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Modeling and Analysis of Self Excited Slip Ring Induction Generator Using Newton Raphson Method

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Abstract—In this paper deals with steady state analysis of self-excited slip ring induction generator (SESRIG) is performed using Newton- Raphson method. By varying effective rotor resistance of a self excited slip ring induction generator, the magnitude and frequency of the output voltage can be controlled over a wide speed range. A steady state analysis based on normalized equivalent circuit enables the control characteristics to be deduced. In the wind driven SESRIG system the rotor speed is varied along with wind speed. For a given stator load, both frequency and voltage can be maintained constant as speed is varied by changing rotor resistance, with constant excitation capacitance. The proposed scheme may be used in low cost variable speed wind energy system for providing good quality electric power to remote regions.

Keywords—SESRIG, Newton- Raphson Method, Rotor Resistance

I. INTRODUCTION

Self-excitation in an induction generator occurs when the rotor is driven by a Prime mover and a suitable capacitance is connected across the stator terminals. Under such conditions, the terminal capacitance furnishes the lagging reactive power necessary for establishing the air gap flux and the machine is often referred to as a self-excited induction generator (SEIG). SEIGs increasingly utilized in stand-alone generation systems that employ wind or hydro power. Unlike introduction generators connected to the power utility grid, both the frequency and the terminal voltage of the SEIG vary with load even when the rotor speed is maintained constant. An increase in the rotor speed will result in a proportionate increase in frequency, often accompanied by severe over voltage and excessive current. Recently, there has been rigorous research on the voltage and frequency control of squirrel – cage type SEIGs, but relatively little research efforts have been devoted to the use of the slip ring induction machine for generator applications.

a. Advantages

- When a grid connection is permissible, the slip-ring machine may be operated as a double-output induction generator (DOIG) using the slip-energy recovery technique.
- In the case of a self-excited slip-ring induction generator (SESRIG), the system cost can be further reduced by the use of a simple rotor resistance controller.
- Only a capacitor bank needs to be connected to the stator terminals, the SESRIG provides a good quality ac source with little harmonic distortion to the stator load.
- Advantageous feature of the SESRIG is that independent control of the voltage and frequency can be achieved easily. Even with a wide variation in speed, the generator frequency can be maintained reasonably constant by rotor resistance control, while the voltage can be controlled by varying the excitation capacitance.
- Although the slip-ring machine is more expensive and requires more maintenance, it permits rotor slip-power control when driven by a variable-speed turbine.

II. CIRCUIT ARRANGEMENT

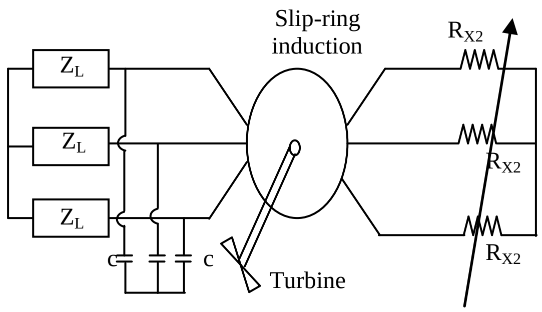


Fig. 2.1. **The circuit arrangement of a three phase SESRIG**

In this paper, the voltage and frequency control of a three phase SESRIG by variation of external rotor resistance will be investigated. Based on a normalized equivalent circuit model, the frequency and voltage characteristics are deduced and experimental results are presented to verify the feasibility of the control method. Practical implementation of a closed loop scheme that uses chopper-controlled rotor resistance will also be described.

Fig. 2.1 shows the circuit arrangement of a three phase SESRIG. The excitation capacitance 'C' is required for initiating voltage buildup and maintaining the output voltage. It is noticed that the electrical output power is dissipated in both the stator impedance Z_L as well as the external rotor resistance R_{X2}. Hence, the machine may also be regarded as a DOIG if the power is R_{x2} is effectively utilized.

III. MATHEMATICAL MODELING

3.1. Equivalent circuit analysis of SESRIG

The SESRIG is actually an induction motor that driven by a prime mover while its stator excitation provided by an external capacitor connected to the stator. The excitation capacitance is required for initiating voltage buildup and maintaining the output voltage.

