ANALYSIS ON THE EFFECT OF DYNAMIC MUTUAL INDUCTANCE IN VOLTAGE BUILD-UP OF A STAND-ALONE BRUSHLESS ASYNCHRONOUS GENERATOR

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Abstract— **This paper presents the effect of magnetizing inductance in self-excitation and also finds that speed too plays an important role necessary to initiate and to sustain the self excitation process in an isolated three phase induction generator for a given capacitance value and load. During self excitation the variation in the value of magnetizing inductance, due to saturation, is the main factor that stabilizes the growing transient of generated voltage and then to continue to oscillate at a particular frequency and voltage in the steady state. Normally attention is given to the value of magnetizing inductance around the rated voltage for motoring application, but for stand-alone brushless asynchronous generator, the value of magnetizing inductance varies, due to saturation, as the generated voltage grows. The variation of magnetizing inductance, increasing at lower voltage and then decreasing at higher voltage until it reaches the rated voltage, and its effect on self-excitation is discussed in this paper. Also the transients of active and reactive power transfer between the capacitor bank and induction machine is shown along with the developed electromagnetic torque. The simulation results from MATLAB code also are shown.**

***Index terms*— Brushless asynchronous generator, self excited induction generator, prime mover, d-q model, mutual**

INTRODUCTION

Self-Excited Induction Generators (SEIG) are also known as Brushless Asynchronous Generators (BAG) for its brushless construction. These are good candidates for wind powered electric generation application especially in remote areas, because they do not need external power supply to produce the magnetic field. The stand-alone BAG has a self-protection mechanism against the voltage collapses when there is a short circuit at its stator terminals. Further self excited induction generators have more advantages such as low cost, reduced maintenance, rugged and simple construction, brush-less rotor (squirrel cage), etc. [1]. It is well known that when capacitors are connected across the stator terminals of an induction machine, driven by an external prime mover, voltage will be induced at its terminals [14]. The induced emf and current in the stator windings will continue to rise until steady state is attained, influenced by the magnetic saturation of the machine. At this operating point the voltage and current will continue to oscillate at a given peak value and frequency. In order for self-excitation to occur with a particular capacitance value there is a corresponding minimum speed of prime mover [11]. The characteristics of the magnetizing inductance as their air gap voltage increases from zero is that it starts at a given value, increases until it reaches its maximum value and then decreases to attain saturated value which is lower than maximum value. The reason for this variation in magnetizing reactance and the effect on self-excitation is discussed in this paper. As the magnetizing reactance, X_m is dependent on frequency, magnetizing inductance L_m is used in the analysis [7]. Wang and Huei proposed an analysis to predict both minimum and maximum values of capacitance required for self-excitation of a three phase induction generator at a particular speed [3]. Wind speed can change from the minimum set point to the maximum set point randomly and the SEIG can be started at any point within the range of speed. It is essential to find the minimum and maximum speed required for self-excitation, when the generator is loaded [4]. In this paper the MATLAB simulation results of output voltage and variation in mutual inductance with different excitation capacitance values at different prime mover speeds along with transients of active power flow and reactive power flow are discussed. The variation of minimum capacitance requirement for self excitation to begin under varied resistive load conditions is studied through simulation results.

MODELING OF BAG IN STAND-ALONE MODE

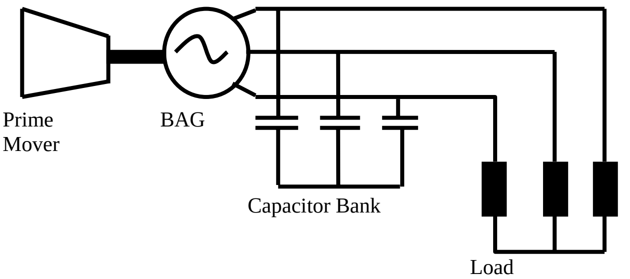

Fig. 1 Self excited induction generator system

The induction machine of Fig.1, used as the SEIG in this investigation is a three phase 22kW squirrel cage induction machine, specifications is given in Appendix I-A. In this paper the d-q model in stationary reference frame is used because it is easier to get the complete solution, transient and steady state, of the self-excitation. For motoring application these parameters can be used directly. However, for SEIG application the variation of L_m with voltage should be taken into consideration. The initial conditions for self-excitation, namely the remnant magnetic flux in the rotor and/or the initial charge in the capacitors are well considered for simulation. The respective equation for an SEIG with a RL load in parallel with the self-excitation capacitor is governed by:

$$\begin{bmatrix} V_{ds} \\ V_{qs} \\ V_{dr} \\ V_{qr} \end{bmatrix} = \begin{bmatrix} R_s + L_s p + \left(\frac{R+Lp}{RCp+LCp^2+1} \right) & 0 & L_m p & 0 \\ 0 & R_s + L_s p + \left(\frac{R+Lp}{RCp+LCp^2+1} \right) & 0 & L_m p \\ L_m p & w_r L_m & R_r + L_r p & w_r L_r \\ -w_r L_m & L_m p & -w_r L_r & R_r + L_r p \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \end{bmatrix} \quad (1)$$

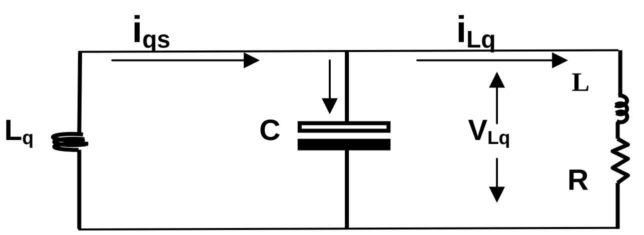

Fig. 2 Stator quadrature axis equivalent circuit with an RL load

The corresponding differential equations of state variables of the induction machine in d-q stationary reference frame are derived. These are

$$pi_{qs}=L_m k(v_{qr}+ wL_m i_{dr}- R_2 i_{qr}+ wL_2 i_{dr})- L_2 k(v_{qs}- R_1 i_{qs} - v_{Lq}) \quad (2)$$

$$pi_{ds}=L_m k(v_{dr} - wL_m i_{qr}- R_2 i_{dr} - wL_2 i_{qr}) - L_2 k(v_{ds}- R_1 i_{ds} - v_{Ld}) \quad (3)$$

$$pi_{qr}=L_m k(v_{qs} -R_1 i_{qs} -v_{Lq}) -L_1 k(v_{qr}+ wL_m i_{ds} - R_2 i_{qr}+ wL_2 i_{dr}) \quad (4)$$

$$pi_{dr}=L_m k(v_{ds} - R_1 i_{ds} - v_{Ld}) - L_1 k(v_{dr} - wL_m i_{qs} - R_2 i_{dr} - wL_2 i_{qr}) \quad (5)$$

$$k = 1 / (L_m^2 - L_1 L_2) \quad (6)$$

SEIG state matrix with RLC load

$$pv_{Ld} = (i_{ds}/C) - (i_{Ld}/C) \quad (7)$$
$$pv_{Lq} = (i_{qs}/C) - (i_{Lq}/C) \quad (8)$$
$$pi_{Ld} = (v_{Ld}/L) - (R^* i_{Ld}/L) \quad (9)$$
$$pi_{Lq} = (v_{Lq}/L) - (R^* i_{Lq}/L) \quad (10)$$

As the magnetizing characteristic is nonlinear in nature, the magnetizing current is found for each iteration in terms of stator and rotor currents as

$$I_m = \{(i_{ds} + i_{dr})^2 + (i_{qs} + i_{qr})^2 \}^{1/2} \quad (11)$$

The magnetizing inductance is calculated from the magnetizing characteristic relation between

L_m and I_m, as given by

$$L_m = (0.4123^*\exp (-0.0035^* I_m^2)) + 0.0236 \quad (12)$$

The instantaneous active and reactive power is given by the relation:

$$P = v_{ds} * i_{ds} + v_{qs} * i_{qs} \quad (13)$$
$$Q = v_{qs} * i_{ds} - v_{ds} * i_{qs} \quad (14)$$

Developed electromagnetic torque relation is given by:

$$T_e = (3P/4) * L_m * (i_{qs} * i_{dr} - i_{ds} * i_{qr}) \quad (15)$$

D-Q stationary reference frame to abc phase transformation is given by the relation:

$$v_{as} = v_{qs}^s \quad (16)$$
$$v_{bs} = - (1/2) * v_{qs}^s - (\sqrt{3}/2) * v_{ds}^s \quad (17)$$
$$v_{bs} = - (1/2) * v_{qs}^s + (\sqrt{3}/2) * v_{ds}^s \quad (18)$$

