ANALYSIS OF AN ISOLATED SELF-EXCITED INDUCTION GENERATOR DRIVEN BY A VARIABLE SPEED PRIME MOVER

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Abstract

This paper presents the effect of magnetizing inductance in self-excitation and also the minimum and maximum value of speeds necessary to initiate the self-excitation process in an isolated three-phase induction generator for a given capacitance value and load. Wind powered self-excited induction generators (SEIG) have an input which is not controllable, wind, but they can be set to operate within a given variation of speed. 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 SEIG the value of the 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. The simulation and experimental results are compared.

1. INTRODUCTION

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 [1]. 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, for a particular capacitance value there is a corresponding minimum speed [2-4].

Self-excited induction generators are good candidates for wind powered electric generation application specially in remote areas, because they do not need external power supply to produce the magnetic field. Permanent magnet generators can also be used for wind energy applications but they suffer from uncontrollable magnetic field, which decays over a period due to weakening of the magnets, and the generated voltage tends to fall steeply with load. The SEIG has a self-protection mechanism because the voltage collapses when there is a short circuit at its terminals. Further, the SEIGs have more advantages such as cost, reduced maintenance, rugged and simple construction, brush-less rotor (squirrel cage), etc.

In several papers, it has been reported that the value of magnetizing reactance verses air-gap voltage is given as a constant for the unsaturated, low value of air-gap voltage, and then decreases when it saturates [5-8]. However, this representation does not reflect the actual variation of magnetizing inductance and as a result it does not show the actual phenomena during the initiation of self-excitation. The magnetizing inductance should be represented in such a way that it depicts the actual value for each voltage. The characteristics of the magnetizing inductance as the air gap voltage increases from zero is that it starts at a given value, increases until it reaches its maximum value and then starts to decrease up to its rated value, which is a saturated 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.

Wang et al [9] and others [10-11] proposed an analysis to predict both minimum and maximum values of capacitance required for self-excitation of a three-phase induction generator. Economically and technically it is not advisable to choose the maximum value of capacitance. This is due to the fact that for the same voltage rating the higher capacitance value will cost more. In addition, if the higher capacitance value is chosen then there is a possibility that the current flowing in the capacitor might exceed the rated current of the stator, due to the fact that the capacitive reactance reduces as the capacitance value increases.

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. In this paper the authors have also developed the analysis and calculation of the minimum and maximum speeds, for self-excitation to occur, for a particular value of capacitance.

2. SELF-EXCITED INDUCTION GENERATOR MODELLING

The model for the SEIG is similar to that of the induction motor. To model the SEIG effectively, the parameters should be measured accurately. The parameters used in the SEIG can be obtained by conducting tests on the induction generator when it is used as a motor. The traditional tests used to determine the parameters are the open circuit (no load) test and the short circuit (locked rotor) test. Grantham et al. [12] described a method of determining the actual values of parameters rapidly and this method of parameter determination is used in this paper.

The induction machine used as the SEIG in this investigation is a three-phase wound rotor induction motor with specification: 415V, 7.8A, 3.6kW, 50Hz, and 4 poles. The conventional or the steady state model is used by other authors to model the SEIG [10, 11, 13]. In this paper the d-q model is used because it is easier to get the complete solution, transient and steady state, of the self-excitation. The parameters given in the d-q equivalent circuit shown in Fig.1 are obtained by conducting parameter determination tests on the above mentioned induction machine. As it is a wound rotor induction machine there is no variation of rotor parameters with speed. The parameters obtained from the test at rated values of voltage and frequency are $L_{ls}=L_{lr}=11.4$mH, $L_m=180$mH, $R_s=1.66\Omega$, $R_r=2.74\Omega$. 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.

