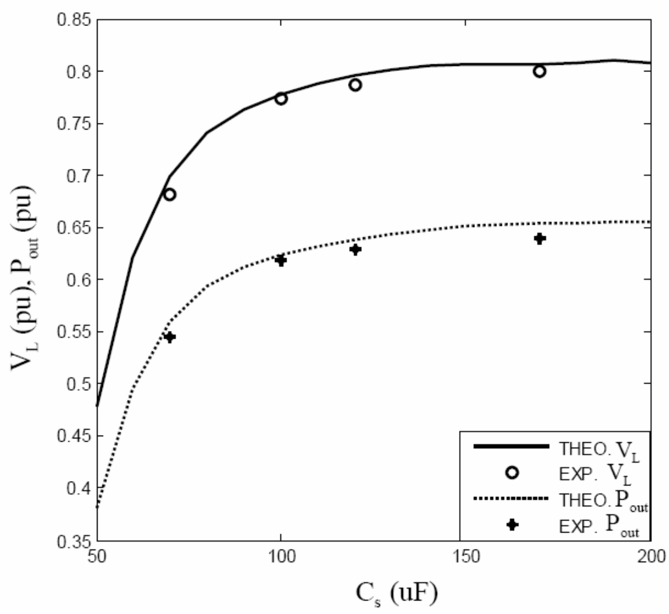


Figure 6 shows the variation of the output power and load voltage with series capacitance C_S. During this test the generator is run at a speed of 1,430 rpm and it feeds a resistive load which draws a current of 0.8 pu. As the capacitance varies from 50 to 200 μF, the behaviour for each of the two characteristics can be divided into three regions: linear, knee and saturation regions. As the saturation region is reached, the increase in the output voltage and power is small even if C_S is highly increased. This confirms the finding in Figures 4 and 5 that high generator's performance could be acquired if the series capacitance is selected properly. Figures 4 to 6 show a close agreement between the computed results and their corresponding experimental results. This confirms the validity, the accuracy and the feasibility of the present work.

The variation of the load voltage and output power with speed is presented in Figure 7. In this test, the connected resistive load draws a current of 0.8 pu, and the excitation capacitors used are C_S = 170 μF and C = 50 μF. It can be seen from this figure that the output power as well as the output voltage increases approximately linearly with rotational speed. However the number of test points is small, a close agreement between simulations and these experimental points can be observed.