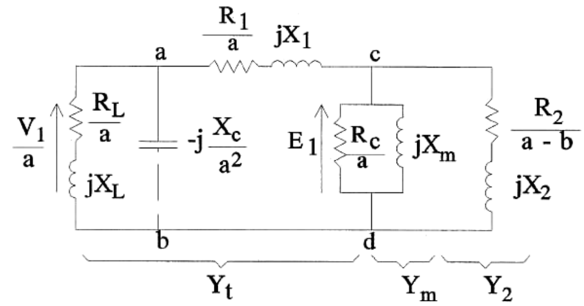


Figure.3.1 **Per-phase Equivalent circuit of SESRIG**

Fig 3.1 Shows the per phase equivalent circuit of SESRIG where the rotor resistance R2 is the sum of the rotor winding resistance and external rotor resistance. The circuit has been normalized to the base (rated) frequency through the introduction of the per- unit frequency '*a*' and the per-unit speed '*b*'. Various methods have been developed for solution of the SESRIG equivalent circuit. Adopting the nodal admittance, the following relation ship may be established for successful voltage build-up.

3.2. Nodal admittance method

This method considers the admittances connected across the nodes which define the air gap. By equating the sum of real parts to zero (which is equivalent to active power balance), a polynomial in "*a*" is obtained. X_m can be determined upon equating the sum of imaginary parts to zero, using the value of "*a*" obtained after solving the polynomial.

$$Y_t+Y_m+Y_2=0 \tag{1}$$

Where,

$$Yt = \frac{1}{z_t} = \frac{1}{Zac + Zab} = G_t + jB_t \tag{2}$$

$$Ym = -j\frac{1}{Xm} = G_m + jB_t \tag{3}$$

$$Y_2 = \frac{1}{\frac{R_2}{a-b} + jX_2} = G_m + jB_t \tag{4}$$

Equating the real and imaginary parts in 1 to zero respectively, the following equations in real number are obtained.

$$G_t+G_m+G_2 = 0 \tag{5}$$

$$B_t+B_m+B_2 = 0 \tag{6}$$

REAL PARTS($G_t+G_m+G_2$)=

$$-aX_mbX_CX_2+ aX_mX_LX_C- aX_mbX_LX_C- aX_mbR_1R_L- aX_mbX_1X_C- abX_2X_LX_C- abX_2R_1R_L- abX_2X_1*X_C +a^2X_mR_LR_2+ a^2X_mX_CX_2+ a^2X_mR_1R_L+ a^2X_mX_1X_C+ a^2X_2X_LX_C+ a^2X_2R_1R_L+ a^2X_2X_1X_C+ a^2X_1R_LR_2+ a^2X_LR_1R_2 +a^3X_mbX_LX_2+ a^3X_mbX_1X_L+a^2bX_1X_LX_2- a^4X_mX_LX_2-a^4X_mX_1X_L+a^4X_1X_LX_2-R_LR_2X_C \tag{7}$$

IMAGINARY PARTS(B_t+B_m+B_2)=
$aX_mX_CR_2$- $aX_mR_LX_C$- $aX_mR_1X_C$ - $aR_2X_LX_C$- $aR_1R_LR_2$- $aR_2X_1X_C$- $aX_2R_LX_C$- $aX_2R_1X_C$- $a^2X_mbX_2R_L$-$a^2X_mbX_1R_L$-$a^2X_mbX_LR_1$-$a^2bX_2X_1R_L$- $a^2bX_2X_LR_1$+ $a^3X_mX_LR_2$+ $a^3X_mX_2R_L$+ $a^3X_mX_1R_L$+ $a^3X_mX_LR_1$ +$a^3X_LX_1R_2$+ $a^3X_2X_1R_L$+ $a^3X_2X_LR_1$+ $X_mbR_LX_C$+ $X_mbR_1X_C$+ $bX_2R_LX_C$ +$bX_2R_1X_C$ (8)

3.3. Newton-Raphson method

By taking the Coefficients a and X_m in the equations(7), (8) the real and imaginary parts can be given by

$$h_1 = (f_0 X_m + f_1)a + (f_2 X_m + f_3)a^2 + (f_4 X_m + f5)a^3 + (f_6 X_m + f_7)a^4 + f_8 \quad (9)$$

$$h_2 = (g_0 X_m + g_1)a + (g_2 X_m + g_3)a^2 + (g_4 X_m + g5)a^3 + (g_6 X_m + g_7)a^4 + g_8 \quad (10)$$

