

A NOVEL STAND-ALONE SINGLE-PHASE INDUCTION GENERATOR USING A THREE-PHASE MACHINE AND A SINGLE-PHASE PWM INVERTER

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Abstract A new type of single-phase stand-alone induction generator using a three-phase induction machine and a single-phase voltage-source PWM inverter is introduced. The generator scheme is capable of producing constant load frequency with a very well regulated output voltage. A small lead acid battery and a single-phase full diode-bridge rectifier are used to feed the inverter. The inverter feeds one of the stator phases. During the generator voltage build up, the inverter supplies the battery first and after a while a diode-bridge rectifier, which is fed by the generator, replaces it. The system steady state and dynamic equations are derived and are solved to obtain the performance characteristics of the generator scheme. A digital simulation study is carried out for a 2.2 KW three-phase induction machine. The simulated results obtained confirm that this generator can achieve an output power of about 0.6 pu.

Key Words Generation of Electrical Energy, Induction Motors, Modeling, Converter Control

چکیده با بکارگیری یک ماشین سه فاز و یک اینورتر PWM تکفاز، یک نوع ژنراتور القایی تکفاز ایزوله معرفی می شود. ولتاژ خروجی این ژنراتور قابل تنظیم و فرکانس آن ثابت است. این ژنراتور توسط یک باتری خشک کوچک و یک یکسو کننده پل دیودی تکفاز که به ترمینالهای خروجی یک ژنراتور متصل می گردد، تحریک می شود. ابتدا اینورتر توسط باتری تغذیه می شود و بعد از زمان کوتاهی این باتری با یکسو کننده جایگزین می گردد. از روی معادلات مربوط به حالت‌های پایداری و دینامیکی ماشین، مشخصه های رفتاری سیستم ژنراتور استخراج می شود. با یک مطالعه بر پایه شبیه سازی کامپیوتری برای یک ماشین سه فاز کوچک ۲/۲ کیلو وات، نتایج بدست آمده از استحصالی در حدود ۶۰ درصد توان اسمی ماشین از این ژنراتور را مورد تایید قرار می دهد.

1. INTRODUCTION

Single-phase induction motors can be operated as single self-regulated, self excited induction generators (SEIGs) but in general they are limited to relatively small power outputs and also have the voltage regulation weakness. For power rating above 5KW, three-phase squirrel-cage induction machines are cheaper and are more readily available hence, a recent trend has been to employ three-phase machines for single-phase (SEIG) applications [1-6].

Since last decade, the single-phase induction generators driven by prime movers such as wind and hydro-turbines, kerosene or diesel engines have been considered as stand-alone sources of regulated electric power for small application requiring less

10KW where frequency regulation is not an application requirement [7].

More recently, Fukami et. al. and T.F Chan etc. all have studied the two types of single-phase SEIGs, using three-phase induction machines. The single-phase induction generator scheme reported in [5], has used a three phase induction machine Y connected to series compensation capacitors to improve the voltage regulation. Reference [6] has presented a steady-state analysis of a single-phase SEIG which employs a three-phase squirrel-cage induction machine Δ -connected with two series and shunt capacitors. Using these capacitors, a nearly balanced operating was obtained for a certain load.

The single-phase SEIGs proposed so far are not

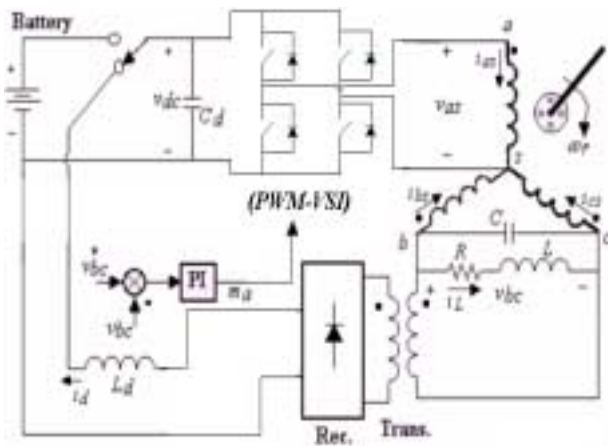


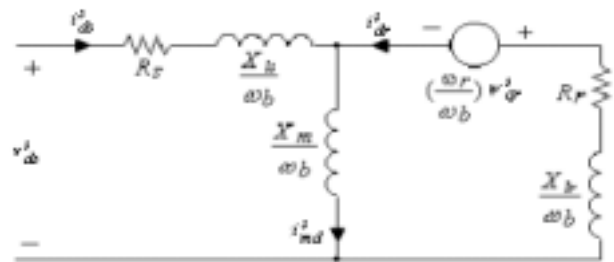
Figure 1. Electrical circuit configuration of the generator system.

suitable for commercial applications where both the regulated load-voltage or current and frequency are required. A single-phase induction generator has been presented in [7] which uses a single-phase motor and a single-phase PWM inverter. In that generator system, a lead acid battery feeding the inverter supplies real power to the generator when the load demand is greater than the power supplies by the prime mover. When the real power supplied by prime mover exceeds the load demand, the excess power charges the battery.

