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A Review on Various Approaches for Determination of Excitation Capacitance of a Three Phase Self Excited Induction Generator

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ABSTRACT*: The depletion of fossil fuels in the world, has given rise to the importance of non-conventional energy sources. Wind turbines and micro hydro generators with induction generators are considered as an alternative choice. Wind turbines with Self-excited Induction Generators (SEIGs) are increasingly being used to generate clean renewable energy. SEIGs are widely being used in isolated areas (rural areas) to generate electrical energy. Capacitor banks are used with a purpose to provide reactive power for its excitation. This paper presents the various approaches for determining the excitation capacitance required to build-up voltage for isolated operation of a self-excited induction generator.*

Keywords: self*-excited induction generator, excitation capacitance, steady state model, transient model*

Nomenclature:

S = generator's kVA input

C_o = output coefficient

B_{av} = average flux density in the air gap

a_c = specific electric loading

K_w = winding factor

D = air gap diameter

L = core length

n_s = synchronous speed

X_c = capacitive reactance

F = per unit frequency

I. INTRODUCTION

With the depletion of energy sources worldwide, every effort is made to convert other forms of non-conventional energies into electrical energy. Therefore energy recovery schemes are becoming an important aspect of present day industrial processes. In the coastal areas, wind energy is available in abundance. The wind turbine traps the wind energy and converts mechanical power to electrical power. This can be accomplished by an electric generator which can be a DC machine, a synchronous machine, or an induction machine. The presence of commutators in DC machines makes it low reliable and increases the maintenance costs. The synchronous generators are suitable for constant speed systems. Permanent magnet synchronous generators are not suited for isolated operation, since their generated voltage tends to fall steeply with load.

For the conversion of the wind energy into electrical energy, an induction machine coupled with a windmill offers an ideal solution. They are of two types. Wound rotor type is expensive and requires increased maintenance, therefore only used where (i) the driven load requires speed control or (ii) high starting torque is required. Hence it is a preferred choice in grid connected wind generation schemes. In grid connected mode (without using converters), the terminal voltage and frequency of the generator are fixed and determined by the grid. The squirrel cage type is simpler and more economical in construction. It is more rugged and requires less maintenance. This is widely used in isolated wind power generation schemes.

Roger, Sharaf and Elgammal [1] present the analytical d-q model to obtain maximum wind energy capture. SEIG is modelled from the stator side with eigen value solution of the characteristic equations. Design equations to describe self-excitation, loss of excitation and voltage regulation are presented here.

R.C. Bansal [2] gives an overview of the three phase self excited induction generator, its classification and a detailed survey of the literature on SEIG that discusses the process of self excitation and voltage build up, modelling, steady state, and transient analysis, reactive power control methods, and parallel operation.

A review on the various approaches carried out to determine the excitation capacitance has been discussed here. Section II explains the voltage build up process with the increasing capacitor current. Section III describes the various methods involved in determining the excitation capacitance. It further discusses the approaches involved using both models – Steady state model and Transient model. Section IV concludes the distinctive features observed from the study of different approaches.

II. SELF EXCITED INDUCTION GENERATOR

When an induction machine is driven by an external prime mover at a speed greater than the synchronous speed (negative slip) the direction of induced torque is reversed and it starts working as an induction generator. The real power flows out of the machine but the machine needs the reactive power. The main drawback of induction generator in wind energy conversion systems applications is its need for leading reactive power to build up the terminal voltage and to generate electric power. Using terminal capacitor across generator terminals can generate this leading reactive power. For an isolated mode, there must be a suitable capacitor bank connected across the generator terminals. This phenomenon is referred to as capacitor self-excitation and the induction generator is called a SEIG".