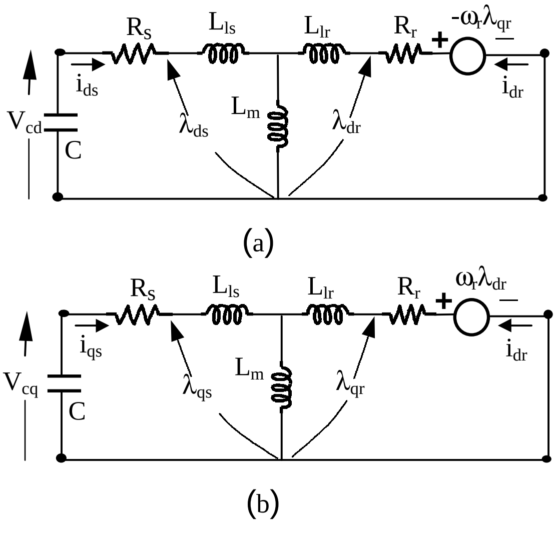


Fig. 1 D-Q model of SEIG at no load a) d-axis b) q-axis.

$$\begin{bmatrix}0\\0\\0\\0\end{bmatrix}=\begin{bmatrix}R_s+pL_s+1/pC & 0 & pL_m & 0\\ 0 & R_s+pL_s+1/pC & 0 & pL_m\\ pL_m & -\omega_r L_m & R_r+pL_r & -\omega_r L_r\\ \omega_r L_m & pL_m & \omega_r L_r & R_r+pL_r\end{bmatrix}\begin{bmatrix}i_{qs}\\i_{ds}\\i_{qr}\\i_{dr}\end{bmatrix} \quad (1)$$

In the above matrix equation $L_s=L_{ls}+L_m$ and $L_r=L_{lr}+L_m$. The initial conditions for self-excitation, namely the remnant magnetic flux in the rotor and/or the initial charge in the capacitors are not considered because they will be cancelled when both sides are differentiated. Later the initial conditions will be taken into consideration for simulation.

As given by Grantham et al. [2], the expansion of Equation (1) leads to an 8th order differential equation given by:

$$[Ap^4+Bp^3+Cp^2+Dp+E]^2+[Gp^2]^2=0 \quad (2)$$

(Correct expression, there is an error in the paper Reference [2])

Where

$$A=L_r^2L_sc-L_m^2cL_r$$

$$B=L_r^2R_sc+2R_rL_rL_sc-L_m^2cR_r$$

$$C=L_r^2+2R_rL_rcR_s+(R_r^2+\omega^2L_r^2)L_sc-L_m^2c\omega^2L_r$$

$$D=2R_rL_r+(R_r^2+\omega^2L_r^2)R_sc$$

$$E=R_r^2+\omega^2L_r^2$$

$$G=L_m^2c\omega R_r \text{ and } p=d/dt$$

During the steps in the analysis of the above differential equation, the final 8th order differential equation can be divided, or reduced, by the term $L_r^2p^2+2R_rL_rp+\omega_r^2L_r^2+R_r^2$ and this results in an expression with a sixth order differential equation. Whether it is an 8th order or a 6th order differential equation the points of self-excitation remains the same, because the two roots that can be obtained by factorizing $L_r^2p^2+2R_rL_rp+\omega_r^2L_r^2+R_r^2=0$ are $p+(R_r-j\omega_rL_r)/L_r=0$ and

$$p+(R_r+j\omega_rL_r)/L_r=0 .$$

The real part of these two roots will always be negative, whatever the speed and capacitance values are, whereas a positive root is required for self-excitation. However, the mathematics for finding the roots in the 6th order case is simpler than for the 8th order case.

3. MINIMUM SPEED AND CAPACITANCE FOR SELF-EXCITATION

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. The minimum speed for the onset of self-excitation can be obtained by solving the roots of the 8th order polynomial equation give in Equation (2) or its simplified version which is a 6th order and then searching if there is a positive real part of the root. Using this technique, at no load, the points of self-excitation are given in Fig. 2.

