A Detailed Investigation on Performance Analysis of Self-Excited Induction Generator

Sunil Kumar Goyal[1], D.K. Palwalia[2]

Abstract— This paper presents a direct method derived from nodal analysis for computing the minimum value of capacitance required for initiating voltage build-up in a three-phase, self-excited induction generator. Steady state equivalent circuit model is taken into consideration for determination of p.u. frequency by solving a simple polynomial. All the real roots of the polynomial gives the corresponding value of excitation capacitance at no load as well as on load. This paper also deals with the detailed investigation of performance characteristics of self-excited induction generator. The effect of speed, magnetizing reactance, load impedance and power factor on the value of per-unit frequency, required excitation capacitance and their interdependence on each other is analyzed.

Keywords— induction generator, self-excitation, capacitance requirement

I. INTRODUCTION

The conventional source of generation of electrical energy are through conventional sources such as coal, oil, gas etc. The rapidly increasing use of conventional energy resources has resulted in increased energy cost, environmental pollution, green-house gas emission and global warming. Major limitations for electrification of rural, remote, hilly and far-flung areas are low electric load demands, uneconomical and technically difficult extensions of grid, which reflects requirement of stand-alone generating units for harnessing of electrical energy from nonconventional sources such as small hydro heads, wind and biogas [1]. It can be achieved by developing low cost isolated power generators. Induction generators are preferred over the synchronous alternators for stand-alone electric generation because of their relative advantages such as lower unit cost, little maintenance, operational simplicity, brushless and rugged construction, absence of DC source, good dynamic response, self-protection against faults and ability to generate power at varying speed [2]. In spite of a number of advantages, the self-excited induction generator suffers from inherent poor voltage and frequency regulation. The poor voltage regulation is the result of gaps between VARs supplied by capacitors and VARs demanded by load and machine [3-4].

Self-excitation is the major concern in the operation of stand-alone induction generator that needs leading reactive power to build up the terminal voltage and to generate electric power. This leading reactive power can generate by connecting capacitor across generator terminals. Total active power of load and other losses of the machine are supplied by the induction generator. Reactive power supplied by the capacitor bank meets the reactive power requirements of the load and the machine. The value of capacitance of terminal capacitor is not constant but it is varying with many system parameters like shaft speed, load power and its power factor. Self-excitation of induction generator is depending on the appropriate combination of speed, load and terminal capacitance in reference to the non-linear magnetization characteristics. The induction machine can be used as a Self-Excited Induction Generator (SEIG) [5-6] by connecting an appropriate capacitor bank across the terminals of induction machine. The exact value of excitation capacitance is required as the generation of voltage by induction generator is depending upon it [7]. Capacitance requirement of SEIG have investigated [8]. The process of voltage build-up in SEIG by using generalized theory and onset theory of self-excitation has analyzed [9]. Trial-and-error method is used to calculate excitation capacitance by [10], which is very complicated and gives the approximate value of excitation capacitance. Determination of exact value of excitation capacitance by some simple technique is required for the proper design and operation of induction machine as self-excited induction generator [11].

A small emf is induced at the terminals of induction machine due to the presence of residual magnetism in the rotor. With the speed increases, the capacitor impedance decreases, the excitation increases, and therefore the terminal voltage of the machine increases [12]. As the magnetic circuit of machine is saturated, this rise of voltage is small. The terminal voltage of induction generator depends upon the speed, load and value of capacitor. Murthy et al. [13] have presented the effect of variation in the machine parameters on its performance using design based computation procedure. Effect of speed and capacitance is also to be analyzed.

This paper presents a technique to analyze the steady state behavior by using per-phase equivalent circuit of SEIG and proposes a simple and more precise method to evaluate the value of excitation capacitance. This paper also deals with the computed performance of self-excited induction generator. The effect of speed, load, and magnetization reactance on excitation capacitance and p.u. frequency is analyzed.

II. STEADY STATE EQUIVALENT CIRCUIT

A simple method to compute the capacitance requirement of

[1]Department of Electrical Engg., Manipal University Jaipur-India
[2]Department of Electrical Engg., UCE, RTU, Kota-India).

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a Self-Excited Induction Generator is described in this paper. Main features of proposed method are;

i. It is based on Nodal Admittance method for steady state analysis of self-excited induction generator.
ii. In the equivalent circuit, the load and excitation capacitance branches are decoupled.
iii. A 6th degree polynomial is to be solved to compute the value of Cmin.
iv. As it is a direct method, no trial and error procedure is needed.