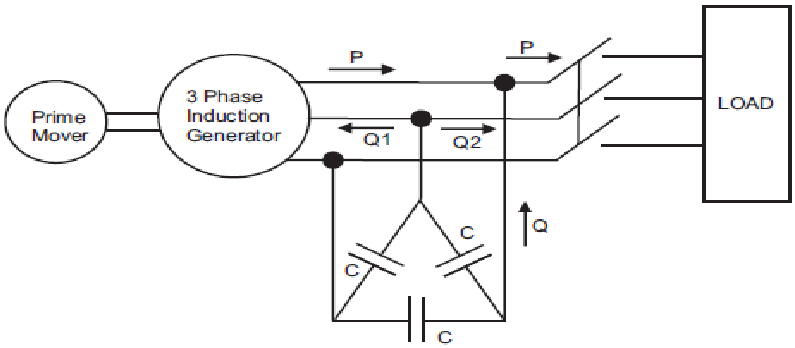


Fig. 2(a) self excited induction generator

The voltage build up process in an induction motor has been explained.

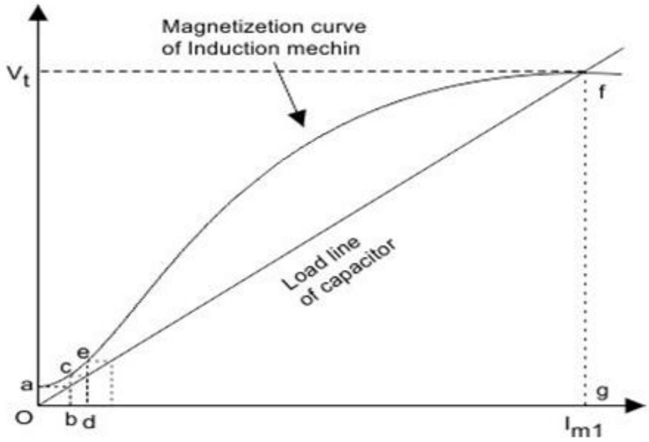


Fig. 2(b) voltage build up in a 3ϕinduction generator.

When the rotor of induction machine is run at the required speed, residual magnetism present in the rotor iron generates a small terminal voltage o-a across stator terminals. This voltage produces a capacitor current o-b. This current creates a flux which aids the residual flux, thus producing more flux and therefore more generated voltage across stator terminals represented by b-c. This voltage sends a current o-d in the capacitor bank which eventually generates voltage d-e. This cumulative process of voltage build up continues till the saturation curve of induction generator intersects the capacitor load line as shown by point f, thus giving a no-load generated emf. The voltage build up depends upon the value of capacitor. Higher the value of capacitance, greater is the voltage build up.

The connection of a set of three static condensers across the terminals of a 3- □ induction motor results in the addition of a constant leading component to the current taken.

III. DETERMINATION OF EXCITATION CAPACITANCE

The design and construction of three phase, 220/380V, 3.4/2.0A, 4 poles, 0.75 kW self-excited induction generator is explained. The design is based on the output equation of A. C. machines i.e. the generator kVA input that depends on the size of the capacitor used [3].

$$S = C_o D^2 L n_s \tag{1}$$
$$C_o = 1.1\pi^2 B_{av} a_c K_w \times 10^{-3} \tag{2}$$

If B_{av} is high, C_o will be high which means that the input kVA is high. The efficiency is given as the ratio of output power to input kVA.

$$\text{efficiency} = \frac{\text{output power}}{\text{inputkVA}} \tag{3}$$

High input kVA gives larger values of the capacitor for self-excitation but a reduced efficiency. The larger value of the capacitor gives an increased build up voltage as explained earlier and hence better excitation. But at the same time, reduced efficiency gives lower capability of generation and higher cost of construction.
The voltage and frequency of an isolated self-excited induction generator (SEIG) are not fixed and depends upon the generator parameters and excitation capacitance. Hence it is necessary to determine the sufficient value of the excitation capacitance. Various approaches to determine the capacitance required to excite a self-excited induction generator have been reported here. There are two approaches:

- Steady state model (Per Phase Equivalent Circuit Approach)
  - ➢ Loop Impedance Approach
  - ➢ Nodal Admittance Approach
  - ➢ LC Resonance Principle

- Transient model (d-q axis model approach)

3.1 The per phase equivalent circuit involving Loop impedance method and Nodal admittance method is suitable for studying machines steady state characteristics. In these methods iterative solutions are used to solve non-linear simultaneous equations in per unit frequency. This gives the maximum and minimum values of the excitation capacitance.

