NOVEL METHOD OF EVALUATING THE STEADY- STATE PERFORMANCE CHARACTERISTICS OF THREE PHASES SELF EXCITED INDUCTION GENERATOR

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Abstract - *A 3 phase self-excited induction generator (SEIG) as a source of isolated power supply driven by non-conventional energy sources such as wind and biogas has recently gained importance. In this paper, the steady state analysis of SEIG has been made using Gauss-Newton or Levenberg-Marquardt method (Nonlinear least-squares) and different performance characteristics as a function of speed, capacitance and load have been obtained. The procedure used is simple, comprehensive, efficient and well suited for optimization tool box of MATLAB. A computer algorithm is presented to predict the various performance characteristics using the proposed method. Core loss has been incorporated in the analysis of improves accuracy in the simulated results. The effect of various system parameters such as stator resistance and speed on the steady state characteristics are studied and the results are presented to get the maximum output power for selection of capacitor required and operation of self-excited induction generator.*

Key Words: Self-excited Induction Generator, Wind Energy, Magnetizing Reactance etc.

1. Introduction

The increasing concern to the environment and fast depleting conventional resources have motivated the researchers towards rationalizing the use of conventional energy resources and exploring the non-conventional energy resources to meet the ever-increasing energy demand. A number of renewable energy sources [1] like small hydro, wind, solar, industrial waste, geothermal, etc. are explored. Since small hydro and wind energy sources are available in plenty, their utilization is felt quite promising to accomplish the future energy requirements. Harnessing mini-hydro and wind energy for electric power generation is an area of research interest and at present, the emphasis is being given to the cost-effective utilization of these energy resources for quality and reliable power supply. Induction generators are often used in wind turbines and some micro hydro installations due to their ability to produce useful power at varying speeds.

Usually, synchronous generators are being used for power generation but induction generators are increasingly being used these days because of their relative advantageous features over conventional synchronous generators. Induction generators require an external supply to produce a rotating magnetic flux. The external reactive supply can be supplied from the electrical grid or from the externally connected capacitor bank, once it starts producing power. Induction generators are mechanically and electrically simpler than other generator types. Induction generators are rugged in construction, requiring no brushes or commutators, low cost & low maintenance, operational simplicity, self-protection against faults, good dynamic response, and capability to generate power at varying speed. These features facilitates the induction generator operation in stand-alone/isolated mode to supply remote areas where extension of grid is not economically viable, in conjunction with the synchronous generator to fulfill the increased local power requirement, and in grid-connected mode to supplement the real power demand to the grid by integrating power from resources located at different sites [2, 3].

Several types of generators are available; such as DC and AC types, with permanent magnets, synchronous and asynchronous (induction generators). Induction generators are widely used in non-conventional power generation. Self-excited or stand-alone self-excited induction generator can be used with conventional as well as non-conventional energy sources available at semi isolated and isolated locations and can feed remote families, village community, etc [4].

A detailed study of the performance of the induction generator operating in the above referred modes during steady-state and various transient conditions is important for the optimum utilization. The steady-state performance is important for ensuring good quality power and assessing the suitability of the configuration for a particular application. While the transient condition performance helps in determining the insulation strength, suitability of winding, shaft strength, value of capacitor, and devising the protection strategy.

Induction generator is the most common generator in wind energy systems because of its simplicity, ruggedness, little maintenance, price etc. The main drawback in induction generator its need of reactive power to build up the terminal voltage and to maintain the voltage. Using terminal capacitor across generator terminals can generate this leading reactive power. The process of voltage build up in an induction generator is very much similar to that of a dc generator. There must be a suitable value of residual magnetism present in the rotor. So it is desirable to maintain a high level of residual magnetism, as it does ease the process of machine excitation.