Per-phase equivalent circuit is used for calculating the capacitance requirement of the self-excited induction generator for maintaining a specific terminal voltage under load [14]. All the circuit parameters are assumed to be constant and unaffected by saturation except magnetizing reactance.

Fig. 1 shows the per-phase equivalent circuit [15] for steady state analysis of self-excited induction generator in which all the reactance and voltages are referred to the stator at base frequency. A minimum value of excitation capacitance is required to self-excite the machine. For that, machine must operate at threshold of saturation. Therefore, machine core losses can be ignored. According to magnetization curve it is clear that the magnetizing reactance Xm is varies with the load and circuit conditions.

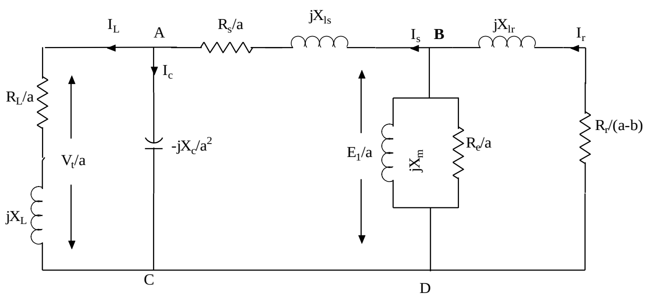

Fig. 1: Per-phase equivalent circuit of SEIG

Loop Impedance method and Nodal Admittance method are the two different approaches applied in the steady state analysis of self-excited induction generator. If the speed of machine is fixed and Xm is kept at minimum value, then the per unit frequency 'a' and capacitive reactance 'Xc' are the only variables in Fig. 1.

III. CALCULATION OF CAPACITANCE

Nodal admittance method is used in this paper. The calculation of per unit frequency a is independent of Xc, as load and excitation capacitance branches can easily be decoupled. For this purpose, Fig. 1 is redrawn as Fig. 2.

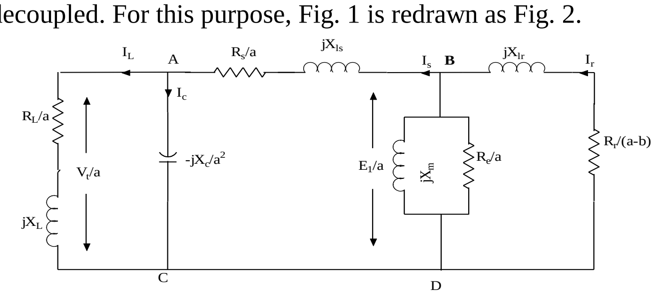

Fig. 2 Per-phase Simplified equivalent circuit of SEIG

Where

$$R_{cd} = \frac{(a-b)R_2X_m^2}{R_2^2 + (a-b)^2(X_m + X_2)^2} \quad ;$$

$$X_{cd} = \frac{R_2^2X_m + (a-b)^2 X_m X_2 (X_m + X_2)}{R_2^2 + (a-b)^2(X_m + X_2)^2}$$

The total impedance of branch ACDis given by

$$Z_{ad} = R_{ad} + jX_{ad} \tag{1}$$

Where

$$R_{ad} = \frac{R_1}{a} + R_{cd} \quad ; \quad X_{ad} = X_1 + X_{cd}$$

The relation for different admittances are;

$$Y_L = \frac{aR_L}{R_L^2 + a^2X_L^2} - j\frac{a^2X_L}{R_L^2 + a^2X_L^2}$$

$$Y_{ad} = \frac{R_{ad}}{R_{ad}^2 + X_{ad}^2} - j\frac{X_{ad}}{R_{ad}^2 + X_{ad}^2} \quad ; \quad Y_c = j\frac{a^2}{X_c} \tag{2}$$

Apply nodal admittance method in Fig. 2

$$Y_sV_s = \frac{V_1}{a}(Y_L + Y_{ad} + Y_c) = 0 \tag{3}$$

Since the stator voltage will not be zero for successful voltage build-up, V1 ≠ 0, hence Ys = 0.

$$(Y_L + Y_{ad} + Y_c) = 0 \tag{4}$$

By separating real and imaginary terms of the above equation (10) to zero respectively;

$$\frac{aR_L}{R_L^2 + a^2X_L^2} + \frac{R_{ad}}{R_{ad}^2 + X_{ad}^2} = 0 \tag{5}$$

$$\frac{a^2}{X_c} - \frac{a^2X_L}{R_L^2 + a^2X_L^2} - \frac{X_{ad}}{R_{ad}^2 + X_{ad}^2} = 0 \tag{6}$$

The value of per unit frequency a will be determined from equation (5), as per unit frequency is the only variable in equation (5) and is independent of Xc. The value of Xc can be calculate from equation (6) by putting the value of a from equation (5).

