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Selection of Capacitors for the Self Excited Slip ring Induction Generator with External Rotor Capacitance

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Abstract

The self regulating feature of a Self Excited Induction Generator (SEIG) by connecting additional capacitors is examined with the slip ring induction generator. The system consisting of external rotor capacitors at rotor has been analyzed. A methodology has been explained to choose appropriate set of values of these rotor capacitors for desired voltage regulation. Based on the steady-state equivalent circuit model, consideration of the circuit conductances yields a 7th-degree polynomial in the frequency. The polynomial can be solved for real roots, which enables the value of C, to be calculated. Critical values of load impedance and speed, below which the machine fails to self-excite irrespective of the capacitance used, are found to exist. Closed form solutions for C are derived for different loads. Using the Same numerical approach, an iterative procedure is also developed for predicting the capacitance required for maintaining the terminal voltage at a preset value when the generator is supplying load. Results of a detailed investigation on a conventional 3.5 kW induction motor operated as a SEIG are presented to illustrate the effectiveness of the proposed method. Close agreement between predicted and test results has been observed thereby establishing the validity of the analysis carried

Keywords: capacitance requirements, self-excitation, slip ring induction generator, external rotor capacitance

1. Introduction

Capacitor self excitation of induction machine is now a well known phenomenon which has been researched in depth. If an appropriate capacitor bank is connected across the terminals of an externally driven induction machine, a voltage is developed across its terminals. The residual magnetism in the rotor initiates voltage build-up which is augmented by the capacitor current to cause a continuous rise in voltage. A steady state voltage results due to the magnetic saturation which balances the capacitor and the machine voltage. Brushless rotor construction, lower unit cost, absence of a separate dc source, better stability and self protection under fault conditions are the major reasons for preferring SEIG over conventional alternator in such generating units. But poor voltage regulation of SEIG even at regulated speeds has been a major bottleneck in its application. Steady increase in capacitor VAR with load has to be achieved to maintain good voltage regulation. Steady increase in capacitor VAR with load has to be achieved to maintain good voltage regulation. Several voltage regulating schemes have been tried to achieve this aim. These schemes mostly utilize switched capacitor or variable inductor or saturable core reactor based close loop schemes using relay/contactors or semiconductor switches. But complex system configuration, intricate control circuit design and operational problems like harmonics and switching transients, associated with voltage regulators vitiate the very advantages of recommending induction machines for autonomous power generation In case of Squirrel Cage Induction Generator, the slip varies and increases with increasing load. The major problem is that, because of the magnetizing current supplied from the grid to the stator winding, the full load power factor is relatively low. This has to be put in relation to the fact that most power distribution utilities penalize industrial customers that load with low power factors. Clearly, generation at a low power factor cannot be permitted here either. Slip-ring induction machine is expensive and requires more maintenance, but it allows rotor slip-power control when driven by variable speed turbine. When it is connected to grid, it works as doubly output induction generator [DOIG]. Slip power recovery concept is utilized to variable speed operation for wind power plants or small hydro power plants.In case of self-excited induction generator, system cost can be further reduced by use of rotor resistance control. Fixed valued capacitor bank is only needed to connect stator terminals [2]. Based on the work reported so far, it was felt necessary not only to develop analytical techniques to predict the performance of SEIG with external rotor capacitance, but also to evolve a methodology to select the most appropriate pair of capacitors. An ideal combination of shunt and external rotor capacitors is the one for which the load voltage can be maintained within acceptable limits from no load to full load power output. The study would involve modeling, analysis, identification of constraints and estimation of desired parameters. Further, comparison of SEIG with external rotor capacitance performance with SEIG configuration to assess their relative merits and demerits is also desired. In this paper a simple and general mathematical formulation for short shunt configuration has been presented. From the equivalent circuit parameters a method to evaluate the performance characteristics has been explained. A simple methodology has been proposed for the selection of suitable values of capacitors to obtain minimum regulation. The effect of capacitors on performance quantities like winding current and machine voltage has been discussed so as to evolve guidelines for designing the system. A series of tests have been performed and relevant experimental results are presented along with theoretical ones. It is shown that once the mathematical foundation is laid and the methodology is understood the design of a self-regulating SEIG becomes relatively simple. The study is extended to long shunt configuration and the two configurations are compared.

The system we tested has the following components:

- a wind turbine
- a three-phase, 3-hp,slip ring induction generator driven by the wind turbine
- various sets of capacitors at stator terminals to provide reactive power to the induction generator
- a three-phase external rotor capacitance at rotor terminals
- a three phase RL load

2. System Description and Model Derivation

In the proposed system, a power generation system consisting of a wind turbine with SEIG connected to the grid and an external capacitance is connected to the rotor is considered. A proposed method based wind driven SEIG fed to grid is shown in Fig.1.

