

The influence of iron losses on selecting the minimum excitation capacitance for self-excited induction generator (SEIG) with wind turbine

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ABSTRACT

The capacitance selection of the three-phase self-excited induction generators (SEIG) driven by wind energy is influenced by the iron losses. This paper is dealing with this problem by constructing a steady state model of the generator supplying an induction oil pump. No previous literature studying the requirements of selecting the minimum excitation capacitance under the iron loss impact is found. This work is focusing on: (i) a novel evaluation of the characteristics of the induction generator taking iron loss into account. (ii) the errors caused by neglecting the iron loss. (iii) the importance of including the iron-loss in any accurate analysis. (iv) the errors occurred in the selection of the precise excitation capacitance (C_{exc}) when the iron-loss neglected. Nodal analysis is suggested to describe the study-state performance of the proposed model. A Matlab/simulation is established to validate the proposed model.

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1. INTRODUCTION

The SEIG usage was started at 20th century, at its earlier years till 1960 were its almost disappeared [1]. At the 1970s, the petroleum and gas prices were dramatically increased which is causing a return to the use of induction generators (IG). Using IG in a wind power generation system is having many positive returns in comparison to the conventional synchronous generators. It is simple, robust, dependable, economy, lightweight, long lasting (50 years). IG is suitable for little wind and hydro power plants [2, 3]. The negativity of IG is its low power-factor and poorness in the regulating of frequency and voltage regulation. Connecting IG to a network can contribute 100kw or more [1]. A turbine (regulated and unregulated) driving SEIG to supply a load (static or dynamic) has been thoroughly discussed by many researchers [4-5]. A three-phase induction machine operation studying at a study-state is basically depending on the per-phase equivalent circuit analysis and on either the loop impedance [5-13]. To operate the SEIG a necessary magnetic field is needed to convert the machine shaft's mechanical power to electrical. The needed active power which is generating this magnetic field is externally produced. This is provided by externally reactive source connected permanently to the stator windings of the IG. If IG is externally connected to capacitors, the machine is called SEIG. The engine shaft is rotated by an external force. The residue of magnetic field, with this movement, is inducing a voltage across capacitors, the result is a current passing through a parallel circuit. This current is reinforcing the magnetic field and an excitation is increasingly building up. The SEIG is usually used in a minor power-plant because of the capacitors high cost and a maintenance needs [5].

None of the [7] and [14-16] is considering the notable iron losses effect in the d-q axis model and steady state operation of SEIG. For the more accuracy of the predicted behavior of the SEIG, there is a great need to take this effects in consideration especially when the wind energy is driving the machine. A model of enhanced IG which is taking the iron losses in consideration is suggested in this paper. The losses are a function of air-gap flux and a stator frequency. The machine performance analysis is done at various operating conditions. Most times, the effects of the iron-losses are excluded for simplicity which will resulting in a non-accurate analysis. In fact, the iron-losses effect is having a non-negligible impact on the SEIG operation.

Problem Statement

Power production using wind-turbine is depending on the speed of the wind. The excitation capacitance of the SEIG driven by a wind turbine is an essential part and needs to be accurately calculated. Many papers were published regarding discussing this issue. Most of them are neglecting an important factor in the calculations. The iron losses is having a noticeable effect on choosing the excitation capacitance and must not be neglected for a highly accurate calculation. This work is studying and analyzing the mathematical model of the SEIG system using MatLab software which is tacking the iron losses effects into consideration especially at low wind speeds.

Proposed System

The projected power generating system is consisting of SEIG which is actuated by a wind turbine. The SEIG is linked to an exciting capacitor externally. This system is feeding a 1.5 KW induction oil pump load as in Figure 1. The used SEIG's parameters was exactly measured by testing the induction generator when using it as a motor [17-19].

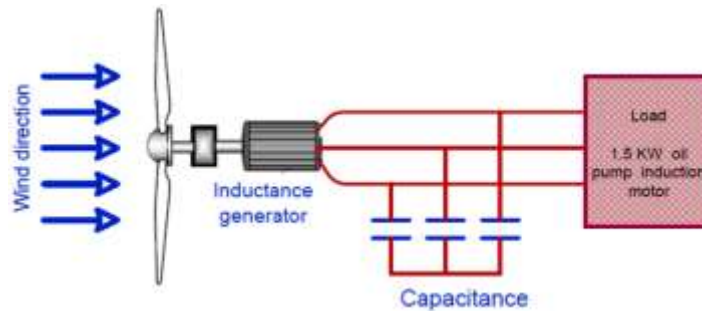


Figure 1. Model of SEIG driven by wind turbine

2. MATHEMATICAL ANALYSIS OF SEIG WITH IRON LOSSES

In order to find the required capacitance value, nodal analysis is used which does not need to calculate X_c as in loop technique. The frequency due to the resultant equation $Y_t = 0$ is deduced from the equation real part which is used in the imaginary part to calculate the capacitance. The per-phase equivalent Circuit of (SEIG) with equivalent iron-loss resistance is shown in Figure 2 and the nodal admittance equations are found from the equivalent circuit in Figure 2.

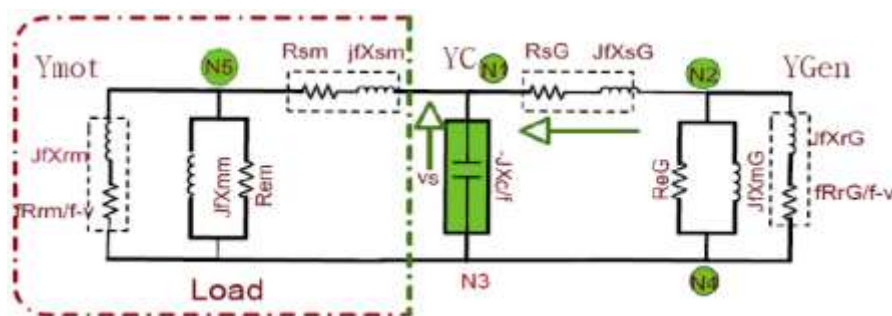


Figure 2. SEIG with equivalent iron loss resistance

Y_{Gen} , Y_{mot} have been formed as follows:

$$Y_{Gen} = \frac{1}{R_{SG} + jX_{SG} + [(R_{eG} // jX_{mG}) // (jX_{rG} + \frac{R_{rG}}{f-v})]} \quad (1)$$

$$Y_{mot} = \frac{1}{R_{Sm} + jX_{Sm} + [(R_{em} // jX_{mm}) // (jX_{rm} + \frac{R_{rm}}{f-v})]} \quad (2)$$