The constants are given in appendix A-1.

$$\frac{\partial h1}{\partial a} = (f_0 X_m + f_1) + 2(f_2 X_m + f_3)a + 3(f_4 X_m + f_5)a^2 + 4(f_6 X_m + f_7)a^3 \quad (11)$$

$$\frac{\partial h2}{\partial a} = (g_0 X_m + g_1) + 2(g_2 X_m + g_3)a + 3(g_4 X_m + g_5)a^2 + 4(g_6 X_m + g_7)a^3 \quad (12)$$

$$\frac{\partial h1}{\partial X_m} = f_0 a + f_2 a^2 + f_4 a^3 + f_6 a^4 \quad (13)$$

$$\frac{\partial h_2}{\partial X_m} = g_0 a + g_2 a^2 + g_4 a^3 + g_6 a^4 \quad (14)$$

The ‘J’ matrix is given by

$$J = \begin{bmatrix} \frac{\partial h_1}{\partial a} & \frac{\partial h1}{\partial X_m} \\ \frac{\partial h_2}{\partial a} & \frac{\partial h2}{\partial X_m} \end{bmatrix} \quad (15)$$

From the equations (7) & (8), the matrix ‘K’ is given by

$$[K] = \begin{bmatrix} -h_1 \\ -h_2 \end{bmatrix} \quad (16)$$

The inverse of ‘j’ matrix is given by

$$J^{-1} = \frac{1}{|J|} adj[J] \quad (17)$$

The value of Δa and ΔX_m is calculated by

$$\begin{bmatrix} \Delta a \\ \Delta Xm \end{bmatrix} = [J]^{-1}[K] \tag{18}$$

The value of 'a' and 'X_m' is calculated using -R method from equations (19) and (20).

$$a^{new} = a^{old} + \Delta a \tag{19}$$

$$Xm^{new} = Xm^{old} + \Delta X_m \tag{20}$$

The induction machine used here is given in appendix A-2 The air gap voltage E_1 is expressed in terms of X_m by a piece wise linerized equation of the form.

A stable operating point exists, provided that X_m is less than the actuated value having determined all constants including X_m and E_l. The equivalent circuit of fig is complexly solved for the steady state performance of the induction generator.

The stator phase current is given by

$$I_1 = \frac{E_1}{Z_{LC} + Z_1} \tag{22}$$

where,

$$\left.\begin{aligned} Z_1 &= \frac{R_1}{a} + jX_1 \\ Z_2 &= \frac{R_2}{a-b} + jX_2 \\ Z_L &= \frac{RL}{a} + jX_L \\ Zc &= -j\frac{Xc}{a^Z} \\ Z_{LC} &= Z_L \,//\, Z_C \end{aligned}\right\} \tag{23}$$

The stator phase voltage is given by ,

$$V_1 = (I_L * Z_L * a) \tag{24}$$

$$P_{out} = 3 * I_L^2 * R_L \tag{25}$$

Where,

$$I_L = (I_1 * Z_C) / (Z_L + Z_C) \tag{26}$$

3.4. Computational Algorithm

1. Read all the machine required parameters.
2. Determine the value of the constants given in appendix A-1.
3. Assume the initial value of $\boldsymbol{a}$ and $\boldsymbol{X_m}$ ($\boldsymbol{a} = \boldsymbol{b}$ in p.u and $\boldsymbol{X_m}$= saturated value in p.u).
4. Determine the value of real and imaginary terms given in equations (7) and (8).
5. If the value of h1 and h2 are greater than tolerance (0.0001)go to next Step otherwise go to step 11.
6. From the '**K**' matrix given in equation (16).
7. Determine the partial derivatives of h1 and h2 with respect to $\boldsymbol{a}$ and $\boldsymbol{X_m}$ given in equation (11), (12), (13) and (14).
8. Form 'J' matrix and inverse of 'J' matrix given in equ (15),(17)steps.
9. Determine the value of Δa and ΔXm given in equation (18).
10. Update the value of a and X_m given in the equation (19) and (20) and go to step 4.
11. Obtain the air gap voltage $\boldsymbol{E_1}$ expressed in terms of $\boldsymbol{X_m}$ given in equation (21).
12. Determine the stator phase current $\boldsymbol{I_1}$ given in equation (22).
13. Determine the stator phase voltage $\boldsymbol{V_1}$ and output power P_{out} given in equation (24) & (25).
14. Stop.