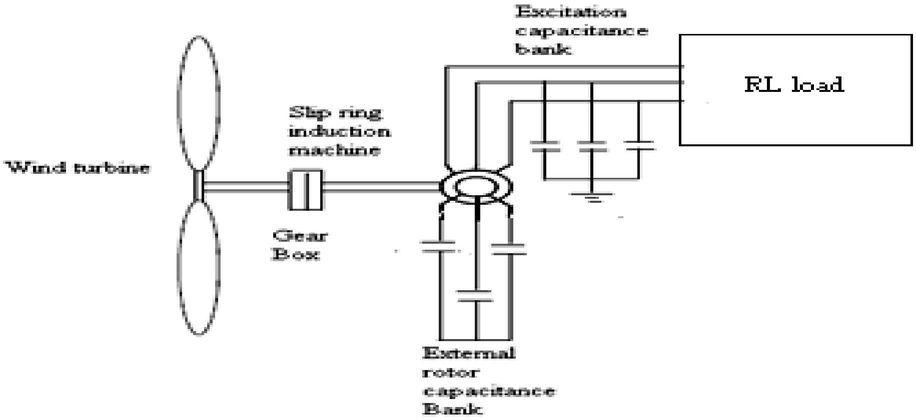


Fig.1.Slip ring induction generator with rotor capacitance

In this system, Turbine coupled with gearbox, generator connected with external rotor resistance is connected with supply grid. Control of slip (speed) and reactive power is possible with an external rotor capacitance by adjusting with power electronic converters like chopper with high frequency switching up to1kHZ. Here ideal system is assumed and external rotor capacitance can be changed according to the requirement as shown in Fig. 1.

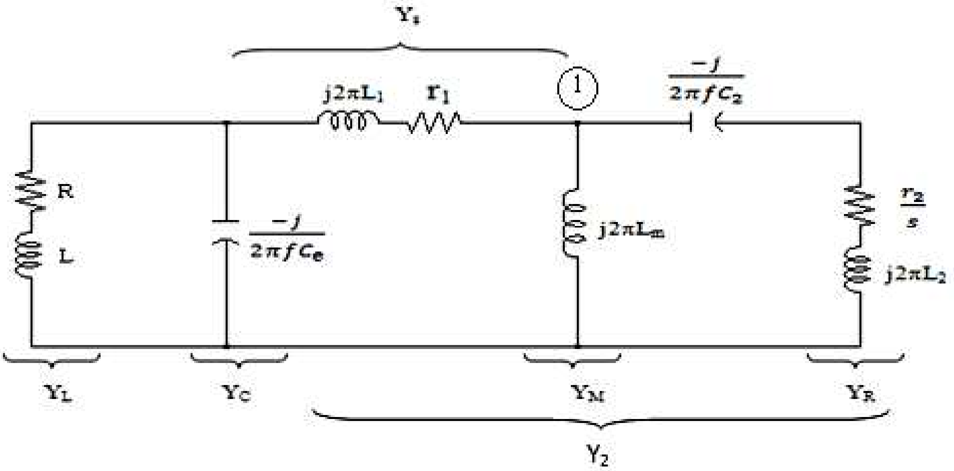


Fig.2. Equivalent circuit of SEIG with external rotor capacitance

The present study uses the standard steady state equivalent circuit of the SEIG with the usual assumptions considering the variation of magnetizing reactance with saturation as the basis for calculation. The equivalent circuit of SEIG with capacitors connected in configuration is shown in Fig. 2.

A. Mathematical model

Fig.2.shows the per phase equivalent circuit used for the steady state analysis of the SEIG with external rotor capacitance. For the machine to self excite on no load, the excitation capacitance must be larger then some minimum value, this minimum value decreasing as speed decreases. For on load self-excitation, the impedance line corresponding to the parallel combination of the load impedance and excitation capacitance should intersect the magnetization characteristic well into the saturation region. The condition yields the minimum value of excitation capacitance below which the SEIG fails to self-excite. For the circuit shown in Fig.2.,by Kirchhoff's law, the sum of currents at node(1) should be equal to zero, hence

$$VY=0 \qquad (1)$$

Where Y is the net admittance given by

$$Y= Y_L+Y_C+Y_2 \qquad (2)$$

The terminal voltage cannot be equal to zero hence

$$Y=0 \qquad (3)$$

By equating the real and imaginary terms in equation(3) respectively to zero.

$$\mathrm{Real}(Y_L+Y_C+Y_2)=0$$

$$\mathrm{Imag}(Y_L+Y_C+Y_2)=0$$

Where Y_L ,Y_C,Y_2 are

$$Y_L= \frac{1}{R+j2\pi fL} ; \qquad Y_2= \frac{(Y_R+Y_S)Y_M}{Y_R+Y_S+Y_M} ; Y_C=j2\pi fC; \qquad (4)$$