And:

$$Y_C = \frac{1}{-jX_C} \quad (3)$$

At node “N1” in Figure 2, the relation between IM , IG and IC can be written as:

$$I_M + I_C - I_G = 0 \quad (4)$$

The above equation can be expressed as follows:

$$V(Y_M + Y_G + Y_C) = 0 \quad (5)$$

The real as well as imaginary parts of the admittance are zeros at steady-state excitation $V_s \neq 0$:

$$(Y_M + Y_G + Y_C) = 0 \quad (6)$$

Equation 5 can be separated for real and imaginary parts as follows:

$$\begin{cases} [R_e (Y_M + Y_G + Y_C) = 0] \\ [I_m (Y_M + Y_G + Y_C) = 0] \end{cases} \quad (7)$$

During steady-state situation $I \neq 0$. As a result, $Y = 0$, equating real and imaginary parts of Y to zeroes. The real part yields

$$P(X_m, F) = (A_1 X_m + A_2) F^3 + (A_3 X_m + A_4) F^2 + (A_5 X_m + A_6) F + (A_7 X_m + A_8) \quad (8)$$

Coefficients A1 to A8 can be determined as shown in Appendix 1. X_m is chosen equal to X_{msat} and (7) is an equation with unknown X_C . Other equations are obtained and trial and error procedure is followed to determine relation between X_C and X_m . When (7) is rearranged versus X_C , the following equation is obtained:

$$- a_1 F^3 + a_2 F^2 + (a_3 X_c + a_4) F - a_5 X_c = 0 \quad (9)$$

where a1 to a5 are calculated as shown in Appendix 1. From (8):

$$X_c = \frac{a_1 F^3 - a_2 F^2 - a_4 F}{a_3 F - a_5} \quad (10)$$

If the imaginary part of (6) is put equal to zero, then:

$$Q(X_m, F) = (B_1 X_m + B_2) F^4 + (B_3 X_m + B_4) F^3 + (B_5 X_m + B_6) F^2 + (B_7 X_m + B_8) F + B_9 \quad (11)$$

Coefficients of X_m are calculated as reported in Appendix 1. Eqn. (10) can be written versus X_C as follows:

$$- b_1 F^4 + b_2 F^3 + (b_3 X_c + b_4) F^2 - (b_5 X_c + b_6) F - b_7 X_c = 0 \quad (12)$$

$$X_c = \frac{b_1 F^4 - b_2 F^3 - b_4 F^2 + b_6 F}{b_3 F^2 - b_5 F - b_7} \quad (13)$$

The Constants from a1 to a5 as well as b1 to b7 are calculated as shown in Appendix 1. The following equation is resulted from (9) and (12).

$$\frac{a_1 F^3 - a_2 F^2 - a_4 F}{a_3 F - a_5} = \frac{b_1 F^4 - b_2 F^3 - b_4 F^2 + b_6 F}{b_3 F^2 - b_5 F - b_7} \quad (14)$$

After a tedious elaboration, (13) can be reduced to the 4th order equation:

$$C_0 F^4 + C_1 F^3 + C_2 F^2 + C_3 F + C_4 = 0 \quad (15)$$

The Coefficients C_n , $n=0, 1, 2, 3$ and 4 are given in Appendix I. It is clear that these coefficients do not involve X_c . Solving (14) helps effectively in calculating the operating frequency. The solution of (14) has four roots (*two real and two imaginary*); largest positive real root gives the minimum capacitance C_{min} [21-23].

Moreover, smaller real root gives the maximum capacitance. The absence of positive real root means there is no self-excitation. Value of operating frequency it can be put in (9) or (12) in order to evaluate X_c . Finally the capacitance Without Iron Losses is obtained as follows:

$$C_{min} = \frac{1}{2\pi} \left[\frac{X_{mot} * F}{Z_3} + \frac{Z_4}{Z_1^2 + Z_2^2} \right] \quad (16)$$

The capacitance With Iron Losses is obtained as follows:

$$C_{min-new} = \frac{1}{2\pi} \left[\frac{X_{mot} * F}{W_3} + \frac{W_4}{W_1^2 + W_2^2} \right] \quad (17)$$

The coefficients Z_1, Z_2, Z_3 and Z_4 of (15) and coefficients W_1, W_2, W_3 and W_4 are shown in Appendix I. In short, the excitation capacitance is measured by using any program computer.

3. THE CHARACTERISTICS OF SEIG WITH IRON LOSSES (REG)

The accuracy of the machine's parameters represents one of the main design factors. Using induction generator as motor, during conducting tests, helps effectively in calculating the parameters of SEIG. In clear, the main two tests are open and short circuit tests. The parameters which are calculated from these tests are $L_s=L_r=10.286\text{mH}$, $L_m=252.5\text{mH}$, $R_c=603.3 \Omega$, $R_s=2.37\Omega$, $R_r=1.53\Omega$. These tests had been performed at rated values of voltage and frequency. Moreover, this data is useful for wide motoring applications. However, the deviation of voltage with L_m and R_{eG} represents one of the factors should be taken into consideration in SEIG applications.

The accuracy of the parameters such as the output power, induced electromagnetic torque, and dynamic currents support largely in design applications. To calculate magnetizing inductance practically, induction machine has to be operated at synchronous speed and it is measured when applied voltage starts varying. Figure 3 demonstrates the connection between saturated inductance (L_m) with phase voltage.