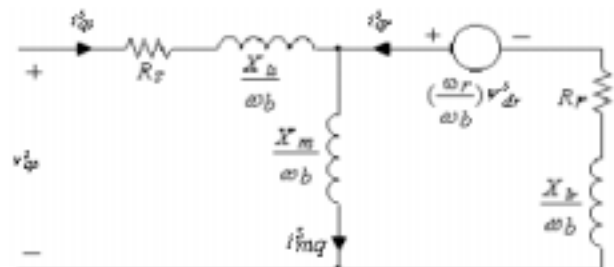
The above generator scheme has the following drawbacks:

a) Using a single-phase induction motor, the generator real output power therefore is limited to below the 5KW. b) A high capacity battery is required to feed the inverter hence the generator system is not economical. c) During the generator voltage build up, a nearly large transient current may be inrushed into the machine which cause a damage to the battery and the generator system.

To come up with the above mentioned drawbacks, in this paper, a new type of single-phase stand-alone induction generator proposed which employs a three-phase star connected squirrel cage induction machine and a single-phase PWM inverter. During the generator voltage build up, a small lead acid battery is used to feed the inverter first and after while, it is replaced by a single-phase full diode-bridge rectifier. The generator supplies the rectifier itself.



2-1) D axis equivalent circuit.



2-2) Q axis equivalent circuit.

Figure 2. Representation of equivalent D axis and Q axis models of a three-phase induction machine in the stator stationary reference frame.

2. SYSTEM DESCRIPTION

Figure 1 shows the electrical configuration of a single-phase induction generator, which uses a three-phase induction machine and a single-phase PWM inverter. As can be seen in this figure, the PWM inverter feeds the stator reference phase (a_s), here after termed the generator exciting winding. A small lead acid battery and a single-phase full diode-bridge rectifier also supply the inverter. The rectifier is connected to the stator terminals (b_s and c_s), here after termed the load terminals.

Also, an inductive load with a shunt capacitor bank is connected between the stator terminals (b_s and c_s). In addition, a conventional PI controller is also used to regulate the generator load voltage.

3. SYSTEM DYNAMIC MODEL

With reference to [8], the D axis and Q axis equivalent circuits of a three-phase induction machine in the stator stationary reference frame are shown in Figure 2. In this figure, all parameters are

referred to the stator and indices (s) and (r) refer to the stator and rotor quantities respectively.

The electrical parameters used in Figure 2 are defined as:

- R_s, R_r : stator and rotor resistances
- X_{ls}, X_{lr} : stator and rotor leakage reactances
- X_m : magnetizing reactance
- ω_r : rotor angular velocity
- ω_b : synchronous base angular velocity

From Figure 2, the machine D axis, Q axis and zero sequence voltage equations are:

$$\begin{aligned} v_{qs}^s &= R_s i_{qs}^s + \frac{1}{\omega_b} \frac{d}{dt} \psi_{qs}^s \\ v_{ds}^s &= R_s i_{ds}^s + \frac{1}{\omega_b} \frac{d}{dt} \psi_{ds}^s \end{aligned} \quad (1)$$

$$\begin{aligned} v_{os}^s &= R_s i_{os}^s + \frac{1}{\omega_b} \frac{d}{dt} \psi_{os}^s \\ v_{qr}^s &= R_r i_{qr}^s + \frac{1}{\omega_b} \frac{d}{dt} \psi_{qr}^s - \frac{\omega_r}{\omega_b} \psi_{dr}^s \\ v_{dr}^s &= R_r i_{dr}^s + \frac{1}{\omega_b} \frac{d}{dt} \psi_{dr}^s + \frac{\omega_r}{\omega_b} \psi_{qr}^s \\ v_{or}^s &= R_r i_{or}^s + \frac{1}{\omega_b} \frac{d}{dt} \psi_{or}^s \end{aligned} \quad (2)$$

Also, the machine flux linkages (in volt units) are:

$$\begin{aligned} \Psi_{ds}^s &= \Psi_{md}^s + X_{ls} i_{ds}^s \\ \Psi_{qs}^s &= \Psi_{mq}^s + X_{ls} i_{qs}^s \\ \Psi_{os}^s &= X_{ls} i_{os}^s \end{aligned} \quad (3)$$

$$\begin{aligned} \Psi_{dr}^s &= \Psi_{md}^s + X_{lr} i_{dr}^s \\ \Psi_{qr}^s &= \Psi_{mq}^s + X_{lr} i_{qr}^s \\ \Psi_{or}^s &= X_{lr} i_{or}^s \end{aligned} \quad (4)$$

$$\Psi_{md}^s = X_m (i_{ds}^s + i_{dr}^s), \Psi_{mq}^s = X_m (i_{qs}^s + i_{qr}^s) \quad (5)$$

One may be noted that in Equations 1-5 as well as in Figure 2, the flux linkages are expressed in terms of reactances rather than inductances. As a result the flux linkages now become flux linkages per second with the units of volts. The inductive reactances are obtained by multiplying ω_b times inductance [8].