B. Proposed method to find general solution for excitation and rotor capacitances

The required values of the excitation and rotor capacitances are calculated from the equations (1)-(4). After separating the real parts and imaginary parts from the solution the real part yields the equation to solve for the frequency, which is of 7th order polynomial equation, given by:

$$A_7f^7+A_6f^6+A_5f^5+A_4f^4+A_3f^3+A_2f^2+A_1f+A_0 \qquad (5)$$

Where the coefficients A_7,A_6,A_5,A_4,A_3,A_2,A_1 and A_0 are defined in APPENDIX
And imaginary part yields rotor capacitance,given by:

$$C_2 = \frac{B_3f^3+B_2f^2+B_1f+B_0}{D_3f^3+D_2f^2+D_1f+D_0} \qquad (6)$$

From the frequency and rotor capacitance values the excitation capacitance can be calculated, given by:

$$C_e = \frac{E_1f+E_0}{G_3f^3+G_2f^2+G_1f} \qquad (7)$$

Slip,s is given by:

$$s = \frac{kf-N}{kf} \qquad \text{where } k=30 \qquad (8)$$

The derivation for these constant coefficients A_4 to A_0 , B_3 to B_0 ,D_3 to D_0,E_1 to E_0 and G_3 to G_0 is given in Appendix-A. Equation (4) can be solved numerically to yield all the real and complex roots. Only the real roots have physical significance and the largest positive real root yields the frequency. The corresponding capacitance can be calculated.

An investigation on the solutions for various load impedances and speed conditions reveals that for RL loads, there are in general two real roots and a pair of complex roots.The computed results reveal that there exist critical values of load impedance or speed below which the induction generator fails to excite irrespective of the value of capacitance used.

3. Computed results and discussions

In this paper, the computed results are obtained by the procedures and calculations outlined above, number of experiments are conducted using three phase induction machine coupled with a wind turbine. The induction machine was three phase, 3.5kW, 415V, 7.5A, 1500r.p.m, star connected stator winding. The machine was coupled to a D.C.shunt motor to provide different constant speeds. A 3-Φ variable capacitor bank or a single capacitor was connected to the machine terminals to obtain self-excited induction generator action.

The measured machine parameters were:

r_1=11.78Ω; r_2=3.78Ω; L_1=L_2=10.88H. L_m=227.39H

Consider the case when the machine is driven at rated speed with a connected load impedance of 200Ω.Solve the frequency polynomial using MATLAB software. The solution yielded the following complex and real roots.

f_1=50.06Hz; f_2=17.33Hz;
f_3=1.275+j0.3567Hz; f_4=1.275-j0.3567Hz;
f_5=2.03+j1.295Hz; f_6=2.03-j1.295 Hz; f_7 =-2.55Hz

As only the real roots have physical significance and the largest real root yields the maximum frequency that corresponds to the minimum frequency. Since all these values and capacitance and sufficient to guarantee self-excitation of induction generator, it follows that the minimum capacitor value required. It is seen that only the larger positive real root gives the feasible value of the capacitance.

The smaller real root on the other hand gives the value of the excitation capacitance above which the machine fails to excite. However such condition is unpractical as the corresponding excitation current would far exceed the rated current of the machine.If the polynomial is having no real roots, and then no excitation is possible. Also, there is a minimum speed value, below which equation (5)have no real roots. Correspondingly no excitation is possible.

When the SEIG is operating under no load condition, there will current through the rotor capacitor (C_2) and only shunt capacitor (C_e) will be effective in the circuit. Therefore, effect of C_2 is reflected on the no load performance of the SEIG. But when loaded, both shunt and rotor capacitors will be effective. Hence, proper value of these elements can be chosen by first studying the variation of no load terminal voltage with C_e. Having chosen a suitable value for C_e from this curve, the influence of C_2 can be studied by observing the effect of C_2 on voltage regulation of the SEIG. Appropriate value of C_2 can be selected from the range of values thus obtained depending upon the desired regulation and other operating constraints.

