International Journal of Engineering and Advanced Technology (IJEAT)
ISSN: 2249-8958 (Online), Volume-1 Issue-2, December 2011

Performance Analysis of Self-Excited Induction Generator Driven At Variable Wind Speeds

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Abstract: ***This paper discusses steady state analysis and performance characteristics of a three-phase induction generator self excite with capacitor per phase. It is shown that for this mode of operation, there are certain ranges over which the values of the terminal capacitor, C, machine speed and load impedance have to be kept in order to maintain self excitation. In general, the performance characteristics are strongly influenced by the value of C and guidelines are suggested for selecting its proper value. This paper also presents the theoretical and experimental results of self excited induction generator under varying rotor speed operation of research. Three phase 3.7kW induction machine excited with symmetrical capacitor bank and loaded with symmetrical three phase resistive load, was the subject of investigation. Experimentally obtained results have been compared with calculated performance curves and very good agreement between them has been achieved.***

Index Terms: ***wind turbine, self-excited induction generator, steady state analysis, performance characteristics***

I. Introduction

The self-excited induction generators (SEIG) have been found suitable for energy conversion for remote locations. Self-excited induction generators (SEIG) are frequently considered as the most economical solution for powering costumers isolated from the utility grid. SEIG has many advantages such as simple construction, absence of DC power supply for excitation, reduced maintenance cost, good over speed capability, and self short-circuit protection capability. Unlike induction generators connected to the power utility grid, both frequency and voltage are not fixed but depend on many factors, such as generator parameters, excitation capacitor, speed, and load. This makes the SEIG steady state analysis is more difficult. Major drawbacks of SEIG are reactive power consumption, its relatively poor voltage and frequency regulation under varying prime mover speed, excitation capacitor and load characteristics [1], [2].
SEIG are found to be most suitable for many applications including wind energy conversion systems. Such generators may also be used in remote areas in the absence of grid. Therefore methods to analyze the performance of such machines are of considerable practical interest. The terminal capacitance of such machines is of considerable practical interest [3]. The terminal capacitance on such machines must have a minimum value so that self-excitation is possible. When the SEIG has successfully built up its voltage, the next question of interest is to maintain the terminal voltage at a preset value as the load increases. The motivation for the work presented in this paper was to identify how the variation of rotor speed affects voltage, frequency, stator current, generated power and shaft torque of the SEIG[4]. Theoretical and experimental research was done assuming that SEIG was loaded with three-phase symmetrical resistive load and excited with symmetrical capacitor bank connected to the stator. Experimented results obtained on a laboratory machine are presented to verify the accuracy and validity of the present approach.

It is observed that winds carry enormous amount of energy and could meet sufficient energy needs for the world. It has been found that cost of the wind generation is comparable to that of hydro and thermal power plants. In addition to this wind energy provides a clean and pollution free environment [5]. An induction motor connected to constant voltage, constant frequency supply system behaves as a generator if made to run at a speed higher than synchronous speed. In such an operation, the exciting current is provided by the supply system, to which the machine is connected and the frequency of the voltage generated by the induction generator is the same as that of the supply system.

For wind mill drives, the speed of the induction machine depends upon the velocity, volume and the direction of the wind. These parameters may vary in wide limits. It is found that such machine exhibits poor performance in terms of voltage and frequency under frequent variations of operating speeds, which is common feature in wind energy conversion. [6],[7].It is therefore, desirable to investigate the behavior of a self excited induction generator suitable for wind mill drive under controlled and uncontrolled speeds operation. It is realized that such variations in operating speeds may be compensated by proper handling of load and rotor resistance. In this paper, performance analyses of SEIG operating with fluctuations in the wind speed have been obtained experimentally on a test machine.

II. THREE PHASE SELFEXCITED INDUCTION GENERATOR MODEL

When an induction machine operates as a SEIG, there is no external power grid that defines voltage and frequency on the stator terminals. Thus, both of them are unknown variables whose values change independently, being affected by rotor speed, capacitance of excitation capacitors and loading conditions. Saturation level of the magnetic circuit is also variable, which means that magnetizing inductance can not be considered constant.