With reference to Figures 1-2 and Equations 1-5, express the load voltage v_{bc} in terms of v_{qs}^s , v_{ds}^s , v_{os}^s as well as i_{as} , i_{bs} and i_{cs} in terms of Ψ_{qs}^s , Ψ_{ds}^s and Ψ_{os}^s , the generator performance equations are derived as:

$$\begin{aligned} \frac{d}{dt} v_L &= \frac{-1}{C} (i_L + i_{cs}) \\ \frac{d}{dt} i_L &= \frac{v_L}{L} - \frac{R}{L} i_L \end{aligned} \quad (6)$$

Using the Park inverse transformation, therefore:

$$[f_{abc}] = \begin{bmatrix} 1 & 0 & 1 \\ -1 & -\sqrt{3} & 1 \\ 2 & 2 & 1 \\ -1 & \sqrt{3} & 1 \\ 2 & 2 & 1 \end{bmatrix} [f_{qdos}^s] \quad (7)$$

Where the letter f can be either letter v (voltage) or letter i (current). Also, the superscript s denotes that the stator phase voltages or currents are transformed on to the stator stationary reference frame.

From Equation 7, it results that

$$\begin{aligned} v_L &= v_{bc} = -\sqrt{3} v_{ds}^s \\ v_{as} &= v_{qs}^s + v_{os}^s \end{aligned} \quad (8)$$

Also

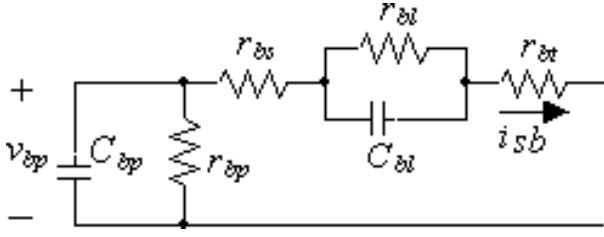


Figure 3. Equivalent circuit of a lead acid battery.

$$\begin{aligned}
 i_{as} &= i_{qs}^s + i_{os}^s \\
 i_{bs} &= -i_{cs} = \frac{-1}{2}(i_{qs}^s) - \frac{\sqrt{3}}{2}(i_{ds}^s)
 \end{aligned} \tag{9}$$

From Equation 3

$$\begin{aligned}
 i_{qs}^s &= \frac{\Psi_{qs}^s - \Psi_{mq}^s}{X_{ls}}, i_{ds}^s = \frac{\Psi_{ds}^s - \Psi_{md}^s}{X_{ls}}, \\
 i_{os}^0 &= \frac{\Psi_{os}^s}{X_{ls}}
 \end{aligned} \tag{10}$$

Linking Equations 6, 9 and 10, it gives

$$\frac{d}{dt} v_L = \frac{-1}{C} [i_L + \frac{1}{2} (\frac{\Psi_{qs}^s - \Psi_{mq}^s}{X_{ls}}) + \frac{\sqrt{3}}{2} (\frac{\Psi_{ds}^s - \Psi_{md}^s}{X_{ls}})] \tag{11}$$

$$i_{bs} = -i_{cs} = \frac{-1}{2} (\frac{\Psi_{qs}^s - \Psi_{mq}^s}{X_{ls}}) - \frac{\sqrt{3}}{2} (\frac{\Psi_{ds}^s - \Psi_{md}^s}{X_{ls}}) \tag{12}$$

Where R and L are the load resistance and inductance, C is the shunt capacitor bank, v_L and i_L are the load voltage and current. Note that the variables with superscript s are defined in the stator D axis and Q axis reference frame.

Considering the equivalent circuit of a lead acid battery as shown in Figure 3 [7], the following equations can be derived:

$$C_{bp} \frac{d}{dt} v_{bp} = i_{sb} - \frac{v_{bp}}{r_{bp}}, C_{bt} \frac{d}{dt} v_{bt} = i_{sb} - \frac{v_{bt}}{r_{bt}} \tag{13}$$

$$v_{dc} = v_{bp} - v_{bt} - i_{sb}(r_{bs} + r_{bt}) \tag{14}$$

$$i_{sb} = i_{as} \cdot [\text{sign}(v_{as})] \tag{15}$$

Where C_{bp} and v_{bp} are the battery capacitance and voltage respectively. The initial open circuit battery voltage is v_{bpo} , the self-discharging resistance is r_{bp} , while the capacitance and resistance simulating battery charging and discharging are C_{bt} and r_{bt} respectively. i_{sb} is the current flowing out of the battery and output voltage is v_{dc} . r_{bt} denotes the equivalent resistance of the parallel/series battery connection. Also, $\text{sign}(v_{as})$ is defined as:

$$\text{sign}(v_{as}) = \begin{cases} +1 & , v_{as} > 0 \\ -1 & , v_{as} < 0 \end{cases} \tag{16}$$

Based on Equations 1-16, a C++ computer program has been developed which can be used to model the generator system of Figure 1 on a PC. The flowchart of this program is shown in Figure 4. In this program, the nonlinear differential equations are solved by a static Runge-Kutta fourth order method and variables to solve for are:

$$x = [\Psi_{qs}^s, \Psi_{ds}^s, \Psi_{os}^s, \Psi_{qr}^s, \Psi_{dr}^s, v_{dc}, v_{bp}, v_{bt}, i_L]^T \tag{17}$$