Saturated inductance (L_m) increases gradually from lower value at the beginning and continues increasing up to maximum value then decreases at the end. This property of L_m is useful for the voltage stability as well as in determining the smallest generated voltage during self-excitation. The variation of R_c increases with increasing generated voltage. Moreover, neglecting R_c increases analysis error especially during the equality between the per-unit value of R_c and X_m . Moreover, polynomial equation below shows magnetizing inductance (L_m) with phase voltage at 50Hz [24, 25].

$$L_m = 2E-13V^6 - 1E-10V^5 + 5E-08V^4 - 7E-06V^3 + 0.0004V^2 - 0.0058V + 0.2266 \quad (18)$$

$$L_m = -0.0783\text{Im}^6 + 0.8477\text{Im}^5 - 3.6608\text{Im}^4 + 8.0005\text{Im}^3 - 9.1999\text{Im}^2 + 5.0953\text{Im} - 0.6177 \quad (19)$$

The interpretation of the curve in Figure 3 as follows. Between point O and N is the unstable area. If the self-induction generator (SEIG) starts in this area, a slight decrease in speed will lead to a decrease in voltage and this will lead to a decrease in L_m , which in turn leads to a decrease in voltage and eventually the voltage will collapse to zero. If the speed increases slowly and sometimes without zero acceleration so that the operating point remains in the area between O and N, there will be no self-excitation even at high speed. When wind speed increases with this characteristic, there is the possibility that there will be no self-excitation.

For the purpose of solving this problem, the capacitors must be connected when the speed reaches the set-point. This is because the built-up of the voltages requires passage in the transient state of the specified area between O and N. While the area between points N and P represents the stable operating

area. but when the speed is decrease leads to decrease voltages also, while there is an increase in the value of the inductance (L_m), this leads to have a new steady state operating point at lower voltage. The magnetizing inductance with magnetizing current at 50Hz and the polynomial equation used in this investigation in Figure 4.

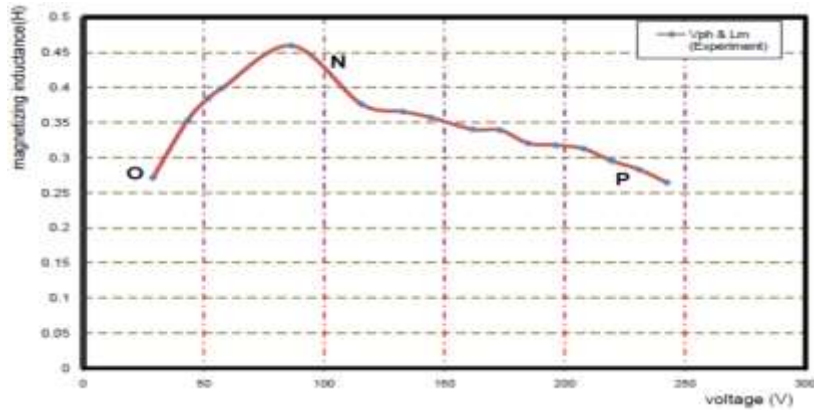


Figure 3. Variation of magnetising inductance with phase voltage at 50Hz

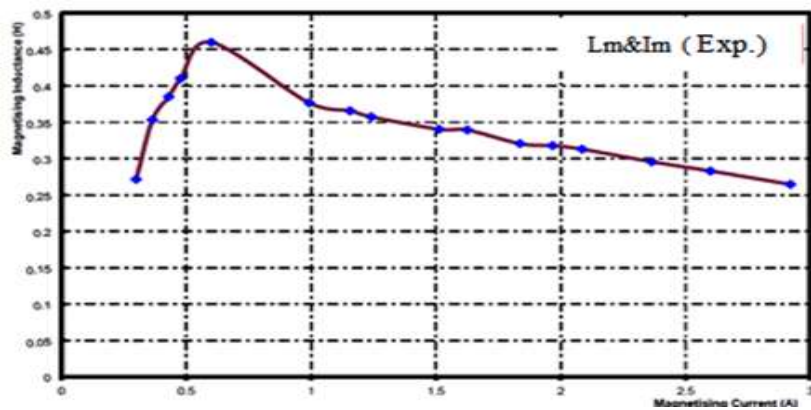


Figure 4. L_m as a function of the magnetizing current

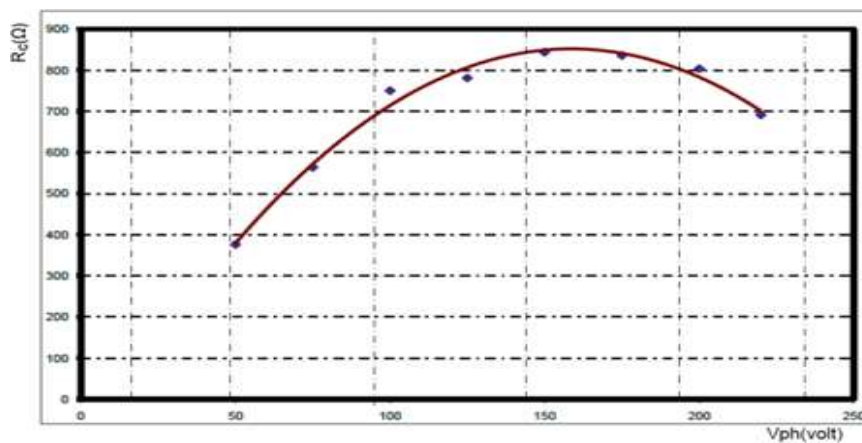


Figure 5. Variation of R_{eG} with phase voltage

The variation of R_{eG} with phase voltage is shown in Figure 5. Grantham [9] was reported the value of R_{eG} for IM. The variation in the R_{eG} is formulated according to the following curve.

$$R_{eG} = -0.04V_{ph}^2 + 12.72 V_{ph} \tag{20}$$

Where,

V_{ph}: rms phase voltage across RC. V_{ph} for generator can be estimated by summation the voltage across the impedance of the machine stator and voltage appearance on the terminals of its. K_d and K_q in (21) considered the initial induced voltages along the d-axis and q-axis respectively due to the residual magnetic flow in the core, the primary voltages (V_{cqo} and V_{cdo}) are on the capacitors.

$$\begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} L_{SG} + \left(L_{SG} + \frac{R_{eg}L_{mg}P}{R_{eg}+L_{mg}P}\right)P + \frac{1}{PC} & 0 & 0 & 0 \\ 0 & w_r \left(L_{rg} + \frac{R_{eg}L_{mg}P}{R_{eg}+L_{mg}P}\right) & \frac{R_{eg}L_{mg}P}{R_{eg}+L_{mg}P} & \frac{R_{eg}L_{mg}P}{R_{eg}+L_{mg}P} \\ \frac{R_{eg}L_{mg}P}{R_{eg}+L_{mg}P} & \frac{-w_r R_{eg}L_{mg}P}{R_{eg}+L_{mg}P} & 0 & 0 \\ \frac{w_r R_{eg}L_{mg}P}{R_{eg}+L_{mg}P} & \frac{R_{eg}L_{mg}P}{R_{eg}+L_{mg}P} & R_{rg} + \left(L_{rg} + \frac{R_{eg}L_{mg}P}{R_{eg}+L_{mg}P}\right)P & w_r \left(L_{rg} + \frac{R_{eg}L_{mg}P}{R_{eg}+L_{mg}P}\right)P \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix} + \begin{bmatrix} V_{cdo} \\ K_q \\ K_d \end{bmatrix} \tag{21}$$

The residual magnetic remnants in the rotor and charge due to from capacitance initial value are not take in the considered because they will be cancelled from two sides of (21) these initial values can be obtain from derivation this equation [9].

