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EXPERIMENTAL DESIGN OF CAPACITANCE REQUIRED FOR SELF-EXCITED INDUCTION GENERATOR

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ABSTRACT

This paper presents the no-load practical synchronous speed characteristics of a laboratory model induction machine of 120 W capacity. Critical, minimum and maximum capacitance required for excitation are calculated from the no load curve for voltage buildup, rated voltage and current respectively; at various super synchronous speeds. A realistic model of the machine is presented on Matlab/Simulink. Theoretical and practical results are compared for model validation.

Keywords: *Excitation Capacitance, Magnetization Curve, Synchronous Speed Test, Self-Excited Induction Generator, Wind Energy*

1. INTRODUCTION

Electrical energy is vital in every aspect of our day-to-day life. Keen interest is taken in all possible sources of energy from which it can be generated. Our industrialized economic system depends heavily on fossil energy sources such as oil, gas, hydro, coal and nuclear. We will exhaust these valuable assets in a matter of few tens of years in case of oil and few hundred years for coal. Unfortunately, both coal and nuclear energy present serious environmental hazards.

In recent times, there has been a considerable upsurge in exploring new ways to supply energy from renewable energy sources. Wind energy is one of the most important and promising sources of renewable energy all over the world. It is non-polluting and economically viable and has very large potential. An upper limit for the utilization of earth's wind power supply is estimated to be 1.3×10^{13} kW. It is predicted that nearly 10% of the world energy needs could be met by the wind energy by the year 2020 [1].

The wind turbine converts mechanical power into electrical power. This can be accomplished by an electrical generator which can be a DC machine, a synchronous machine, or an induction machine. DC machine was used widely until 1980s, in smaller power installation below 100 kW, because of its extremely easy speed control. The presence of commutators in DC machines contributes to low reliability and high maintenance costs.

The second kind of electric generators are synchronous generators, suitable for constant speed systems. Requirement of DC field current and reduced wind energy capture of constant speed systems are its disadvantages as compared to variable speed systems.

Another choice for the electric generator is a permanent magnet synchronous generator. But PMSGs suffer from uncontrollable magnetic field decaying over a period of time. Their generated voltage tends to fall steeply with load and is not suitable for isolated operation.

The other alternative is induction machines of wound and squirrel cage rotor type. Wound rotor machine can produce high starting torque and is the preferred choice in grid-connected wind generation schemes. Squirrel cage rotor construction is popular because of its ruggedness, low maintenance requirements, reliability, low cost, simplicity of construction and good transient performance. This is widely used in stand-alone wind power generation schemes [2].

Connection of induction generators to large power systems to supply electric power can also be achieved when the rotor speed of an induction generator is greater than the synchronous speed of the air-gap revolving field. When an induction

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machine is driven by a prime mover, the residual magnetism in the rotor produces a small voltage that causes a capacitive current to flow. The resulting current provides feedback and further increases the voltage. It is eventually limited by the magnetic saturation in the rotor. Variable capacitance is required for self-excited induction generator [3-5]. These machines are available in the ranges of fractional horse power to multi-megawatt capacity.

The steady-state performance of a self-excited induction generator has been modelled; one is the per-phase equivalent circuit model using loop impedance method [6, 7] and nodal admittance method [8, 9]. The second d-q axis equivalent circuit model is based on different reference frames and generalized machine theory [10-12]. The per phase equivalent circuit model is obtained from a steady state condition and can not be used for transient condition.

This paper clearly demonstrates the calculation of the critical, minimum and maximum value of capacitance required for self-excitation of induction generator using synchronous speed test. The dynamic performance of the self-excited induction generator is analyzed with and without load conditions. Experimental results of voltage built-up process obtained from a practical 120 W induction machine are also presented for validation.

2. DESIGN OF EXCITATION CAPACITANCE

2.1. Synchronous Speed Test

The no load saturation curve of the machine is obtained at normal rated frequency. The voltage source is applied to the stator of the induction machine while its rotor is driven by the dc motor at a constant speed corresponding to the synchronous speed of the machine.