According to the configuration of Figure 1, when the PWM inverter is switched over from the battery, and supplied from the rectifier therefore, the battery dynamic equations used in 12-14 have to be replaced by the rectifier dynamic equations given by:

$$\frac{d}{dt} v_{dc} = \frac{i_d}{C_d} - \frac{1}{C_d} [\frac{\Psi_{qs}^s - \Psi_{mq}^s}{X_{ls}} + \frac{\Psi_{os}^s}{X_{ls}}] \cdot \text{sign}(v_{as}) \tag{18}$$

$$\frac{d}{dt} i_d = \frac{v_L}{L_d} - \frac{v_{dc}}{L_d} \tag{19}$$

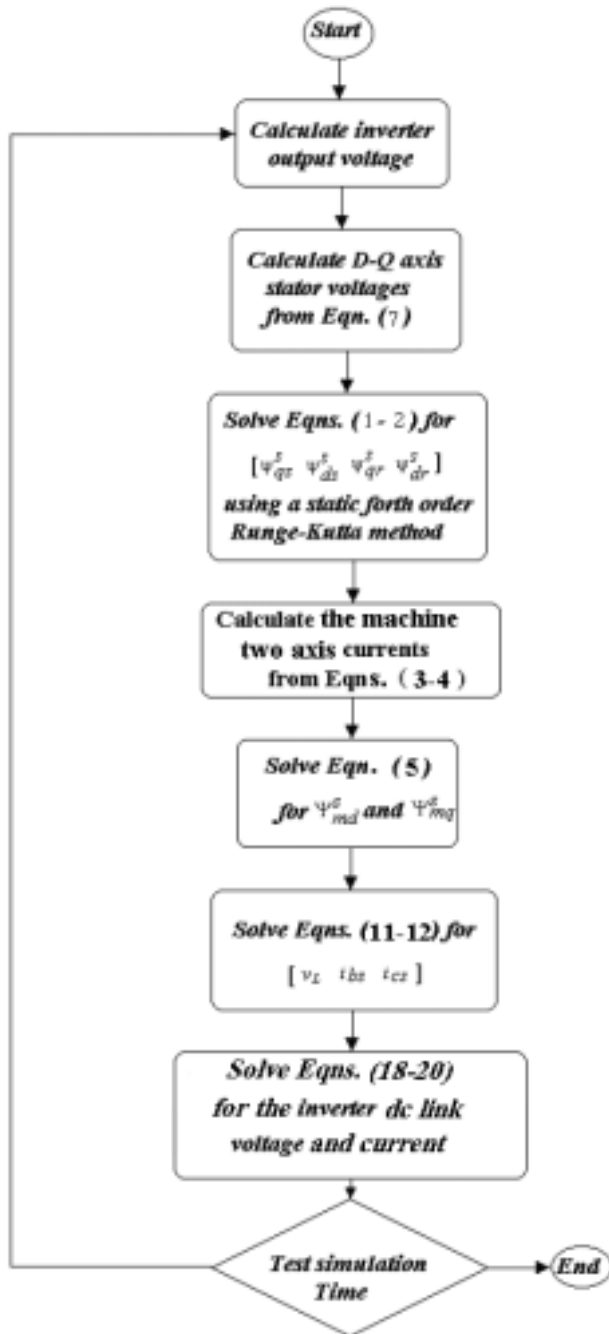


Figure 4. Flowchart of the developed computer program.

In such situation, the variables to solve for are:

$$x = [\Psi_{qs}^s, \Psi_{ds}^s, \Psi_{os}^s, \Psi_{qr}^s, \Psi_{dr}^s, v_{dc}, i_L, i_d]^T \quad (20)$$

Where L_d is the rectifier filter inductance. i_d and

v_{dc} are the rectifier output current and voltage respectively.

To solve the system equations, at each step Δt of time, it is required to know the stator voltages v_{qs}^s , v_{ds}^s and v_{os}^s .

Starting from first iteration, assuming that:

$$v_{ds}^s(0) = 0, \text{ and } v_{as}(0) = v_{dc}(0) = v_{bpo} \quad (21)$$

Therefore, from following equation $v_{os}^s(0)$ is also zero.

$$v_{os}^s = \frac{1}{\omega_b} \frac{d}{dt} \Psi_{os}^s + \frac{R_s}{X_{ls}} \Psi_{os}^s \quad (22)$$

Once v_{ds}^s and v_{as} are known, then from Equation 8, v_{qs}^s is obtained equal to v_{bpo} . This procedure is equally repeated for the subsequent iterations with notice to that, v_{as} is either $+v_{dc}$ or $-v_{dc}$.