Figure 7 The variation of the load voltage and output power with speed

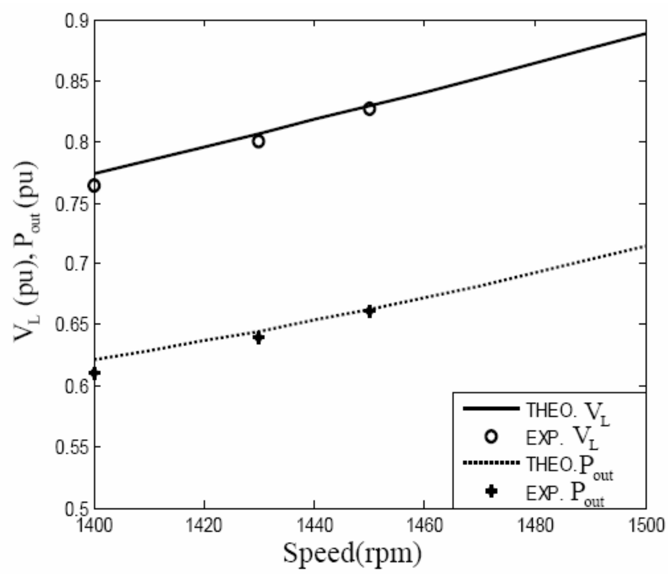


Figure 8 Variation of the phase currents with load

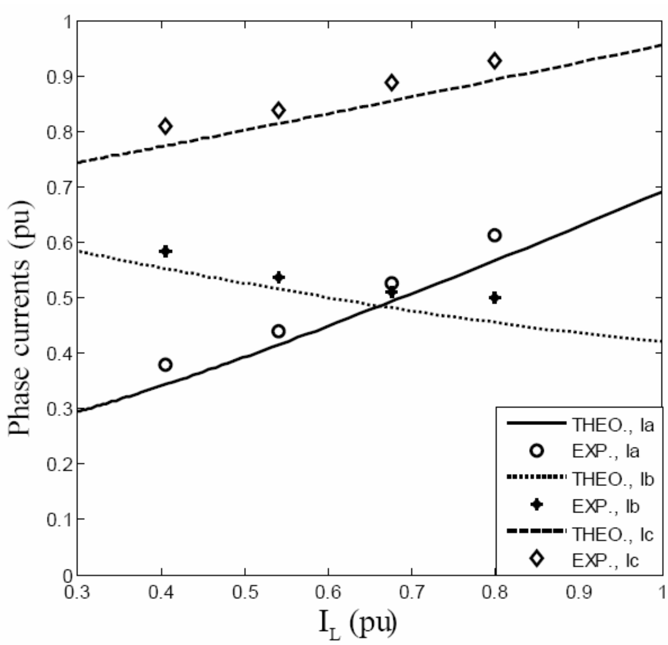
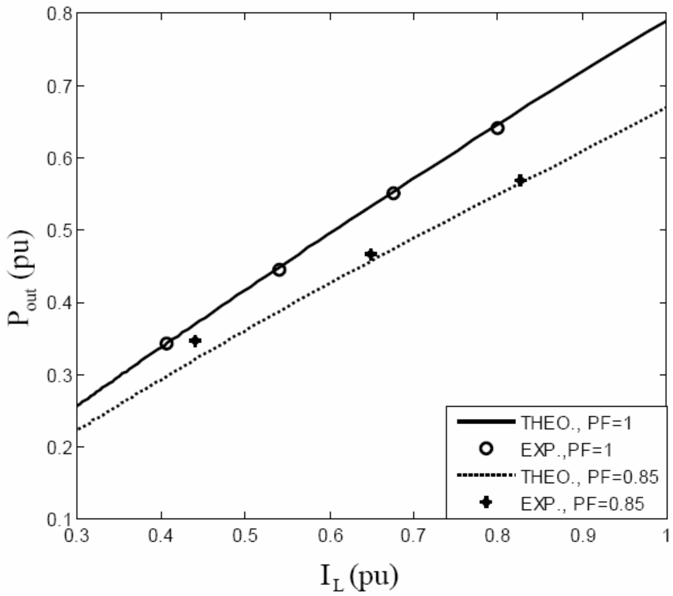


Figure 9 Variation of the P_{out} with I_L for two load types



The variation of the stator phase currents with load is shown in Figure 8. During the test, the excitation capacitors are maintained fixed; C_S = 170 μF and C = 50 μF, and the generator was rotated at a speed of 1,430 rpm to supply a unity PF single-phase load. Although perfect balance point could not attain, it can be seen that the generator can be operated from no-load condition all the way up to its full load condition with no problem of temperature rise in the stator windings. Figure 9 presents the variation of the output power with load current for resistive and inductive loads. As can be seen the output power decreases when the generator feeds an inductive load. Again, the predicted results given in Figures 8 and 9 are very close to their counterpart test results.

The simulation results representing the variations of the operating frequency and magnetising reactance with the series capacitance C_S are shown in Figure 10. The results of this figure are acquired when the generator is run at a speed of 1,430 rpm to supply a resistive load drawing a current of 2.96 A (0.8 pu). It can be noticed that the output frequency is slightly decreases in a non-linear manner by increasing the series capacitance value. On the other hand, the magnetising reactance increase exponentially with the series capacitance; it varies from 1.25 pu to about 1.6 pu when C_S is increased from 50 to 200 μF. Figure 11 shows the behaviour of the output frequency and magnetising reactance as the rotational speed is changed. In this test, it is assumed that the series capacitance and load current drawn be the supplied resistive load are maintained fixed: C_S = 170 μF and I_L = 5.12 A. It can be observed that the operating frequency increases linearly with speed, but the magnetising reactance decreases linearly as the rotational speed increase.