Equation (5) can be expressed as a 6th degree polynomial as follows after a series of algebraic manipulations [16];

$$h_6a^6 + h_5a^5 + h_4a^4 + h_3a^3 + h_2a^2 + h_1a + h_0 = 0 \tag{7}$$

All the real and complex roots can be determined by solving equation (7). Only real roots are to be considered, and the largest positive real root gives the minimum capacitance Cmin [17].

IV. RESULTS AND OBSERVATIONS

Frequency and magnetizing reactance are calculated for known load, speed and capacitance to estimate the functioning of machine. The excitation requirement in terms of capacitance is computed for a desired level of voltage and speed. An algorithm is developed to calculate the value of capacitance required for obtaining constant terminal voltage by using magnetization curve between Vg/f and Xm.

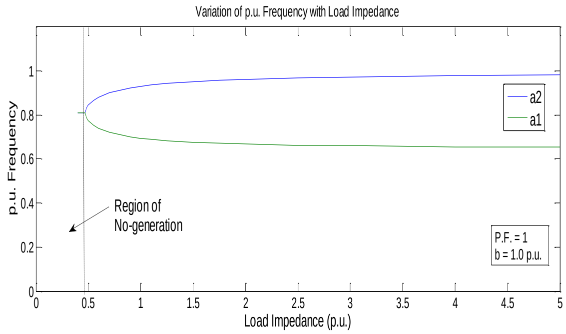

Fig. 3 Variation of p.u. frequency with Load Impedance (at unity power factor, b=1.0 p.u. and X_m = 1.5)

Roots of equation (13) is evaluated for various load impedance, speed and power factor condition for R-L loads. There are six roots, out of which, two roots are real and remaining four roots are in form of two pair of complex conjugate roots in general. The degree of equation is 4 for purely inductive load and there are two real and one pair of complex conjugate roots. The induction generator fails to excite irrespective of the value of excitation capacitance below a pre-specified value of load impedance or speed. The computed variation of p.u. frequencies a1 and a2 with load impedance with unity power factor at 1.0 p.u. speed is shown in Fig. 3. It is noticed that when ZL is greater than 1.0 p.u., the p.u. frequencies are varying slightly with increase in ZL. When ZL is less than 1.0 p.u., two roots rapidly approaches to each other and at ZL=0.47 p.u., two roots are equal. All the roots are imaginary for all values of ZL below 0.47 p.u. ZL=0.47 p.u. is termed critical load impedance for given speed and power load as below this value repeated real roots occur and there is no generation.

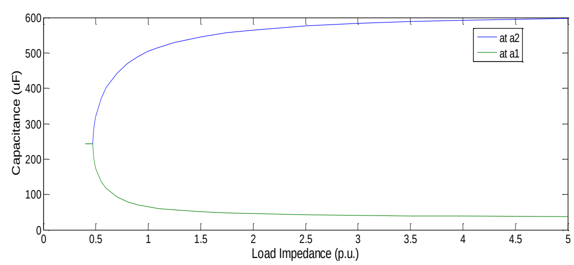

Fig. 4 Variation in Capacitance with Load Impedance (at unity power factor, b=1.0 p.u. and X_m = 1.5)

The values of capacitance can be evaluated for the corresponding value of p.u. frequency a1 and a2. Fig. 4 shows the computed variation of both the values of excitation capacitance at p.u. frequency a1 and a2 with load impedance at unity power factor and 1.0 p.u. speed. It has been seen that the value of excitation capacitance are varying slightly with increase in ZL. Lower value indicates the minimum value of excitation capacitance for voltage generation, below which no generation of voltage and the system is under-excited. Higher value indicates the maximum value of excitation capacitance, above which the system is over-excited and no generation of voltage.