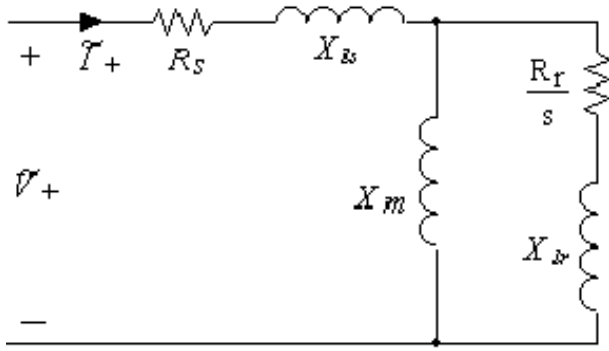
4. GENERATOR STEADY-STATE MODEL

With reference to Figure 1, assume the PWM inverter is replaced for an ideal sinusoidal ac voltage source ($v_{as}(t)$) as shown in Figure 5, consider sinusoidal steady-state conditions therefore, from Figure 5:

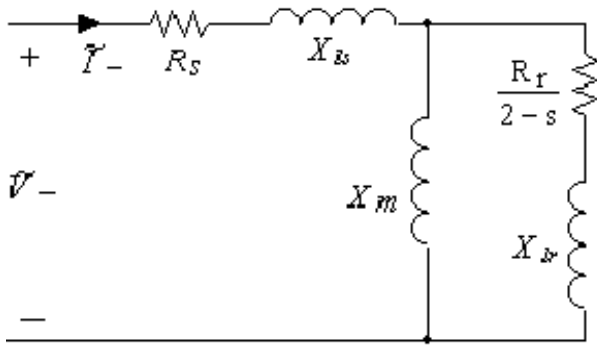
$$\begin{aligned} \tilde{V}_{bc} + \frac{\tilde{I}_{bs}}{-Y_L} &= 0 \\ \tilde{I}_{bs} &= -\tilde{I}_{cs} \end{aligned} \quad (23)$$

Considering the steady-state forward, backward and zero sequence equivalent models of a three-phase induction machine as shown in Figure 5, it follows that

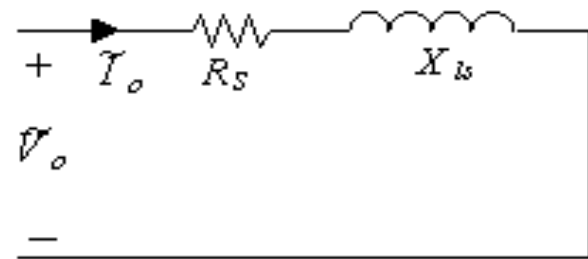
$$\begin{aligned} \tilde{I}_+ &= Y_f \tilde{V}_+, \tilde{I}_- = Y_b \tilde{V}_-, \tilde{I}_0 = Y_o \tilde{V}_0 \\ \tilde{I}_{bs} &= a^2 Y_f \tilde{V}_+ + a Y_b \tilde{V}_- + Y_o \tilde{I}_0 \end{aligned}$$



(a)



(b)



(c)

Figure 5. Machine forward (a), backward (b) and zero sequence (c) steady-state equivalent circuits.

$$\tilde{I}_{cs} = a Y_f \tilde{V}_+ + a^2 Y_b \tilde{V}_- + Y_o \tilde{I}_o \quad (24)$$

Also

$$\tilde{V}_{as} = \tilde{V}_+ + \tilde{V}_- + \tilde{V}_o,$$

$$\tilde{V}_{bc} = (a^2 - a) Y_f \tilde{I}_+ + (a - a^2) Y_b \tilde{I}_- \quad (25)$$

Combining Equations 24 and 25 with Equation 23, it gives

$$\begin{bmatrix} 1 & 1 & 1 \\ -Y_f & -Y_b & 2Y_o \\ a^2 - a + a^2 \frac{Y_f}{Y_L} & a - a^2 + a \frac{Y_b}{Y_L} & \frac{Y_o}{Y_L} \end{bmatrix} \begin{bmatrix} \tilde{V}_+ \\ \tilde{V}_- \\ \tilde{V}_o \end{bmatrix} = \begin{bmatrix} \tilde{V}_{as} \\ 0 \\ 0 \end{bmatrix} \quad (26)$$

$$\tilde{I}_+ = Y_f \tilde{V}_+, \quad (27)$$

$$\tilde{I}_- = Y_b \tilde{V}_-, \quad \tilde{I}_o = Y_o \tilde{V}_o$$

Where

$$a = e^{j\frac{2\pi}{3}} \quad (28)$$

and Y_f , Y_b and Y_o are the forward, backward and zero sequence admittances of a three-phase induction machine at a specific negative slip of s , Y_L is sum of the load and shunt capacitor admittances. $(\tilde{V}_+, \tilde{V}_-, \tilde{V}_o)$ and $(\tilde{I}_+, \tilde{I}_-, \tilde{I}_o)$ are the three phase symmetrical components of the stator voltages and currents respectively.

The magnetic saturation can be modelled by the induction machine $E_g - X_m$ curve where, E_g is the machine airgap voltage. This curve is obtained from a synchronous test and is approximated by a piecewise linear function [5].

Having known s and \tilde{V}_{as} , Equations 26 are solved for \tilde{V}_+ , \tilde{V}_- and \tilde{V}_o . Following to this step, the current components, \tilde{I}_+ , \tilde{I}_- and \tilde{I}_o , are also obtained from Equation 24. In addition, the active and reactive powers (consumed by the load and generator exciting winding) can be calculated from following equations:

$$P_L = -\text{Re}(\tilde{V}_{bc} \cdot \tilde{I}_b^*), \quad Q_L = -\text{Im}(\tilde{V}_{bc} \cdot \tilde{I}_b^*)$$

$$P_{as} = \text{Re}(\tilde{V}_{as} \cdot \tilde{I}_{as}^*), \quad Q_{as} = \text{Im}(\tilde{V}_{as} \cdot \tilde{I}_{as}^*) \quad (29)$$

TABLE 1. Induction Machine Parameters.

