Validation of Solar-Powered Squirrel Cage Induction Motor Driven Electric Generators: A Soft Testing Approach*

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Abstract

Recent research employs the use of solar-powered squirrel cage induction motors as prime movers of electric generators. The use is to mitigate the high fuel, operating and maintenance costs, air and noise pollution and low performance efficiency of the internal combustion engine. Successful soft testing of a system minimizes associated costs and could culminate in practical implementation of system. This paper reports validation outcomes of soft testing conducted on a solar-powered squirrel-cage induction motor-driven electric generator. The solar irradiations considered were 1000 W/m^2, 750 W/m^2 and 250 W/m^2 at temperatures of 25 ^{o}C and 20 ^{o}C. The soft tests in MATLAB/Simulink software environment were conducted on four models namely, the solar PV array, DC-AC converter, squirrel cage induction motor and the synchronous electric generator. For the three solar irradiance values, the output power and output voltage of the generator remained same at 24.7 kW and 400 V_{ac}, respectively. However, the reductions in solar irradiance from 750 W/m^2 to 250 W/ m^2 at same temperature of 20 ^{o}C gave a reduction of 2.75 V_{dc} from 36.57 V_{dc} to 33.82 V_{dc}. This reduction in voltage could not prevent the induction motor from rotating at the nominal speed of 1500 rpm to drive the generator.

Keywords: Electric Generator, Squirrel Cage Induction Motor, Manufacturer's Data, Soft Testing, Solar Power

1 Introduction

Industrial, commercial and domestic usage of electrical energy is a necessity today and will remain so for many decades. Diesel electric generators are normally driven by Internal Combustion (IC) engines which are mostly considered problematic due to low performance efficiency, high running costs due to fuel hikes, and air and noise pollution. Though recent research employs the use of solar-powered squirrel cage induction motors as prime movers of electric generators, any feasible replacement of the IC engine entails some form of validation of the resulting motor-generator set prior to practical implementation. Formal testing is the verification that a specification requirement has been met by measuring, recording, or evaluating qualitative and quantitative data obtained during controlled exercises under all appropriate conditions using real and/or simulated stimulus. This includes verification of system performance, system functionality, and correct data distribution. Testing however, could be experimental, operational, physical, diagnostic, virtual or simulation based and can give significant time and cost savings.

Typically, testing of electrical equipment involves some instrumentation entailing a number of devices such as clamp-on ammeter, temperature sensors, meggers, winding analysers and oscilloscopes. The Fluke 438-II power quality and motor analyser for example uses proprietary algorithms to analyse three-phase power quality, motor torque, efficiency and speed to determine system performance and detect overloaded conditions by comparing measured values with rated specifications, eliminating the need for motor load sensors (Budimir, 2017). Other devices integrate multiple instrument functionality into one unit. For instance, a new thermal imaging clamp-on ammeter could have a built-in infrared camera, which gives the user visual indication of temperature differences and thermal anomalies (Brooks, 2015).

Typical electrical machine tests include the Hipot test for dielectric strength, the surge test for isolating and detecting burnout, the voltage drop test to analyse resistance in high-amperage circuits, core loss test to ensure quality and reliability and the megger test to evaluate critical insulation performance (Anon., 2020). These tests are conducted in accordance with ANSI/EASA standard AR100-2105. From the literature however, Kacor (2015) operationally tested the Adams' permanent magnet electric DC motor-generator system to obtain the speed-torque characteristic which aided in determining machine efficiency. Jordan *et al.* (2007) used an inverter power supply to conduct a complete series of performance tests on two high-speed, high-power density induction motors. An automatic procedure for testing wound and squirrel cage induction motors in MATLAB software with test model validation via virtual load test was developed by Bentounsi *et al*. (2011). Gaerke and Hernandez (2017) gave detailed technical analysis on the in-process insulation testing during motor stator manufacturing processes to ensure dielectric integrity of product resulting in reduction of stator