It is customarily assumed that the magnetizing current is the difference between stator current and rotor current referred to the stator. In the present case the slip is very small (practically zero) which implies that the magnetizing branch current is essentially equal to no load current. The no load test single phase equivalent circuit as shown in Fig. 1.

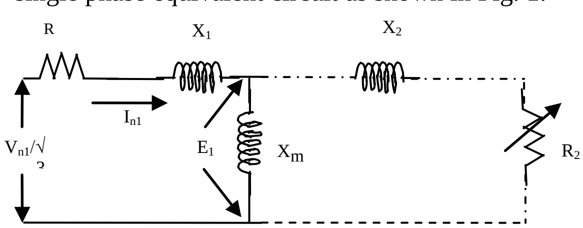

***Fig. 1:** No Load Test Single Phase Equivalent Circuit*

The rms magnetizing branch voltage is given by

$$E_1 = X_m I_{n1} \tag{1}$$

$$I_{n1} = \frac{V_{n1}/\sqrt{3}}{Z_{n1}} \tag{2}$$

$$Z_{n1} = R_1 + j(X_1 + X_m) \tag{3}$$

$$Z_{n1}^{\,2} = R_1^{\,2} + (X_1 + X_m)^2 \tag{4}$$

The magnetizing reactance is given by

$$X_m = \sqrt{(Z_{n1}^{\,2} - R_1^{\,2})} - X_1 \tag{5}$$

$$E_1 = \left[\sqrt{(Z_{n1}^{\,2} - R_1^{\,2})} - X_1\right] I_{n1} \tag{6}$$

Fig. 2 shows circuit details of synchronous speed test. The performance details are presented in Fig.3. The capacitance required to generate voltage is calculated from the slope of the curves.

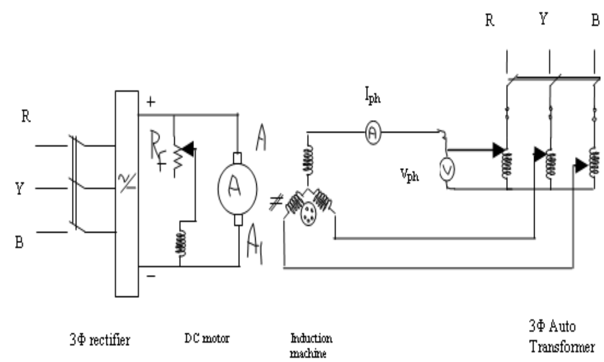

***Fig. 2:** Circuit Diagram For Synchronous Speed Test*

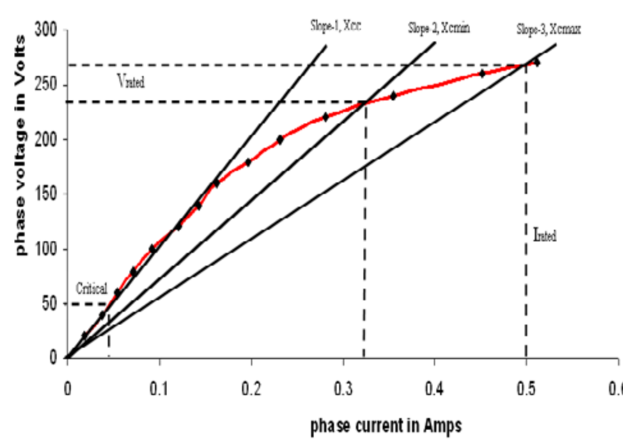

Fig. 3: No Load Characteristics Of Induction Machine

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2.2. Determination Of Excitation Capacitance

2.2.1 Critical capacitance (C_{cri})

X_{cc} is determined by the slope of the linear region.

$$X_{CC} = \frac{\Delta V}{\Delta I} = \frac{20}{0.019} = 1052.63\Omega \tag{7}$$

$$Xcc = \frac{1}{2\pi f C_{cri}}$$

$$C_{cri} = \frac{1}{2\pi f X_{CC}} = \frac{1}{2*\pi*50*1052.63}$$

$$C_{cri} = 3.02\times10^{-6}$$

$$C_{cri} \cong 3\mu F$$

The critical capacitance is the slope-1 of the linear region of no load curve. If the capacitance is chosen below the critical capacitance 3 μF, the voltage will never buildup and excitation fails initially.