Figures 12 to 14 show the behaviour of the generator when its out terminals are shorted out. The variations of the output frequency and magnetising reactance with series capacitance, when a short circuit is applied to the generator's output, are shown in Figure 12. It can be observed that the magnetising reactance decreases exponentially with series capacitance and the output frequency is slightly decreases with C_S. The effect of changing the series capacitance on the load current and phase currents under short circuit condition is presented in Figure 13. The behaviour of the phase voltages under the same condition is shown in Figure 14. It can be seen that the load current as well as a phase current increases with series capacitance in a non-linear manner. As can be noticed in Figure 14, the voltages of phase A and phase C increase with C_S, but the voltage of phase B decreases by increasing C_S. When the series capacitance reaches the value of 50 μF, a balance point is attained. A this point, the generator's phase currents are equal and the phase voltages are also equal.

Figure 10 The variation of the output frequency and magnetising reactance with C_S (see online version for colours)

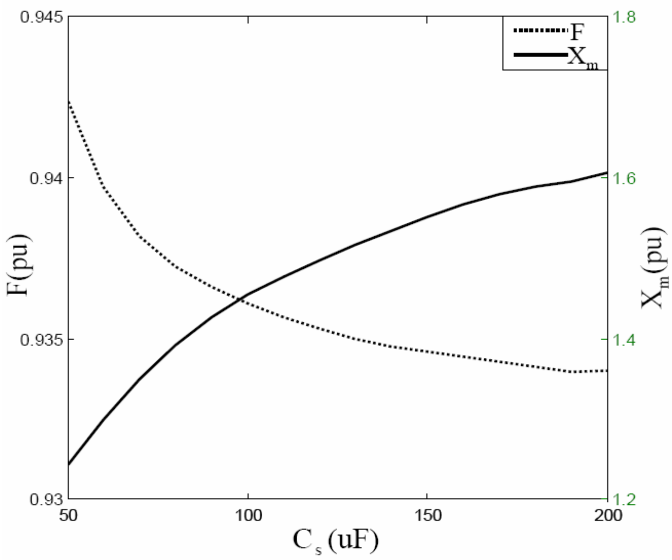


Figure 11 The variation of frequency and magnetising reactance with speed (see online version for colours)

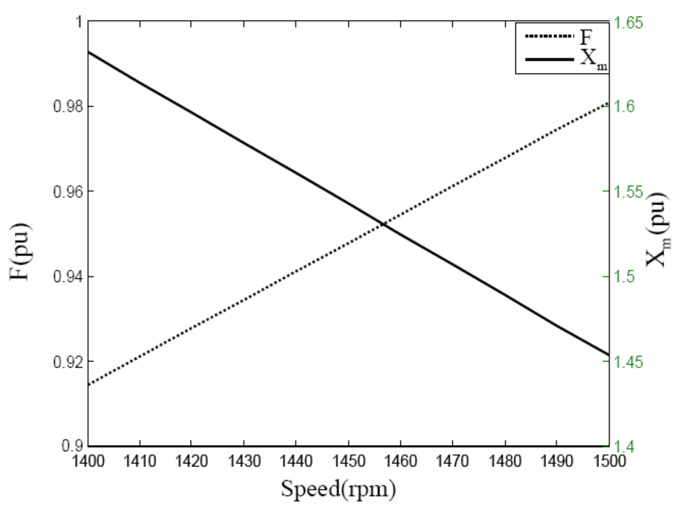


Figure 12 The variations of the magnetising reactance and frequency with series capacitance