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failures and hence, cost savings. The theories and implementation techniques relating to virtual testing of mechanical systems are covered in the works of Sivertsen and Haugen (2019). Faruque *et al.* (2015) focused on simulation-based testing of modern power systems in real time. Penrose (2001) in a white paper reported on the use of ALL-TEST IV PRO 2000 software to non-destructively test condition of large synchronous motor stators and rotors. Sulemana and Normanyo (2021) modelled and simulated a Squirrel Cage Induction Motor – Synchronous Electric Generator (SCIM-SEG) set to technically ascertain by examining the output rotational speed and the generated output power, the viability of IC engine replacement in powering the SEG. According to them, the SCIM-SEG set could be deployed for sustainable electric power generation in standalone systems without the need for an IC engine in order to offer an output power efficiency of 96.1% at 1 pu of SEG excitation. In another reported research, Normanyo and Sulemana (2021) confirmed the feasibility of solar photovoltaic powering of the SCIM-SEG set from the perspectives of system output voltage, stator current, rotor speed, and capital and maintenance costs. They cited environmental friendliness, minimal maintenance and operating costs as the positives of the new system.

From the reported works, DC motor-generator soft testing research by Kacor (2015) did not involve the solar-powered SCIM and the focus of the paper was on machine efficiency determination. However, the research on SCIM-SEG so far as reported, focused on modelling and simulation for IC engine replacement using SCIM with or without solar photovoltaic powering of motor (Normanyo and Sulemana, 2021; Sulemana and Normanyo, 2021). Soft test validation of the SCIM-SEG was not considered in these works. This paper conducts validatory soft tests on the solar-powered SCIM-SEG system in a MATLAB/Simulink software environment and our contributions to the research domain are as follows: A soft – test validation of replacement of the IC engine and also, validation of solar powering of new system. The rest of the paper is organised as follows: Section 2 gives the system concept, the resources and the methods employed. The results of testing are provided in Section 3. Section 4 discusses the results and the conclusions are given in Section 5.

2 Resources and Methods Used

2.1 Concept

The system presented in this paper is meant to tap solar energy from the sun. The output of the solar PV array is used to charge a bank of heavy duty batteries, whose outputs are then inverted to serve as input supply to the Squirrel Cage Induction Motor (SCIM), which is mechanically coupled to a Synchronous Electric Generator (SEG). With the initial excitation provided by the batteries, the controlled electrical energy output of the SEG can feed any desired load.

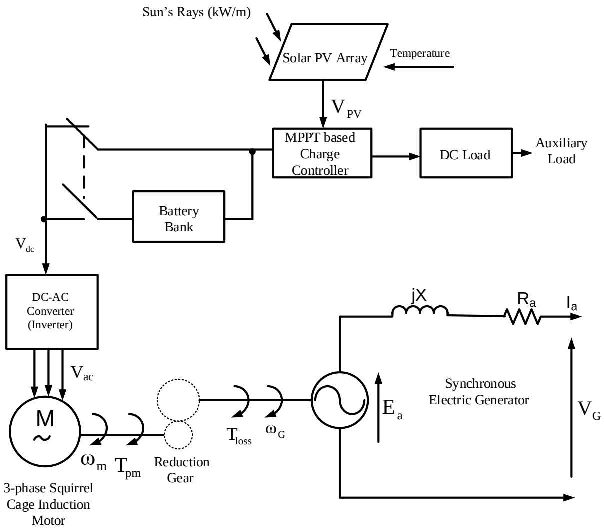

Fig. 1 Functional Diagram of the Solar Powered Motor – Generator System

2.2 Resources Used

The resources utilised in this paper include the manufacturer's data, mathematical models, and the software implemented models.

2.2.1 Manufacturer's Data

Firstly, field data on an existing IC engine driven SEG powering a rural bank were taken. The specifications of the SEG driven by IC engine having maximum torque of 25 Nm are presented in Table 1. Table 2 gives the modelling parameters of the SEG whose specifications were given in Table 1.