2.2.2 Minimum capacitance (C_{min})

It is defined as ratio of rated voltage to corresponding magnetizing current.

$$Xc_{\min} = \frac{V_{rated}}{I} = \frac{240}{0.34} = 705.88\Omega \tag{8}$$

$$C_{\min} = \frac{1}{2\pi f X_{c\min}} = \frac{1}{2*\pi*50*669.45}$$

$$C_{\min} = 4.5\times10^{-6}$$

$$C_{\min} \cong 5\mu F$$

It is minimum capacitance required to generate the rated voltage. If we choose below this value, the rated voltage will not be generated.

2.2.3 Maximum capacitance (C_{max})

It is defined as ratio of voltage generated at rated current to the current itself.

$$Xc_{\max} = \frac{V}{I_{rated}} = \frac{270}{0.5} = 540\Omega \tag{9}$$

$$C_{\max} = \frac{1}{2\pi f X_{c\max}} = \frac{1}{2*\pi*50*540}$$

$$C_{\max} = 5.89\times10^{-6}$$

$$C_{\max} \cong 6\mu F$$

The maximum value of capacitance used should not exceed 6 μF. If the capacitance exceeds the maximum value, the current flow will be more than the rated value. This may lead to heating of stator core.

3. MODELING OF SELF-EXCITED INDUCTION GENERATOR

The dynamics of a self-excited induction generator are detailed in many papers [13, 14] and can be expressed by the following electromechanical equations derived in the synchronously rotating q-d reference frame.

$$pi_{qs} = -K_1 r_s i_{qs} - (\omega_e + K_2 L_m \omega_r) i_{ds} + K_2 r_r i_{qr} - K_1 L_m \omega_r i_{dr} \tag{10}$$

$$pi_{ds} = (\omega_e + K_2 L_m \omega_r) i_{qs} - k_1 r_s i_{ds} + K_1 L_m \omega_r i_{qr} + K_2 r_r i_{dr} - K_1 V_{ds} \tag{11}$$

$$pi_{qr} = k_2 r_s i_{qs} + K_2 L_s \omega_r i_{ds} - [(r_r + K_2 L_m r_r)/L_r] i_{qr} + (K_1 L_s \omega_r - \omega_e) i_{dr} \tag{12}$$

$$pi_{dr} = k_2 r_s i_{ds} - K_2 L_s \omega_r i_{qs} - (K_1 L_s \omega_r - \omega_e) i_{qr} - [(r_r + K_2 L_m r_r)/L_r] i_{dr} + K_2 V_{ds} \tag{13}$$

$$p\omega_r = -(B/J)\omega_r + (3P^2 L_m/8J)(i_{qs} i_{dr} - i_{ds} i_{dr}) + (P/2J) T_m \tag{14}$$

$$pV_{ds} = (i_{dc}/C) \tag{15}$$

where,

$$K_1 = L_r/(L_s L_r - L_m^2), \quad K_2 = L_m/(L_s L_r - L_m^2)$$

The above equations are derived assuming that the initial orientation of the q-d synchronously rotating frame is such that d-axis is lagging q-axis and aligned with the stator terminal voltage phasor (i.e. $v_{qs} = 0$).