P_n	2.2	kW
$(V_{L-L})_n$	220	V
I_n	9.1	A
f	50	Hz
P	4	poles
R_s	0.8	Ω
R_r	0.64	Ω
L_s	105.27	mH
L_r	105.27	mH
L_m	102.5	mH

5. SIMULATION RESULTS AND DISCUSSION

A digital simulation study was carried out for a 2.2KW three-phase induction machine with parameters shown in Table 1 and a $E_g - X_m$ curve described as [5]:

$$E_g = \begin{cases} 156.32 - 1.92 X_m, & X_m \leq 25.51 \\ 191.80 - 3.31 X_m, & 25.51 < X_m \leq 31.29 \\ 470.15 - 12.21 X_m, & 31.29 < X_m \leq 32.19 \\ 0, & 32.19 < X_m \end{cases} \quad (30)$$

The simulated results of Figure 6 obtained for $R_L = 28.3\Omega$, $L = 2\text{mH}$, $C = 100\mu\text{F}$ and $s = -0.03$. To obtain these results, a 12 volts lead acid battery is used to feed the inverter first. Then, as long as the rectifier DC voltage reaches to the level of battery voltage, the battery is disconnected and replaced for the rectifier. In addition, assuming an ideal a.c. voltage source feeding the diode bridge rectifier, the generator steady-state performance are obtained and shown in Figure 7. The results of Figure 7 demonstrate the plots of V_L , I_{bs} , I_{as} , P_L , P_{as} , Q_L versus the modulation index, m_a . The curves marked with (o) obtained by a load same as above and confirm

that upon the machine's voltage and current ratings and approximately a unity power factor operation (measured at the generator load terminals included the capacitance C), approximately a real power of about 0.6 p. u. absorbed by the load while no real power is pushed into the a.c. voltage source. The plots marked with (*) and (\square) obtained by $L = 2\text{mH}$, $C = 100\mu\text{F}$, $s = -0.03$ and $R_L = 40\Omega$ and $R_L = 22\Omega$ respectively. From the second plots (marked with *), is seen that a real power of about 0.5 p. u. and 0.18 p. u. are absorbed by the load and a.c. voltage source, respectively. The third plots (marked with \square) show that a real power of about 0.7 p. u. is consumed by the load, 0.55 p. u. supplied by the prime mover and the remain provided by the a.c. voltage source. From these results, it can be concluded that such a generator system could be beneficial in the remote areas where a wind or a hydro turbine can be applied and a single-phase a.c. distribution network also exists. When the load demand is greater than the power supplied by the prime mover, the single-phase a.c. line supplies the real power to the generator and when the power supplied by the turbine exceeds the load demand, the a.c. line absorbs the excess power. Because, the generator rotational and iron losses are supplied by a prime mover with constant speed therefore these losses are not taken into account in our system simulation.

6. CONCLUSION

A new type of single-phase stand-alone induction generator has been introduced which employs a three-phase squirrel cage induction machine and a single-phase PWM voltage source inverter. The proposed generator scheme is a self excited self regulated generator system. The generator output frequency is always constant and is equal to the PWM inverter main frequency. In addition, the generator system has a nearly good sinusoidal output voltage and that is because of canceling out the lower order harmonics by the inverter itself as well as filtering out the higher harmonics by the three-phase machine leakage inductances. The higher amount of mechanical power injected, the higher amount of real power can be achieved. Therefore if it is necessary, a bigger three-phase machine can be employed. One may be noted that

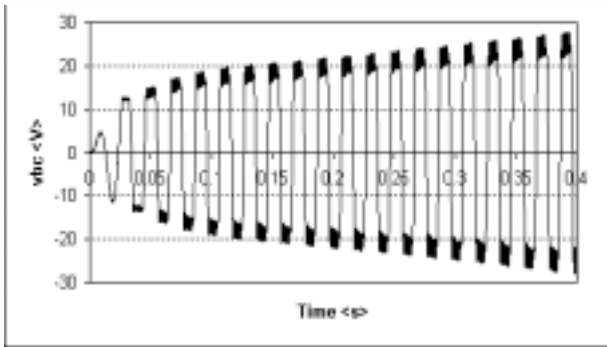


Figure 6.1. Generator voltage build up.

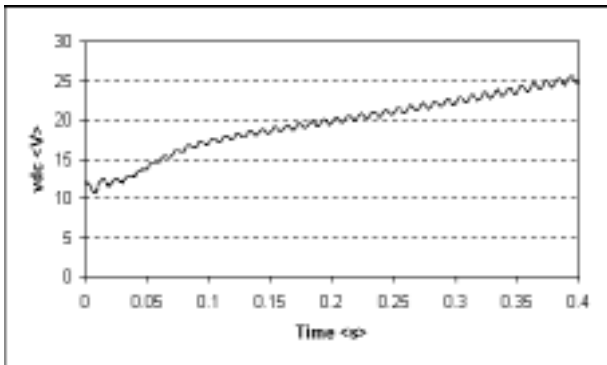


Figure 6.2. Dc-link voltage.