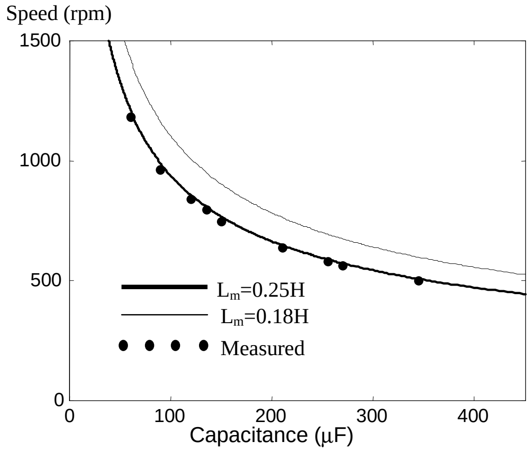


Fig. 2 Values of capacitance and speed for self-excitation at no load.

Fig. 2 compares calculated and measured results and also shows the effect of magnetizing inductance on the onset of self-excitation by using the rated voltage value of L_m (i.e. 0.18H) and the unsaturated value of 0.25H. The different values of L_m are obtained from Fig.3.

4. EFFECT OF MAGNETISING 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 up and stabilization.

If the rated L_m, 0.178H, is used for determining the onset of self-excitation there will be an error as shown in Fig. 2 represented by the curve in broken line.

The magnetizing inductance, L_m, used in this experimental setup is given in Fig. 3, where the dots are experimental results and the curve is fourth order curve fit given by

$$L_m = -1.56\times10^{-11}V_{ph}^4 + 2.44\times10^{-8}V_{ph}^3 - 1.19\times10^{-5}V_{ph}^2 + 1.42\times10^{-3}V_{ph} + 0.245 \quad (3)$$

Where V_{ph} is the phase voltage. As can be observed in Fig. 3, L_m starts from a smaller value then increases to reach its peak value and finally starts to drop. This change in L_m is due to the characteristics of the magnetizing curve and the fact that

$$L = N\frac{d\phi}{di} \quad (4)$$

As can be seen in Fig. 3, at the start of self- excitation-point *A*, where the voltage is close to zero, L_m is close to 0.25H. Once self-excitation starts the generated voltage will grow and then L_m also increases up to point *B*. 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.

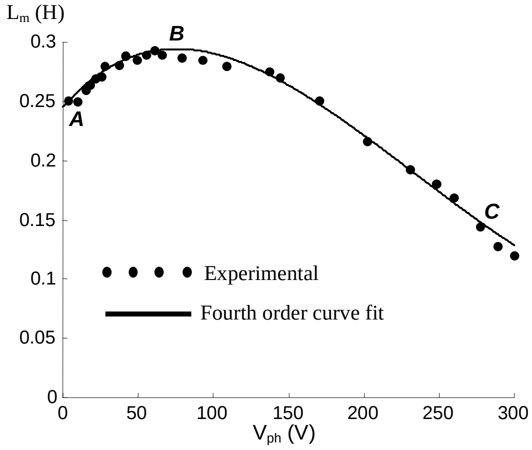


Fig. 3 Variation of magnetizing inductance with phase voltage.

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 a 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 L_m increases to have a new steady state operating point at lower voltage.

5. VARIATION OF SPEED WHILE THE SEIG IS CONNECTED TO A LOAD

The SEIG can be loaded with a resistive load by connecting a resistive load, R_L, across the capacitor, C, shown in Fig. 1. With resistive load Equation 1 is modified to the following equation.

$$\begin{bmatrix}0\\0\\0\\0\end{bmatrix}=\begin{bmatrix}R_s+pL_s+\dfrac{R_L}{1+R_LpC} & 0 & pL_m & 0\\ 0 & R_s+pL_s+\dfrac{R_L}{1+R_LpC} & 0 & pL_m\\ pL_m & -\omega_rL_m & R_r+pL_r & -\omega_rL_r\\ \omega_rL_m & pL_m & \omega_rL_r & R_r+pL_r\end{bmatrix}\begin{bmatrix}i_{qs}\\i_{ds}\\i_{qr}\\i_{dr}\end{bmatrix} \quad (5)$$

Solving Equation (5) gives a solution similar to that for Equation (2). Analyzing in a similar way, as discussed in Section 2, the curves in Fig. 4 are obtained for different load resistors.

