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ADAPTATION OF THREE PHASE INDUCTION MOTOR AS A STANDALONE SELF EXCITED GENERATOR, (SEIG).

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Abstract

The increasing importance of energy demand has been responsible for the revival of interest in so-called alternative source of energy. Thus, the drive towards the decentralization of power generation and increasing use of non-conventional energy sources such as wind energy, bio-gas, solar and hydro potential, etc. have become essential to adopt a low cost generating system, which is capable of operating in the remote areas, and in conjunction with the variety of prime movers. A self-excited (Stand-Alone) asynchronous machine (SEIG) to generate sustainable AC voltage was investigated experimentally in this work. Using evaluated three power capacitors connected in delta with the output leads of the induction machine, enabled a maximum phase voltage of 245 volts at a speed of 1500 rpm. The self-excited induction generator performance characteristics were investigated by carrying out no-load test and load test using resistive, capacitive, inductive and a combination of these loads as long as the machine was not overloaded. Apart from the capacitors acting as the exciter, it also plays the role of compensating for the reactive power in the system. Effects of various system parameters on the steady-state performance have been studied, and the results presented provided guidelines for optimum design of such systems.

Key word: SEIG, inductor, generator, capacitor, machine, synchronous, voltage and frequency.

Introduction

Induction generators are increasingly being used in nonconventional energy systems because of its ruggedness such as wind, micro/mini hydro, etc., apart from their general use as motors. Renewable energy sources, such as wind, photovoltaic, and hydropower plants are recently being paid much attention universally due to excess exploitation of fossil fuels and associated environment pollution. The self-excited induction generator (SEIG) is suitable to generate electrical power from these nonconventional energy sources Rahim et al, (2009) and (Grantham & Seyoum 2008) Three-phase Induction Machines (IMs) are also used as generators in electric power systems as demonstrated by Ueda, (1986) and Bansal et al (2003). The scheme is meant to be a cheaper and efficient method of generating AC power (usually a few kilowatts). It is well known that a conventional induction machine can work as a generator if sufficient amount of capacitance is connected across the machine terminals to sustain the excitation requirements, while the rotor speed is maintained by some mechanical power. The induction generator offers advantages over hydro and wind applications in terms of cost and simplicity as applied by Smith, (1990) and it plays an important part in the renewable energy industry today. Other advantages of using an induction generator instead of a synchronous generator are ruggedness, brushless (in squirrel cage construction), absence of separate dc source exciter, ease of maintenance, self-protection against severe overloads and short circuits. In isolated systems, squirrel cage induction generators with capacitor excitation, known as Self-Excited Induction Generators (SEIGs), are very popular in renewable energy system applications (Kumaresan, 2005; Singh *et* *al*, 2006). The induction generator also has the limitations of the need for an external power source to provide its excitation (i.e. either from excitation capacitor or grid connected system).

The SEIG is used where a three - phase capacitor bank is connected across the stator terminals to supply the reactive power requirement of a load and generating system (Singh et al, 2012). When such an induction machine is driven by an external mechanical power source, the residual magnetism in the rotor produces an Electromotive Force (EMF) in the stator windings. This EMF is applied to the shunt connected capacitor bank causing current flow in the stator winding and establishing a magnetizing flux in the machine. An induction machine connected and excited in this manner is capable of acting as a standalone generator supplying real and reactive power to the connected load. In this mode of operation, the capacitor bank supplies the reactive power requirement of the load and generator and the real power demand of the terminal load is supplied by the prime mover. This principle is applied in the design and construction of three phase of 3.5kW petrol engine driven self-excited induction motor, adapted as a generator in this paper.

The main drawback of the SEIG system is that the voltage and frequency produced by the system is highly dynamic under variable load conditions and this can be improved upon in future research work. The main aim of this paper is to demonstrate the adaption of 3 phase squirrel cage induction motor as a standalone induction generator for domestic applications in remote areas, where transmission lines are not available or easily accessible.

Proposed Seig System Configuration

The SEIG system is composed of four main items: the prime mover, the induction machine, the load, and the self-excitation capacitor bank. The general layout of the SEIG system is shown in Figure 1.