IV. PERFORMANCE CHARACTERISTICS OF SESRIG

4.1. Results and discussion

The variation of per unit frequency, magnetizing reactance, air gap voltage, stator phase voltage, stator phase current and output power with respect to change in per unit speed at different rotor resistance are given in tables 4.1,4.2, and 4.3. The stator voltage, stator current, frequency and output power characteristics of the SESRIG for different values of external rotor resistance R_{X2} shown in figures 4.1, 4.2 and 4.3 respectively. These figures show that, increase in speed has proportionate increase in output voltage, current, frequency and power. It is observed that increasing R_{x2} has the effect of shifting the performance characteristics to the right-hand side of the speed axis. At a rotor speed of 1.05 p.u or above, the generator voltage or frequency can be maintained at rated value by varying $R_{X2.}$ This feature will be employed for voltage and frequency control of the SESRIG. It is observed that increasing R_{x2} has the effect of shifting the performance characteristics to the right-hand side of the speed axis. At a rotor speed of 1.05 p.u or above, the generator voltage or frequency can be maintained at rated value by varying $R_{X2.}$ This feature will be employed for voltage and frequency control of the SESRIG. The operating speed range of the SESRIG depends upon the maximum value of R_{X2} available, the rated voltage of the rotor winding, as well as the mechanical constraints of the turbine The result shows that by varying rotor resistance values, the magnitude and frequency of voltage can be controlled over a wide speed range. The variation of per unit frequency, magnetizing reactance, air gap, stator phase voltage, and stator phase current, with respect to change in per unit speed at different stator resistance are given in tables 4.4, 4.5 and 4.6. The stator voltage, stator current, frequency characteristics of the SESRIG for different values of external stator resistance R_{X1} shown in figures 4.4, 4.5 and 4.6. respectively. The results from the figures show that, by varying stator resistance values, the magnitude of stator phase voltage and current can be controlled. But the frequency is remaining unchanged with respect to various stator resistances. The stator resistance has considerable influence over the stator voltage and current. So the characteristics are useful to design the machine for specified system.

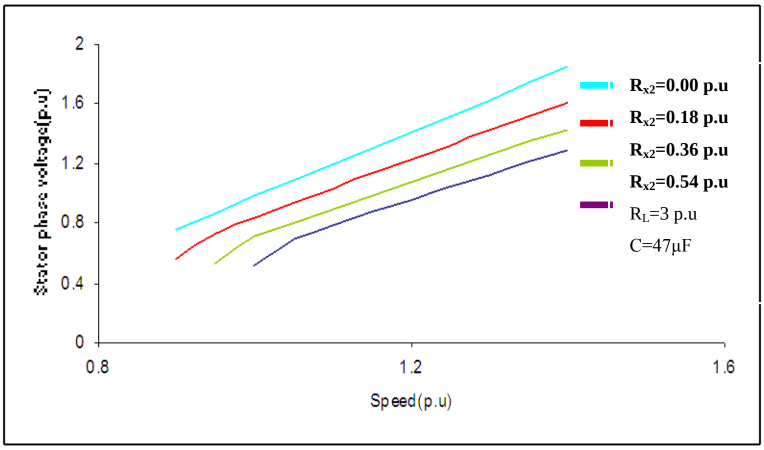
4.2. Tabulation of Results

4.2.1 Effects of rotor resistance variations

For, R_{x2}=0.00 p.u ; C=47µF ; R_L=3 p.u

b	a	X_m	E_1	V_1	I_1	P_{out}
0.9000	0.8663	1.8645	0.8375	0.7567	0.5348	0.5726
0.9500	0.9137	1.6671	0.9067	0.8702	0.6414	0.7572
1.0000	0.9610	1.4988	0.9627	0.9791	0.7515	0.9586
1.0500	1.0080	1.3542	1.0108	1.0870	0.8676	1.1816
1.1000	1.0550	1.2290	1.0524	1.1945	0.9901	1.4268
1.1500	1.1017	1.1200	1.0887	1.3018	1.1193	1.6946
1.2000	1.1482	1.0246	1.1204	1.4093	1.2553	1.9860
1.2500	1.1945	0.9406	1.1484	1.5172	1.3985	2.3019
1.3000	1.2406	0.8663	1.1731	1.6259	1.5491	2.6436
1.3500	1.2864	0.8004	1.1950	1.7356	1.7073	3.0122
1.4000	1.3320	0.7417	1.2145	1.8464	1.8734	3.4092