Table 1 Parameters of the Existing Synchronous Electric Generator

Parameter	Symbol	Value
Terminal Voltage	V_G	380 – 400 V
Frequency	f	50 Hz
Speed	N	1400 - 1500 rpm
Active Power	P_G	24.7 kW
Apparent Power	S_G	30.9 kVA
Power Factor	p f	0.8
Voltage Regulation no Load to Full Load	V_{reg}	± 1%
Random Voltage Variation	V	± 1%
Number of Poles	N	4

Table 2 Modelling Parameters of the Selected Synchronous Electric Generator

Modelling Parameter	Symbol	Value
Short Circuit Ratio	R	0.43
Quadrature Axis Synchronous Reactance	X_q	145
Direct Axis Synchronous Reactance	X_d	260
Direct Axis Transient Reactance	X'_d	22.0
Direct Axis Sub Transient Reactance	X''_d	10.5
Quadrature Axis Sub Transient Reactance	X''_q	12.4
Negative Sequence Reactance	X_2	115
Zero Sequence Reactance	X_0	1.5
Open Circuit Reactance	T'_{do}	0.66
Transient Reactance	T'_d	0.045

2.2.2 Mathematical Models

Solar PV Array

The appropriate PV array model is given in Fig. 2 and its mathematical model is expressed by equation (1) (Srushti and Vaidya, 2013).

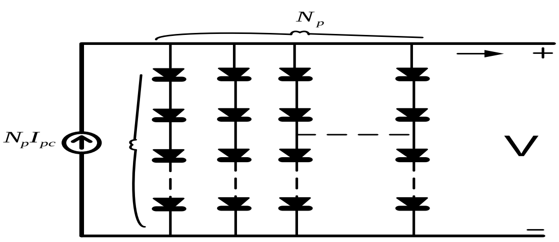

Fig. 2 Appropriate PV Array Model

$$I = N_P I_P - N_P\ I_o \left[\exp\left(\frac{q\left(\frac{V}{N_S} + \frac{I_{RS}}{N_P} \right)}{kT_c A_{PV}} \right) - 1 \right] \quad (1)$$

where, I is the output terminal current in (A), N_P is array modules in parallel, N_s is array modules in series, I_P is photocurrent of the PV module in (A), I_o is diode saturation current in (A), V is terminal voltage of the module in (V), I_{RS} is cell's reverse saturation current at a reference temperature and a solar radiation in (A), q is the electric charge magnitude of the electron (C), T_c is the cell temperature in (°F), A_{PV} is ideal factor, k is Boltzmann's constant.

DC-AC Converter

A 3-phase DC-AC IGBT-based PWM VSI Converter is employed. The phase-to-neutral voltages of the load are given by equations (3), (4) and (5) (Kumar *et al.*, 2012).

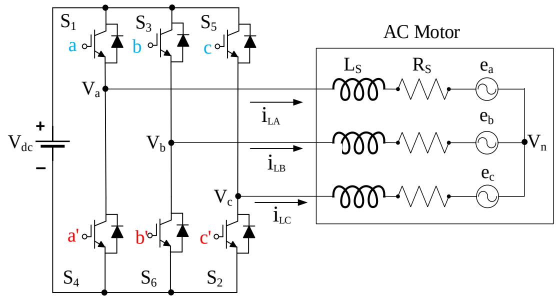

Fig. 3 Circuit Diagram of the 3- Phase Voltage Source Inverter

$$v_a = (2/3)v_A - (1/3)(v_B + v_C) \quad (3)$$

$$v_b = (2/3)v_B - (1/3)(v_A + v_C) \quad (4)$$

$$v_c = 2/3\ v_C - 1/3\ \ v_B + v_A \quad (5)$$

Squirrel Cage Induction Motor

The electromagnetic torque and rotor speed of the SCIM can be determined using equation (6) and equation (7) (Alsammak and Thanoon, 2014).

$$T_e = \left(\frac{3}{2}\right)\left(\frac{p}{2}\right)\left(\frac{1}{\omega_b}\right)\left(\psi_{ds} i_{qs} - \psi_{qs} i_{ds}\right) \quad (6)$$

$$\omega_b = \int\left(\frac{p}{2J}\right)(T_e - T_l) \quad (7)$$

where, T_e is electrical output torque of SCIM, p is number of poles of machine, d is direct axis, q is quadrature axis, s is stator variable, ψ_{ds} is *d*-axis stator magnetising flux, ψ_{qs} is *q*-axis stator magnetising flux, i_{qs} is *q*-axis stator currents, i_{ds} is *d*-axis stator currents, p is number of poles, J is moment of inertia of rotor , T_l is load torque, ω_b is motor angular electrical base frequency.