SELF EXCITATION REQUIREMENT

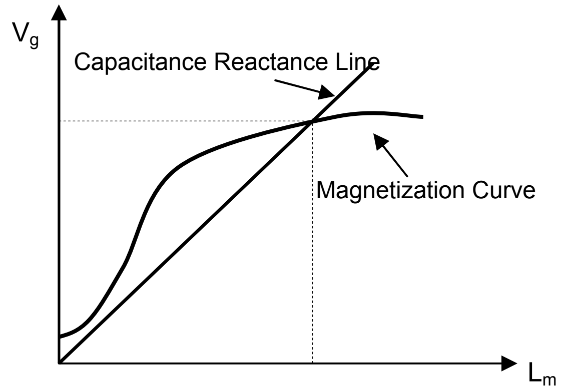

Fig. 3 No-load magnetization characteristic and capacitive reactance line

When the induction machine with capacitance connected at its stator terminals, shown in Fig 1, is driven by a prime mover, such as a wind turbine, voltage will start to develop at a corresponding minimum speed also with a minimum capacitance for a particular speed. The value of capacitance required for self- excitation is chosen for a given rotation in such a way that the straight line of the capacitive reactance intercepts the magnetizing curve shown in Fig.2, at the point of the desired rated voltage .This means that the intersection of these two lines is the point at which the necessary reactive power of the generator is supplied only by capacitors (the resonant point). The current corresponding to the interception point should not be much above the rated current of the machine.

EFFECT OF MAGNETIZING INDUCTANCE ON SELF-EXCITATION

To model an induction machine when used for motoring application, it is important to determine the magnetizing inductance at rated voltage. In the SEIG the variation of magnetizing inductance is the main factor in the dynamics of voltage build of and stabilization. As can be observed in Fig.3, L_m for a fourth order curve fit starts from a smaller value then increases to reach its peak value and finally attains its saturated value. This change in L_m is due to the characteristics of the magnetizing curve as can be seen in Fig.3, at the start of self-excitation point A, where the voltage is close to zero, Lm has a definite value. Once self-excitation starts the generated voltage will grow and then L_m also increases up to point B.

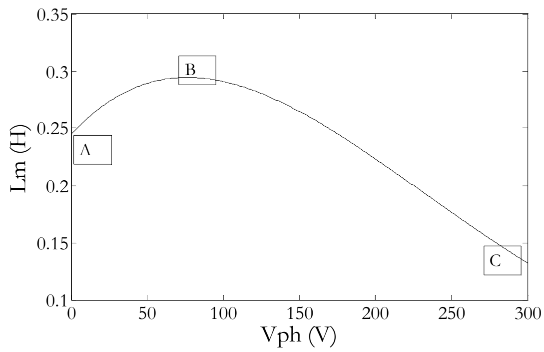

Fig. 4 Variation of magnetizing inductance with phase voltage

Beyond point B, up to point C, L_m starts to decrease while the voltage continues to grow until it reaches its steady state value. Between point A and B is the unstable region. If the SEIG starts to generate in this region, a small decrease in speed will cause a decrease in voltage and this will bring a decrease in L_m which in turn decreases the voltage and finally the voltage will collapse to zero. If the speed increases slowly and sometimes with zero acceleration so that the operating point remains in the region between A and B, there will not be any self-excitation even at high speed. When the increase of wind speed has this characteristic then there is a possibility that self-excitation will not occur. To avoid this problem the capacitors should be connected when the speed reaches its set point because voltage build up requires transient phenomena in the region between A and B. Between point B and C is a stable operating region. When the speed decreases voltage will decrease and Lm increases to have a new steady state operating point at lower voltage.

SIMULATION RESULTS AND DISCUSSION

MATLAB code is used to predict the generated voltage from a 22kW three phase squirrel cage induction machine with an initial residual voltage of 10 V rotating at a given speed with appropriate capacitors connected at the stator terminals to provide the necessary magnetizing current to establish the required flux in the air-gap. The simulation result shows that self excitation can be identified and the effects of different values of excitation capacitance and speeds on self-excitation investigated. Fig.5 shows the output voltage of SEIG for a capacitance value of 48μF at a speed of 1310 rpm at no load along with the variation in mutual inductance. The voltage could not build up due to lack of necessary flux in the air gap. Fig. 6. shows the phase 'a' output voltage for an excitation capacitance of 48μF and 1750 rpm which builds up around 1.9s and reaches steady state at about 3.2s developing a voltage of about 1000V peak with a line current of 18A peak. The dynamic mutual inductance saturates at 3.5s within a span of 1.4s. There