Table. 4.1. **Results for various speed values at R_{X2}=0.00 (all the values are in p.u)**

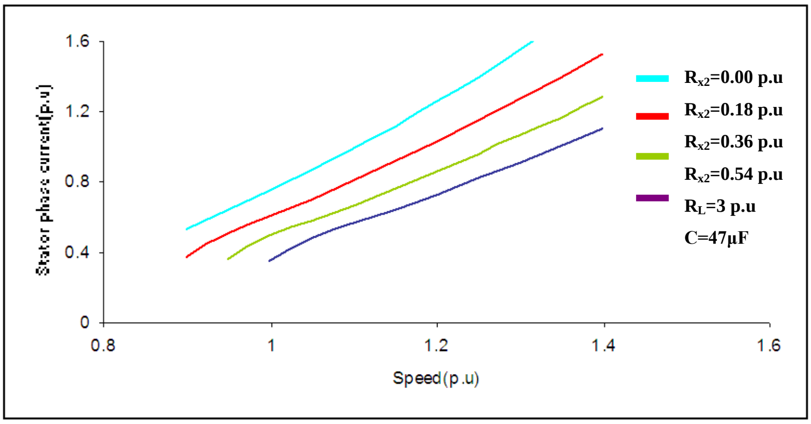


Graph.4.1.**Stator phase voltage with respect to per unit speed for various Rotor resistance values.**

For, **R_{x2}=0.18p.u ; C=47µF ; R_L=3 p.u**

B	**a**	**X_m**	**E_1**	**V_1**	**I_1**	**P_{out}**
0.90	0.8125	2.1321	0.6736	0.5664	0.3812	0.3208
0.95	0.8561	1.9113	0.8201	0.7312	0.5120	0.5346
1.00	0.8994	1.7229	0.8881	0.8372	0.6093	0.7008
1.05	0.9424	1.5610	0.9420	0.9367	0.7077	0.8774
1.10	0.9851	1.4208	0.9886	1.0349	0.8105	1.0710
1.15	1.0274	1.2986	1.0292	1.1321	0.9180	1.2816
1.20	1.0695	1.1916	1.0649	1.2285	1.0301	1.5093
1.25	1.1111	1.0973	1.0962	1.3244	1.1471	1.7542
1.30	1.1524	1.0139	1.1240	1.4201	1.2689	2.0166
1.35	1.1932	0.9397	1.1487	1.5155	1.3956	2.2968
1.40	1.2336	0.8735	1.1707	1.6110	1.5273	2.5953