[5] have presented the process of self-excitation in induction generators. The capacitance value of the terminal capacitor is not constant but it is varying with many system parameters like shaft speed, load power and its power factor. If the proper value of capacitance is selected, the generator will operate in self-excited mode. The capacitance of the excitation capacitor can be changed by many techniques like switching capacitor bank [l, 2], thyristor controlled reactor [3] and thyristor controlled DC voltage regulator. Many researchers have determined the minimum capacitor for self-excited induction generator. Most of these researches use loop equations in the analysis of induction generator equivalent circuit [6]. Most of these researches have much difficulty and it needs numerical iterative techniques to obtain the minimum capacitance required. Some of these researches require large computational time to obtain accurate value for the minimum capacitor required and described a method for accurately predicting the minimum value of capacitance necessary to initiate self-excitation with stand-alone induction generator. [7] has presented a paper for 6-phase induction generator using capacitive self-excitation.

2. MODELLING OF SELF EXCITED INDUCTION GENERATOR

2.1 Per-Phase Equivalent Circuit

The per-phase equivalent circuit of a three-phase SEIG [8-10] with an R–L load and an excitation capacitor is shown in Figure.1, where R_1, X_1, R_2, X_2, R_c, and X_m represent the stator resistance, stator leakage reactance, rotor resistance, rotor leakage reactance, core loss resistance, and magnetizing reactance, respectively. R_L, X_L, and X_C represent the load resistance, load reactance, and excitation capacitor reactance, respectively, and F and v represent the per unit (p.u.) frequency and speed, respectively. The reactance's are specified at a base or rated frequency. Note that the earlier circuit is normalized to the base frequency by dividing all parameters and voltages by the p.u. frequency [1].

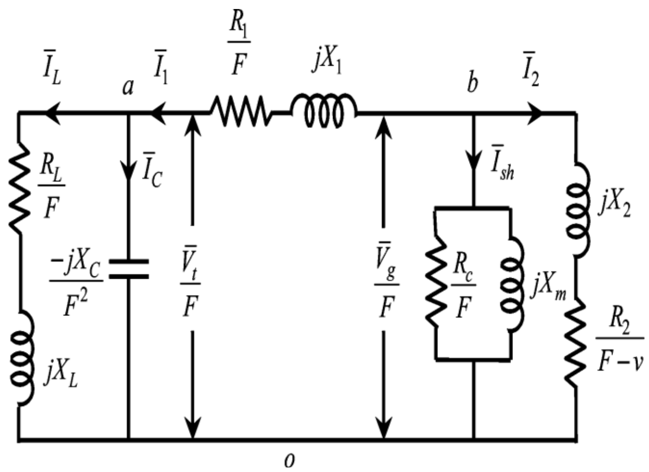


Fig-1: Per-phase equivalent circuit of a three-phase SEIG.

All parameters of the generator, except the magnetizing reactance, are considered as constant. The magnetizing reactance X_m is assumed to be a variable and depends on magnetic saturation. Other variables or adjustable parameters in the circuit are X_C, F, v, and load impedance. Note that the load power factor angle θ at a base frequency is considered as constant and thus the load impedance (at 1.0 p.u. frequency) becomes $Z_L = Z_L\angle\theta = (R_L + jX_L)$. Thus, the circuit of Fig. 1 has five variables (X_m, X_C, F, v, and Z_L) and the knowledge on all the variables is necessary to evaluate the performance of the generator.

2.2 Simplified representation per-phase equivalent circuit

The ratio of air gap voltage to frequency (Vg/F) depends on the magnetic flux and hence magnetizing reactance Xm [11-12]. The relationship between Vg/F and Xm can be established