4. APPLICATIONS AND RESULTS

The results using these technique must be close to (15, 16, and 17) Table 1 shows the results obtained using these method. Figure 6 (a, b) minimum capacitance with load reactance at different speeds (28rpm, 56rpm, 84rpm and 112rpm) (a- without iron losses b-With iron losses). It is seen that the capacitance increases rapidly with increases in load reactance and then decrease. Also It is seen the induction generator fails to excite irrespective of the value of excitation capacitance at speeds (28rpm and 56rpm).

Table 1. Frequency &Speed Variation at base speed is 1400rpm

Speed (pu)	Without Iron Losses		Capacitance (µF)	With Iron Losses		Capacitance (µF)
	Roots	Roots		Roots	Roots	
1	0.9997 0.0002 + 0.0491i	0.6194 0.0002 - 0.0491i	47.6249	0.9995 0.0002 + 0.049	0.6219 0.0002 - 0.0491i	52.5269
0.9	0.8823 + 0.9938i 0.8854	0.8223 - 0.9938i 0.5910	106.3582	0.8222 + 0.9940i 0.8818	0.8222 - 0.9940i 0.5954	113.4791
0.8	0.7444 + 0.9507i 0.7859	0.7444 - 0.9507i 0.5181	114.3463	0.719 + 0.9341i 0.7826	0.719 - 0.9341i 0.5219	123.7555
0.7	0.7446 + 0.9610i 0.6858	0.7446 - 0.9610i 0.4471	117.6768	0.728 + 0.9471i 0.6824	0.728 - 0.9471i 0.4508	128.3868
0.6	0.727 + 0.9685i 0.5862	0.727 - 0.9685i 0.3776	120.0382	0.712 + 0.9557i 0.5828	0.712 - 0.9557i 0.3809	132.4273
0.5	0.687 + 0.9774i 0.4869	0.687 - 0.9774i 0.3098	121.1769	0.678 + 0.9665i 0.4836	0.678 - 0.9665i 0.3127	135.6226
0.4	0.621 + 0.9851i 0.3882	0.621 - 0.9851i 0.2440	122.6575	0.616 + 0.9768i 0.3852	0.616 - 0.9768i 0.2464	139.7903
0.3	0.524 + 0.9899i 0.2900	0.524 - 0.9899i 0.1803	128.6802	0.523 + 0.9849i 0.2873	0.523 - 0.9849i 0.1823	150.4189
0.2	0.0389 + 0.9880i 0.1922	0.0389 - 0.9880i 0.1188	152.6214	0.0390 + 0.9859i 0.1900	0.0390 - 0.9859i 0.1205	184.2516
0.1	0.0214 + 0.9748i 0.0944	0.0214 - 0.9748i 0.0598	259.6760	0.0215 + 0.9749i 0.0924	0.0215 - 0.9749i 0.0615	325.0065
0.09	0.0096 + 0.4940i 0.0839	0.0096 - 0.4940i 0.0531	389.3625	0.0098 + 0.4889i 0.0816	0.0098 - 0.4889i 0.0549	467.0672
0.08	0.0093 + 0.5302i 0.0741	0.0093 - 0.5302i 0.0476	404.2504	0.0095 + 0.5279i 0.0717	0.0095 - 0.5279i 0.0495	491.4755
0.07	0.0089 + 0.5735i 0.0642	0.0089 - 0.5735i 0.0422	430.6683	0.0091 + 0.5724i 0.0616	0.0091 - 0.5724i 0.0444	531.1832
0.06	0.0085 + 0.6211i 0.054	0.0085 - 0.6211i 0.0371	476.4450	0.0087 + 0.6220i 0.0510	0.0087 - 0.6220i 0.0399	594.8757
0.05	0.0079 + 0.6724i 0.0437	0.0079 - 0.6724i 0.0323	550.8193	0.0081 + 0.6779i 0.0378 + 0.0024i	0.0081 - 0.6779i 0.0378 - 0.0024i	No excitation
0.04	0.0070 + 0.7272i 0.0304 + 0.0006i	0.0070 - 0.7272i 0.0304 - 0.0006i	No excitation	0.0065 + 0.6781i 0.0303 + 0.0060i	0.0065 - 0.6781i 0.0303 - 0.0060i	No excitation

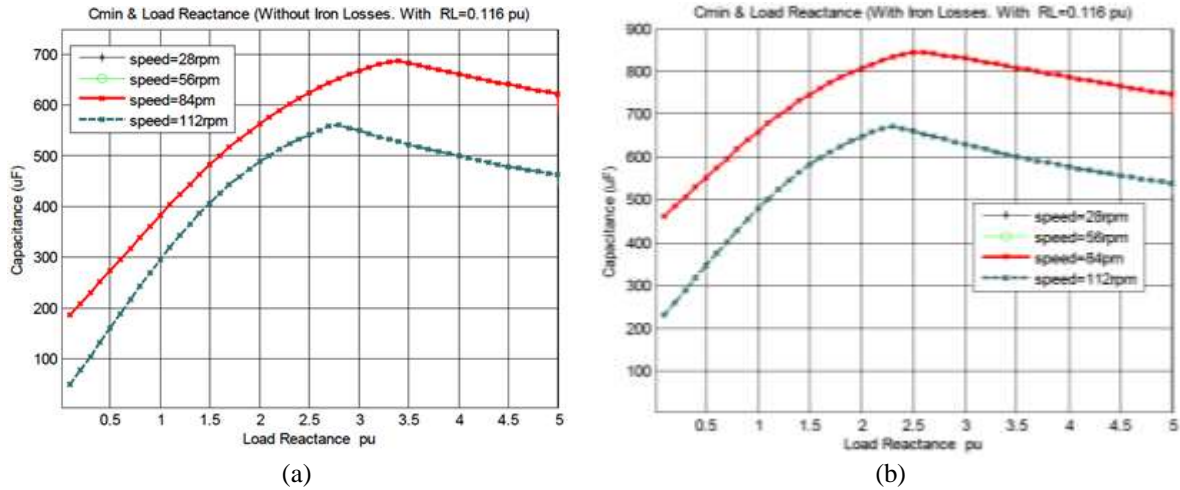


Figure 6. (a) C_{min} and load reactance (RL=0.116pu) with different speed, (b) C_{min} and load reactance (RL=0.116pu) with different speed