Manuscript published on 30 December 2011.
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In such circumstances, the standard equivalent circuit of an induction machine is not suitable for analysis, and specific modifications have to be made. Several different variants of SEIG's equivalent circuit can be found in literature [1]-[2], but common point for all of them is that they neglect power losses in the magnetic core of the machine. Since SEIG always operates in the saturated region of the magnetizing curve, it is clear that such simplification can diminish accuracy of prediction. For the modeling of the self-excited induction generators, the main flux path saturation is accounted for while the saturation in the leakage flux path , the iron and rotational losses are neglected. Therefore in the following analysis the parameters of the induction machine are assumed constant except the magnetizing inductance which varies with saturation[5].

A. *Steady-state circuit model*

The steady state circuit of a self-excited induction generator under RL load is shown in Fig.1

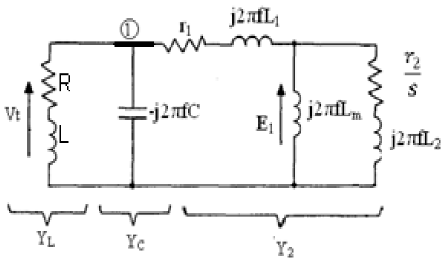

Fig.1.Equivalent circuit of SEIG

Here the machine core losses are have been ignored. Considering these losses increases the mathematical work involved in obtaining the results, without increasing the accuracy of the analysis substantially. All the circuit parameters are assumed to be constant and unaffected by saturation. Machine parameters except capacitance and frequency all are known values [6]

B. *Mathematical model*

Fig1.shows the per phase equivalent circuit commonly used for the steady state analysis of the SEIG.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[4].For on load self-excitation, the impedance line corresponding to the parallel combination of the load impedance and excitation capacitance should intersect the magnetisation characteristic well into the saturation region[7].The condition yields the minimum value of excitation capacitance below which the SEIG fails to self-excite

For the circuit shown in Fig.1.,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.

$$\left.\begin{array}{l} \text{Real } (Y_L+Y_C+Y_2)=0 \\ \text{Imag } (Y_L+Y_C+Y)=0 \end{array}\right\} \qquad (4)$$

Where Y_L ,Y_C,Y_2 are

$$\left.\begin{array}{l} Y_L = \dfrac{1}{r_L+j2\pi fL} \\ Y_C = j2\pi f C_e \\ Y_R = \dfrac{1}{\frac{r_2 fk}{kf-N}+j2\pi f L_2} \\ Y_M = \dfrac{1}{j2\pi f L_M} \\ Y_S = \dfrac{1}{r_1+2\pi f L_1} \end{array}\right\} \qquad (5)$$

C. *Proposed method to find general solution for capacitance*

The real part yields

$$A_4f^4+A_3f^3+A_2f^2+A_1f+A_0=0 \qquad (6)$$

And the imaginary part yields

$$C=\frac{af+b}{cf^3+df^2+ef} \qquad (7)$$

$$Y_2=\frac{(Y_R+Y_M)Y_S}{Y_R+Y_M+Y_S}; \qquad (8)$$

$$\text{Slip,}s=\frac{kf}{kf-N} \qquad (9)$$

Where k=30;

The derivation for these constant coefficients A_4 to A_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.

III. 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

D.C.shunt motor. The induction machine was three, phase3.5kW, 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.

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International Journal of Engineering and Advanced Technology (IJEAT)
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f_1=50.06Hz;
f_2=17.33Hz;
f_3=1.275+j0.3567Hz;
f_4=1.275-j0.3567Hz;

As only the real roots have physical significance and the largest real root yields the maximum frequency that corresponds to the minimum frequency.

Load Impedance	Magnetizing reactance Experimental	Magnetizing reactance Calculated
80	70	67
100	124.5	123.318
120	147.39	146.776
150	168.56	167.19
180	169.45	168.67
200	221.45	220.89
220	221.45	220.89

Fig.2.Comparision of magnetizing reactance of both experimental and calculated results.

Using the equation (5) for capacitance, the value of the capacitive reactance can be calculated. Using the steady state equivalent circuit,$X_C=X_m$.In this paper, the values of X_m calculated theoretically using the above derived expressions are know compared with the magnetizing reactance that is obtained from the experimental calculations. The machine is tested for different wind speeds. Very good correlation between the computed and experimental results is observed.