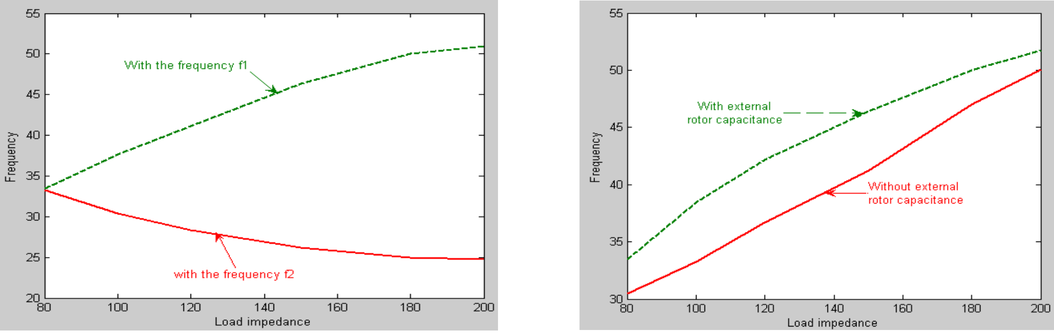
With the real root of the frequencies from the above it is possible to calculate the values of the C_2 and C_e. From the frequencies it is estimated that the values of the rotor capacitances are 10μF and 1.2 μF respectively. And from these frequencies and from the given machine parameters the excitation capacitance is estimated to be 13 μF and 1.1 μF respectively.

It is noted that for R-L loads, there are in general two real roots and one pair of complex conjugate roots. This restricts to the set of two capacitors. It is also noted that N_s<N, the slips = $\frac{kf-N}{kf}$ is always negative as it should be for generator action.

The variation of frequency with the load is as shown in Fig.3.

Fig.3(a).shows the computed variation of the self excited frequencies f and f_2 with load impedance at 80Ω.It is noticed that the roots vary only slightly with the load impedance. One is slightly decrease with load impedance and another is increasing with the same. When load impedance is less than80Ω, however the two roots will approach rapidly. At load impedance 80Ω, the two roots are equal, while all value below 80Ω yields imaginary roots.

The value of load impedance that results in repeated real roots of the polynomial thus defines a region of no-generation and it may be termed the critical load impedance for a given speed and power factor. Fig.3(b).shows the variation of load impedance with the frequency under two different conditions i.e with considering the rotor capacitance and without considering the rotor capacitance. The frequency is more with the external rotor capacitance when compared with the SEIG without external rotor capacitance and the frequency reaches to stable state faster than the other. Hence with this we can conclude that with the external rotor capacitance the frequency of variation is high



(a). two real roots of frequency with load. (b).frequency with load impedance

Fig.3. Variation of frequency with the load impedance

The variation of the excitation capacitance with the load impedance is as shown in Fig.4. Fig.4.shows the variation of capacitance with the load impedance. It is noticed that, in general, capacitance increases with decrease in load impedance. The increase in more gradual at large values of impedance but becomes more abrupt as the critical value 80Ω is approached. Here also it can be observe that below certain value of load impedance i.e of 80 Ω there is no excitation possible.

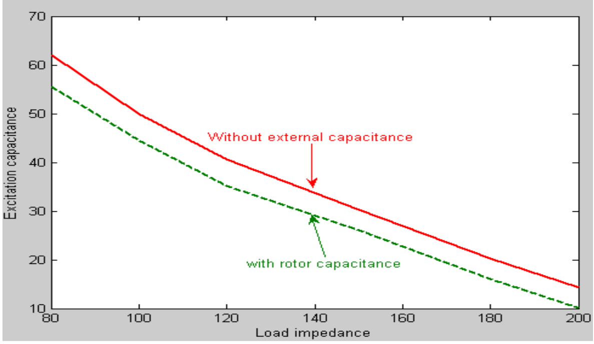
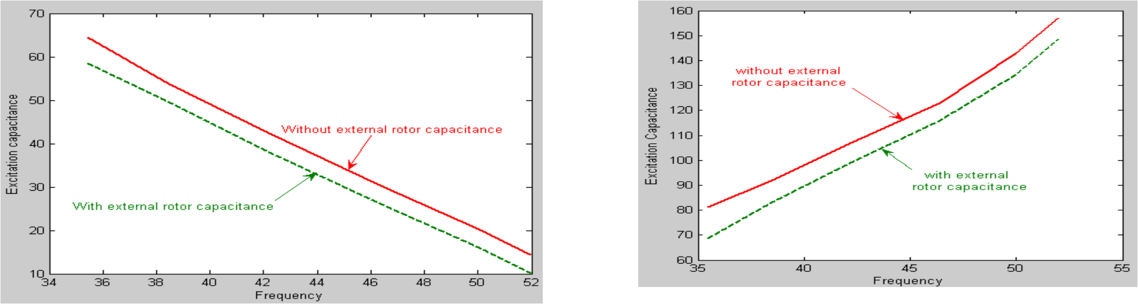


Fig.4. Variation of capacitance with the load impedance

Fig.5(a) and 5(b) shows the minimum capacitance required for the self-excited induction generator. These values can be used to predict the theoretically the minimum values of the terminal capacitance required for self-excitation. Of course, for stable operation of the machine C must be slightly greater than the minimum capacitance. Exact expressions for capacitor values under no-load, resistive loads and corresponding output frequencies are derived.