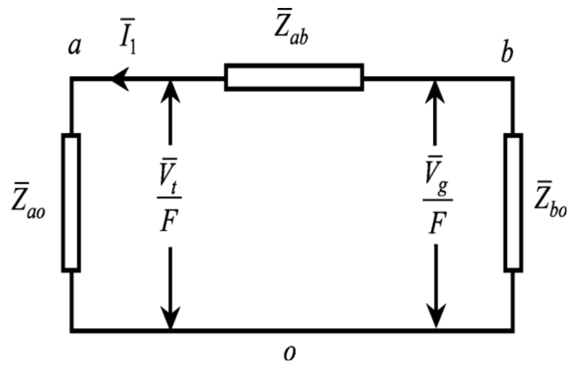


Fig-2: Simplified representation of the circuit

from the synchronous speed test data . Mathematically, the earlier relationship can be expressed in many ways, such as an exponential function a linear function a piece-wise linear function or a higher order polynomial. In this study, Vg/F is expressed by the following third-order polynomial of X_m in the normal operating region.

$$\frac{V_g}{F} = k_1 + k_2 X_m + k_3 X_m^2 + k_4 X_m^3 \qquad (1)$$

Coefficients k's of the previous polynomial can be obtained from the synchronous speed test results.

3. EXPERIMENTAL SETUP

To study the performance characteristics of self-excited induction generator, the induction motor is ran as an induction generator with the help of DC Compound motor in the laboratories. Figure.3 shows the experimental setup for project on self-excited induction generator for various operating conditions. The three capacitors of 32 uF were connected across the stator terminals for exciting the stator winding. The main requirements for the setup are prime mover (D.C Motor), synchronous induction motor, TPDT switch, DSO, Three-phase star connected resistive load etc.

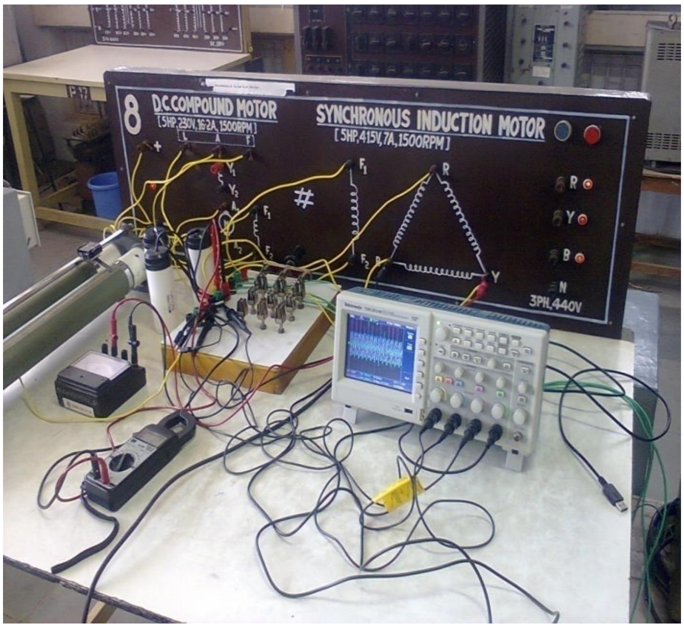


Fig-3: Practical Experimental setup of Self-Excited Induction Generator

Figure.4 shows experimentally observed the terminal voltage at load against the output power. As load decreases, the output power increases and the terminal voltage Vt reduces at normal operation up to certain point for getting maximum power and also it shows the abnormal behavior after a particular condition of load

A 5-HP, 415 V, 7A, 50 Hz, 3-Phase, Delta connected, 4-pole, 1500 rpm, Synchronous induction motor was operating as induction generator. The 3-phase star connected Load and the 3 capacitors of 32uF connected across the stator terminals. The experiments results are found in the Laboratory.