Magnetizing inductance is the main factor for voltage buildup and stabilization of generated voltage for the unloaded and load conditions of the induction generator. In self-excited induction generators, the magnitude of the generated air-gap voltage in the steady state equation is given by

$$V_g = \omega_e L_m |i_m| \tag{16}$$

where,

$$\omega_e = i_{qc}/(CV_{ds}), \quad |i_m| = \sqrt{(i_{qs} + i_{qr})^2 + (i_{ds} + i_{dr})^2}$$

The magnetizing inductance L_m is not constant but a function of the magnetizing current i_m is given as

$$L_m = f(|i_m|) \tag{17}$$

The relationship between L_m and i_m is obtained by using synchronous speed test and described by a set of linear piecewise approximate equation as overleaf [13].

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$$L_m = 0.0898 - 0.0107|i_m|, \qquad |i_m| \le 2 \qquad (18)$$
$$= 0.0747 - 0.0027|i_m|, \qquad 2 \le |i_m| \le 16$$
$$= 0.0472 - 0.0010|i_m|, \qquad 16 \le |i_m| \le 28$$
$$= 0.0189 \qquad |i_m| \ge 28$$

The electromagnetic braking torque T_e developed by the induction generator is expressed as

$$T_e = -1.5\,(P/2)\,L_m\,(i_{qs}\,i_{dr} - i_{ds}\,i_{qr}) \qquad (19)$$

The a, b, c variables are obtained from the d, q variables through the inverse of the Park transform defined below:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta) & 1 \\ \cos(\theta - 2\pi/3) & \sin(\theta - 2\pi/3) & 1 \\ \cos(\theta + 2\pi/3) & \sin(\theta + 2\pi/3) & 1 \end{bmatrix} \begin{bmatrix} V_q \\ V_d \\ V_0 \end{bmatrix} \qquad (20)$$

Note that these transformations apply equally well to currents and flux linkages.

Fig. 4 displays the simulink model of the self-excited induction generator represented by equation (10) - (20). Matlab/Simulink is employed to study the dynamic performance of the machine.

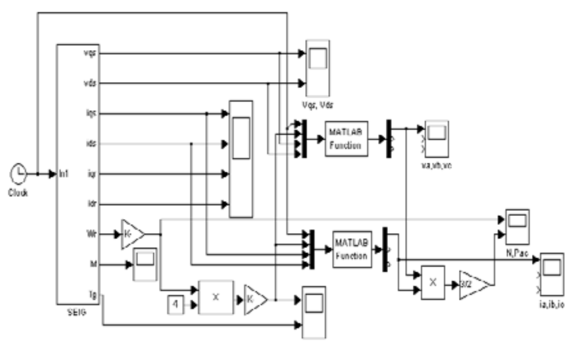

Fig. 4: Simulink Model Of Self-Excited Induction Generator

(i) Theoretical kVAr calculation

$$X_C = \frac{1}{2\pi * 50 * 6\times10^{-6}} = 530.51\Omega$$
$$I_{ph} = \frac{240}{530.51} = 0.452A$$
$$kVAr = \frac{V_{ph} I_{Ph}}{1000}$$
$$kVAr = \frac{\sqrt{3} * 240 * 0.452}{1000} \qquad (21)$$
$$kVAr = 0.187$$

4. SELF-EXCITATION EXPERIMENT

The induction machine is coupled with dc motor drive. The capacitance of 6 μF is connected in star and grid supply is given to the stator terminals, Fig. 5. The dc motor is made to run at speed higher than synchronous. Then grid supply is suddenly disconnected. The voltage across the stator remains same due to self-excitation created by the capacitors.