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, then no excitation is possible. Also, there is a minimum speed value, below which equation (4) have no real roots. Correspondingly no excitation is possible.

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

The computed values reveals 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.Fig.2.shows the computed variation of the self excited magnetizing reactances with load impedance at 80Ω.

IV. EXPERIMENTAL RESULTS AND DISCUSSIONS

When balanced sinusoidal currents flows through the stator phases of an induction machine, the rotating magnetic field is produced in the air gap of the machine, with the flux/pole Φ which is proportional to the R.M.S value of the currents. Φ is fixed by the value of magnetizing current; the induced E.M.F is proportional to the speed. The magnetization characteristic determines the minimum value of the capacitance, below which self excitation does not take place.

The magnetization characteristics at different speeds are as shown in Fig.3.To verify the validity ,the authors of this paper under study was tested experimentally .Noload test as a motor under variable voltage yielded the magnetization curve of Fig.3-5shows some results and their counter part experimental measurements.

From these curves it can be observed that as the speed is increasing the magnetizing reactance are also increasing. And it can also be observed from the Fig.4-5,the magnetizing reactance will be high initially for lower values of phase current and phase voltages. As these values are increasing the magnetizing reactance is decreasing. From these observations it can be concluded that to initiate the self excitation process there should be some residual magnetism i.e E_{rem} has to be non zero

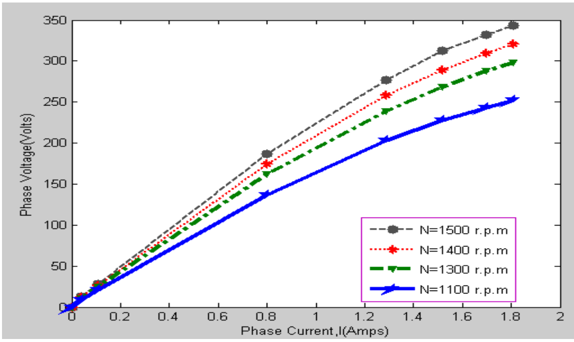

Fig.3.Magnetizing characteristics of Induction machine at different wind speeds

The magnetization curve of the SEIG, obtained from typical motor no-load tests, has to advance he non linear zone in order to firmly intersect the capacitor straight line voltage characteristic and thus produce the no-load voltage E_1. The piecewise linearization of magnetization characteristic of machine is given in APPENDIX-A

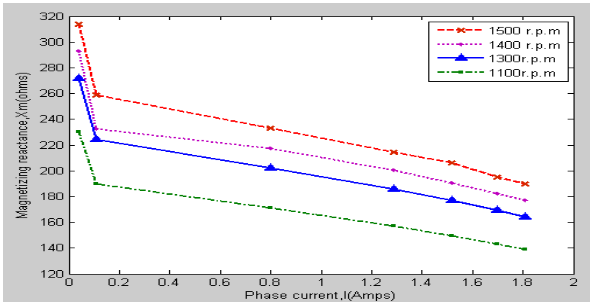

Fig.4.Magnetizing reactance Vs Phase current

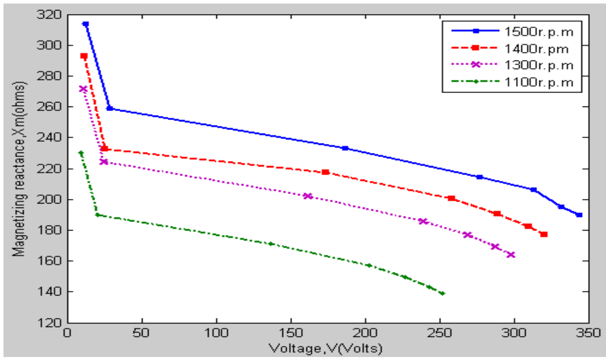

Fig.5.Magnetizing reactance Vs Voltage at different speeds

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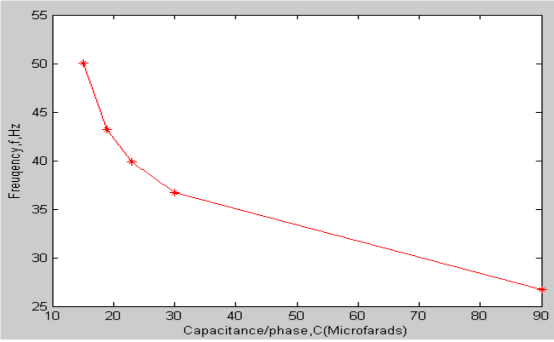