3.1.1 Loop impedance approach

The basic equations using loop impedance approach are derived from Fig. 3(a) . The method evaluates the steady state performance characeristics of a SEIG under various operating conditions. It is evaluated on a 1.5-kW induction generator driven by a regulated prime mover for various operating conditions. The stator current is found to be sensitive to the excitation capacitors used but insensitive to the output power of the generator[4].

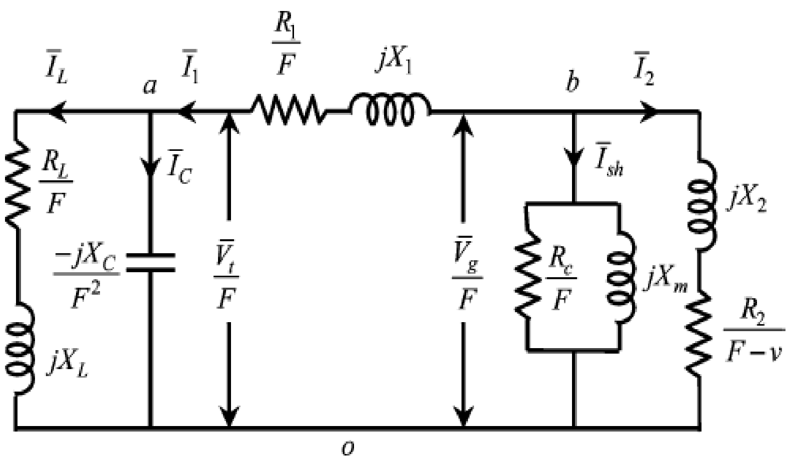


Fig. 3 (a) per phase equivalent circuit of a three phase SEIG

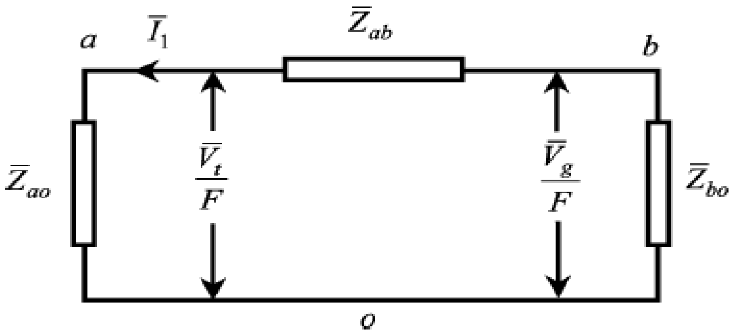


Fig. 3 (b) simplified representation of circuit of Fig. 3 (a)

The ratio of airgap voltage to frequency $\left(\frac{V_g}{F}\right)$ is expressed as:

$$\frac{V_g}{F} = k_1 + k_2 X_m + k_3 {X_m}^2 + k_4 {X_m}^3 \tag{4}$$

Synchronous speed test is used to find the coefficients k.
The series impedances are:

$$\bar{Z}ao = \left(\frac{1}{-\frac{jX_c}{F^2}} + \frac{1}{\frac{R_L}{F} + jX_L}\right)^{-1} \tag{5}$$

$$\bar{Z}ab = \left(\frac{R_1}{F} + jX_1\right) \tag{6}$$

$$\bar{Z}bo = \left(\frac{1}{\frac{R_c}{F}} + \frac{1}{jX_m} + \frac{1}{\frac{R_2}{(F-v)} + jX_2}\right)^{-1} \tag{7}$$

The loop equation is

$$I_1 (Z_{ao} + Z_{ab} + Z_{bo}) = 0 \tag{8}$$

Since $I_1 \neq 0$, $Z_{ao} + Z_{ab} + Z_{bo} = 0$ (9)

On separating the real and imaginary parts, non linear equations are obtained that are solved to obtain the magnetising reactance (X_m) and F for fixed values of capacitive reactance (X_c), machine speed(v) and load impedance (Z_L).