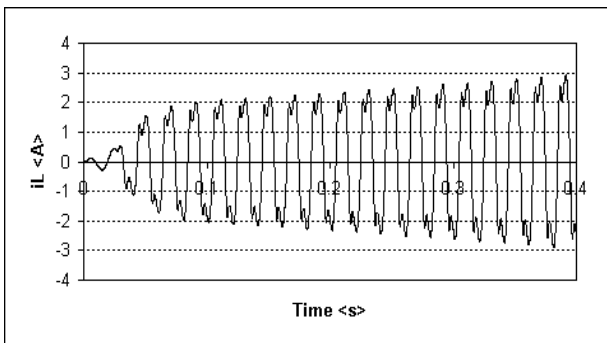


Figure 6.3. Load current waveform.

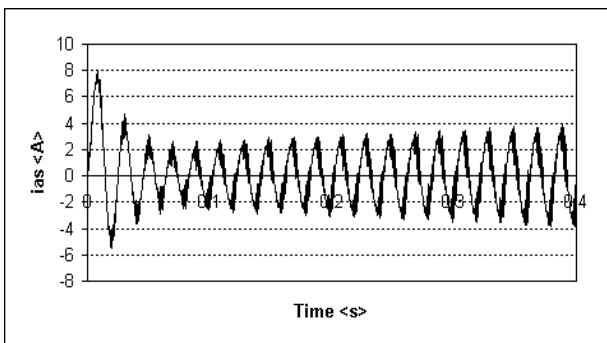


Figure 6.4. Transient waveform of the stator current.

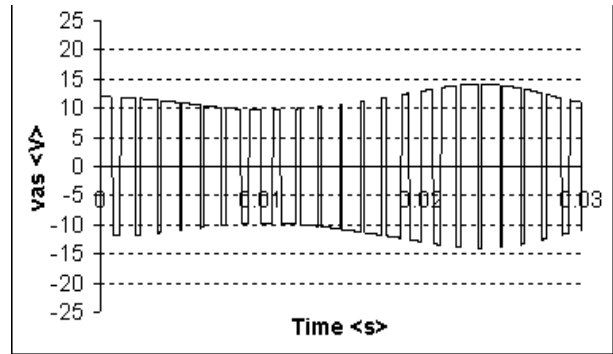


Figure 6.5. Inverter output voltage for modulation frequency factor of $m_1=15$.

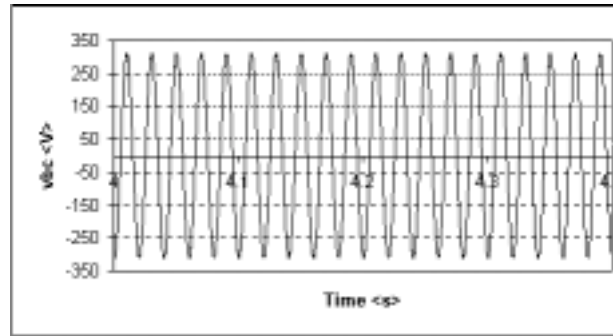


Figure 6.6. Steady-state waveform of the load voltage.

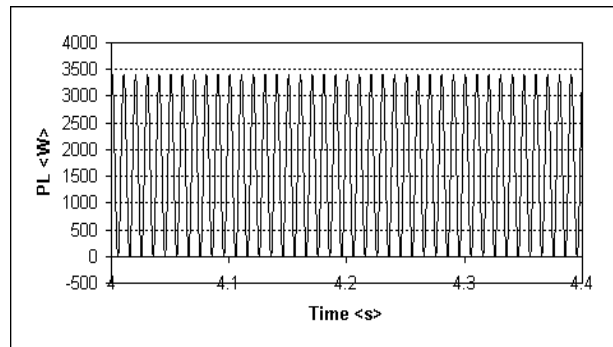


Figure 6.7. Steady-state waveform of the load instantaneous power.

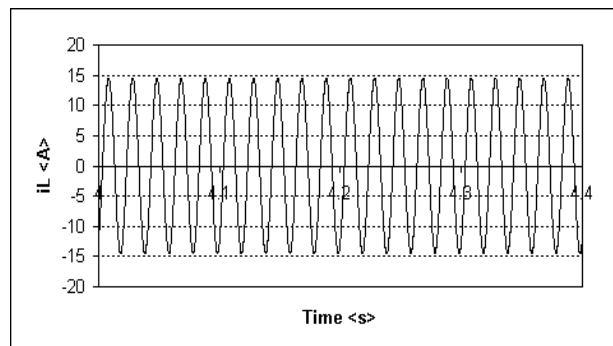


Figure 6.8. Steady-state waveform of the load current.

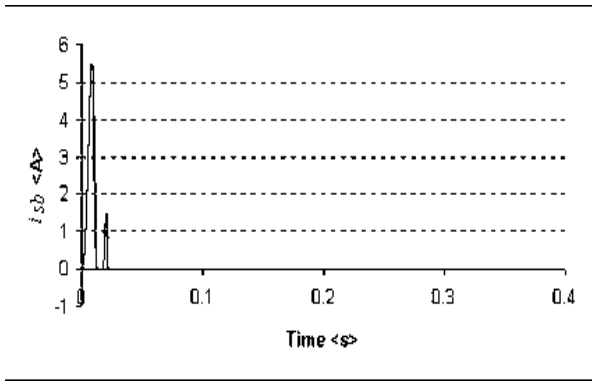


Figure 6.9. Battery output current.