Fig.6.Capacitance Vs Frequency

Fig6.shows the minimum capacitance required for the self-excited induction generator. These values can be used to predict the theoretically the minimum value of the terminal capacitance required for the self-excitation .Ofcourse,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.

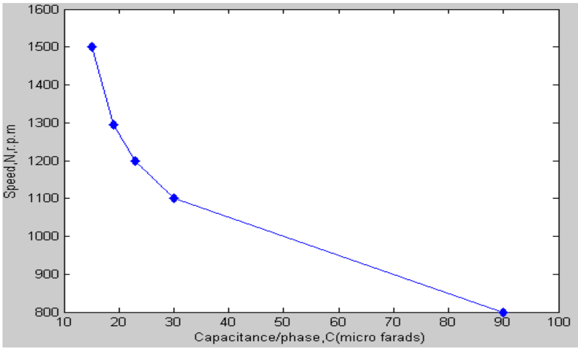

Fig.7.Capacitance Vs Speed.

For certain excitation capacitance and load conditions(impedance anf p.f),there is a certain cutoff speed N_{co}.At this speed,MMF is at its minimum level; therefore the saturation effects and iron losses can be neglected by using unsaturated value of the magnetizing reactance and D.C resistance for R_1Fig.7. shows the speed N against the excitation connected phase capacitance c for a specified values of star connected unity power factor load. As the value of the excitation capacitance is decreasing the frequency is increasing. With the increasing this frequency the rotor speed of the SEIG is increasing which is as shown in Fig.8.

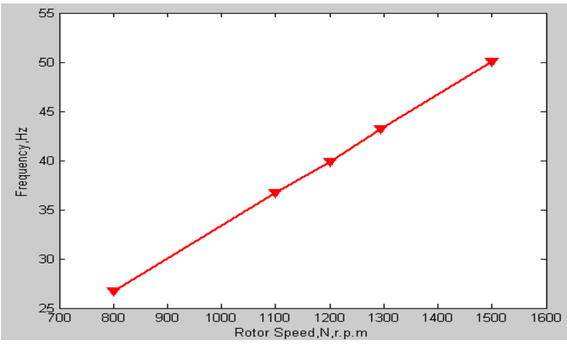

Fig.8.Frequency Vs Rotor speed

The variation of frequency with rotor speed is as shown in Fig.8.Frequency varies linearly with the rotor speed. There is a certain cutoff speed below which there is no excitation is possible. At 1500r.p.m the frequency obtained is 50Hz.As the rotor speed is increasing, experimentally, the frequency is 49.88Hz.

The relation between the output power and the load current is as shown in Fig.9 for C=15μF for different values of the rotor speed. It is noted that that load power increases with the increase in C.The current rating of the induction machine used imposes a restriction on attaining the higher values of the output power. It should be pointed out that the machine used needs parameter optimization to yield acceptable power levels.

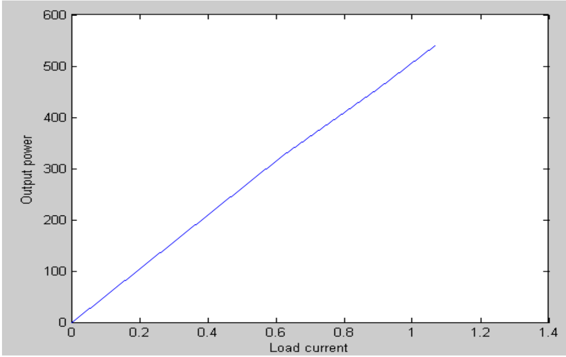

Fig.9.Load current Vs Output Power/Phase

One of the important parameters is the ratio between stator and rotor number of turns per phase.Mathematically, change in turns ratio will vary the saliency ratio with maximum value obtained when stator and rotor turns per phase are equal.