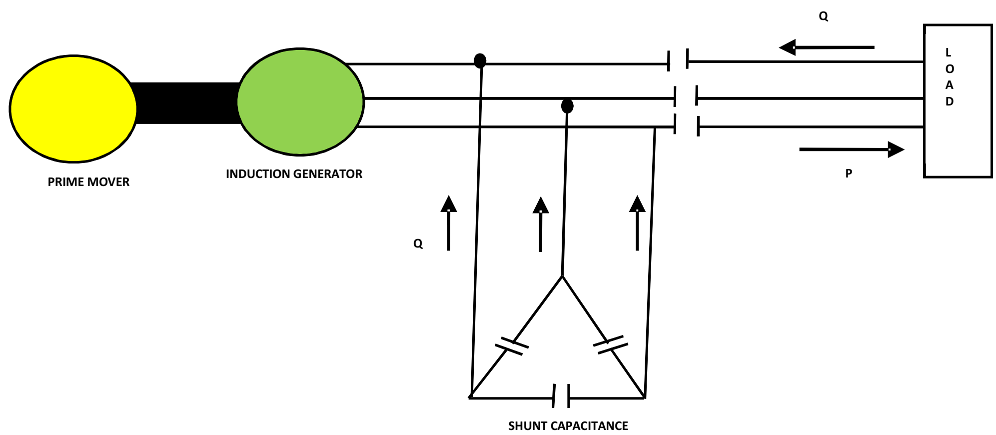

Figure 1 Schematic diagram of a standalone self-excited induction generator.

The hydro/wind turbine is assumed to operate with constant input power transferred to the induction generator. The real power required by the load is supplied by the induction generator by extracting power from the prime mover (turbine). When the speed of the turbine is not regulated, both the speed and shaft torque vary with variations in the power demanded by the loads. The self-excitation capacitors connected at the stator terminals of the induction machine must produce sufficient reactive power to supply the needs of the load and the induction generator.

A SEIG is more attractive than a conventional synchronous generator in this type of application because of its low unit cost, absence of dc excitation source, brushless cage rotor construction, and lower maintenance requirement (Bansal, (2005); Singh 2004). A suitably sized three-phase capacitor bank connected at the generator terminals is used as a variable lagging VAr source to meet the excitation demand of the cage machine and the load. The machine operated in this mode is SEIG (Simoes and Farret 2011). The main drawback of the standalone SEIG is its poor voltage and frequency regulations under variable loads. A change in the load impedance directly affects the excitation of the machine because the reactive power of the excitation capacitors is shared by both the machine and the load, which causes the generating voltage drop when the impedance of the load is increased resulting in poor voltage regulation. Poor frequency regulation occurs when the load is increased, (with an increase in the slip of the induction machine).

System Turbine Modeling

Considering the use of 3.5kW (4.7HP), 1500 rpm, 440V the wound three phase, SEIG with shunt excitation capacitors VAR calculations. Motor Parameters from the name plates are applied in the design base on the stator properties; Wire gauge of: 0.71mm^2 with 8A rating selected from table to match up with current rated output for the desired power output.
Frequency of the motor: 50Hz
Output Power Rating: 3.5KVA or 4.7HP
Power Factor: 0.76
Expected Terminal Voltage = 440V line voltage and 240V phase voltage.
No of turns per slot is 35turns maximum capacity of each slot base on the selected wire gauge
No of turns per pole is 70turns base on the gauge selected.
Note that apparent power of a three phase system is given from the power triangle as;

$$Apparent\ Power = \sqrt{3}XVXI \quad (1)$$

[Power supplied by the motor to the connected load rated in VA]
But, the rated power of the motor from the name plate is 3.5KVA

$$Output\ Current\ (I_{output)} = \frac{(Rated\ Power\ of\ the\ generator\ in\ KVA)}{(Expected\ output\ voltage)} \quad (2)$$

$$I_{output)} = \frac{(3.5X10^3)}{440} = 7.96A$$

Expected rated output current of the motor used in selecting the cable size from the wire and gauge data sheet, from equation (1)