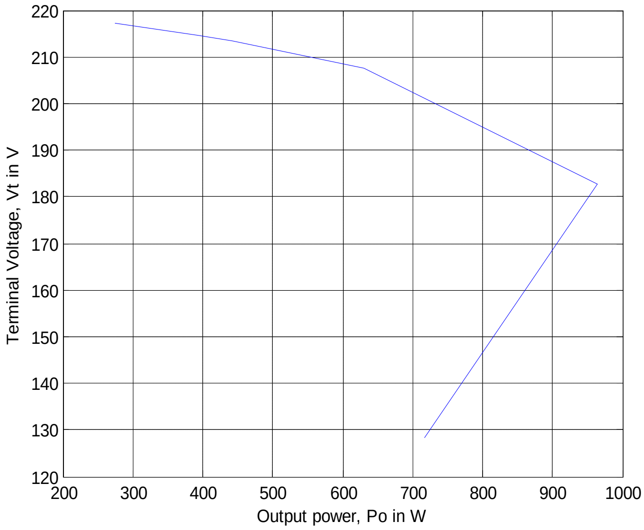


Fig-4: Experimentally observed terminal voltage vs. output power

Table -1: Experimental Results

Sr. No	I_L (Amp)	I_C (Amp)	I_1 (Amp)	V_t (Volt)	P_0 (Watt)	R_L (Ohm)
1	0.42	2.51	2.936	217.34	273.98	517
2	0.613	1.62	2.24	214.67	394.55	350
3	0.69	1.56	2.25	213.42	442.11	309
4	1.012	1.31	2.32	207.47	629.84	205
5	1.75	0.81	2.56	182.80	963.15	104
6	1.86	0.4	2.26	128.35	716.29	69

Where,

I_L - Load Current, I_C - Capacitor Current
I_1 - Stator Current, V_t - Terminal Voltage
P_0 - Output Power, R_L -Load Resistance

4. RESULTS AND DISCUSSION

4.1 No load Characteristics

The proposed method of evaluating the performance characteristics of a SEIG is tested on a 1.5-kW, 220-V, 50-Hz, four-pole, Δ-connected squirrel cage induction motor operated as a generator. The fixed parameters of the generator are R_1 =5.033 Ω , R_2 =4.667 Ω ,R_c=5.0147 kΩ and X_1=X_2=5.605 Ω Using the synchronous speed test results, the coefficients of (1) are found as k_1 =596.03, k_2= -12.035, k_3=0.1374 and k_4= -5.636×10-4.

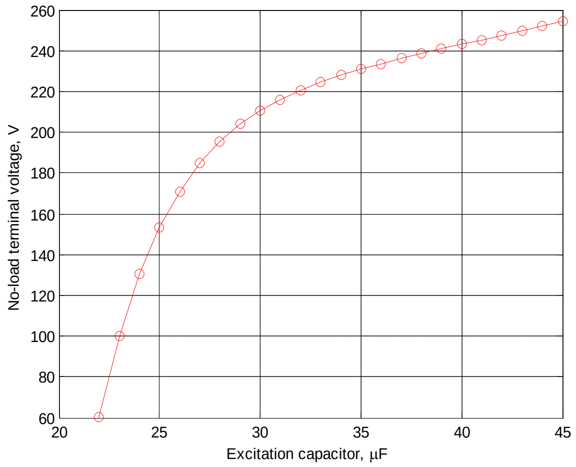


Fig-5: No-load characteristic of the generator.

It is considered that the generator is driven by a regulated turbine that is emulated by a four-pole, 50-Hz synchronous motor in the laboratory. Thus, the speed v is constant at 1.0 p.u. For simplicity, the load power factor is considered as unity. A brief description of the results obtained is given further.

First, the no-load terminal voltage Vt, of the generator is determined for various values of excitation capacitor C. The simulation results as well as the experimental results found for this case are shown in Figure. 5, which indicates that the simulation results are very close to the corresponding experimental values. The maximum error occurred for C = 23 μF for which the experimental voltage is found as 114 V. However, to get the same voltage through simulation, a capacitor of 23.41 μF is needed, i.e., the error is only 1.78% and is within the tolerance level (±5%) of the capacitors used.