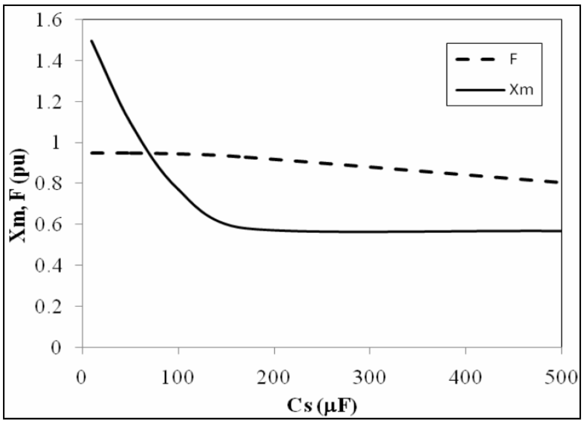


Figure 13 The variations of the load current and phase currents with series capacitance

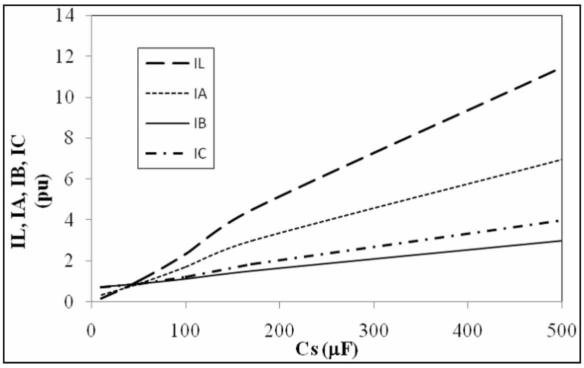
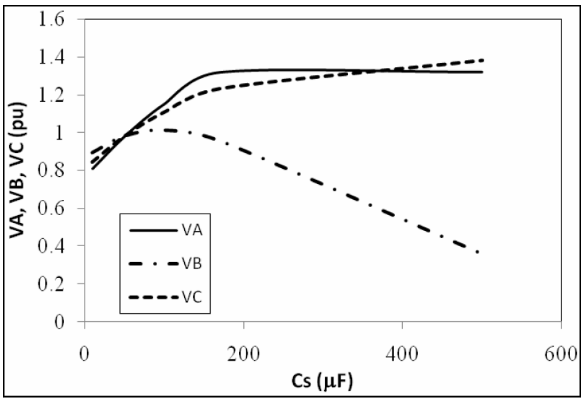


Figure 14 The variations of the phase voltages with series capacitance



4 Conclusions

In this publication, the steady-state performance for a new scheme of three-phase SEIG feeding a single phase load is analysed using the method of symmetrical components. The total impedance equation is solved numerically to acquire the operating frequency and magnetising reactance. The effect of varying the load impedance, rotational speed and the series capacitance on the generator's output characteristics is investigated. It is found that the proposed configuration can provides self-excitation, small voltage regulation, and high output power. Moreover, the generator can be safely operated up to its full load condition. Simulation results are compared with their corresponding experimental results. The reasonable correlation observed between the predicted and test results confirm the validity of the proposed configuration.

List of symbols

a	the complex operator
C	the excitation capacitance connected in parallel with phase b or c, μF
C_S	the series capacitance, μF
E_{gf}	per-unit internal generated voltage
F	per-unit frequency
f_{base}	base frequency, Hz
I_1, I_2, I_3	currents flowing in the excitation capacitors, A
I_A, I_B, I_C	stator phase currents, A
I_L	the load current, A
I_n	the negative sequence component of the generator's currents, A
I_p	the positive sequence component of the generator's currents, A
P_{out}	per-unit output power
r_1, r_2	resistances of stator winding and rotor winding, Ω
R_L, X_L	the load resistance and load reactance, Ω
v	per-unit rotational speed
V_A, V_B, V_C	stator phase voltages, V
V_L	the load voltage, V
V_p, V_n	the positive and negative sequence components of stator voltages, V
X_1, X_2	reactance of stator winding and rotor winding, Ω
X_C, X_{CS}	reactance of the shunt capacitance c and series capacitance C_S, Ω
Z_1, Z_2	stator winding impedance and rotor winding impedance, Ω
Z_{2f}, Z_{2b}	the forward and backward impedances of the rotor winding, Ω
Z_{gp}, Z_{gn}	the positive and negative sequences of the generator's impedances, Ω

Z_L, Z_C, Z_{CS} impedances of the load, the capacitance C and series capacitance C_S, Ω

Z_m, X_m magnetising impedance and magnetising reactance, Ω.