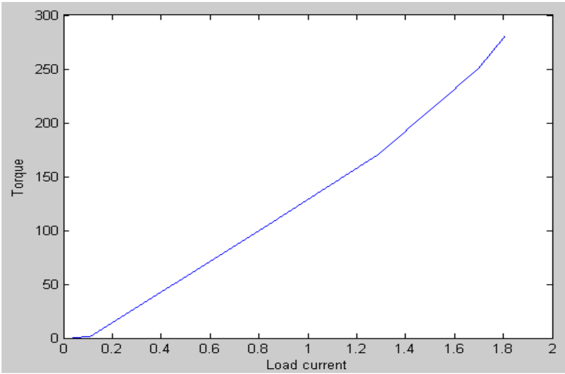

Fig.10.Load current Vs Torque

The relation between the torque and load current is as shown in Fig.10. for C=15μF for different values of the rotor speed. It is noted the torque is increasing with the increase in load current. The torque is calculated by neglecting iron losses and considering the saturation. It confirms the linear relationship between speed and torque according to the assumed turbine speed-torque characteristics. These are calculated for 0.8p.f lag load impedance. The base torque is defined as the electromagnetic torque of the induction machine when running at normal speed and developing its rated power P_{rated}.

This method of calculating the torque can be used for both regulated and unregulated

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wind turbines. The relation between torque and speed is nonlinear for the unregulated wind turbines.

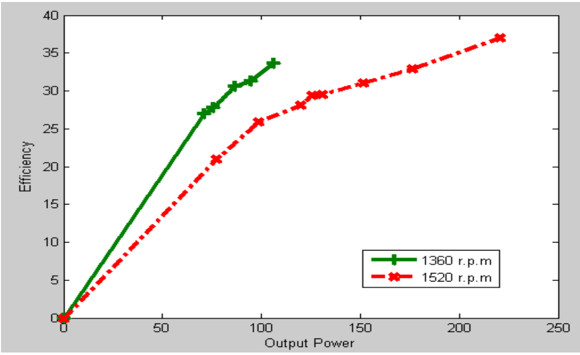

Fig.11.Output power Vs Efficiency

For a given value of the shunt capacitance the output power depends on the excitation capacitance.Fig.11.shows the variation of the output with efficiency. Due to the self regulation in the load voltage, the power output increases linearly as the load current increases..The frequency drops slightly with the increase in the load current :at perfect balance, the frequency is equal to49.88Hz.

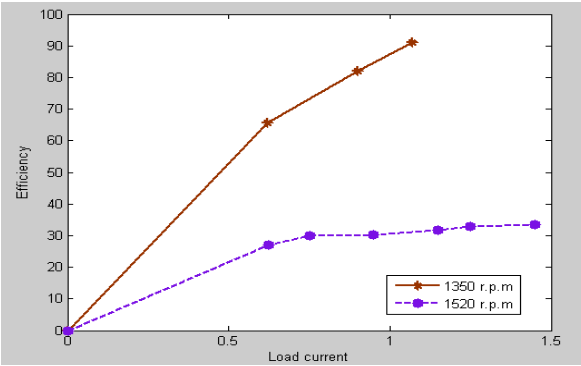

Fig.12.Load current Vs Efficiency

The relation between generator efficiency and load current is as shown in Fig.12. It is noted that generator efficiency is acceptable in general, although the machine used was not designed for this mode of operation. This may be owing to the low value of the frequency of the generated voltage, which reduces the iron losses appreciably.

To validate the performance analysis of the SEIG, load tests were performed on the experimental machine. Attention was focused on the constant-speed mode of operation and resistive,RL loads. Results of load tests on the machine for 0.8p.f and the excitation capacitance is C=15μF and at different rotor speeds, the wind speed is at 6.5m/s. The analysis of the machine is based on the assumption that:

1. Of all machine parameters, only the magnetizing reactance is affected by the magnetic saturation.
2. Core losses are neglected.
3. Space harmonics in the air-gap flux is neglected.