Synchronous Electric Generator

The torque equation of the SEG is given by Equation (8) (Chowdhury, 2014).

$$T_g = -\frac{3}{2} p\left(\lambda_d i_q - \lambda_q i_d\right)$$
$$= -\frac{3}{2} p\left[\lambda_M i_q + \left(L_d - L_q\right) i_d i_q\right] \quad (8)$$

where, T_g is torque developed by SEG, v_d and v_q are the d and q axes stator voltages, i_d and i_q are the d and q axes stator currents, L_d and L_q are the d and q axes inductances, L_{md} and L_{mq} are the d and q axes stator magnetising inductances, L_{ls} is stator leakage inductance, p is number of pole pairs, R is rotor resistance. If λ_M is the rotor magnetic flux produced, then the stator flux can be written in the form presented in Equation (9) and (10).

$$\lambda_d = -L_d i_d + \lambda_M \tag{9}$$

$$\lambda_q = -L_q i_q \tag{10}$$

Hence, Equations (11) to (15) hold valid.

$$L_d = L_{ls} + L_{md} \tag{11}$$

$$L_q = L_{ls} + L_{mq} \tag{12}$$

$$\lambda_s = \lambda_d + j\lambda_q \tag{13}$$

$$V_s = V_d + jV_q \tag{14}$$

$$i_s = i_d + ji_q \tag{15}$$

2.2.3 The Software Implemented Models

The mathematical models are implemented in MATLAB/Simulink. The implementations are as shown in Fig. 4 to Fig. 8 for the solar PV array, DC-AC converter, SCIM, SEG and the complete system, respectively.