$$Apparent\ Power = \sqrt{3}X\ 440\ X\ 7.96 = 6.07KVA$$

$$Active\ Power = \sqrt{3}XVXIX\ Cos\theta \quad (3)$$

[Actual power consumed by connected load in KW]

$$\sqrt{3}\ X\ 440\ X\ 7.96\ X\ 0.76 \text{ [for three phase system]}$$

$$= \sqrt{3}\ X\ 440\ X\ 7.96\ X\ 0.76$$

Active power = 4.61KW
The reactive power needed for excitation is given from the power triangle, this determines the size of the generator, and size of capacitor required

$$Reactive\ power = \sqrt{(Apparent\ Power)^2 - (Active\ power)^2} \quad (4)$$

$$Reactive\ power = \sqrt{(0.67)^2 - (4.61)^2}$$

Reactive Power = 3.95KVAR [for the entire three phase system]

$$Reactive\ power\ per\ phase = \frac{3.95}{3}$$

Reactive Power per phase = 1.32 KVAR per Phase

Current through the shunt connected excitation Capacitor [$\mathbf{I}_{cap}$] (5)

$$\mathbf{I}_{cap} = \frac{1.32 \text{ X } 10^2}{440V}$$

Current through capacitor (I_{cap}) = 3A

Note that capacitance reactance is given as

$$X_c = \frac{1}{2\pi fc} \quad (6)$$

from Ohm's Law

$$Z = \frac{V}{I} \quad (7)$$

Equating equation (6) and (7):

$½\pi fc = V/I_{cap}$

$1/ 2\pi fc = (440 / 3)$

$1/ 2\pi fc = 146.67\Omega$

Making C the subject of the formula

$C = 2\pi f \text{ X } 146.49$

$C = 1/(2 \text{ X } \pi \text{X } 50 \text{ X } 146.49)$

$C = 1/ \text{ X } 46076.69$

The value of shunt excitation capacitor required = 21.7μF ≅ 22μF

The theory that presents the characteristics of this element makes its useful in induction generator application (Igbinovia, 2007). The use of single phase systems requires more capacitance, the induction generator operates at lower efficiency, and not easily excited. But small (minimum) capacitors excitation to the auxiliary winding is required to produce output voltage as voltage rises (www.qsl.net/ns8o/Induction_Generator.html, 2014).

The three units of shunt capacitors were connected in delta configuration for effective provision of the required reactive power for excitation and inductive load performance. The series capacitor for voltage regulation per phase was selected randomly base on the connected load capacity for stable voltage output to the load. This will enhance the output voltage stability performance of the generator when an inductive load is connected to its terminals. The effect of output voltage variation is not felt much when a resistive loads is connected.

Generator Rotor Modeling

When the speed approaches synchronous speed, the slip = 0, and the rotor resistance (R_s/s) becomes infinite, rotor current I_r = 0, and no motor torque is developed. (The motor is neither a motor nor a generator it is "floating" on the bus. The only stator current is the exciting current to supply the rotating magnetic field and the iron losses. The operating slip in a self-excited mode is generally small and the variation of the frequency depends on the operating speed range (Smith, 2005).

The speed of the rotating flux is independent of the rotor speed but dependent only on the function of the number of poles and the frequency of the applied voltage. *Increasing the rotor speed above the synchronous speed causes the slip = [(n_s - n_r)/n_s] to become negative! The gap power,*
P_{gap} = P_{rcl}/s becomes negative, now supplying power to the system.

$$Slip\ (S) = \frac{N_s - N_r}{N_s} \tag{8}$$

where;

n_s is synchronous speed of the rotating magnetic field
n_r is rotor speed of the machine directly coupled to the prime mover
s is slip, a speed difference between the rotor and changing field in the stationary coils (www.qsl.net/ns8o/Induction_Generator.html, 2014).

But the synchronous speed

$$N_s = \frac{120\ X f}{Pole\ pair\ (P)} \tag{9}$$

where;
f is frequency (50H_Z)
p is pole pair of the stator windings of the machine
n_s is 120 50/4 = Synchronous Speed of the Motor.
n_s is 1500 r. p. M

For Motor to generate need a negative slip, this can only be achieved by running the Motor above the synchronous speed (1500 r. p. m), speed greater than 1500 rpm for four pole wound motors.