The terminal capacitor must have its value within a certain range to start self-excitation, beyond which self excitation is not possible [5]. Moreover, if the load impedance is below a certain value, self-excitation will not be achieved irrespective of the value of the excitation capacitor used. Here, the above mentioned loop impedance equations are used giving two simultaneous non-linear equations (generator impedance and the external impedance equations) equation (9), that are further solved using Newton Raphson method to obtain the capacitive reactance and hence the excitation capacitance. The value of capacitance can be selected so that the terminal voltage is constant, irrespective of the generator output power. It is further shown that under such conditions, the value of capacitance is influenced by the load as well as by the load power factor. The generator performance is however independent of the load power factor and is only affected by the magnitude of the load impedance.

The loop equations obtained from Fig. 3(a) for resistive load are solved using Newton Raphson method [6]:

$$Z_s = \frac{-\frac{jx_c R_L}{F^3}}{\frac{R_L}{F} - \frac{jx_c}{F^2}} + \left(\frac{R_s}{F} + jx_{ls}\right) + \frac{\left\{jx_m\left(\frac{R_r}{F-v} + jx_{lr}\right)\right\}}{\frac{R_r}{F-v} + j(x_m + x_{lr})} \tag{10}$$

On separating the real and imaginary parts, non linear equations are obtained that are solved to obtain the magnetizing reactance (X_m) and F for fixed values of capacitive reactance (X_c), machine speed(v) and load (R_L).

3.1.2 Nodal admittance approach

Nodal admittance equations are obtained for the following equivalent circuit [7]

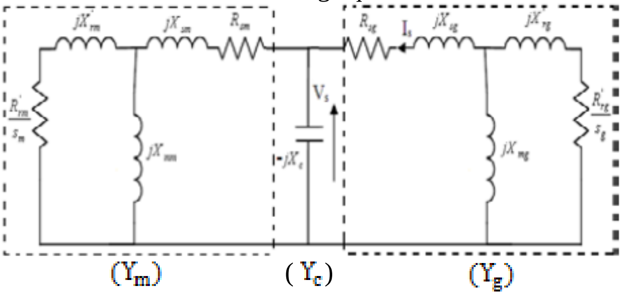


Fig. 3 (c) Per Phase Equivalent Circuit of Self Excited Induction Generator Feeding an Induction Pump Motor

The nodal current equation is given as:

$$V_s\left(Y_g + Y_c + Y_m\right) = 0 \tag{11}$$

where

$$Y_c = j\frac{a}{X_c} \tag{12}$$

$$Y_g = \frac{Y_{g_1}(Y_{g_2}+Y_{g_3})}{Y_{g_1}+Y_{g_2}+Y_{g_3}} \tag{13}$$

$$Y_{g_1} = \frac{1}{R_{sg}+jaX_{sg}}, Y_{g_2} = \frac{1}{jaX_{mg}}, Y_{g_3} = \frac{1}{\frac{aR_{rg}}{a-b}+jaX_{rg}} \tag{14}$$

where a is p.u frequency and b is p.u speed

$$\mathrm{Y_m} = \frac{1}{\mathrm{R_M} + \mathrm{jX_M}} = \frac{\mathrm{R_M}}{\mathrm{R_M}^2 + (\mathrm{X_M})^2} - \frac{\mathrm{X_M}}{\mathrm{R_M}^2 + (\mathrm{X_M})^2} \tag{15}$$

Under steady state self excitation, $Y_m \neq 0$, therefore $Y_g + Y_c + Y_m = 0$. On solving the real and imaginary terms we get

$$\frac{\mathrm{R_G}}{\mathrm{R_G}^2+(\mathrm{X_G})^2} - \frac{\mathrm{R_M}}{\mathrm{R_M}^2+(\mathrm{X_M})^2} = 0 \tag{16}$$

$$\frac{\mathrm{a}}{\mathrm{X_c}} - \frac{\mathrm{X_G}}{\mathrm{R_G}^2+(\mathrm{X_G})^2} - \frac{\mathrm{X_M}}{\mathrm{R_M}^2+(\mathrm{X_M})^2} = 0 \tag{17}$$