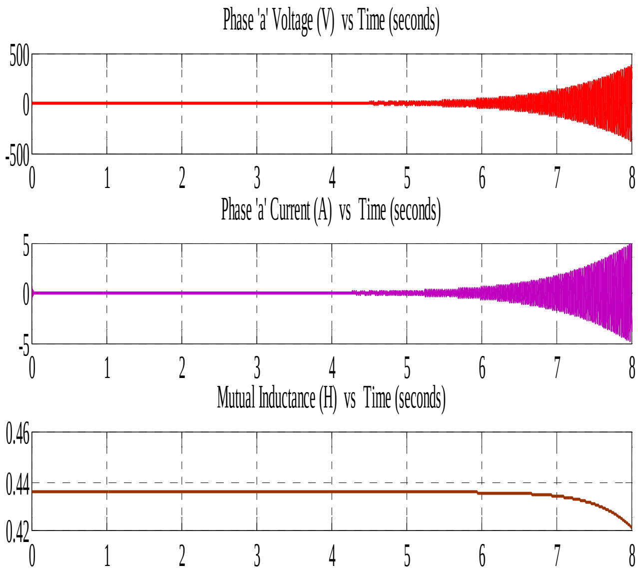

Fig. 5 Phase 'a' voltage, current and variation in mutual inductance for an excitation capacitance of 48μF and 1310 rpm

is a surge in active power flow between 2.0s to 3.4s, the peak being 112 watts. A good amount of reactive (negative) power flows when the brushless asynchronous generator starts to build up and reaches steady state. For an excitation

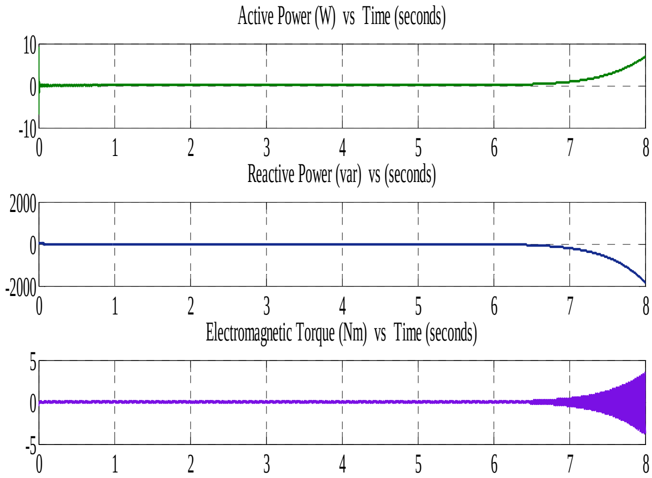

Fig. 6 Active power, reactive power, and electromagnetic torque for the same excitation capacitance of 48μF and 1310 rpm

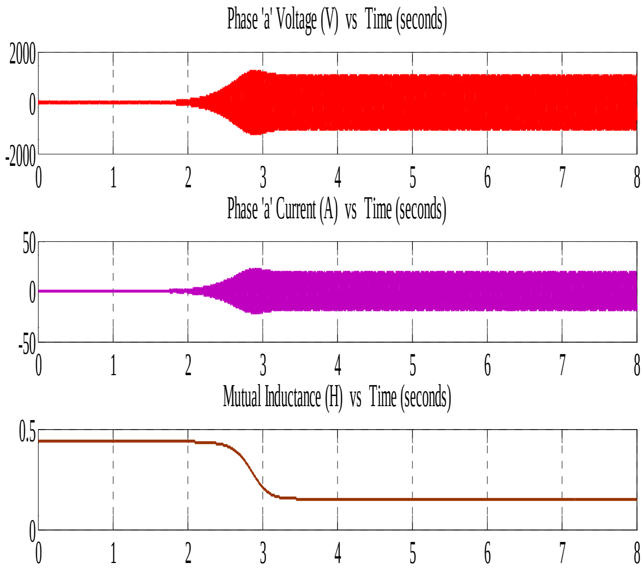

Fig. 7 Phase 'a' voltage, current and variation in mutual inductance for an excitation capacitance of 48μF and 1750 rp