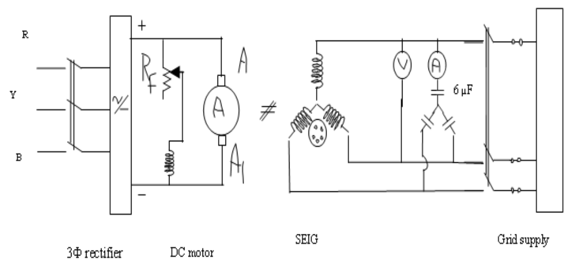

Fig. 5: Circuit Diagram For Self-Excitation Using C_{max}

(ii) Practical kVAr calculation

$$kVAr = \frac{V_{ph} I_{Ph}}{1000}$$
$$kVAr = \frac{\sqrt{3} * 235 * 0.413}{1000} \qquad (22)$$
$$KVAr = 0.168$$

The calculated kVAr is nearly 10% more than the practical value.

5. RESULTS AND DISCUSSION

Fig. 6 exhibits the d-axis stator voltage with respect to time.

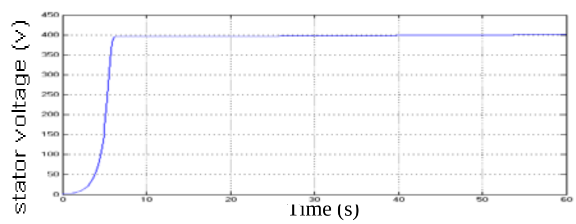

Fig. 6: D-Axis Stator Voltage

Fig. 7 presents the self-excitation process initiated at t = 0s without any load at the stator terminals. It is observed that voltage buildup reaches the first steady-state value at t = 6s.

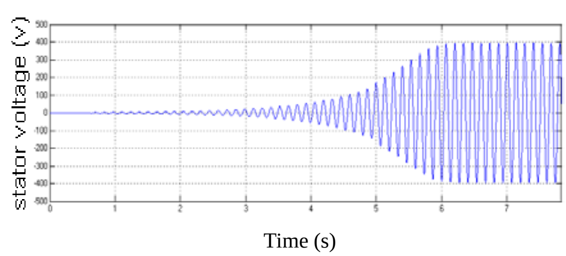

Fig. 7: Dynamic Response Of The Induction Generator During Voltage Build-Up Process (No Load Condition).

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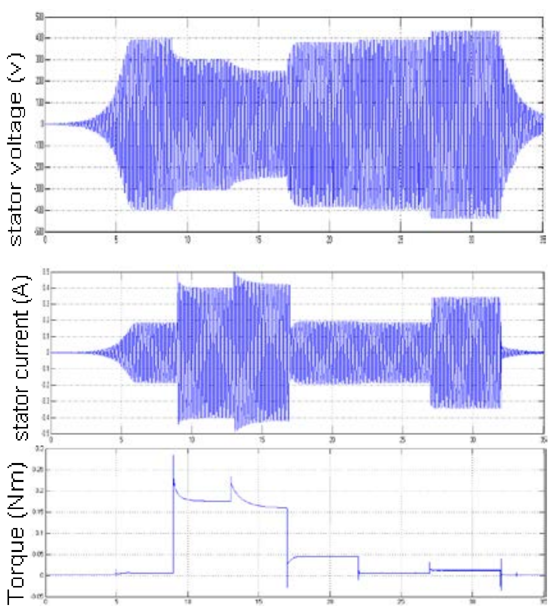
Fig. 8 demonstrates the variation in generated voltage for step changes in the load for a generator speed of 1300 rpm with 6 µF capacitor connected across the stator terminals.

As the load on the generator increases, the stator voltage decreases with an increase in the stator current and required torque. The loads and the corresponding duration are tabulated below.

Duration in seconds	Resistance in kΩ
9 - 13	1.1
13 - 17	0.9
32 - 35	0.2

The generator fails to self-excite for a load resistance of 0.2 kΩ. At t = 17s, a 1.1 kΩ load resistor is applied. The generated voltage rises to a value higher than the no load voltage. The current and toque decrease.