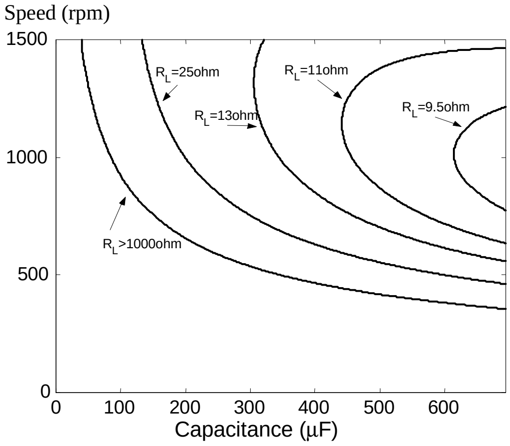


Fig. 4 Required capacitance and speed for self-excitation with load, R_L.

At a given capacitance value the wind speed can vary without any warning. Without load the SEIG requires only a minimum speed for self-excitation, but loaded SEIG requires a minimum and maximum speed for self-excitation as shown in Fig. 4. When R_L is large the characteristic is similar to the no load self-excitation case. If R_L is small, larger load, there is a minimum and maximum speed to produce self-excitation at a particular capacitance value.

The curves in Fig. 4 help to find the minimum and maximum speed set points for a given capacitance value. Once the minimum and maximum speed points are obtained, the speed range for a safe generating range can be identified. It is clear that a loaded generator has different onset of self-excitation characteristics at different load resistance. This helps also to determine the speed range for the steady-state generating characteristic of the SEIG. At high load resistance or at no load the maximum speed is so high that it is not necessary to take that into consideration.

6. SIMULATION OF SEIG USING SIMNON

SIMNON [14] simulation software is used to predict the generated voltage from a given three phase induction machine rotating at a given speed with appropriate capacitors connected at the stator terminals. The simulation result shows that self-excitation can be identified and the effects of different values of initial conditions on self-excitation investigated.

Derived from Equation (1) and including initial conditions, i.e. initial voltage in the capacitors and remnant magnetic flux in the core, one can obtain the following differential equation.

$$pI = AI + B \quad (6)$$

Where $I=\begin{bmatrix}i_{qs}\\i_{ds}\\i_{qr}\\i_{dr}\end{bmatrix}$ $\quad B=\dfrac{1}{L}\begin{bmatrix}L_mK_q-L_rV_{cq}\\L_mK_d-L_rV_{cd}\\L_mV_{cq}-L_sK_q\\L_mV_{cd}-L_sK_d\end{bmatrix}$

$$V_{cq}=\frac{1}{C}\int i_{qs}dt+V_{cq}\Big|_{t=0},\ V_{cd}=\frac{1}{C}\int i_{ds}dt+V_{cd}\Big|_{t=0}$$

$$A=\frac{1}{L}\begin{bmatrix}-L_rR_s & -L_m^2\omega_r & L_mR_r & -L_m\omega_rL_r\\ L_m^2\omega_r & -L_sR_s & L_m\omega_rL_r & L_mR_r\\ L_mR_s & L_s\omega_rL_m & -L_sR_r & L_s\omega_rL_r\\ -L_s\omega_rL_m & L_mR_s & -L_s\omega_rL_r & -L_sR_r\end{bmatrix}$$

and $L = L_sL_r - L_m^2$.

K_d and K_q are constants which represent the initial induced voltages along the d-axis and q-axis respectively due to remnant magnetic flux in the core. The simulation of self-excitation in one of the phases of the SEIG, using SIMNON, is given in Fig. 5.