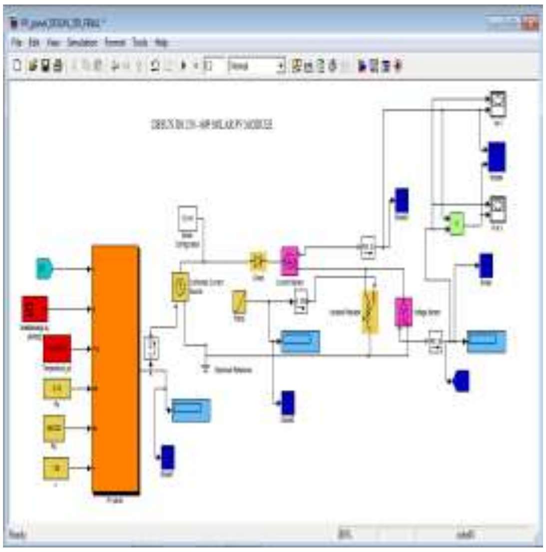

Fig. 4 Final Model of the Photovoltaic Array in MATLAB/Simulink

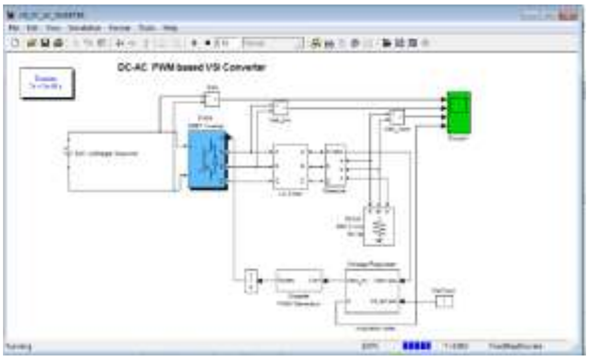

Fig. 5 PWM based VSI Converter Modelled in MATLAB/Simulink

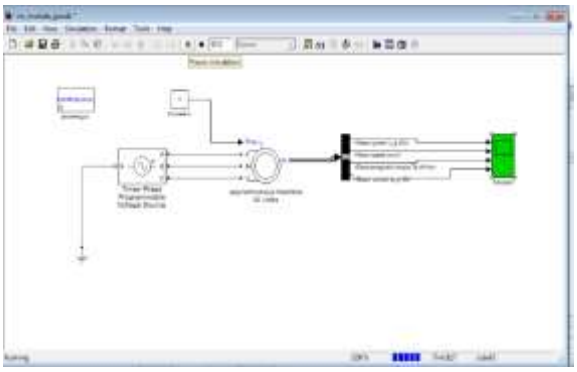

Fig. 6 Squirrel Cage Induction Motor Modelled in MATLAB/Simulink

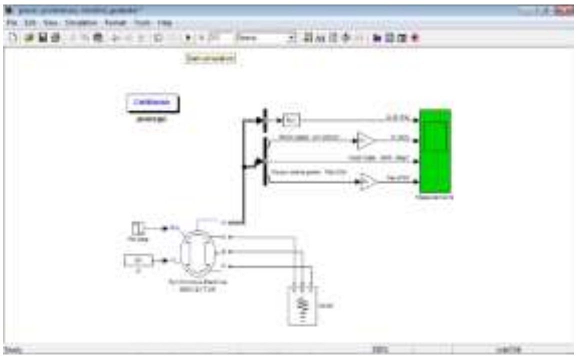

Fig 7 Synchronous Electric Generator Modelled in MATLAB/Simulink

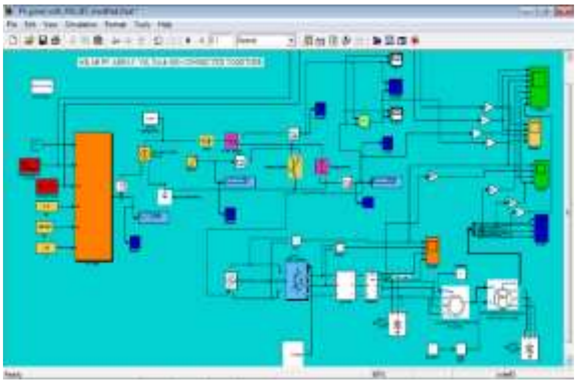

Fig. 8 Solar PV Powered Motor-Generator System Modelled in MATLAB/Simulink

2.3 Methods Used

The four individual models were soft-tested in MATLAB/Simulink software to ascertain agreement with manufacturer's data. Tests were then conducted on the overall system at varying solar irradiance and ambient temperature.

2.3.1 Testing of the Solar PV Array Model

Sixty (60) pieces of solar cells were selected from MATLAB /Simulink library and interconnected into a sub system of modules, panels and finally into an array. They were electrically interconnected and their specific values defined based on their modelling equations. Fig. 9 and Fig. 10 respectively show the normal P-V and I-V curves of the DS 250 – 60P solar PV module under standard test conditions, i.e., 1000 W/m^2 and 25 ºC. The values of maximum power, open circuit voltage and short circuit current obtained from the tests are in perfect agreement with the manufacturer's standard values.

2.3.2 Testing of the DC-AC Converter Model

Individual components of the converter were selected and interconnected in Simulink. Equations defining their transient response were coded into the sub-systems. Input values given by the manufacturer were used for evaluation. Fig. 11 and Fig. 12 show the test results of the DC-AC converter at manufacturer's specified maximum and minimum voltages of 48 V and 24 V, respectively. The test results are accurate with reference to the data sheet specifications of an output voltage of 380 – 400 V_{ac} at 50 – 60 Hz.