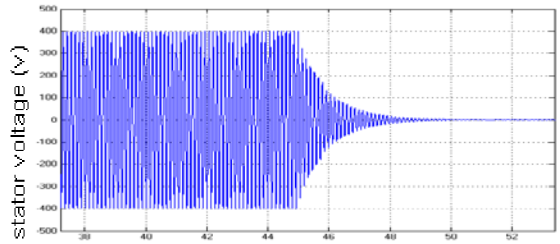
At t = 23s, a load resistor is suddenly removed. The generated voltage quickly reaches its new steady-state value. Similar voltage fluctuations will occur when the load is suddenly switched off. At t = 27s, the capacitance is increased to 8 µF to compensate for the voltage drop. The voltage rises to its no load value resulting in increase of current and torque.



Time (s)

Fig. 8: Stator Voltage, Stator Current And Torque As A Function Of Time

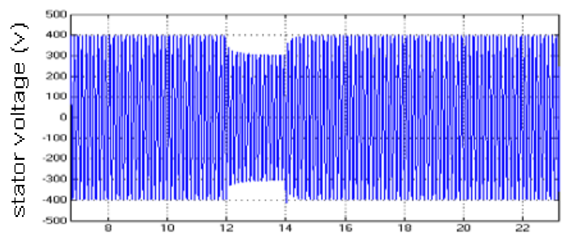
At t = 45s, Fig. 9, the capacitance is suddenly removed, the resistive load causes machine voltage to reach zero level abruptly.



Time (s)

Fig. 9: Stator Voltage Disturbance When C Is Removed.

Dynamic response of voltage variations with time for a load of 1.1 kΩ between 12s and 14s is depicted in Fig.10. It can be observed the machine voltage reaches its steady state value immediately after 14s.



Time (s)

Fig. 10: Stator Voltage Disturbance When Pulse Changed.

6. COMPARISON BETWEEN ANALYTICAL AND EXPERIMENTAL RESULTS

The values of X_m, P_m, V_s, on no load and I_L, V_L, P_L on load are computed and plotted, Figs. 11 - 16. The corresponding experimental ones are shown for comparison.

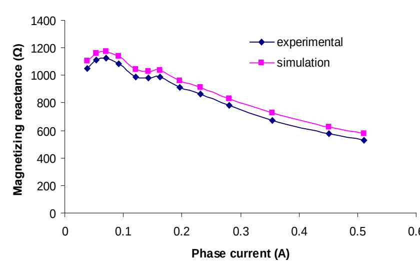


Fig. 11: X_m Vs I_{ph} Characteristics Of Induction Machine

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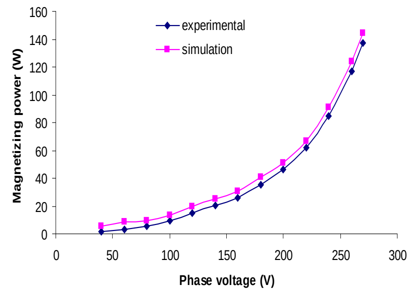

Fig. 12: P_m Vs V_s Characteristics Of Induction Machine

During no load condition the speed of the dc motor is reduced in steps until the voltage across the capacitance drops suddenly to zero, Fig. 13. This is called excitation failure stage.

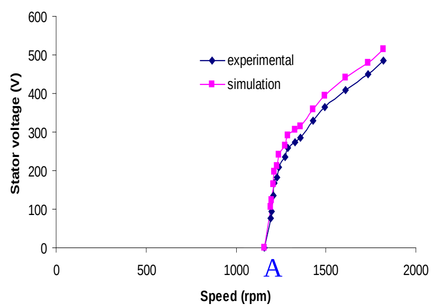

Fig. 13: Excitation Failure Without Load By Varying Speed

It is concluded that the excitation fails for a speed of 1160 rpm for a capacitance of 6 µF, point A.

A three phase resistive load is connected across the star connected capacitor bank. Again, the speed of the drive is gradually decreased to obtain zero voltage point, Fig. 14. This is termed excitation failure stage at full load.