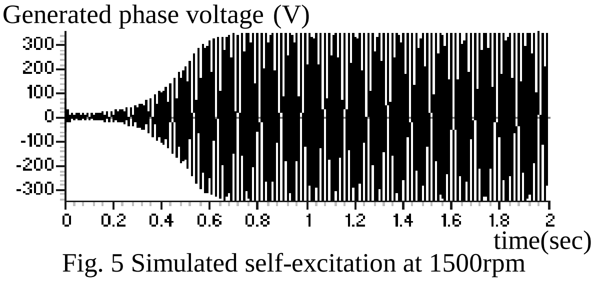
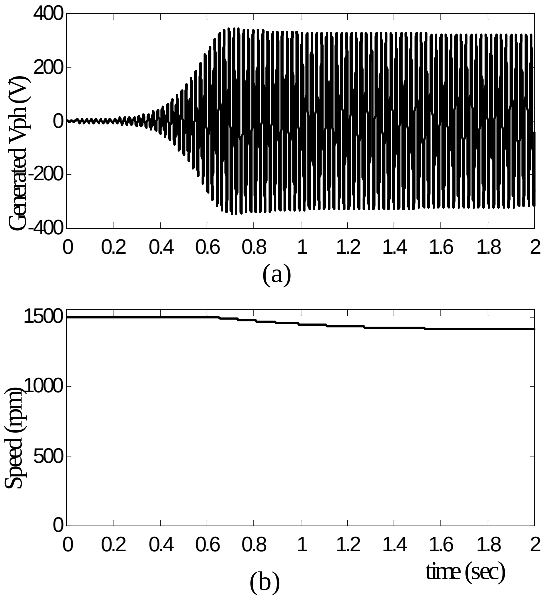


Fig. 5 Simulated self-excitation at 1500rpm and 60μF.

7. EXPERIMENTAL RESULTS

The induction machine was operated at 1500rpm driven by a DC motor. Then a star connected capacitor bank of 60μF was switched across the terminals of the stator of the induction machine.

The developed rated voltage in phase-a and the variation of speed are shown in Fig. 6. As can be observed from Fig. 6, the magnitude of the voltage obtained experimentally is in agreement with the simulated one shown in Fig. 5. The speed has dropped because of the electrical losses in the induction machine associated with the developed voltage. Due to this drop in speed there is a slight drop in the magnitude of the generated voltage.



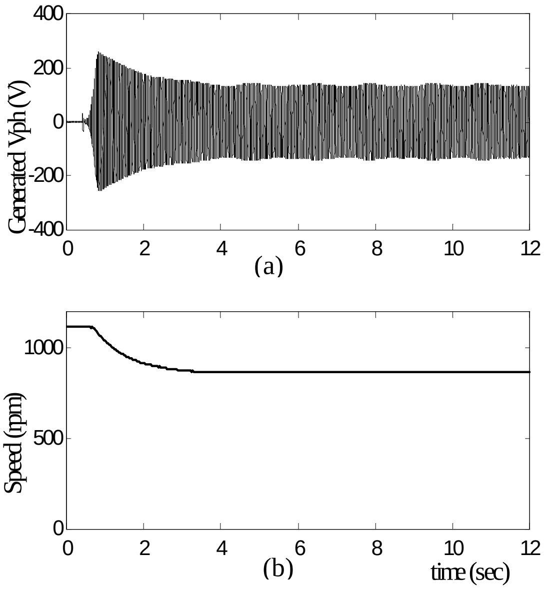
(a)

(b)

Fig. 6 Measured self-excitation at 60μF
(a) generated voltage (b)speed.

Fig. 7 shows self-excitation at lower speeds and the corresponding generated lower voltage. At start due to the transient the voltage builds up to its maximum value. Due to the kinetic energy stored in the rotating parts the speed will take some time to drop. The speed drops due to the electrical power losses in the induction motor and the DC motor that was used as a prime mover. Here the drop in speed is exaggerated because of the power loss in the resistor inserted in series with the DC armature to control the speed by armature voltage control.