Figure 7 (a, b) shows the variation minimum capacitance with load Resistance at different speeds (28rpm, 56rpm, 84rpm and 112rpm) (a- without iron losses b-With iron losses). It is seen that the capacitance decrease rapidly with increases in load Resistance. also It is seen the induction generator fails to excite irrespective of the value of excitation capacitance at speeds (28rpm and 56rpm without iron losses). While with iron losses there will not be any excitation Below the speed 112rpm.

Figure 8 (a, b) minimum capacitance with load reactance at different speeds (70rpm, 140rpm, 210rpm and 280rpm) (a- without iron losses b-With iron losses). It is seen no exaction with iron losses at speeds 70rpm while the exaction occur when iron losses neglected at the same speed .

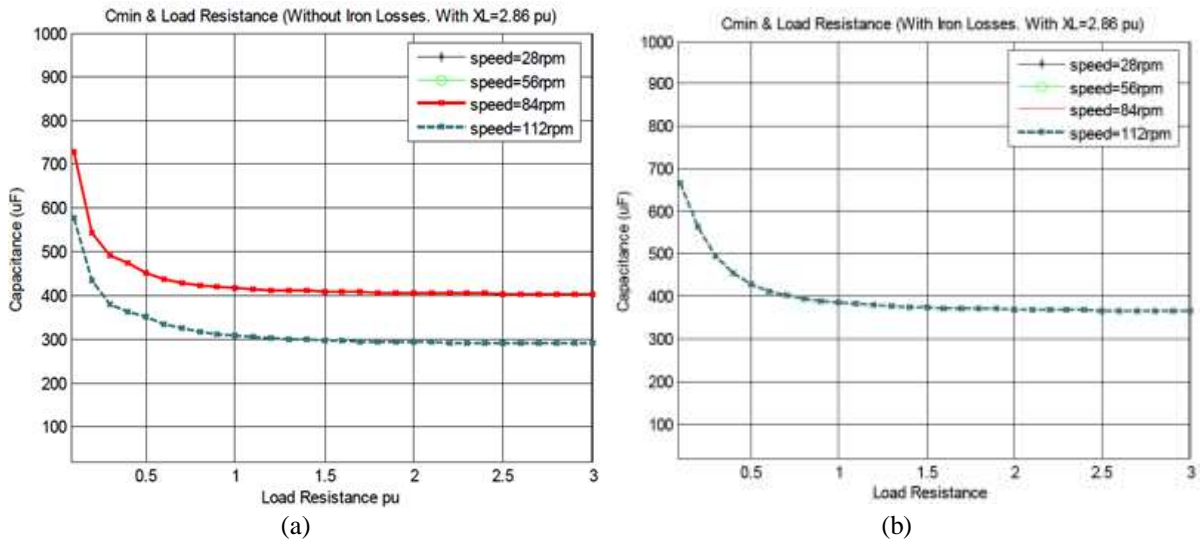


Figure 7. (a) C_{min} and load resistance (XL=2.86pu) (28-112)rpm , (b) C_{min} and load resistance (XL=2.86pu) (28-112)rpm

Figure 9 (a, b) relation between minimum capacitance with load reactance at different speeds It is observed the value of minimum capacitance at minimum speed(140 rpm) is much smaller than the value at higher speed. Also, It is observed minimum capacitance with iron losses is higher than without iron losses at the same load reactance (0.1pu) and speed (140rpm). We see from both cases in the figures the minimum excitation capacitance value with iron loss is strongly influenced when the speed decreased.

Figure 10 (a, b) observe the difference values of capacitance required with load resistance when the Load reactance 2.86pu varies for different values of rotor speed. It is noted that increasing in load Resistance requires decreasing capacitance value. Also It is observed that actual value of minimum exaction capacitance for the given when iron losses neglected which is much smaller than the value obtained with iron losses included.

By comparing the results obtained after taking into consideration the effect of iron losses observed in the Table 1, and without consideration in [10-13]. They have ignored the iron losses in calculating the minimum capacitance, this is because they consider the effect is small. But in this paper, we demonstrate that the influence of iron losses is little only at a rated speed of generators. While at low wind speeds, this effect becomes high. This is meaning the influence of iron losses on determining minimum capacitance increases gradually with wind speed decreases.

Figure 11 shows the percentage difference of minimum excitation capacitance obtained with and without a core-loss resistance varies with different values of speed (Load- Induction Pump Motor). The average difference of capacitance reaches to 13.48%.