Substituting $R_M = \infty$ and $X_M = 0$ in (16) gives

$$a_{max} = b - \frac{b}{2}\left[\frac{1-\sqrt{1-\left(\frac{b_c}{b}\right)^2}}{1+\frac{R_{sg}}{R_{rg}}\left(1+\frac{X_{rg}}{X_{mg}}\right)^2}\right] \tag{18}$$

where

$$b_c = \frac{2R_{sg}}{X_{ms}}\sqrt{\frac{R_{rg}}{R_{sg}}\left(1+\frac{X_{rg}}{X_{mg}}\right)^2} \tag{19}$$

Substituting $R_M = 0$ and $X_M = \infty$ in (17) gives

$$X_c = a_{max}{}^2\left[X_{sg} + \frac{aX_{mg}\left((a-b)^2X_{rg}\left(X_{mg}+X_{rg}\right)+R_{rg}{}^2\right)}{(a-b)^2\left(X_{mg}+X_{rg}\right)^2+R_{rg}{}^2}\right] \tag{20}$$

Thus

$$C_{min} = \frac{1}{2\pi 50.X_c} \tag{21}$$

C_{min} is the minimum capacitance to provide the self excitation. Practically, terminal capacitor C with a value slightly greater than C_{min} should be selected to provide self excitation.
A method based on the combination of the principle of L-C resonance [8] and non linear magnetization characteristic of the generator is used from Fig. 3(d).

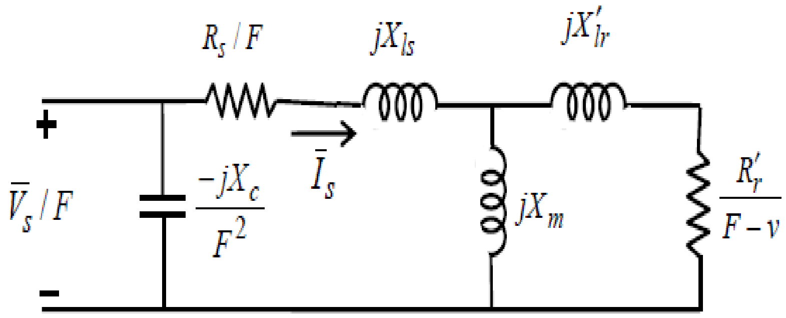


Fig. 3 (d) per phase steady state equivalent circuit of SEIG

The analysis is made by short circuiting the rotor terminals and adding an excitation capacitance across the stator terminals.

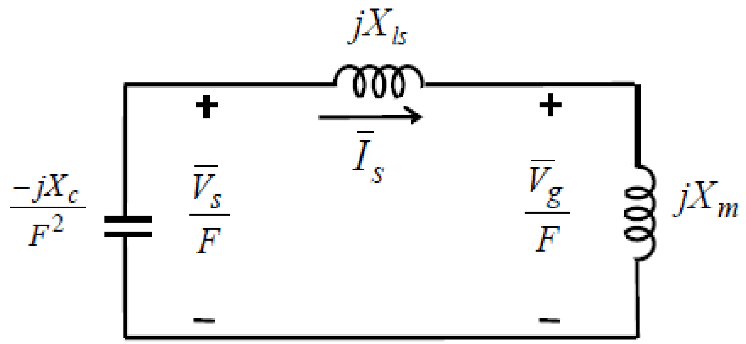


Fig. 3 (e) per phase equivalent circuit of a SEIG at no load

At no load the rotor is considered as an open circuit and the L-C circuit obtained in Fig. 3 (e) is used to determine the value of excitation capacitance. To generate a voltage, the circuit must be at resonance.
Therefore,

$$\frac{X_c}{F^2} = (X_{l_s} + X_m) \tag{22}$$

$$\frac{V_g}{F} = \frac{V_s}{F}\left[\frac{X_m}{X_{l_s}+X_m}\right] \tag{23}$$

Synchronous speed test results are obtained to find the relationship between $\frac{V_g}{F}$ and X_m, where V_g is airgap voltage, F is p.u frequency and X_m is the magnetising reactance. The relationship between V_s and X_m is obtained as

$$\frac{V_s}{F}\left[\frac{X_m}{X_{l_s} + X_m}\right] = k_0 + k_1 X_m + k_2 X_m{}^2 + k_3 X_m{}^3 \tag{24}$$