***Table 4.2.* Results for various speed values at R_{X2}=0.18 (all the values are in p.u)**

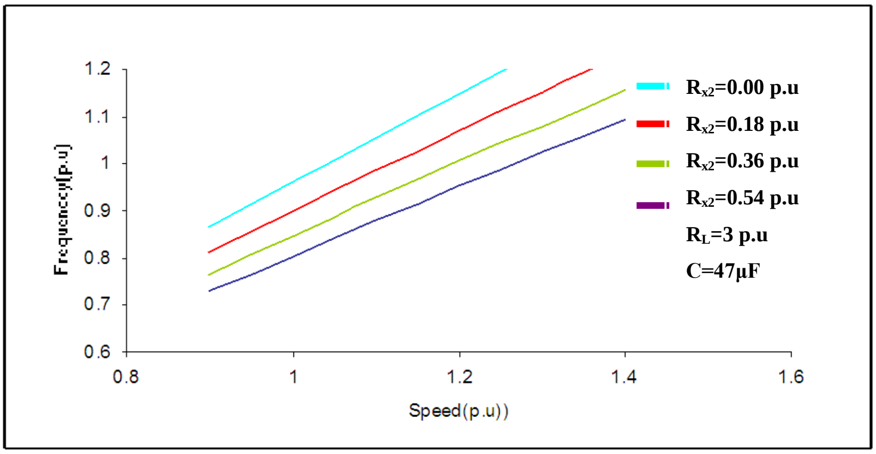


***Graph.4.2.*Stator phase current with respect to per unit speed for various Rotor resistance values.**

For , R_{x2}=0.36 p.u ; C=47µF ; R_L=3p.u

b	**a**	**X_m**	**E_1**	**V_1**	**I_1**	**P_{out}**
0.90	0.7666	2.4069	0.0000	0.0000	0.0000	0.0000
0.95	0.8072	2.1616	0.6407	0.5349	0.3582	0.2861
1.00	0.8475	1.9523	0.8049	0.7095	0.4931	0.5035
1.05	0.8874	1.7723	0.8717	0.8092	0.5828	0.6549
1.10	0.9270	1.6165	0.9235	0.9011	0.6718	0.8119
1.15	0.9661	1.4807	0.9687	0.9914	0.7642	0.9828
1.20	1.0049	1.3617	1.0083	1.0804	0.8601	1.1673
1.25	1.0433	1.2568	1.0431	1.1684	0.9596	1.3652
1.30	1.0812	1.1640	1.0740	1.2555	1.0625	1.5763
1.35	1.1187	1.0815	1.1015	1.3419	1.1690	1.8008
1.40	1.1558	1.0078	1.1260	1.4278	1.2791	2.0386

***Table 4.3.* Results for various speed values at R_{X2}=0.36 (all the values are in p.u)**

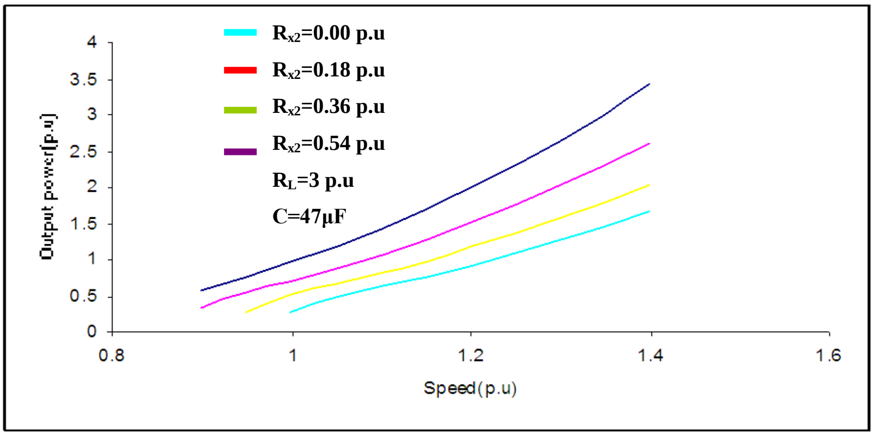


Graph. 4.3. **Per unit frequency with respect to per unit speed for various Rotor resistance values.**

For, R_{x2}=0.54p.u ; C=47µF ; R_L=3 p.u

B	a	X_m	E_1	V_1	I_1	P_{out}
1.00	0.8049	2.1743	0.6266	0.5215	0.3484	0.2720
1.05	0.8425	1.9763	0.7960	0.6971	0.4822	0.4859
1.10	0.8798	1.8048	0.8596	0.7903	0.5653	0.6246
1.15	0.9166	1.6554	0.9105	0.8771	0.6480	0.7692
1.20	0.9530	1.5245	0.9541	0.9611	0.7327	0.9237
1.25	0.9890	1.4090	0.9925	1.0438	0.8201	1.0895
1.30	1.0245	1.3068	1.0265	1.1253	0.9103	1.2662
1.35	1.0596	1.2159	1.0568	1.2057	1.0032	1.4538
1.40	1.0942	1.1348	1.0838	1.2853	1.0988	1.6520

Table 4.4. **Results for various speed values at R_{X2}=0.54 (all the values are in p.u)**



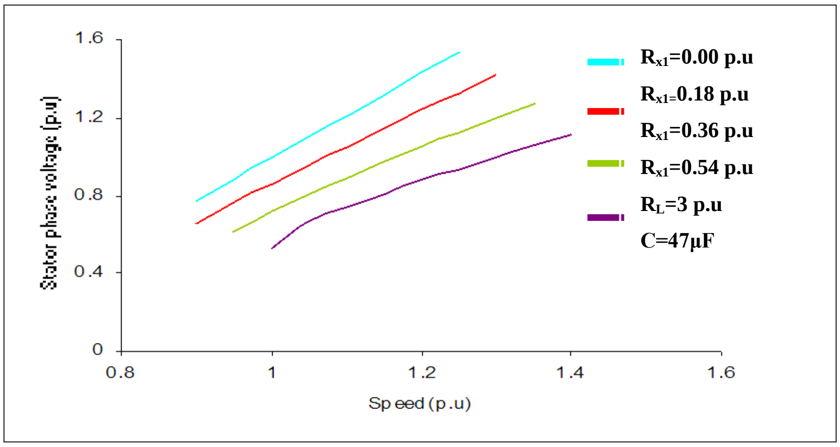
Graph. 4.4. **Per unit Output power with respect to per unit speed for various Rotor resistance values.**