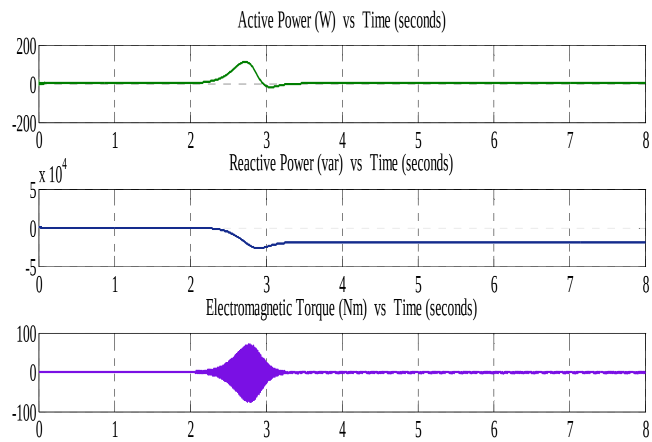

Fig. 8 Active power, reactive power injection, and electromagnetic torque for the same excitation capacitance of 48μF and 1750 rpm

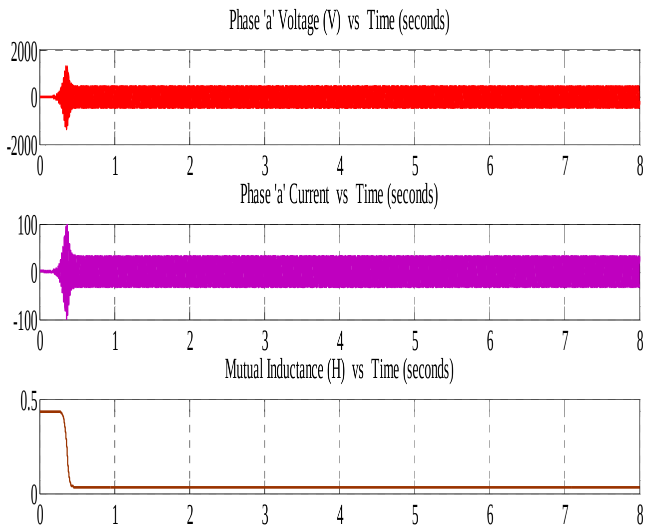

Fig. 9 Phase 'a' voltage, current and variation in mutual inductance for an excitation capacitance of 200μF and 1750 rpm

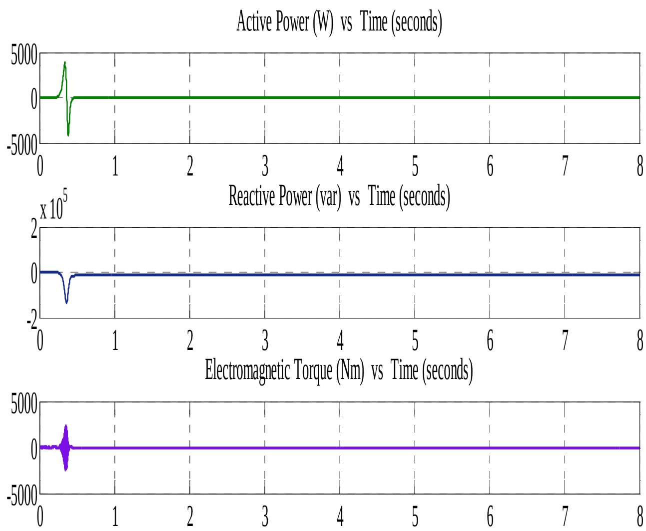

Fig. 10 Active power surge, reactive power injection and developed electromagnetic torque for the same excitation capacitance of 200μF and 1750 rpm

capacitance of 200μF and a rotor speed of 1750 rpm, it is observed that there is an early start up at 0.1s reaching the steady state as early as 0.6s between which the mutual inductance varies and saturating rapidly. The reason being between 0.1s to 0.5s large amount of reactive power transfer occurs the peak being -136 kvar at 0.36 s. A considerable amount of active power transfer occurs between these times the positive peak being 3.8kW at 0.3s. At this capacitance value of 200μF and 1750 rpm, the peak voltage is decreased to about 440V. In Fig. 5 as the machine could not build up voltage but an unstable torque oscillation is observed. A varied electromagnetic torque is developed in the transient period of voltage generation though the BAG is run by a prime mover at a fixed speed as could be observed from the Fig. 6. and Fig. 7. BAG in stand-alone mode requires different values of minimum capacitances for self excitation process to begin and governed by the characteristic equation of induction generator as given in Appendix I-B. In Fig. 11 variation of minimum capacitance value required for self excitation as the load is varied is shown for three different speeds of 1000 rpm, 1250 rpm and 1500 rpm. It is observed that as the speed is increased, minimum capacitance requirement also decreased considerably for small loads. However there is not much variation for loads above 100Ω.