After determining the values of X_m and X_c, C can be obtained as $C = \frac{1}{2\Pi f b F^2 (X_{l_s}+X_m)}$ (25)

The no load saturation curve of induction machine is obtained at normal rated frequency as shown in Fig. 3 (f). The critical, minimum and maximum capacitance [9] required for excitation is calculated from the no load curve for voltage build up, rated voltage and current respectively, using the per phase equivalent circuit in Fig. 3 (a).

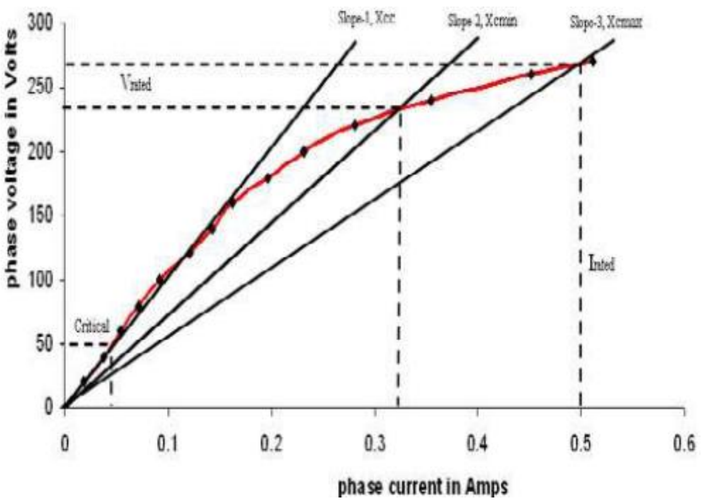


Fig. 3 (f) No Load Characteristics of Induction Machine

The slope of curve Fig. 3 (f) determines the different values of capacitor. It gives the critical capacitance, below which the voltage will never build up, the minimum capacitance to generate the rated voltage, and the maximum capacitance above which the current exceeds its rated value thus heating the stator core.

$$X_{CC} = \frac{\Delta V}{\Delta I} \qquad X_{Cmin} = \frac{V_{rated}}{I} \qquad X_{Cmax} = \frac{V}{I_{rated}} \tag{26}$$

3.2 The d-q axis model based on generalized machine theory is employed to analyze the machines transient as well as steady state characteristics.
The dynamics of an SEIG are expressed by deriving equations in synchronously rotating reference frame [9].

$$pi_{qs} = -K_1 r_s i_{qs} - (\omega_e + K_2 L_m \omega_r) i_{ds} + K_2 r_r i_{qr} - K_1 L_m \omega_r i_{dr} \tag{27}$$

$$pi_{ds} = (\omega_e + K_2 L_m \omega_r) i_{qs} - K_1 r_s i_{ds} + K_1 L_m \omega_r i_{qr} + K_2 r_r i_{dr} - K_1 V_{ds} \tag{28}$$

$$pi_{qr} = K_2 r_s i_{qs} + K_2 L_s \omega_r i_{ds} - [\frac{(r_r + K_2 L_m r_r)}{L_r}] i_{qr} + (K_1 L_s \omega_r - \omega_e) i_{dr} \tag{29}$$

$$pi_{dr} = K_2 r_s i_{ds} - K_2 L_s \omega_r i_{qs} - (K_1 L_s \omega_r - \omega_e) i_{qr} - [\frac{(r_r + K_2 L_m r_r)}{L_r}] i_{dr} + K_2 V_{ds} \tag{30}$$