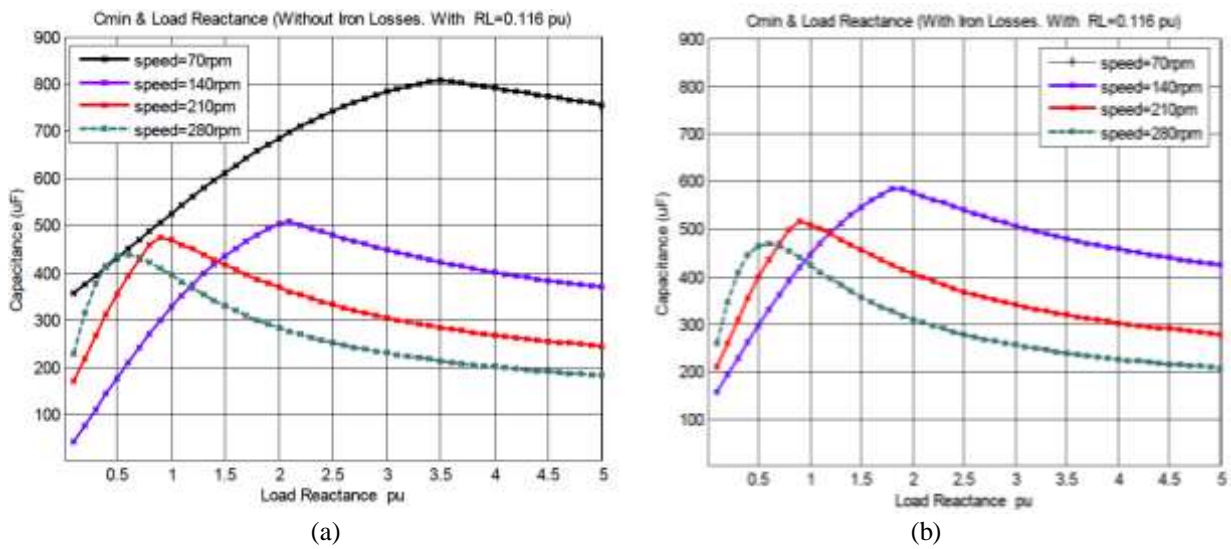


Figure 8. (a) C_{min} and load reactance (70-280)rpm, (b). C_{min} and load reactance (70-280)rpm

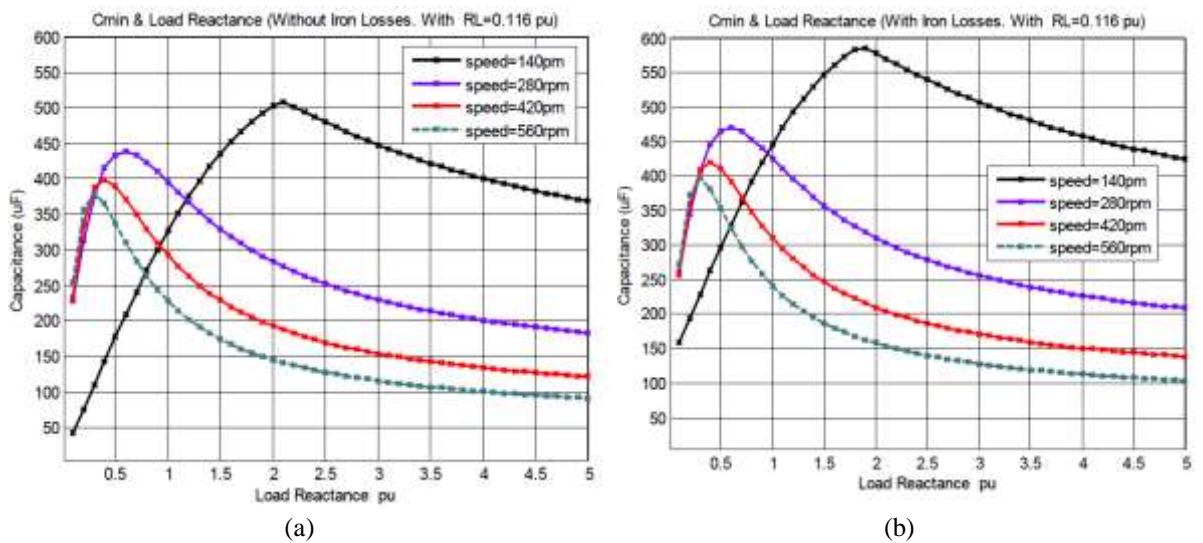


Figure 9. (a) C_{min} and load reactance (RL=0.116pu), (b). C_{min} and load reactance(RL=0.116pu)

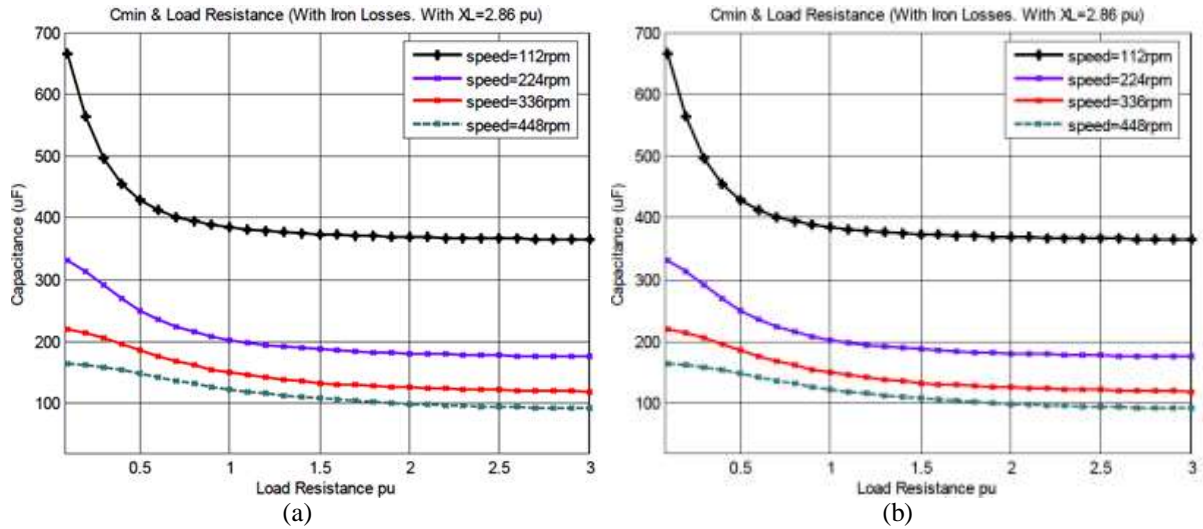


Figure 10. (a) C_{min} and load resistance ($X_L=2.86pu$) (112-448)rpm, (b), C_{min} and load resistance ($X_L=2.86pu$) (112-448)rpm