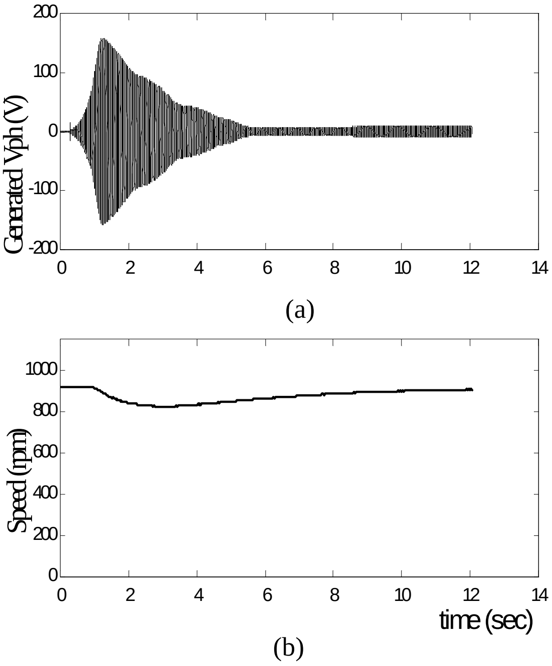
Finally the SEIG was operated between point *B* and *C* of Fig. 3 but very close to point *B*. In this case at the steady lowest speed it will continue to generate minimum steady voltage. Once the speed drops below point *B* there will not be steady voltage generation, i.e. there will be loss of self excitation. If the SEIG is started from zero and reaches the steady low speed mentioned previously, it can not self-excite. From Fig. 3 we can observe that to the right and left of point *B* the magnetizing inductance will have the same value but corresponding to different voltages. L_m to the right of *B* produces steady voltage generation.



(a)

(b)

Fig.7 Measured self-excitation at 60μF
(a) generated voltage (b)speed.



(a)

(b)

Fig.8 Measured self-excitation at 60μF
(a) generated voltage (b)speed.

Fig. 8 explains the operation of the induction generator between point *A* and point *B* of Fig. 3. When the capacitors are connected, due to the transient, voltage will build up but it is not able to go beyond point *B*. Even if it is heading to go beyond point *B* the voltage is dropping to the region to the left of point *B* as a result of speed drop associated with losses in the electrical system. A decrease in voltage will result in a decrease of L_m, which in turn decreases the generated voltage. Once the voltage collapses there is no transient phenomenon and there will not be voltage build up when the speed increases once again to its initial value. Increasing the speed slowly while keeping the operating point between point *A* and *B* has the effect of losing the remnant magnetic flux of the machine and the machine will not self-excite even at 1500rpm. This has also been proved experimentally.

8. CONCLUSION

The variation in magnetizing inductance is the main variable that influences whether there will be steady state voltage generation or not in a SEIG. Use of the variation in magnetizing inductance leads to an accurate prediction of whether or not self-excitation will occur for various capacitance values and speeds in both the loaded and unloaded cases. Once self-excitation has been initiated and a steady state condition has been reached, the speed at which self-excitation ceases is always lower than the speed to initiate self-excitation. A negative slope in whereby the L_m decreases with increased voltages represent a stable operating region. When the voltage drops the L_m increases and sets a new operating point. A positive slope of L_m represents unstable operating region and this is confirmed using the experimental result. As 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.

There is a minimum and maximum speed for which self-excitation can occur without disconnecting the load. A loaded SEIG operating with a specific capacitance can lose its self-excitation if the speed is increased above or decreased below given values. It can be concluded that for a loaded SEIG higher speed is not a guarantee for self-excitation. At no load the limit for high speed is the mechanical rating of the machine.

For self-excitation it is not only the values of capacitance and speed that matters but how these two variables are applied. If the speed is increased slowly such that the voltage does not rise beyond a value corresponding to the maximum L_m, there will be no self-excitation. With this condition there is a possibility of loss of remnant magnetic flux from the core. Once the remnant magnetic flux is lost the induction machine has to be run as a motor or the capacitors should be pre-charged to enable the onset of self-excitation.

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