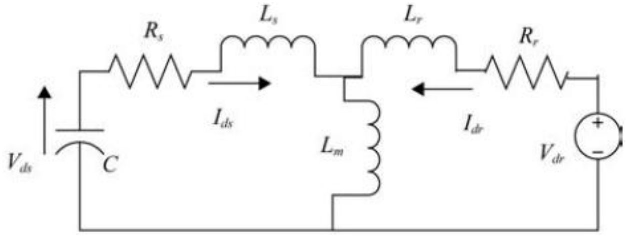
where

$$K_1 = \frac{L_r}{L_s L_r - L_m{}^2} \qquad K_2 = \frac{L_m}{L_s L_r - L_m{}^2} \tag{31}$$

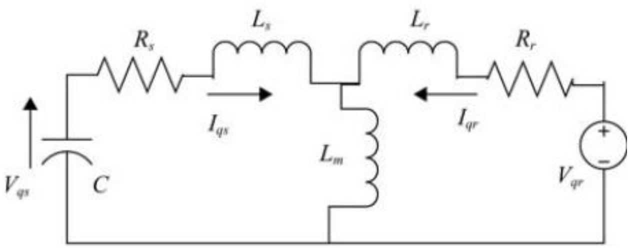
The SEIG is modelled and the dynamic response for varying loads and capacitances is simulated.

An "interval technique" [10] to determine the minimum capacitance required for self - excitation of a 3-phase induction generator using d-q axis model approach is proposed. Here, for a stationary reference frame, the terminal voltage equation is obtained by setting ω = 0. The terminal voltage equations are:

$$\begin{bmatrix} V_{qs} \\ V_{ds} \\ V_{qr} \\ V_{dr} \end{bmatrix} = \begin{bmatrix} R_s + pL_s + \frac{1}{pC} & 0 & pL_m & 0 \\ 0 & R_s + pL_s + \frac{1}{pC} & 0 & pL_m \\ pL_m & \omega_r L_m & R_r + pL_r & \omega_r L_r \\ \omega_r L_m & pL_m & \omega_r L_m & R_r + pL_r \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix} \tag{32}$$



(a)



(b)

Fig. 3 (g) d-q model of SCIG at no load (a) d-axis (b) q-axis

In Laplace form V(S) = A(S) I(S) (33)

where

$$A(s)=\begin{bmatrix} R_s + sL_s + \frac{1}{sC} & 0 & sL_m & 0 \\ 0 & R_s + sL_s + \frac{1}{sC} & 0 & sL_m \\ sL_m & \omega_r L_m & R_r + sL_r & \omega_r L_r \\ \omega_r L_m & sL_m & \omega_r L_m & R_r + sL_r \end{bmatrix}$$

Determinant of A(S) gives a 6th order differential equation, where on solving real and imaginary parts a pair of equations consisting of C and Lm are obtained.

$$-C^2X_1^2\omega^6 + \left(C^2\left(X_2^2 + X_1(2R_1R_2 + \omega_r^2X_1)\right) + 2CL_2X_1\right)\omega^4 - \left(C^2R_1^2X_3 + 2C(R_1R_2L_2 + R_2X_2 + \omega_r^2L_2X_1) + L_2^2\right)\omega^2 + X_3)\omega = 0 \tag{34}$$

$$C^2X_1X_2\omega^5 - (R_1(R_2X_2 + L_2\omega_r^2X_1)C^2 + (L_2X_2 + R_2X_1)C)\omega^3 + (R_1CX_3 + R_2L_2)\omega = 0 \tag{35}$$

These equations are solved to obtain the solutions for C and L_m.

Another stationary reference frame [11] (ω=0), to explain the effects of excitation capacitor and magnetization inductance on the induction generator, when operating as a standalone generator is analysed. Here it is shown that the SEIG is inherently capable of operating at variable speeds.