4.2 Load Characteristics

In Figure. 6 shows a typical load characteristic V_t vs P_o of the generator for a fixed-excitation capacitor and its pattern is found to be very similar to that of P–V curve of a load bus in a power system. When Z_L is decreased from infinity (at no-load), initially P_o increases and V_t decreases, and this represents normal operation. The earlier pattern continues until the maximum power point P_{max} is reached. Further reduction of Z_L decreases both P_o and V_t, and this represents abnormal operation. In Figure. 6, the normal operation is represented by a solid line and the abnormal operation by a dashed line. The variation of I1, I_L, and I_c against Po is shown in Figure. 7, and it indicates that, in the normal operating region, IL increases with Po as expected, but I_c decreases with Po because of the reduction of Vt. However, I_1 is found to be very insensitive to Po because it is the phasor sum of I_L and I_c. In this case, reduction of Ic is partially compensated by the increases in I_L and this is why I_1 remains more or less constant.

Figure. 8 shows the comparison of simulation and experiment results of V_t versus P_o characteristic of the generator for various values of excitation capacitors (32, 36, and 40 μF). It can again be observed that the simulation results are slightly lower but

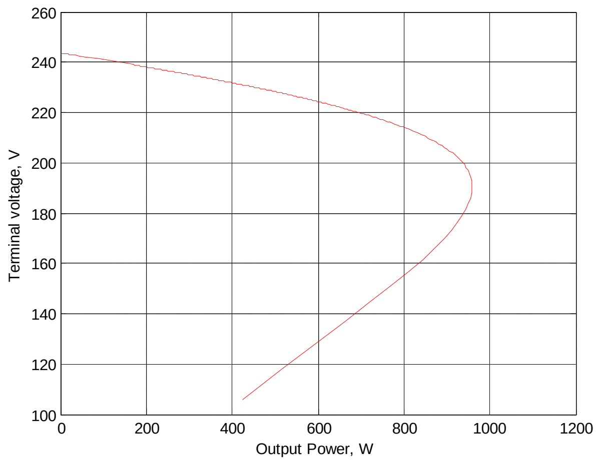


Fig -6: Typical load characteristics Terminal Voltage vs Output power

The error in the maximum power for 32, 36, and 40 μF capacitors is found as 7.45%, 4.01%, and 1.37%, respectively. The maximum error occurred for 32 μF for which the actual maximum power (experimental value) is found as 590 W. However, to get the same maximum power through simulation, a capacitor of 32.65 μF is needed, i.e., the error in capacitor is 2.03% and is within the tolerance level (±5%) of the capacitors used. The variation of stator current and frequency against Po is shown in Figure. 7 and Figure. 9, and it again indicates that, for a given capacitor, the current is very insensitive to output power (in the normal operating region). That is why Xc, instead of load impedance ZL, is considered as an independent variable.

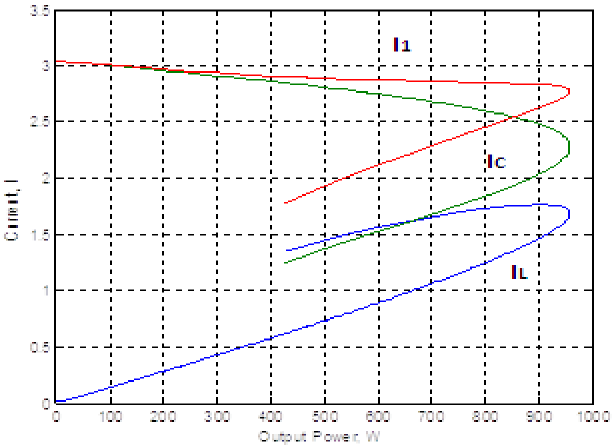


Fig-7: Typical load characteristics Current versus output power

In the normal operating region, the frequency of the generated voltage decreases with load as can be seen in Figure 9. For C =40 µF, the frequency at no load is found as 49.7 Hz and it decreases to 47.5 Hz at the maximum power of 1044.7 W. In determining the characteristics, "fsolve" routine successfully converged to the zero point in all cases and the maximum residual is found as 4.84 ×10-9.