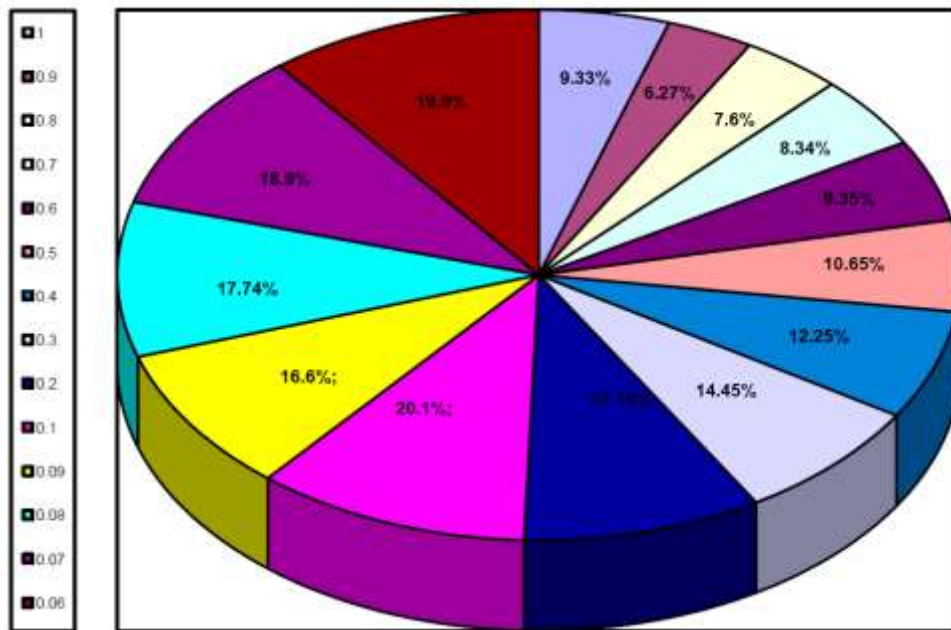


Figure 11. Minimum excitation capacitance with Induction Pump Motor(load)With different speed

5. CONCLUSION

Self excitation in induction machine depends on machine parameters like speed, load and excitation capacitance. If the suitable value of capacitance is selected, the generator will operate in self-excited mode. This paper has described influence the core loss resistance on the choice of minimum excitation capacitance required (C_{min}), this effect is mentioned in the different of an excitation capacitor on the steady state behavior of the SEIG. The presented comparisons between the calculated capacitance with the core loss resistance and them without it prove consistent effect of this parameter on the accuracy of the determined results. The degradation of the accuracy performances due to the neglected core loss resistance leads, revilement, to false results and a bed interpretation and consequently ironed contribution for the drawbacks of the studied minimum excitation capacitance for self excited induction generator.

APPENDIX

Table 2. Induction motor parameters

Rated Power 1.5 kw	
Voltage	380V- Y
Frequency	50Hz
Pair Pole	2
Rated Speed	1440 rpm
Stator Resistance	4.85 Ω
Rotor Resistance	3.805 Ω
Stator Inductance	274 mH
Rotor Inductance	274 mH
Mutual Inductance	258 mH
Moment of Inertia	0.031 Kg.m2

Table 3. Induction Generator Parameters

Rated Power 3 kw	
Voltage	420 V-Y
Frequency	50Hz
Pair Pole	2
Rated Speed	1420 rpm
Stator Resistance	2.37 Ω
Rotor Resistance	1.53 Ω
Stator Inductance	10.28 mH
Rotor Inductance	10.28 mH
Mutual Inductance	252.32 mH
Core loss	603.3

$$A1 = [R_{\text{mot}} (X_{\text{rg}} + X_{\text{s}}) + X_{\text{mot}} (R_{\text{rg}} + R_{\text{s}})],$$

$$A3 = v[R_{\text{mot}} (X_{\text{s}} + X_{\text{rg}}) + R_{\text{s}} X_{\text{mot}}],$$

$$A5 = X_{\text{c}} (R_{\text{rg}} + R_{\text{mot}} + R_{\text{s}}),$$

$$A7 = -v X_{\text{c}} (R_{\text{mot}} + R_{\text{s}}),$$

$$a1 = X_{\text{mot}} [R_{\text{rg}} (X_{\text{mg}} + X_{\text{s}}) + R_{\text{s}} (X_{\text{mg}} + X_{\text{rg}})] + R_{\text{mot}} (X_{\text{mg}} + X_{\text{rg}}) [X_{\text{s}} + (X_{\text{rg}} X_{\text{mg}} / X_{\text{mg}} + X_{\text{rg}})]$$

$$a2 = v (X_{\text{mg}} + X_{\text{rg}}) + [R_{\text{mot}} (X_{\text{s}} + (X_{\text{rg}} X_{\text{mg}} / X_{\text{mg}} + X_{\text{rg}})) + R_{\text{s}} X_{\text{mot}}]$$

$$a3 = R_{\text{rg}} (X_{\text{mg}} + X_{\text{rg}} + X_{\text{s}}) + R_{\text{mot}} (X_{\text{mg}} + X_{\text{rg}}) + R_{\text{s}} (X_{\text{rg}} + X_{\text{mg}})$$

$$a4 = R_{\text{s}} R_{\text{rg}} R_{\text{mot}},$$

$$b1 = X_{\text{mot}} (X_{\text{rg}} X_{\text{mg}} + X_{\text{s}} X_{\text{mg}} + X_{\text{rg}} X_{\text{s}}),$$

$$b3 = (X_{\text{rg}} + X_{\text{mg}}) (X_{\text{rg}} + X_{\text{s}}) + X_{\text{rg}} X_{\text{mg}},$$

$$b5 = v [(X_{\text{rg}} + X_{\text{mg}}) (X_{\text{rg}} + X_{\text{s}}) + X_{\text{rg}} X_{\text{mg}}],$$

$$b7 = R_{\text{rg}} (R_{\text{mot}} + R_{\text{s}})$$

$$A2 = [R_{\text{s}} X_{\text{mot}} X_{\text{rg}} + R_{\text{rg}} X_{\text{mot}} X_{\text{s}} + R_{\text{mot}} X_{\text{s}} X_{\text{rg}}]$$

$$A4 = v [X_{\text{rg}} (R_{\text{s}} X_{\text{mot}} + R_{\text{mot}} X_{\text{s}})]$$

$$A6 = X_{\text{c}} X_{\text{rg}} (R_{\text{mot}} + R_{\text{s}}) + X_{\text{c}} R_{\text{rg}} (X_{\text{mot}} + X_{\text{s}})$$