Capacitance values are found for a step change

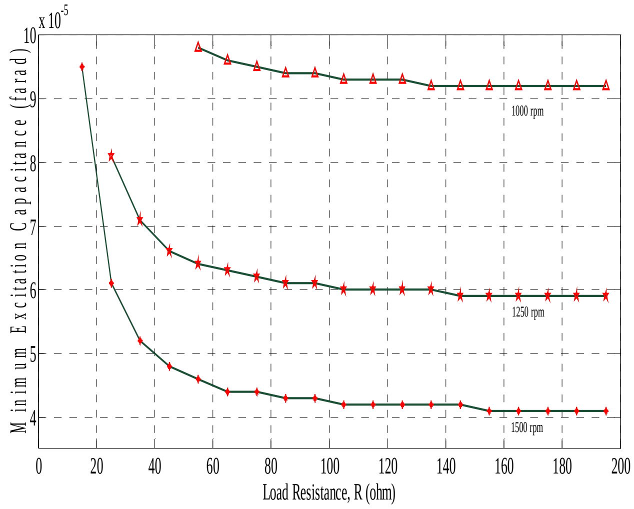

Fig. 11 Minimum excitation capacitance required for voltage build up of the BAG under stand-alone mode with varied resistive load

of 10Ω. For a resistive load of 35Ω the minimum capacitance requirements are found to be 71μF and 52μF for the prime mover speed of 1250 rpm and 1500 rpm respectively.

CONCLUSION

The magnetizing inductance is the main variable that decides whether there will be steady state voltage generation or not in a SEIG. A negative slope in Fig. 4 whereby the L_m decreases with increased voltages represent a stable operating region. As the self-excitation requires a transient phenomenon, the best way to indicate this transient is to switch in the capacitors while the speed reaches the desired value. As the speed increases it affects the voltage build-up process, as the mutual inductance value changes rapidly to its saturated value, reaching the steady state value quite early. Decreased speed does not guarantee a voltage at the output as the absence of necessary flux in the air-gap. The excitation capacitance should be able to supply the necessary magnetizing current to produce the required air gap flux to start the voltage build-up process. Steady state voltage is not fixed at a particular value, rather it fluctuates and changes considerably for different speeds and different excitation capacitances. Load and speed decides the value of minimum capacitance required to begin the self excitation process. As speed of prime mover is increased for a BAG with a resistive load, the minimum excitation capacitance requirement reduces.

APPENDIX I

A. Induction Machine specifications

TABLE I

Machine Parameters	
Power	22KW
Voltage (V)	400
Current (A)	40
R_s (Ω)	0.582
R_r (Ω)	0.814
X_{ls} (Ω)	1.582
X_{lr} (Ω)	1.47

B. Characteristic equation which represents the self excitation process of a brushless asynchronous generator for all types of loads

$$(A_5*s^5+A_4*s^4+A_3*s^3+A_2*s^2+A_1*s+A_0)^2$$

$$+ (B_3*s^3+B_2*s^2+B_1*s)^2 = 0 \quad (19)$$

C. A and B coefficients for resistive load (R)

$$B_1=L_m^{2}*w*R_r \quad (20)$$
$$B_2=L_m^{2}*w*R_r*R*C \quad (21)$$

$$B_3=0 \quad (22)$$

$$A_0=(R+R_s)*(R_r^2+w^2*L_r^2) \quad (23)$$

$$A_1=2*R_r*L_r*(R+R_s) +(R_{r2}+w^2*L_r^2)*(R*C*R_s+L_s)-L_m^{2}*w^2*L_r \quad (24)$$

$$A_2=L_r^{2}*(R+R_s) +2*R_r*L_r*(R*C*R_s+L_s) +(R_r^2+w^2*L_r^2)*(R*C*L_s)-w^2*L_r*R*C*L_m^2-R_r*L_m^2 \quad (25)$$

$$A_3=L_r^{2}*(R*C*R_s+L_s) +2*R_r*L_r*(R*C*L_s) - R_r*R*C*L_m^2- L_r*L_m^2 \quad (26)$$

$$A_4=L_r^{2}*(R*C*L_s) - L_r*R*C*L_m^2 \quad (27)$$

$$A_5=0 \quad (28)$$

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