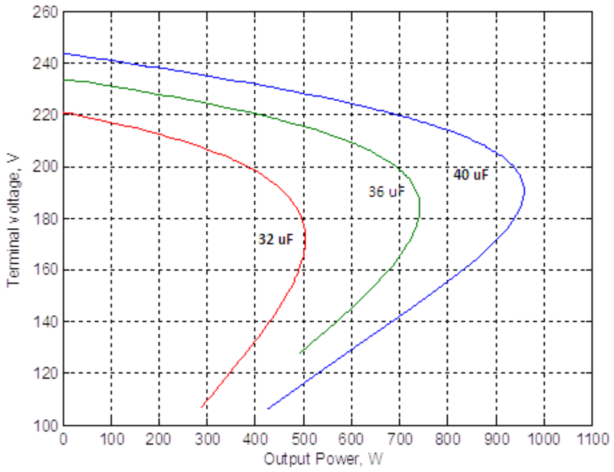


Fig -8: Terminal Voltage vs Output power for Excitation capacitor (C=32uF, 36uF and 40uF)

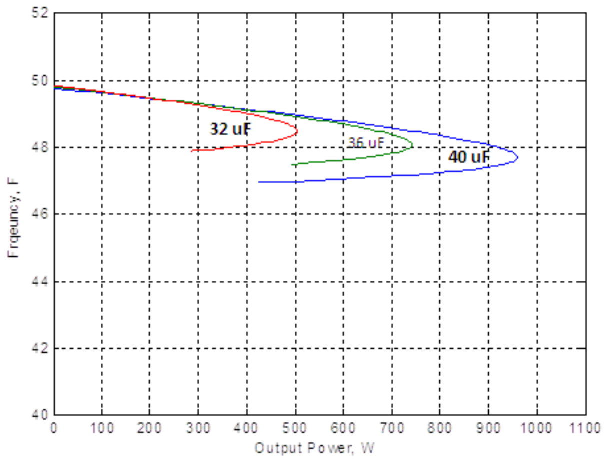


Fig- 9: Frequency vs. Output power for Excitation capacitor (C=32uF, 36uF and 40uF)

4.3 Load characteristics for various excitation capacitors

Next the performance characteristics of the generator for a constant terminal voltage of 220 V are evaluated. The variation of voltages, frequency, capacitor, and currents against Po is shown in Figure. 11. At no-load (when Po=0), the stator current is purely reactive (drawn by the excitation capacitor) and thus the difference between Vt and Vg is high. As the load increases, the angle of the stator current decreases and this causes reduction in the difference between Vt and Vg.