2.3.3 Testing of the Squirrel Cage Induction Motor Model

An induction motor was selected from the Simulink library. The steady state equations and manufacturer's input parameters were fed to the system. The output values and characteristics were observed. Fig. 13 and Fig. 14 show test results of the SCIM at maximum and minimum voltages of 400 V and 380 V, respectively. The exact output values of stator current, rotor speed, electromagnetic torque and rotor current are as shown with regard to the data sheet parameters.

2.3.4 Testing of the Synchronous Electric Generator Model

Fig. 15 and Fig. 16 show the test results of the SEG at field excitation of 1 pu and 0.5 pu, respectively at a constant rotor speed of 1500 rpm. The corresponding values of terminal voltage, stator current and active output power are as displayed on the scopes.

2.3.5 Testing of the Complete System

After successful modelling and testing of all individual components of the system, they were assembled together and the complete unit tested for performance evaluation. For the testing of complete system, the solar irradiations considered were 1000 W/m^2, 750 W/m^2 and 250 W/m^2 whilst 20 ºC and 25 ºC were the temperatures used. The testing was carried out at a constant field excitation of 1 pu. Results are presented in Fig. 17, Fig. 18 and Fig. 19.

3 Results and Discussion

The soft test results are presented in Figs 9 to 19.

3.1 Results of the Testing of Solar PV Panel

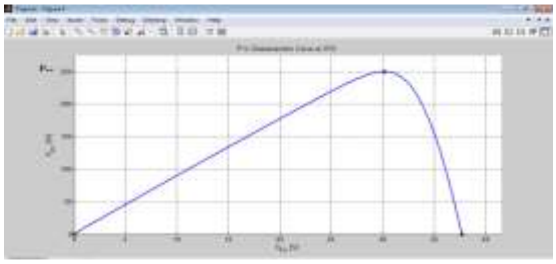

Fig. 9 P-V Curve of DS 250-60P PV Panel at Standard Test Condition

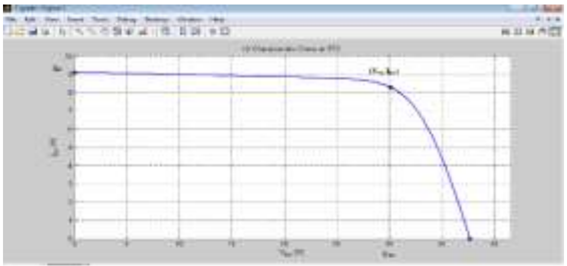

Fig. 10 I-V Curve of DS 250-60P PV Panel at Standard Test Condition

3.2 Results of the Testing of DC-AC Converter

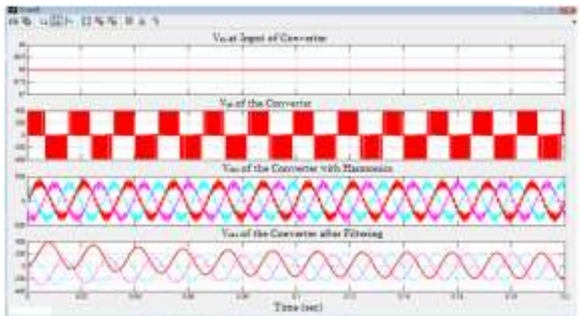

Fig. 11 Test Results of DC-AC Converter at Input Voltage of 48 V

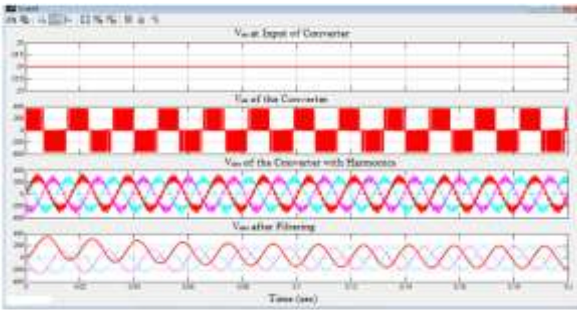

Fig. 12 Test Results of DC-AC Converter at Input Voltage of 24 V

3.3 Results of the Testing of Induction Motor

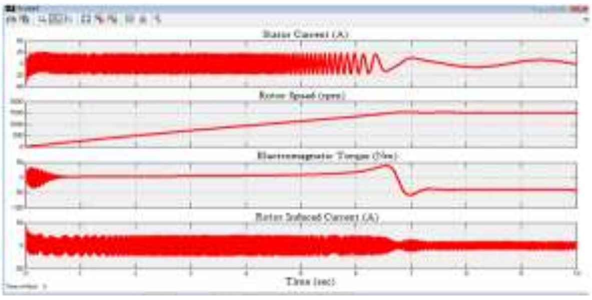

Fig. 13 Test Results of Squirrel Cage Induction Motor at 400 V, 1500 rpm

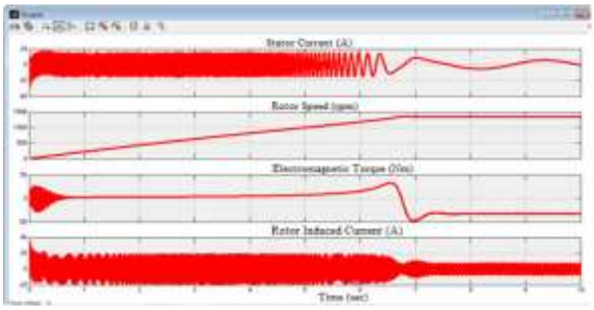

Fig. 14 Test Results of Squirrel Cage Induction Motor at 380 V, 1400 rpm

3.4 Results of the Testing of Synchronous Electric Generator

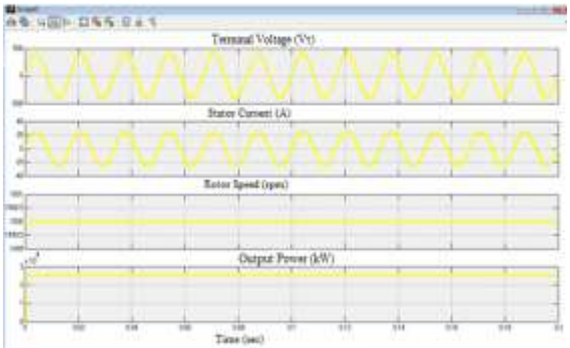

Fig. 15 Test Results of Synchronous Electric Generator at a Field Excitation of 1 pu

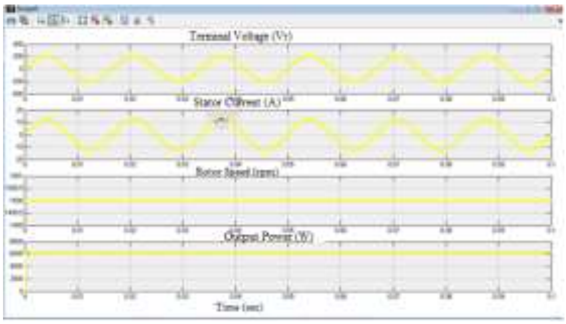

Fig. 16 Test Results of Synchronous Electric Generator at a Field Excitation of 0.5 pu