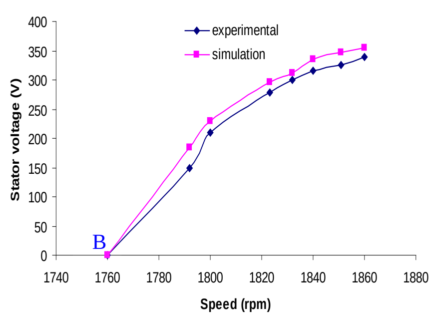

Fig. 14: Excitation Failure With Load By Varying Speed

The excitation failure occurs at 1760 rpm for resistive load of 1.1 kΩ and maximum capacitance of 6 µF, point B; the corresponding load voltage and power vs load current are shown in Figs. 15 and 16 respectively.

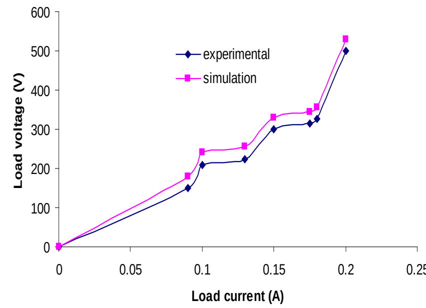

Fig. 15: V_L Vs I_L For R_L = 1.1 KΩ, C_{max} = 6 Mf.

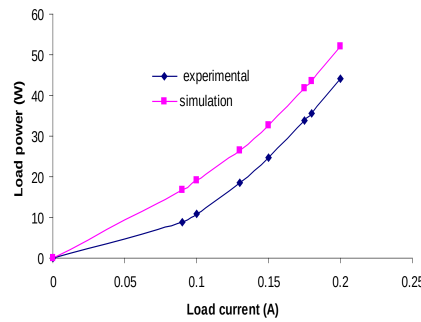

Fig. 16: *P_L Vs I_L For R_L = 1.1 KΩ, C_{max} = 6 Mf.*

7. CONCLUSION

The calculation of the critical, minimum and maximum excitation capacitance from no load characteristics of the induction generator is presented.

The modelling of self-excited induction generator is done and corresponding equations are given. The self-excited induction generator is modelled in synchronously rotating reference frame and it is transformed to abc frame by PARK'S transformation. The dynamic response of self-excited induction generator is simulated under varying loads and capacitances.

The voltage buildup process of the self-excited induction generator under varying generator speeds is investigated for a resistive load through simulated and experimental results which are in close agreement.

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NOMENCLATURE:

C = Self-excitation capacitance
E_1 = No load magnetizing voltage
i_{ds}, i_{qs} = Peak stator d and q axes currents
i_{dr}, i_{qr} = Peak rotor d and q axes currents
i_{dc}, i_{qc} = Peak d and q axes capacitor currents
i_m = Peak magnetizing current
I_{n1} = No load current
J, B = Net inertia & friction of rotating parts of the m/c
L_m = Magnetizing inductance
L_s, L_r = Stator and rotor inductances
P = Number of poles
P_m = Magnetizing power
p = Differential operator d/dt
r_s, r_r = Stator and rotor resistance
T_m = Mechanical toque (Nm)
T_e = Electromagnetic torque (Nm)
v_{ds}, v_{qs} = Peak stator d and q axes voltages
v_g = Peak magnitude of the air gap voltage
v_{n1} = Phase supply voltage
v_L, i_L = Load voltage and load current
ω_r = Shaft speed (rad/sec)
ω_e = Electrical frequency (rad/sec)
x_m = Magnetizing reactance
x_{CC} = Critical capacitive reactance
x_{cmin}, x_{cmax} = Minimum and maximum capacitive reactances
z_{n1} = No load impedance

APPENDEX

Parameters of induction machine (Squirrel Cage rotor):

Rating : 120 W, 240 V, 0.5 A, 1300 rpm, 4 pole
Constants : r_s = 36.658 Ω, r_r = 36.753 Ω
L_s = 0.134 H, L_r = 0.134 H
Bharat Bijlee Ltd.