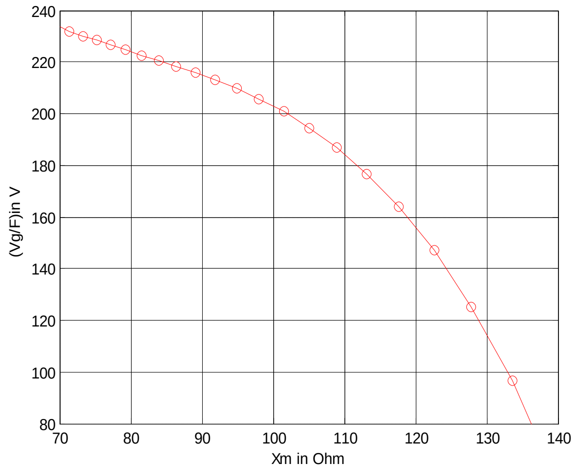
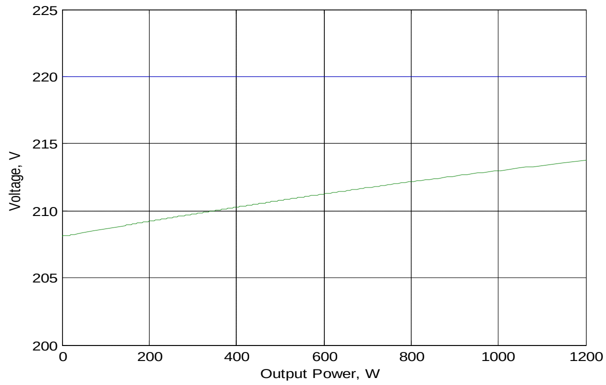
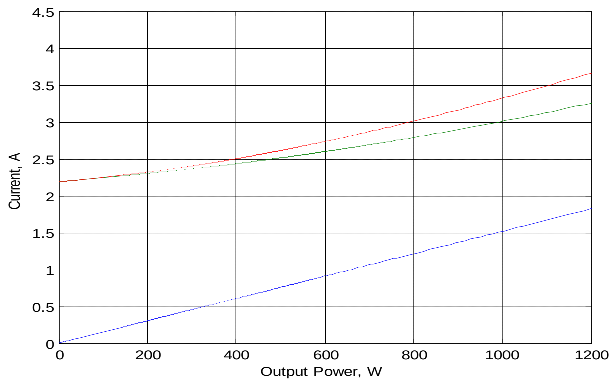
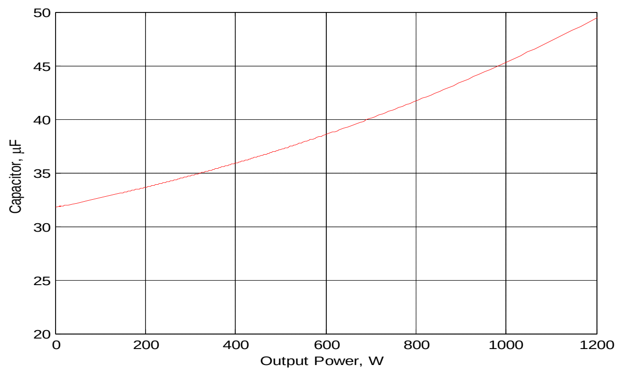


Fig-10: Air gap voltage vs Magnetizing Reactance, Xm

The frequency of the generated voltage decreases with load, as expected. As the load increases, more and more capacitors are needed to maintain the constant terminal voltage, and this leads to increased Ic. The load current increases linearly with Po because of constant terminal voltage. In this case, I_1 increases with Po because of the increase in both I_L and Ic. The experimental results found in this case are also very close to the corresponding simulation results as can be seen in Figure. 11.







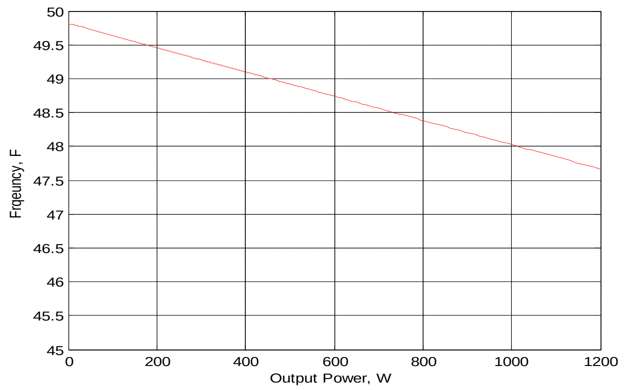


Fig-11: The variation of voltages, frequency, capacitor, and currents against Po

5. CONCLUSIONS

In this paper, Performance Characteristics of a Self-Excited Induction Generator are evaluated by using optimization tool box of MATLAB. The method used is a numerical-based routine that reduced the time and effort needed to formulate the problem. The criteria for constant terminal voltage and constant-stator-current operations are also derived and embedded into the problem. The effectiveness of the proposed method is then evaluated on a 1.5-kW induction generator driven by a regulated prime mover for various operating conditions. Some of the simulation results obtained by the proposed method are also compared with the corresponding experimental values and are observed to be in excellent agreement. It is also observed that the load characteristic (terminal voltage versus power) of the generator is very similar to the P–V curve of a load bus or PQ bus in a general power system. The method described in this paper greatly simplifies the problem formulation and analysis of a SEIG for various operating conditions.

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