Induction Motor Winding and Assembling

A burnt three phase 440V, 50Hz, 4.7 horse power induction motor was procured and rewound to give the required output. The total slots of 48 were sub-divided into four poles per phase for a three phase induction motor windings, as shown in Figures 2 and 3, respectively. A copper wire gauge selection of 0.71mm^2 (selected from data table) was used in the windings with 35turns per slot and 70 turns per pole to give the expected output.


Figure 2: Stator Frame


Figure 3: Sample of Pole Winding

Winding Positioning in Slots Electrically at 120^0 Apart

The phase for each winding in the stator core are presented in sequel order for all the three phase, but only red phase winding is fully represented here both in configuration and in diagram as shown in Figure 4, while the remaining other phase (yellow and blue) are done in the same embedded arrangement. Figure 5 shows the complete stator wound three phase four pole induction motor.

Phase 1 Winding Positions in the Stator Core [Red Phase Winding]

Coil 1
Slot 1 and slot 10 (Inner 35 turns)
Slot 11 and slot 48 (Outer 35 turns)

Coil 2
Slot 13 and slot 22 (Inner 35 turns)
Slot 12 and slot 23 (Outer 35 turns)

Coil 3
Slot 25 and slot 34 (Inner 35 turns)
Slot 24 and slot 35 (Outer 35 turns)

Coil 4
Slot 37 and slot 46 (Inner 35 turns)
Slot 36 and slot 47 (Outer 35 turns)

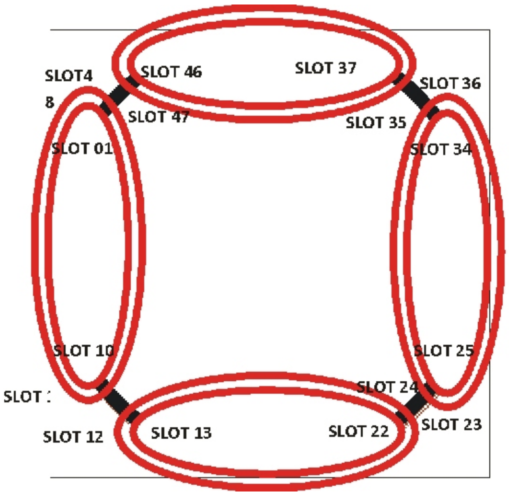

Figure 4: Phase 1 Coils Positions Displacement in the Stator

Figure 5: Complete Stator Wound Three Phase Four Pole Induction Motor

Performance Characteristic of Seig

Several set of experimental readings were taken after the final assembling of all component elements making up the generator and no load and full load tests were carried out with the following readings as shown in Figures 6 to 9.

Shunt capacitors effects as shown in Figures 6 and 7 are plotted from Table 1 indicate the presence of a shunt capacitor of 90µF connected at the end of load terminal results in a gradual change in voltage as the speed of the motor is increased closer and above the synchronous speed of the motor, from motor mode to generator mode. Ideally, the per cent voltage rise at the capacitor is zero at no load and rises to maximum at full load and maximum speed. In order to validate the simulation results we have realized a practical test in the same conditions. The choice of the excitation capacity is essential for maintaining the needed voltage. The required reactive power is delivered by the bank of capacitor for SEIG self-excitation (Gunawan et al, 2015). The minimum terminal capacitor required for induction generator at a rated speed and a rated load is equal to 25μF as it is shown in Table 1. The no-load SEIG is driven at a rated speed. Both per line voltage Vs and the starting-up time are affected by the value of capacitors. When the excitation capacitance is less than 25 μF, the SEIG will fail to build up the voltage and when it is more than 45μF the generator will be operated at a high voltage level. At a constant speed and a constant field of excitation the generated SEIG voltage varies when the load varies. Therefore, automatic switching is required in order to deliver the desired regulation at high loads, but prevent excessive voltage at low loads. This stability or regulation can be achieved by connecting a series capacitor to supply the load. Figure 6 present the results of no-load connected with shunt capacity of 25μF, while Figure 7 presents no-load reading with shunt capacity of 25μF and series capacity of 70μF respectively. Figure 8 present the results of load reading with both shunt and series capacitors of 25 F and 70μF respectively, while Figure 9 present the load reading with both shunt and series capacitors of 25μF and 90 μF respectively.