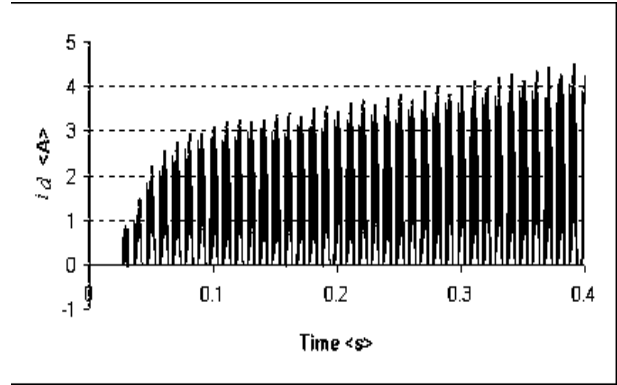


Figure 6.10. Diode bridge rectifier output current.

the generator output power has to be always tracked with the real power which is injected by the prime mover.

A 2.2KW three-phase machine has been

examined and the digital simulation results obtained show that upon the machine voltage and current ratings and approximately a unity power factor operation (measured at the generator load

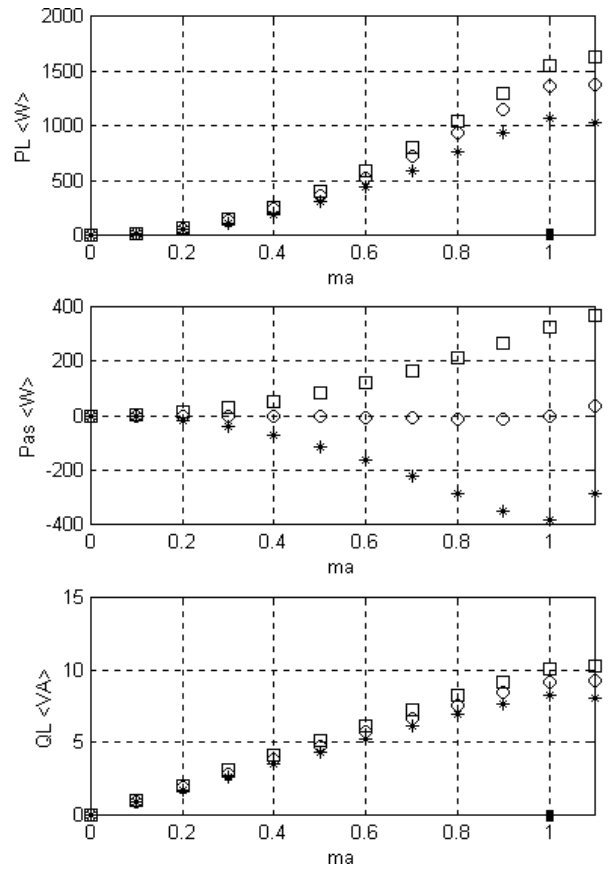
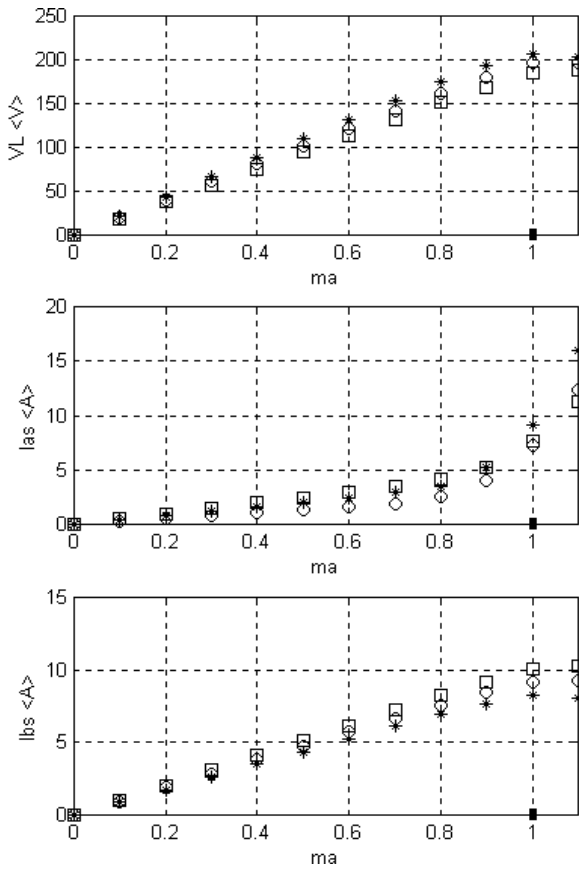


Figure 7. Generator steady-state performance.

terminals with shunt capacitor included), a real power of about 0.6 P.U. can be achieved. Furthermore it is shown that the proposed generator system could be beneficial in the remote areas where either a hydro or a wind turbine is applicable and a single-phase distribution network is also exist. Although the paper has presented only the simulate results but this research project is continued in order to present the practical single-phase and three-phase test machines.

7. REFERENCES

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