References

Abdullah, M., Yung, V., Anyi, M., Othman, A., Hamid, K. and Tarawe, J. (2010) 'Review and comparison study of hybrid diesel/solar/hydro/fuel cell energy schemes for rural ICT Telecenter', *Energy*, Vol. 35, No. 2, pp.639–646.

Alghuwainem, S. (1999) 'Steady-state analysis of self-excited induction generator including transformer saturation', *IEEE Transaction on Energy Conversion*, Vol. 14, No. 3, pp.667–672.

Bahrani, A. and Malik, N. (1990) 'Steady state analysis and performance characteristics of a three-phase induction generator self excited with a single capacitor', *IEEE Transactions on Energy Conversion*, Vol. 5, No. 4, pp.725–731.

Canale, M., Fagiano, L. and Milanese, M. (2009) 'KiteGen: a revolution in wind energy generation', *Energy*, Vol. 34, No. 3, pp.355–361.

Chan, T. (1999) 'Performance analysis of a three-phase induction generator self-excited with a single capacitance', *IEEE Transactions on Energy Conversion*, Vol. 14, No. 4, pp.894–900.

Chan, T. and Lai, L. (2002) 'Capacitance requirements of a three-phase induction generator self-excited with a single capacitance and supplying a single-phase load', *IEEE Transactions on Energy Conversion*, Vol. 17, No. 1, pp.90–94.

Chan, T. and Lai, L. (2004) 'A novel excitation scheme for a stand-alone three-phase induction generator supplying single-phase loads', *IEEE Transactions on Energy Conversion*, Vol. 19, No. 1, pp.136–143.

Chapman, S. (1985) *Electric Machinery Fundamentals*, McGraw-Hill, New York.

Dimitris, I., Spyros, V., Panos, S., Fotis, S., Simira, P. and Costal, E. (2008) 'The effect of the hysteresis band on power management strategies in a standalone power system', *Energy*, Vol. 33, No. 10, pp.1537–1550.

Fukami, T., Kaburaki, Y., Kawahara, S. and Miyamoto, T. (1999) 'Performance analysis of a self-regulated self-excited single-phase induction generator using three-phase machine', *IEEE Transactions on Energy Conversion*, Vol. 14, No. 3, pp.622–627.

Mahato, S., Sharma, P. and Sinph, S. (2007) 'Steady-state and dynamic behavior of a single-phase self-excited induction generator using three-phase machine', *International Journal of Emerging Electric Power System*, Vol. 8, No. 3, pp.1–19.

Mahato, S., Sinph, S. and Sharma, M. (2008) 'Capacitor required for maximum power of a self-excited single-phase induction generator using a three-phase machine', *IEEE Transactions on Energy Conversion*, Vol. 23, No. 2, pp.372–381.

Murthy, S., Malik, O. and Tandon, A. (1982) 'Analysis of self-excited induction generators', *IEE Proceedings Part C*, Vol. 129, No. 6, pp.260–265.

Omer, A. (2010) 'Environmental and socio-economic aspects of possible development in renewable energy use', *Journal of Agricultural Extension and Rural Development*, Vol. 2, No. 1, pp.001–021.

Pilla, R and Baneerjee, I. (2009) 'Renewable energy in India: status and potential analysis of self-excited induction generator including transformer saturation', *International Journal of Energy*, Vol. 34, No. 8, pp.970–980.

Raina, G. and Malik, O. (1983) 'Wind energy conversion using a self-excited induction generator', *IEEE Transactions on Power Apparatus and Systems*, Vol. 102, No. 12, pp.3933–3936.

Singh, B., Saxena, R., Murthy, S. and Singh, B. (1988) 'A single-phase self-excited induction generator for lighting loads in remote areas', *International Journal of Electrical Engineering Education*, Vol. 25, No. 3, pp.269–275.