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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. The nonlinearity of the magnetizing inductance and the varying rotor speeds necessitates the calculation of excitation capacitance required for voltage build up in a SEIG. This paper presents the various approaches for determining the excitation capacitance and evaluates the value of excitation capacitor for 220/380V, 12.4/7.2A, 4 pole, 50Hz induction machine through various approaches, 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

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.

The magnetizing inductance value in an induction machine is a function of rotor speed and is non linear [1]. Therefore a range of capacitance value is required so that the machine is in excitation mode and the generator terminal voltage is within the limits. The capacitance needs to be tuned with varying rotor speeds and loading conditions, which is impractical due to interdependence of system variables, changing rotor speed and the system's nonlinearity. The capacitance value required is such that at a given rotor speed; the generated voltage in the stator windings does not undergo large transients. The induction generator needs to operate smoothly to give sustained generated voltages at the stator windings. Hence, the calculation of the capacitance value of the capacitor bank is very critical for the desired operation of the induction generator.

Roger, Sharaf and Elgammal [2] 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.

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R.C. Bansal [3] 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 calculation using various approaches has been carried out to determine the excitation capacitance for a particular rating of machine. 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 calculates the capacitance value using Steady state model – Nodal Admittance Approach and L C resonance principle for the given rating of machine. Section IV concludes the capacitance values calculated from 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". A 3 phase self excited induction generator is as shown in Fig. 2 (a):

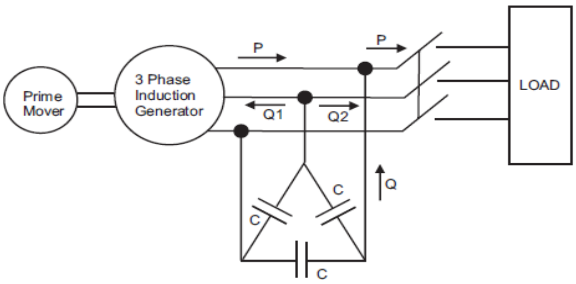

Fig. 2(a) self excited induction generator

The voltage build up process in an induction motor has been explained in Fig. 2 (b):

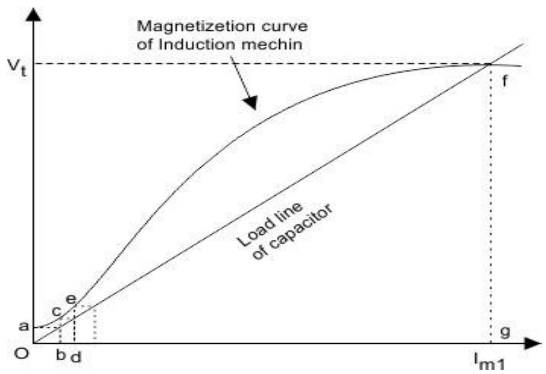

Fig. 2(b) voltage build up in a 3ϕ induction generator

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 3ϕ induction motor results in the addition of a constant leading component to the current taken.

III. DETERMINATION OF EXCITATION CAPACITANCE:

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. There are two approaches:

- Steady state model (Per Phase Equivalent Circuit Approach)
  - Nodal Admittance Approach
  - Loop Impedance Approach
  - LC Resonance Principle
- Transient model (d-q axis model approach)

The value of capacitance for a three-phase squirrel cage induction generator with specification: 3Kw, 220/380V, 12.4/7.2A, 4 pole, 50Hz, R_s=2.2Ω, R'_r=2.68Ω, L_s=L_r=229mH, L_m=f (I_m), has been calculated using different methods.

3.1. Nodal Admittance Approach:

Nodal admittance equations are obtained for the following equivalent circuit [4]

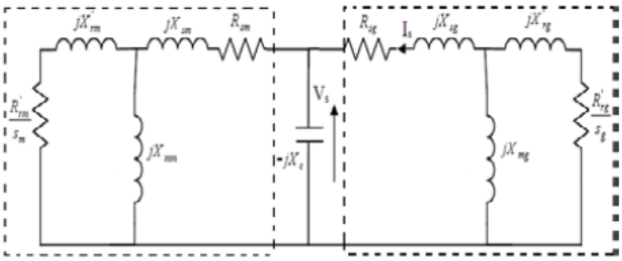

Fig. 3 (a) Per Phase Equivalent Circuit of Self Excited Induction Generator Feeding an Induction Motor Pump

The nodal current equation is given as:

$$V_s(Y_g + Y_c + Y_m) = 0 \quad (1)$$

where

Y_g is the total admittance of induction generator.

Y_c is capacitive admittance

and Y_m is the total admittance of induction motor

$$Y_c = j\frac{a}{X_c} \quad (2)$$

$$Y_g = \frac{Y_{g1}(Y_{g2}+Y_{g3})}{Y_{g1}+Y_{g2}+Y_{g3}} \quad (3)$$

$$Y_{g1} = \frac{1}{R_{sg}+jaX_{sg}}, Y_{g2} = \frac{1}{jaX_{mg}}, Y_{g3} = \frac{1}{\frac{aR_{rg}}{a-b}+jaX_{rg}} \quad (4)$$

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

Table 1: The variation of frequency with speed at base speed = 1500rpm for a 4 pole machine is given as:

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Speed (PU)	Frequency (PU)	Speed (PU)	Frequency (PU)
1	0.9987	0.6	0.5978
0.9	0.8986	0.5	0.4974
0.8	0.7984	0.4	0.3967
0.7	0.6982	0.3	0.2955