$$A8 = -v X_{\text{c}} X_{\text{rg}} (R_{\text{mot}} + R_{\text{s}})$$

$$a5 = v (X_{\text{mg}} + X_{\text{rg}}) [R_{\text{mot}} + R_{\text{s}}]$$

$$b2 = v [X_{\text{mot}} (X_{\text{rg}} X_{\text{mg}} + X_{\text{s}} X_{\text{mg}} + X_{\text{rg}} X_{\text{s}})]$$

$$b4 = R_{\text{mot}} (R_{\text{rg}} + R_{\text{s}}) (X_{\text{rg}} + X_{\text{mg}}) + R_{\text{rg}} R_{\text{s}} X_{\text{mot}}$$

$$b6 = v R_{\text{mot}} R_{\text{s}} (X_{\text{rg}} + X_{\text{mg}})$$

Without Iron Losses

$$R_{\text{mot}} = R_{\text{rm}} + \frac{F(F - V)X_{\text{MM}}^2 R_{\text{rm}}}{R_{\text{rm}}^2 + (X_{\text{rm}} + X_{\text{MM}})^2 + (F - V)^2}$$

$$X_{\text{mot}} = F X_{\text{sm}} + \frac{F X_{\text{sm}} ((F - V)^2 X_{\text{rm}} (X_{\text{MM}} + X_{\text{rm}}) + R_{\text{rm}}^2)}{R_{\text{rm}}^2 + (X_{\text{rm}} + X_{\text{MM}})^2 + (F - V)^2}$$

$$L1 = X_{\text{sg}} * (X_{\text{rg}} + X_{\text{mg}}) + X_{\text{rg}} * X_{\text{mg}},$$

$$L2 = X_{\text{rg}} + X_{\text{mg}},$$

$$L3 = X_{\text{sg}} + X_{\text{mg}}$$

$$C0 = (R_{\text{rg}}^2 + L2^2 * v^2) * R_{\text{mot}} * R_{\text{sg}} * (R_{\text{mot}} + R_{\text{s}}),$$

$$C1 = R_{\text{mot}}^2 * R_{\text{rg}} * v * (L1 - L2 * L3) - 2 * v * R_{\text{mot}} * R_{\text{sg}} L2^2 (R_{\text{sg}} + R_{\text{mot}})$$

$$R_{\text{mot}}$$

$$C2 = R_{\text{mot}}^2 (R_{\text{rg}} L2^2 - R_{\text{rg}} L1 + R_{\text{rg}} L2 L3 + X_{\text{mot}}^2 R_{\text{sg}} (R_{\text{rg}}^2 + L2^2 v^2)) + 2 * R_{\text{mot}} R_{\text{rg}} R_{\text{sg}} (L2 L3 - L1) + R_{\text{mot}} (L2^2 v^2 + R_{\text{rg}}^2 L3 + R_{\text{sg}}^2 L2^2)$$

$$C3 = X_{\text{mot}}^2 R_{\text{rg}} v (L1 - L2 L3) - 2v (X_{\text{mot}}^2 R_{\text{sg}} L2^2 + R_{\text{mot}} L2^2)$$

$$C4 = X_{\text{mot}}^2 R_{\text{rg}} (L2 L3 - L1) + X_{\text{mot}}^2 R_{\text{sg}} L2^2 + R_{\text{mot}} L2^2$$

$$Z1 = R_{\text{sg}} R_{\text{rg}} - F * (F - V) * (X_{\text{sg}} * (X_{\text{rg}} + X_{\text{mg}}) + X_{\text{rg}} * X_{\text{mg}}),$$

$$Z2 = R_{\text{sg}} F (X_{\text{sg}} + X_{\text{mg}}) + R_{\text{rg}} (F - V) (X_{\text{rg}} + X_{\text{mg}})$$

$$Z3 = R_{\text{mot}}^2 + X_{\text{mot}}^2 F^2$$

$$Z4 = R_{\text{rg}} * M2 - (X_{\text{rg}} + X_{\text{mg}}) * F (F - V) * M1$$

With**Iron Losses**

$$X_{\text{mg new}} = \frac{X_{\text{mG}} * R_{\text{eG}}}{X_{\text{mG}} + R_{\text{eG}}}$$

$$L1 = X_{\text{sg}} * (X_{\text{rg}} + X_{\text{mg new}}) + X_{\text{rg}} * X_{\text{mg new}},$$

$$L2 = X_{\text{rg}} + X_{\text{mg new}},$$

$$L3 = X_{\text{sg}} + X_{\text{mg new}}$$

$$C_0 = (R_{rg}^2 + L_2^2 v^2) * R_{mot} * R_{sg} * (R_{mot} + R_{sg}),$$

$$+ R_{mot}$$

$$C_1 = R_{mot}^2 * R_{rg} * v * (L_1 - L_2 * L_3) - 2 * v * R_{mot} * R_{sg} L_2^2 (R_{sg}$$

$$+ R_{mot})$$

$$C_2 = R_{mot}^2 (R_{rg} L_2^2 - R_{rg} L_1 + R_{rg} L_2 L_3 + X_{mot}^2 R_{sg} (R_{rg}^2 + L_2^2 v^2)) + 2 * R_{mot} R_{rg} R_{sg} (L_2 L_3 - L_1) + R_{mot} (L_1^2 v^2 + R_{rg}^2 L_3 + R_{sg}^2 L_2^2)$$

$$C_3 = X_{mot}^2 R_{rg} v (L_1 - L_2 L_3) - 2 v (X_{mot}^2 R_{sg} L_2^2 + R_{mot} L_1^2) \quad C_4 = X_{mot}^2 R_{rg} (L_2 L_3 - L_1) + X_{mot}^2 R_{sg} L_2^2 + R_{mot} L_1^2$$

$$W_1 = R_{sg} R_{rg} F * (F - V) * (X_{sg} * (X_{rg} + X_{mg-new}) + X_{rg} * X_{mg-new}), \quad W_2 = R_{sg} F (X_{sg} + X_{mg-new}) + R_{rg} (F - V) (X_{rg} + X_{mg})$$

$$W_3 = R_{mot}^2 + X_{mot}^2 F^2$$

$$W_4 = R_{rg} * M_2 - (X_{rg} + X_{mg-new}) * F (F - V) * M_1$$

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