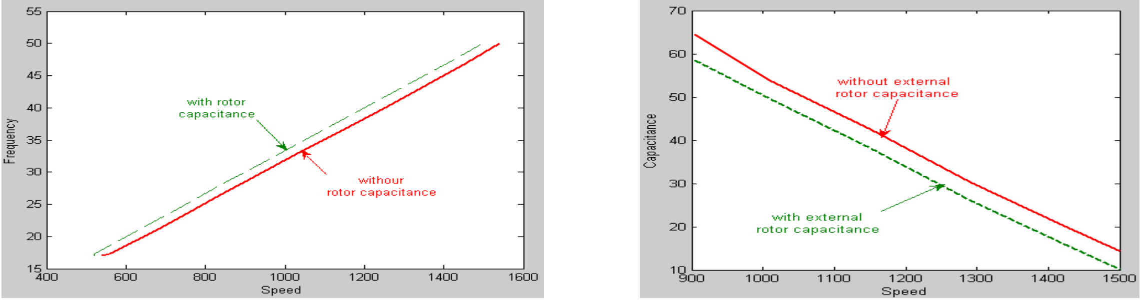


(a). capacitance with highest real root of frequency (b). Capacitance with lowest real root of frequency

Fig.5. Variation of capacitance with the frequency

Fig.6(a). shows the computed variation of self-excited frequencies with speed for load impedance 200Ω.Again a region of no-generation is identified and the critical speed yields the repeated roots of the polynomial may be termed the critical speed for a given load impedance.

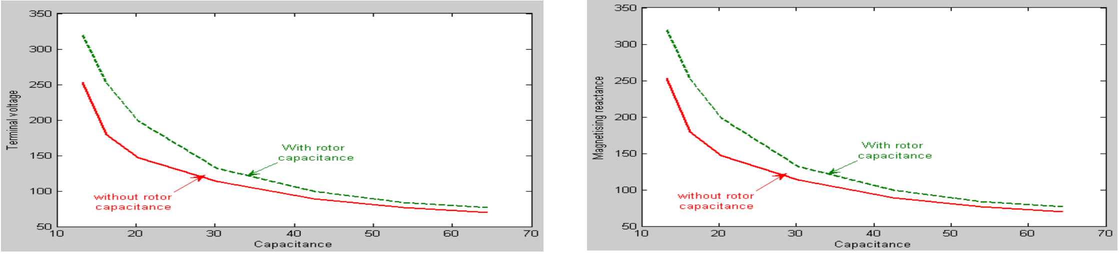
Fig.6(b).shows the computed variations of minimum capacitance with speed at different load impedances. It is seen that the capacitance increases rapidly with the decrease in speed. At speeds nearly to the critical value, minimum capacitance is very large, typically hundreds of microfarads. In practice, however it is unlikely that the SEIG will be operated at such low speeds. As for the no-load case close solutions exist for the self excitation frequency which is maximum and capacitance which is minimum. The self excitation frequency and the critical speed for the inductive load were same as for the no-load case.



(a).frequency with speed (b).capacitance with speed

Fig.6. Variation of frequency and capacitance with the speed

Fig.7(a). shows the variation of capacitance with the terminal voltage. As the capacitance value is increasing the terminal voltage is decreasing and vice versa. When compared with the terminal voltage without rotor capacitance the voltage is increased by an amount of 15%.Fig.7(b).shows the variation magnetization reactance of generator with various capacitances .If the capacitance value is below the minimum value of the capacitance, the magnetization reactance is greater the unsaturated reactance, in which case the machine is failed to excite and the voltage will be zero.

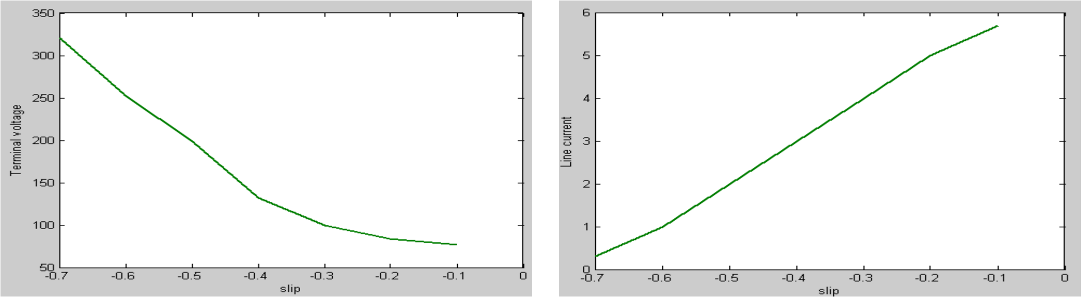


(a).terminal voltage with capacitance (b).magnetizing reactance with capacitance

Fig.7. Variation of capacitance with the terminal voltage and magnetizing reactance

Curves typical of the typical variations of terminal voltage with slip are as shown in Fig.8(a),for negative(generator)slips. At synchronous speed, s=0,terminal voltage is very nearly equal to V:it may be within 2 or 3 percent. Due to the excitation capacitance the voltage increases for the negative slips. Otherwise the voltage falls rapidly with the increase of the slip in either direction and thereafter tends to a constant value.