4.2.2. Effects of stator resistance variations

For , R_{x1}=0.00 p.u ; C=47µF ; R_L=3 p.u

b	a	X_m	E_1	V_1	I_1
0.9000	0.8663	1.8645	0.8375	0.7567	0.5348
0.9500	0.9137	1.6671	0.9067	0.8702	0.6414
1.0000	0.9610	1.4988	0.9627	0.9791	0.7515
1.0500	1.0080	1.3542	1.0108	1.0870	0.8676
1.1000	1.0550	1.2290	1.0524	1.1945	0.9901
1.1500	1.1017	1.1200	1.0887	1.3018	1.1193
1.2000	1.1482	1.0246	1.1204	1.4093	1.2553
1.2500	1.1945	0.9406	1.1484	1.5172	1.3985
1.3000	1.2406	0.8663	1.1731	1.6259	1.5491
1.3500	1.2864	0.8004	1.1950	1.7356	1.7073
1.4000	1.3320	0.7417	1.2145	1.8464	1.8734

Table 4.5. **Results for various speed values at R_{X1}=0.00 (all the values are in p.u)**

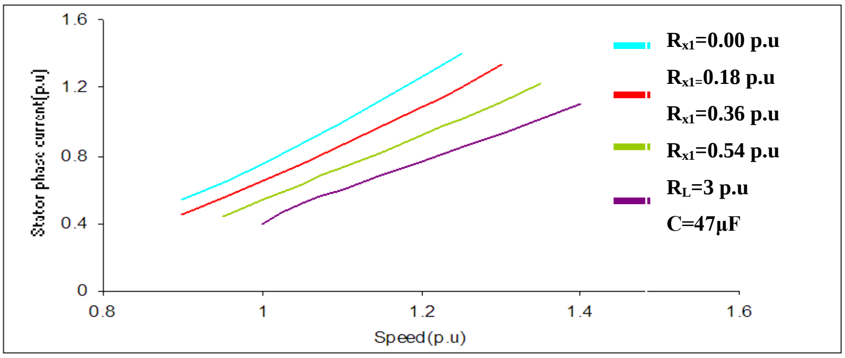


Graph.4.5. **Stator phase voltage with respect to per unit speed for various stator resistance values**

For, R_{x1}=0.18 p.u ; C=47µF ; R_L=3 p.u

b	a	X_m	E_1	V_1	I_1
0.9000	0.8635	2.0729	0.7394	0.6182	0.4358
0.9500	0.9102	1.8658	0.8370	0.7413	0.5447
1.0000	0.9568	1.6897	0.8991	0.8414	0.6435
1.0500	1.0029	1.5370	0.9499	0.9368	0.7446
1.1000	1.0489	1.4060	0.9935	1.0306	0.8502
1.1500	1.0947	1.2921	1.0314	1.1231	0.9605
1.2000	1.1401	1.1926	1.0645	1.2147	1.0755
1.2500	1.1853	1.1053	1.0936	1.3055	1.1952
1.3000	1.2301	1.0283	1.1192	1.3956	1.3198
1.3500	1.2746	0.9603	1.1418	1.4853	1.4492
1.4000	1.3188	0.9000	1.1619	1.5745	1.5834

Table. 4.6. **Results for various speed values at R_{X1}=0.18 (all the values are in p.u)**