For calculations the p.u speed (b) is taken as 0.3 and the p.u frequency (a) as 0.2955.

$$Y_m = \frac{1}{R_M + jX_M} = \frac{R_M}{{R_M}^2 + (X_M)^2} - \frac{X_M}{{R_M}^2 + (X_M)^2} \quad (5)$$

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

$$\frac{R_G}{{R_G}^2 + (X_G)^2} - \frac{R_M}{{R_M}^2 + (X_M)^2} = 0 \quad (6)$$

$$\frac{a}{X_c} - \frac{X_G}{{R_G}^2 + (X_G)^2} - \frac{X_M}{{R_M}^2 + (X_M)^2} = 0 \quad (7)$$

The expression for a_{max} on substituting $R_M = \infty$ and X_M=0 in equation (6), is given as

$$a_{max} = b - \frac{b}{2}\left[\frac{1-\sqrt{1-\left(\frac{b_c}{b}\right)^2}}{1+\frac{R_{sg}}{R_{rg}}\left(1+\frac{X_{rg}}{X_{mg}}\right)^2}\right] \quad (8)$$

Further substituting all the values, we obtain a_{max} = 0.2954

where

$$b_c = \frac{2R_{sg}}{X_{ms}}\sqrt{\frac{R_{rg}}{R_{sg}}\left(1+\frac{X_{rg}}{X_{mg}}\right)^2} = 0.1505 \quad (9)$$

Substituting $R_M = \infty$ and $X_M = 0$ in (7) gives

$$X_c = {a_{max}}^2\left[X_{sg} + \frac{aX_{mg}\left((a-b)^2 X_{rg}(X_{mg}+X_{rg}) + {R_{rg}}^2\right)}{(a-b)^2(X_{mg}+X_{rg})^2 + {R_{rg}}^2}\right] = 6.4078 \quad (10)$$

Thus

$$C_{min} = \frac{1}{2\pi 50.X_c} = 496.75\ \mu F \quad (11)$$

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.

3.2. L C Resonance Principle:

A method based on the combination of the principle of L-C resonance and non linear magnetization characteristic of the generator is used from Fig. 3(b). [5]

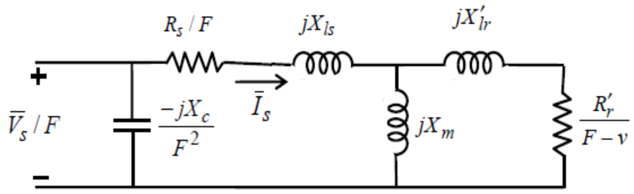

Fig. 3 (b) per phase steady state equivalent circuit of SEIG

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

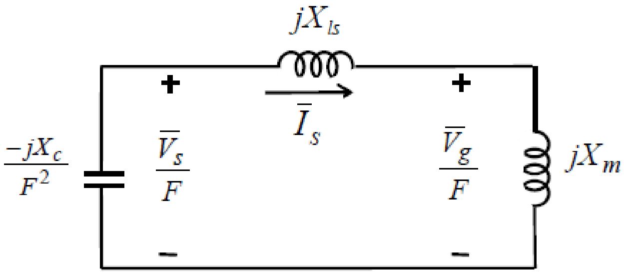

Fig. 3 (c) per phase equivalent circuit of a SEIG at no load

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

Therefore,

$$\frac{X_c}{F^2} = \left(X_{l_s} + X_m\right) \tag{12}$$

$$\frac{V_g}{F} = \frac{V_s}{F}\left[\frac{X_m}{X_{ls} + X_m}\right] \tag{13}$$

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

$$\frac{V_s}{F}\left[\frac{X_m}{X_{ls} + X_m}\right] = k_0 + k_1 X_m + k_2 {X_m}^2 + k_3 {X_m}^3 \tag{14}$$

After determining the values of X_m and X_c, C can be obtained as $C = \frac{1}{2\Pi fb F^2 (X_{ls} + X_m)}$ (15)

On substituting, fb = 50, F = 0.2955 and $X_{ls} + X_m = X_s = 2\pi * 50 * L_s$ as specified above, the value of capacitance obtained is $506.69\mu F$.

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 an SEIG. For efficient conversion of wind energy into electrical energy the induction generator needs to operate smoothly, giving sustained generated voltage at the stator terminals without any transients. Therefore, calculation of the capacitance value of the capacitor bank is critical for the desired operation of the induction generator. Thus the value of excitation capacitance required has been calculated.

The circuit using LC resonance principle simply involves the determination of roots of a polynomial without involving complex algebraic manipulations. The calculated value of C using this principle is 506.69 μF. The nodal admittance approach calculates the value of capacitance as $496.75\mu F$. The per phase equivalent circuit model gives the steady state analysis but not the transient analysis.

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The calculated value of the excitation capacitance for the given input parameters is tabulated below:

Table 2: The calculated capacitance values:

Machine Input Parameters	Results (Calculated C_{min})	
	L C Resonance Principle	Nodal Admittance Approach
3Kw, 220/380V, 12.4/7.2A, 4 pole, 50Hz, R_s=2.2Ω, R_r=2.68Ω, L_s=L_r=229mH, L_m =217mH, p.u frequency a= 0.2955 and p.u speed b = 0.3	506.69 μF	496.75μF

Thus the value of capacitance required for self excitation in an induction generator has been calculated using Nodal admittance approach and LC resonance principle. The Nodal admittance approach gives a lower value of excitation capacitance. It requires greater and lengthy calculations as compared to the other method.

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