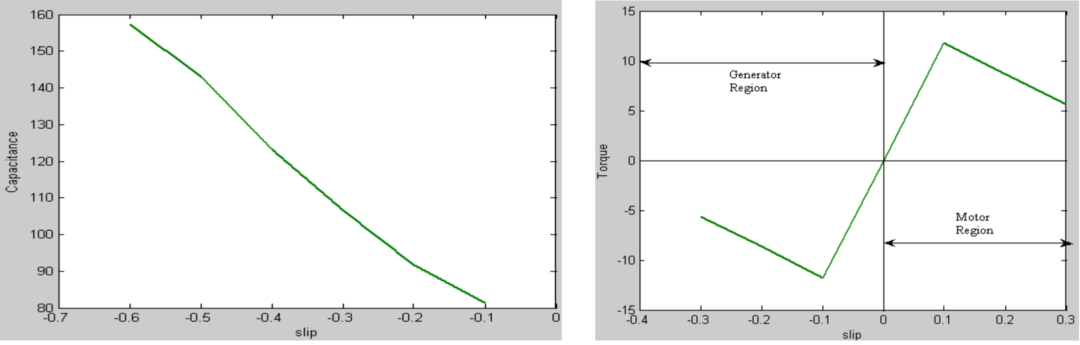
Typical variations of current with the slip is as shown in Fig.8(b).The current is zero at synchronous speed and decreases rapidly with the variation of the slip and thereafter tends to a constant value. The stator current is the magnetizing current at synchronous speed, but soon reaches values very close to those of rotor current, since I_m is comparatively small



(a).terminal voltage with slip (b).Line current with slip

Fig.8. Variation of slip with the terminal voltage and Line current

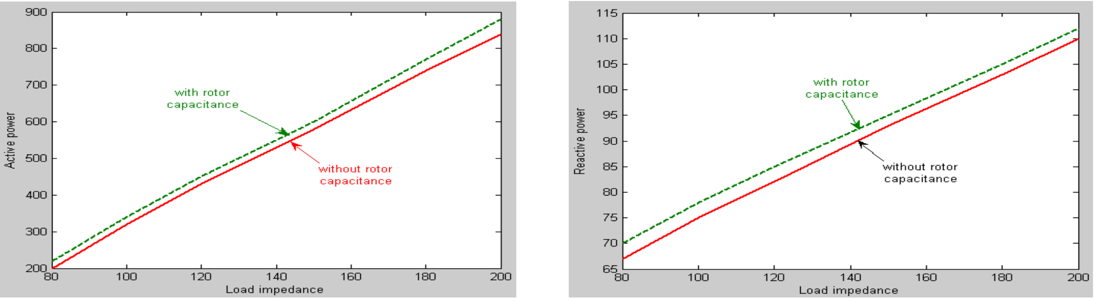
Fig.9(a).shows the variation of the capacitance with slip. Capacitance is maximum at minimum value of slip and then increases as the slip moves in the negative direction. As the slip decreases the values of the frequency also decreases. Fig.9(b).shows the typical characteristics of the slip as a function of torque of the induction generator running at sub synchronous (motor) and super synchronous (generator) speed. For sub synchronous speed, operation, r_1 larger, $x_1$and $x_{2'}$ are reduced. The rotor resistance does not affect the speed at which the maximum torque occurs. The lower the rotor resistance, the nearer to the synchronous speed does the torque to attain a maximum at starting .For super synchronous or generator operation the maximum torque is independent of r_2 as for normal motor condition, and increase with reduction of both stator and rotor reactance. But an increase in stator resistance now increases the maximum torque. If the primary resistance is large, the maximum torque running super synchronously may be very high indeed. With the external rotor capacitance the torque is increased about 5-10% then that of the SEIG without having the rotor capacitance. With the external rotor capacitance, there is increase in the speed of the generator when compared with the machine without rotor capacitance.