Table 1: No- Load Test Terminal Readings with 25μF connected Shunt Capacitor only.

ROTOR SPEED (rpm)	1500	1600	1700	1800	1900	2000	2100	2200	2300	2400	2500	2600	2700	2800
phase voltage (vp)	0	0	0	114	128	138	144	150	176	179	185	194	214	226
LINE VOLTAGE (VL)	0	0	0	203	218	233	255	275	303	322	335	357	377	396
SLIP	0	-0.067	-0.133	-0.2	-0.27	-0.333	-0.4	-0.467	-0.533	-0.6	-0.667	-0.733	-0.8	-0.867
ROTOR FREQUENCY (fr=Sf)	0	0	-3.35	-6.65	-10	-13.3	-16.65	-20	-23.35	-26.65	-30	-33.35	-36.65	-40

Table 2: No-Load Reading Results with Shunt and Series Capacitor of 25μf and 70μf Connected

ROTOR SPEED (rpm)	1500	1600	1700	1800	1900	2000	2100	2200	2300	2400	2500	2600	2700	2800
PHASE VOLTAGE (VP)	0	0	0	0	111	147	155	166	177	188	3200	209	218	231
LINE VOLTAGE (VL)	0	0	0	0	187	259	267	292	310	328	346	360	382	406

Table 3: Load Reading Result with Shunt Capacitor and Series of 25μf and 70μf Connected.

Inductive Load	0	75	150	225	300	375	450	525	600
Current Load	0	0.8	1.4	1.9	2.1	2.3	2.5	2.5	2.5
Terminal Voltage	242	235	190	168	150	130	110	100	86

Table 4: Load Reading Result with Shunt Capacitor and Series of 25μf and 90μf Connected.

Inductive Load	0	75	150	225	300	375	450	525	600
Current Load	0	0.8	1.5	2.0	2.6	2.9	3.1	3.0	4.0
Terminal Voltage	236	216	203	195	172	160	153	130	134

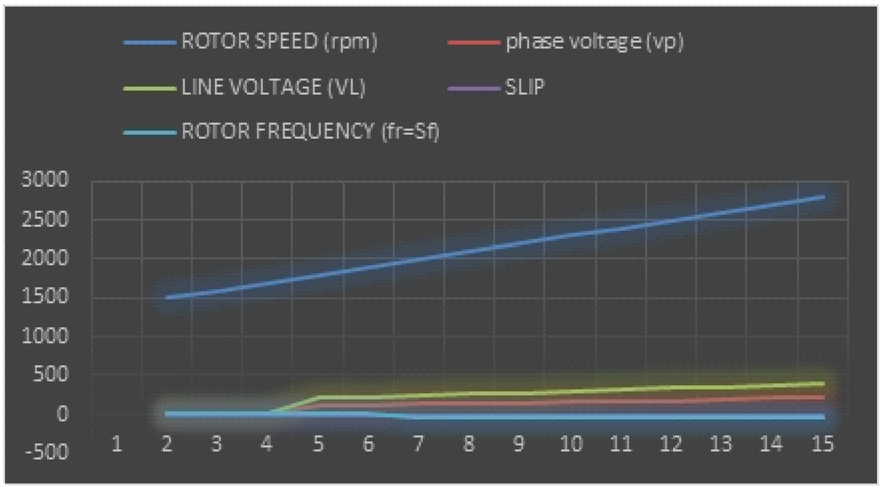

Figure 6: No-Load Output characteristic with Shunt Capacitor of 25µf.