From the results that are obtained from the experimental and theoretical values, the conclusion made is, for constant speed:

1. The no-load voltage increases with the parallel excitation capacitance.
2. The maximum output power and terminal voltage increases significantly with capacitance.
3. For constant load voltage, the required capacitor increases with the delivered power.
4. When no-load voltage increases, the magnetization reactance decreases, due to advancing magnetic saturation.

And for unregulated prime movers the conclusions are:

1. When capacitance is too small to handle the total reactive power of the SEIG's voltage collapses. When parallel capacitance is too large, the rotor impedance of SEIG causes de-excitation, and voltage collapses again. There should be optimum capacitor between C_{min} and C_{max} to provide maximum output power for good efficiency.
2. Constant speed regulated prime movers lead to notably larger power delivered by SEIG for other given data.
3. For no load, the minimum capacitance for self excitation is inversely proportional to speed squared, under load, the minimum capacitance depends on speed, load impedance and load power factor.

V. CONCLUSIONS

The performance of the squirrel cage induction generator SEIG has been studied and theoretically, showing acceptable agreement. In this analysis, the influence of the SEIG resistances, leakage reactances, magnetization reactance and capacitances on SEIG's performance is investigated for constant speedor uncontrolled speed wind turbine.

It was found that generator performance is greatly effected by saturation in both magnetic axes and iron losses.

In future research, accuracy of prediction can be taken to a higher level by considering several non linearities that are neglected at this moment.Also,the mathematical model will be expanded by including equations that describe the actual wind turbine. That will be of essential importance in the study of the practical applications in real environment.

Since the circuit configuration of the proposed SEIG is extremely simple and only static capacitors are required, the generator can be conventionally implemented for use in low cost single phase autonomous systems.

The results of this paper are useful for the analysis of the vriable speed mode of operation of the SEIG,whether speed variation is caused by wind speed variation or due to loading of the turbine.However,wind speed varies randomly from time to time and from season to season, which makes it difficult to incorporate the analysis.

APPENDIX-A

To compute the coefficients A_4 to A_0 of equation(4),the following equations are first defined:

$a=2\pi k(L_M r_1+L_1 r_1+L_2 r_1+L_M r_2+L r_2+r_L L_M+r_L L_2)$;
$b=-2\ \pi N^* r_L(L_M+L_2)$
$c=-8\ \pi^3 k(L L_M r_1+L L_2 r_1+L L_M r_2-r_L L_1 L_M-r_L L_2 L_M)$
$d=-8\ \pi^3 N(r_L L_1 L_M+ r_L L_2 L_1+ r_L L_2 L_M+L L_2 L_M)$
$e=-2\pi k r_L r_1 r_2$
$g=-4\pi^2 k(L_1 L_M+L_1 L_2+L_2 L_M+L L_M+L L_2)$
$h=4\pi^2 N(L_1 L_M+L_1 L_2+L_2 L_M+L L_M+L L_2)$
$i=r_1 r_2+r_L r_2$
$j=-16\pi^4 k(L L_1 L_M+L L_2 L_M+L L_2 L_1)$

$l=16\pi^4N(LL_1L_M+LL_1L_2+LL_2L_M)$
$m=4\pi^2k(Lr_1r_2+r_LL_Mr_1+r_LL_1r_2+r_LL_1r_2+r_LL_2r_1+r_LL_mr_2)$
$p=-4\pi^2Nr_LL_Mr_1;$
$A_4=cg-aj$
$A_3=dg+hc+-al-bj;$
$A_2=eg+hd+ic-ma-bl;$
$A_1=he+id-pa-bm$
$A_0=ie-bp;$

- **Air gap voltage**:

The piecewise linearization of magnetization characteristic of machine is given by

$E_1=0 \quad X_m\geq260$
$E_1=1632.58-6.2X_m \quad 233.2\leq X_m\leq260$
$E_1=1314.98-4.8X_m \quad 214.6\leq X_m\leq233.2$
$E_1=1183.11-4.22X_m \quad 206\leq X_m\leq214.6$
$E_1=1120.4-3.9.2X_m \quad 203.5\leq X_m\leq206$
$E_1=557.65-1.144X_m \quad 197.3\leq X_m\leq203.5$
$E_1=320.56-0.578X_m \quad X_m\leq197.3$

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