(a).Capacitance with slip (b).Torque with slip

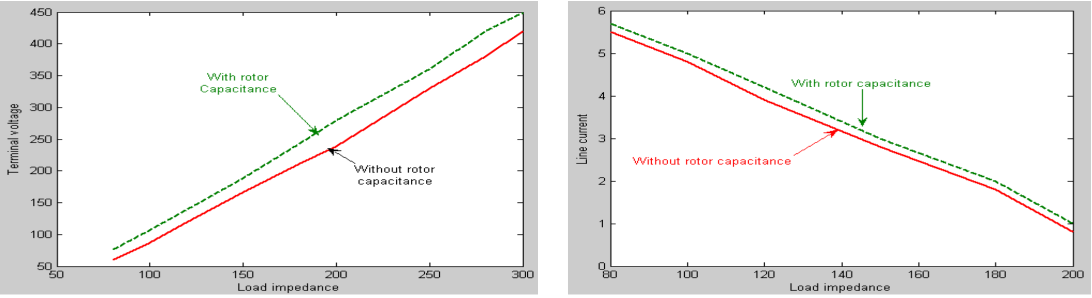
Fig.9. Variation of slip with the capacitance and torque

The variation of the load impedance with the active and reactive power are as shown in Fig.10(a) and (b) respectively. The active and reactive power generated by the machine is increased with the rotor capacitance in the circuit. The comparison is made between the SEIG with rotor capacitance and without rotor capacitance. With this comparison we can conclude that for the improvement of the power we can use the external rotor capacitance in the circuit. But the proper capacitance value should be choosen,other wise the machine may collapse with the drastic increase in the voltage.



(a).Active power with load impedance (b).Reactive power with load impedance

Fig.10. Variation of Load impedance with the active and reactive power



(a).Terminal voltage with load impedance (b).Line current with load impedance

Fig.11. Variation of Load impedance with the terminal voltage and line current

The variation of the load impedance with the terminal voltage and line current is as shown in Fig.11(a) and (b). The voltage is generated by the machine is increased with the external rotor capacitance in the circuit. The comparison is made between the SEIG with rotor capacitance and without rotor capacitance. With this comparison we can conclude that for the improvement of the terminal voltage it is advised to use the external rotor capacitance in the circuit. But the proper capacitance value should be choosen, other wise the machine may collapse with the drastic increase in the voltage.

Since only one single root is required, the Newton-Raphson method was used in solving the polynomial equation. Depending on the circuit conditions, the final value of the frequency could be obtained in 4to10 iterations. It is advised to use MATLAB software to solve the polynomial.

4. Experimental results and discussions

Experiments were performed on the above mentioned induction machine to verify the validity of the computed results. It is found that if a sufficiently large residual flux existed in the rotor core, the machine would always self-excite whenever the capacitance was slightly higher than the computed value.

The value of the rotor capacitance required for the machine from the computation result is obtained as

C=10.35μF.Similrly from the experiment it is of C=10μF.Hence proved that the experimental capacitance value is almost same as the computed result. When the capacitance is greater than this value, the voltage is exceeded and reaches to the dangerous value.

The value of the capacitance required for the machine to self excite from the computation result is obtained as C=14.35μF.Similrly from the experiment, using the magnetization curve, computed resulted is of C=15μF.Hence proved that the experimental capacitance value must be greater than the computed capacitance value. The magnetization curve drawn from the experimental result is as shown in Fig.12.

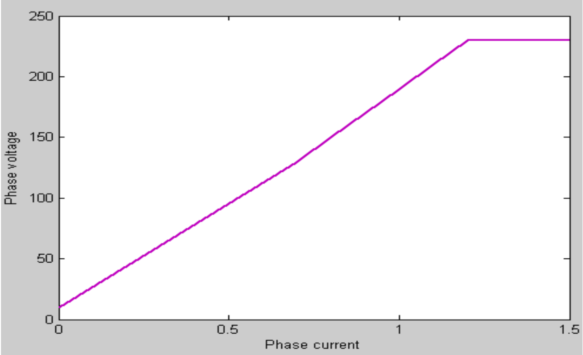


Fig.12. Magnetization Characteristic of SEIG with the rotor capcitance

The calculation of air-gap voltage is given in APPENDIX.

For different values of capacitances the experiment were conducted and it was found that the value of the frequencies calculated from the polynomial and experimental verification are nearly equal.

Very good correlation between the computed and experimental results is observed as shown in fig.13. This verifies the accuracy of the proposed method for computing minimum value of the capacitance for SEIG.

Without rotor capacitance		With rotor capacitance	
Experimental Frequency	Calculated Frequency	Experimental Frequency	Calculated Frequency
30.45	29.98	31.75	31.25
37.01	36.67	39.65	39.15
41.5	41.2	44.89	43.95
47.11	47.01	49.52	48.65
50.09	49.88	51.25	50.55

Fig.13. Comparision between Experimental and calculated frequency

Hence, it is proved that the experimental frequency value must be greater than the computed frequency value. And it is also proved that the frequency is higher for SEIG with external rotor capacitance than with the SEIG without rotor capacitance. So, with the increase in the frequency the speed of the machine is increased, in turn increases the generated voltage, torque, active and reactive power.