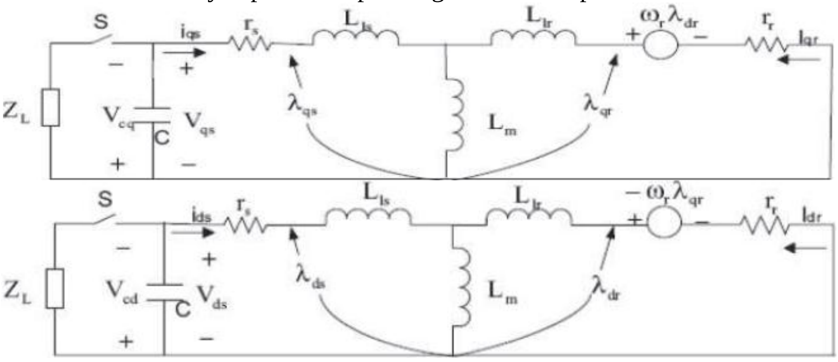


Fig. 3 (h) d-q model of SEIG in stationary reference frame

At no Load, the voltage equations are

$$\begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} r_s + pL_s + 1/pC & 0 & pL_m & 0 \\ 0 & r_s + pL_s + 1/pC & 0 & pL_m \\ pL_m & -\omega_r L_m & r_r + pL_r & -\omega_r L_r \\ \omega_r L_m & pL_m & \omega_r L_r & r_r + pL_r \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix} + \begin{bmatrix} V_{cqo} \\ V_{cdo} \\ K_q \\ K_d \end{bmatrix} \tag{36}$$

Where K_d and K_q are initial induced voltages along the d-axis and q-axis respectively due to the remaining magnetic flux in the core.

The expression for current components in matrix form can be expressed as:

pI = AI + B (37)

$$A = \frac{1}{L}\begin{bmatrix} -L_r r_s & -L_m^2\omega_r & L_m r_r & -L_m\omega_r L_r \\ L_m^2\omega_r & -L_r r_s & L_m\omega_r L_r & L_m r_r \\ L_m r_s & L_s\omega_r L_m & -L_s r_r & L_s\omega_r L_r \\ -L_s\omega_r L_m & L_m r_s & -L_s\omega_r L_r & -L_s r_r \end{bmatrix} \quad B = \frac{1}{L}\begin{bmatrix} L_m K_q - L_r V_{cq} \\ L_m K_d - L_r V_{cd} \\ L_m V_{cq} - L_s K_q \\ L_m V_{cd} - L_s K_d \end{bmatrix}$$

$$I = \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix}; V_{cq} = \frac{1}{C}\int i_{qs}dt + V_{cq}\,|t = 0\ ; V_{cq} = \frac{1}{C}\int i_{ds}dt + V_{cd}\,|t = 0 \qquad (38)$$

$$V_{qs} = -V_{cq} \qquad (39)$$

It is found that when the load is inductive the value of excitation capacitance should be increased in order to meet the reactive power requirement of the SEIG and the load.

IV. CONCLUSION

The squirrel cage induction generator due to its ruggedness, low cost of construction, less maintenance and suitability for isolated operation, is an inexpensive alternative to synchronous generators. For isolated generation in remote areas a variable capacitance is required to build up the voltage in a SEIG. The time required for voltage build up depends on the value of the capacitor used. Hence it is necessary to determine a proper value of the excitation capacitance used for early build up in voltage and better performance. Thus various methods for the determination of the excitation capacitance required in an induction generator have been studied extensively.

The per phase equivalent circuit model using loop and nodal equations involve highly non linear simultaneous equations in per unit frequency or magnetizing reactance using iterative methods that are time consuming. The circuit using LC resonance principle simply involves the determination of roots of a polynomial without involving complex algebraic manipulations. The per phase equivalent circuit model gives the steady state analysis but not the transient analysis.

The approaches involving d-q axis analysis of SEIG keep in consideration the transient behavior of the machine as well, in addition to the steady state performance. The d-q model using “interval technique” based novel method for determining the optimum value of the capacitance gives a range of possible values of excitation capacitances thus helping to select a suitable value for wider operating speed variations.

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