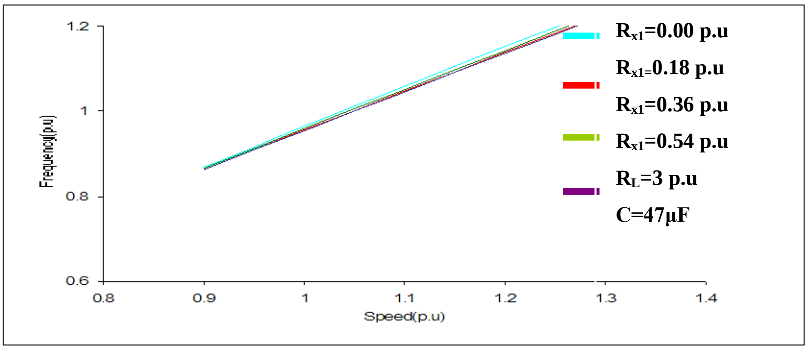


Graph. 4.6. **Stator phase current with respect to per unit speed for various stator resistance values.**

For, R_{x1}=0.36 p.u ; C=47µF ; R_L=3 p.u

B	A	X_m	E_1	V_1	I_1
0.9000	0.8619	2.3320	0.0000	0.0000	0.0000
0.9500	0.9084	2.1153	0.6923	0.5646	0.4142
1.0000	0.9546	1.9316	0.8126	0.6979	0.5328
1.0500	1.0003	1.7736	0.8712	0.7860	0.6234
1.1000	1.0460	1.6379	0.9164	0.8665	0.7131
1.1500	1.0913	1.5204	0.9555	0.9449	0.8059
1.2000	1.1364	1.4183	0.9894	1.0214	0.9017
1.2500	1.1811	1.3292	1.0191	1.0961	1.0005
1.3000	1.2256	1.2512	1.0450	1.1692	1.1022
1.3500	1.2698	1.1829	1.0677	1.2408	1.2066

Table 4.7. **Results for various speed values at R_{X1}=0.36 (all the values are in p.u)**



Graph.4.7. **Per unit frequency with respect to per unit speed for various stator resistance values.**

V. CONCLUSION

In this paper of work the voltage and frequency control of a self excited slip ring induction generator by varying the external rotor resistance have been presented. Steady state modeling, performance and the control characteristic of the SESRIG have been developed from an equivalent circuit analysis. It is shown that with constant load and excitation capacitance, both frequency and the output voltage of the SESRIG can be maintained constant by varying rotor resistance over wide range of speeds without exceeding the specified stator current limit. In future it is planned to develop a suitable technique to vary the external rotor resistance automatically to achieve voltage and frequency control.

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APPENDIX -I

CONSTANTS:

$f_0=(-b*X_C*X_2+X_L*X_C-b*X_L*X_C-b*R_1*R_L-b*X_1*X_C);$
$f_1=(-b*X_2*X_L*X_C-b*X_2*R_1*R_L-b*X_2*X_1*X_C);$
$f_2=(R_L*R_2+X_C*X_2+R_1*R_L+X_1*X_C);$
$f_3=(X_2*X_L*X_C+X_2*R_1*R_L+X_2*X_1*X_C+X_1*R_L*R_2+X_L*R_1*R_2);$
$f_4=(b*X_L*X_2+b*X_1*X_L);$
$f_5=(b*X_1*X_L*X_2);$
$f_6=(-X_L*X_2-X_1*X_L);$
$f_7=(X_1*X_L*X_2);$
$f_8=(-R_L*R_2*X_C);$
$g_0=(-X_C*R_2-R_L*X_C-R_1*X_C);$
$g_1=(-R_2*X_L*X_C-R_1*R_L*R_2-R_2*X_1*X_C-X_2*R_L*X_C-X_2*R_1*X_C);$
$g_2=(-b*X_2*R_L-b*X_1*R_L-b*X_L*R_1);$
$g_3=(-b*X_2*X_1*R_L-b*X2*X_L*R_1);$
$g_4=(X_L*R_2+X_2*R_L+X_1*R_L+X_L*R_1);$
$g_5=(X_L*X_1*R_2+X_2*X_1*R_L+X_2*X_L*R_1);$
$g_6=(b*R_L*X_C+b*R_1*X_C);$
$g_7=(b*X_2*R_L*X_C+b*X_2*R_1*X_C);$

APPENDIX –II

INDUCTION MACHINE PARAMETERS:

Number of phases	=3
Number of poles	=4
Frequency	=50 Hz
Voltage	=380V
Current	=4.5A
Power	=1.8 KW
Connection	=star
Type	=slip-ring
R_1	=0.0597 p.u
X_1	=0.118 p.u
R_2	=0.0982 p.u
X_2	=0.118 p.u