5. Conclusions

A method for computing the minimum value of capacitance to initiate self-excitation in the SEIG has been described with the rotor capacitance. The method is based on the steady state equivalent circuit, but features the separate consideration of the load,rotor capacitance and excitation capacitance branches, which enables the frequency to be determined by solving a single 7th order polynomial .Computation studies on the experimental machine reveals that there exist critical values of load impedance and speed below which self-excitation is impossible irrespective of the capacitance used. Using the same analysis technique, an iterative procedure has also been developed for estimating the capacitance requirements for maintaining the terminal voltage constant when the SEIG is on load. The validity of the proposed methods are confirmed by experimental results obtained on a 3.5kW laboratory induction machine. The roll of the external capacitor here is to minimize the steady state reaching time and stabilize the system within the minimum time. Due to the capacitance the output voltage of SEIG are increased but while choosing the value of the capacitance if the minimum value is selected the machine may not operate and if high value of the capacitance is selected the machine may collapse. Here in this paper the value of the capacitance is selected as per the equation derived for choosing the value of the external capacitance. It is observed that due to this capacitance the active and reactive powers are increased and p.f is decreased which is the requirement of the grid. It is also observed that the fluctuations in the shaft torque is also decreased.

Appendix

- The induction machine was three, phase3.5kW, 415V, 7.5A, 1500r.p.m, star connected stator winding. A 3-Φ variable capacitor bank or a single capacitor was connected to the machine terminals to obtain self-excited induction generator action.

  The measured machine parameters were:
  $r_1=11.78\Omega$; $r_2=3.78\Omega$; $L_1=L_2=10.88H$. $L_m=227.39H$

- To compute the coefficients A_4 to A_0 of equation(10),the following equations are first defined:

  $a=2\pi k(L_M r_1+L_1 r_1+L_2 r_1+L_M r_2+L r_2+r_L L_M+r_L L_2)$; $b=-2\ \pi N^* r_L(L_M+L_2)$

  $c=-8\pi^3 k(LL_M r_1+LL_2 r_1+LL_M r_2-r_L L_1 L_M-r_L L_2 L_M)$; $d=-8\ \pi^3 N(r_L L_1 L_M+ r_L L_2 L_1+ r_L L_2 L_M+LL_2 L_M)$

  $e=-2\pi k r_L r_1 r_2$ $g=-4\pi^2 k(L_1 L_M+L_1 L_2+L_2 L_M+LL_M+LL_2)$

  $h=4\pi^2 N(L_1 L_M+L_1 L_2+L_2 L_M+LL_M+LL_2)$ $i=r_1 r_2+r_L r_2$

  $j=-16\pi^4 k(LL_1 L_M+LL_2 L_M+LL_2 L_1)$; $l=16\pi^4 N(LL_1 L_M+LL_1 L_2+LL_2 L_M)$

  $m=4\pi^2 k(L r_1 r_2+r_L L_M r_1+r_L L_1 r_2+r_L L_1 r_2+r_L L_2 r_1+r_L L_m r_2)$ $p=-4\pi^2 N r_L L_M r_1$;

  $q=c(L_1 L_M+L_1 L_2+L_2 L_M+LL_M+LL_2)$

  $A_7 = eq+cd+hc+ak$; $A_6 = ed+dh+ag-bj$; $A_5 = dh+ie-pb+qa$; $A4=cg-aj$

  $A_3=dg+hc+al-bj$; $A_2=eg+hd+ic-ma-bl$; $A_1=he+id-pa-bm$; $A_0=ie-bp$;

  $B_3=hi+gj+de$; $B_2=-mg-mk$; $B_1=ki$; $B_0=lg+eh$;

  $D_3=-mi$; $D_2= hm-bq$; $D_1=hg+qd-hc-bk$; $D_0=mg-ae+gq$;

  $E_1=mq+dh$; $E_0=ab+ch-ml$;

  $G_3=hi+dj$; $G_2=gf+im-bk$; $G_1=pm-ij+me-cq$;

- **Air gap voltage**:

  The piecewise linearization of magnetization characteristic of machine is given by:

$E_1=0$	$X_m \geq 260$
$E_1=1632.58-6.2X_m$	$233.2 \leq X_m \leq 260$
$E_1=1314.98-4.8X_m$	$214.6 \leq X_m \leq 233.2$
$E_1=1183.11-4.22X_m$	$206 \leq X_m \leq 214.6$
$E_1=1120.4-3.9.2X_m$	$203.5 \leq X_m \leq 206$
$E_1=557.65-1.144X_m$	$197.3 \leq X_m \leq 203.5$
$E_1=320.56-0.578X_m$	$X_m \leq 197.3$

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