3.5 Results of the Testing of the Complete System

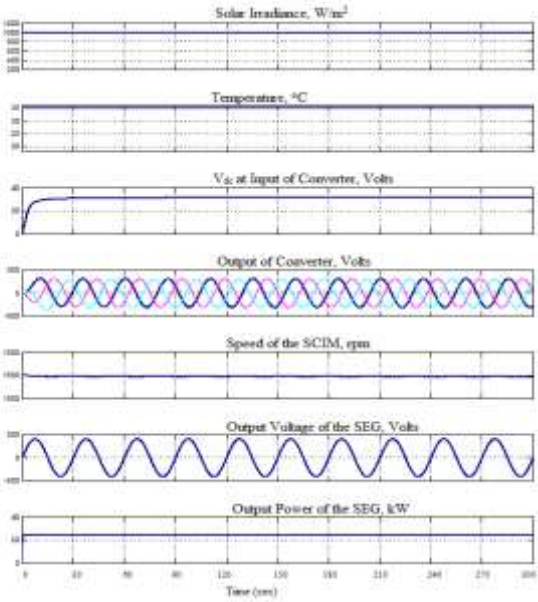

Fig. 17 Results of 1000 W/m^2 Irradiance at a Temperature of 25 °C

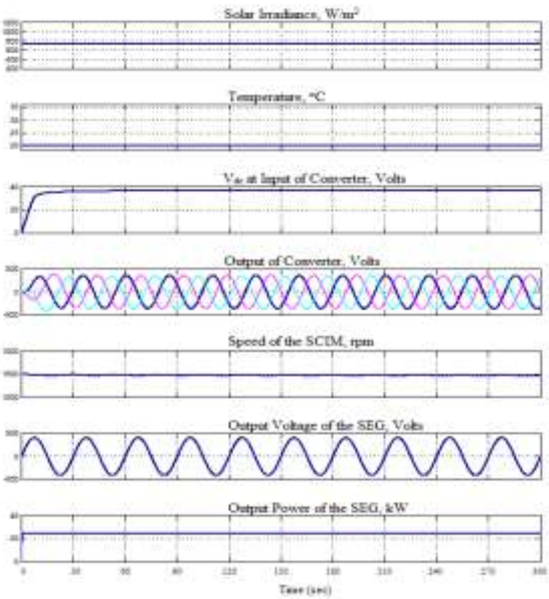

Fig. 18 Results of 750 W/m^2 Irradiance at a Temperature of 20 °C

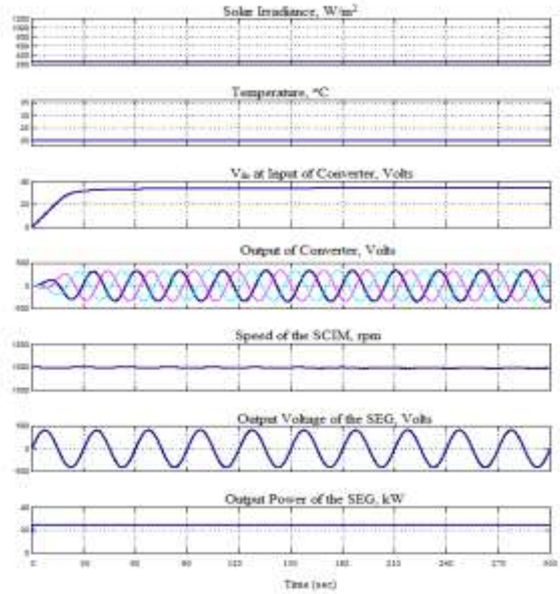

Fig. 19 Results of 250 W/m^2 Irradiance at a Temperature of 20 ^{o}C

3.6 Discussion

From the results of Fig. 17 of the system at 1000 W/m^2 irradiance and 25 ^{o}C, it can be seen that the SEG produced a maximum output of 24.7 kW at 400 V_{ac}, the DC-AC converter gave maximum three phase output voltage of 400 V_{ac} to power the SCIM, the required speed of 1500 rpm was reached at minimal fluctuation, by the SCIM to drive the rotor of the coupled SEG. At 25% reduction in the solar irradiance, the system at a temperature of 20 ^{o}C, 36.57 V_{dc} was recorded for 750 W/m^2 at 20 ^{o}C shown in Fig. 18. The output power of the converter, the output voltage and power of the SEG remained unchanged. Fig. 19 shows the results for further reduction in solar irradiance to 75% of its original value thus, 250 W/m^2 at a temperature of 20 ^{o}C. The result shows further reduction in the V_{dc} at the input of the converter. When the V_{dc} was 33.82 V at 20 ^{o}C, the SEG output voltage and power were not affected at this irradiance level due to the fact that the SCIM still operated at the 1500 rpm.

4 Conclusion

Generating electrical energy using solar powered 3-phase SCIM to drive a SEG proves feasible based on the test results. The soft testing results amply validate the concept of a solar-powered SCIM-SEG system of power generation very useful in standalone applications.

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