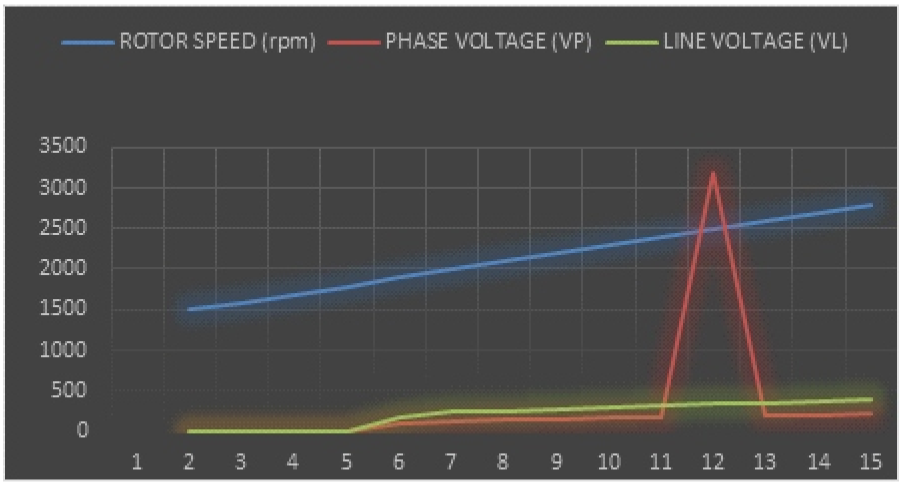

Figure 7: No-Load Output Characteristic series and shunt Capacitor 25µf and 70µf.

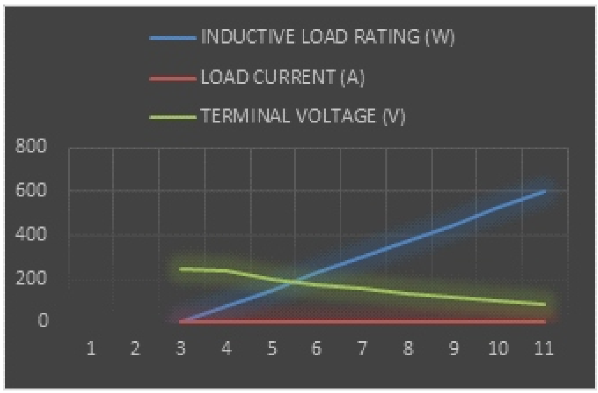

Figure 8: Load Output characteristic with Shunt and Series Capacitor of 25µf and 70µf.

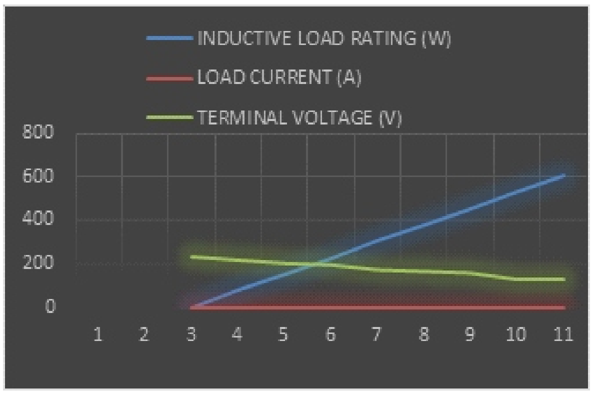

Figure 9: Load Output characteristic with Shunt and Series Capacitor of 25µf and 90µf.

Conclusion

The features of an induction generator in terms of cost and simplicity offer many advantages in today's renewable energy industry. This work leads to the overall characteristics for a SEIG. Three tests were done to identify the circuit parameters, the steady-state and dynamic characteristics of SEIG. From the experimental work it is observed that the prime mover speed, capacitance value and the load profile influence both the dynamic and steady-state behaviours. Voltage regulation in SEIG needs an adjustment of the reactive power injected and a speed control. The developed system satisfies voltage and frequency criteria, at the rotor speed of 2800rpm, the line voltage attained 396V, while the phase voltage was 231V with the inductive load of 600W respectively. The limitation of an induction generator in needing an external reactive power source to provide the machine magnetisation can be overcome by connecting a three-phase capacitor bank to its stator terminals. This capacitor bank supplies reactive power to both the generator and the load, and the real power demand of the terminal load is supplied by the prime mover.

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