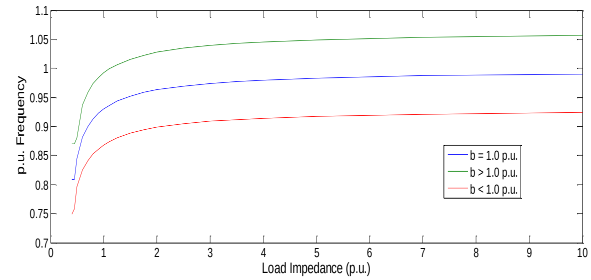

Fig. 5 Variation in p.u. frequency with Load Impedance at different Speed (at unity power factor and X_m = 1.5)

The effect of speed on the variation of p.u. frequency and value of excitation capacitance with load impedance at unity power factor at constant magnetization reactance is shown in Fig. 5 and Fig. 6 respectively. The p.u. frequency is decreases but the value of excitation capacitance is increases as the speed increases for the same load impedance and magnetizing reactance.

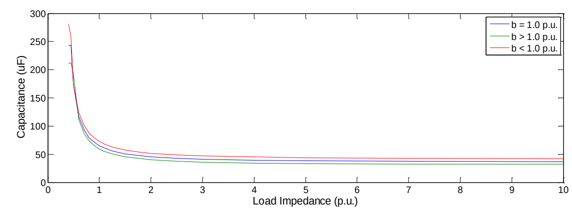

Fig. 6 Variation in Capacitance with Load Impedance at different speed (at unity power factor and X_m = 1.5)

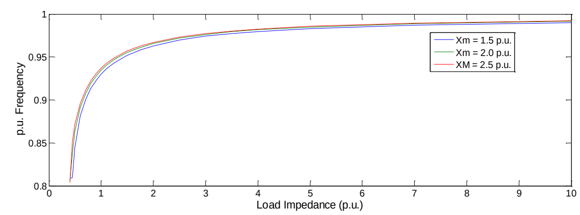

Fig. 7 Variation in p.u. frequency with Load Impedance at different X_m (at unity power factor and b = 1.0 p.u.)

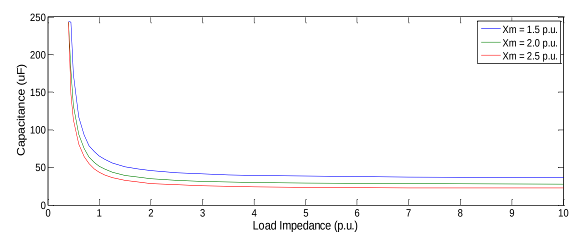

Fig. 8 Variation in Capacitance with Load Impedance at different X_m (at unity power factor and b = 1.0 p.u.)

Fig. 7 and Fig. 8 shows the effect of magnetization reactance on the variation of p.u. frequency and value of excitation capacitance with load impedance at unity power factor at rated speed 1.0 p.u. The p.u. frequency is increases but the value of excitation capacitance is decreases as the magnetizing reactance increases for the same load impedance at rated speed.

The magnetization characteristics furnishes the relation between magnetizing reactance Xm and generated voltage Vg/a. According to magnetization characteristics, the generated voltage is decreases as magnetization reactance increases. Fig. 9 and Fig. 10 shows the effect of speed on the variation of p.u. frequency and excitation capacitance required with magnetizing reactance for unity power factor load ZL=1.0 p.u. It has been seen from the figures that the value of p.u. frequency is increasing rapidly up to base magnetizing reactance (Xmn=2.58 p.u.), after that, the value of p.u. frequency is increasing slightly. Similarly, the excitation capacitance is decreasing rapidly up to base magnetizing reactance, after that, the value of excitation is decreasing slightly.

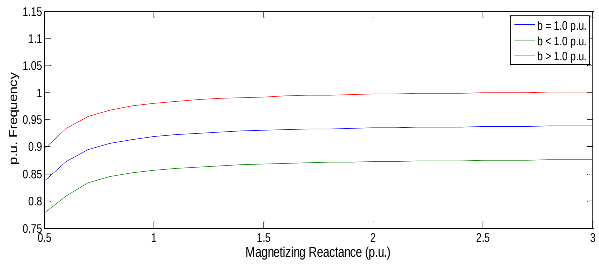

Fig. 9 Variation in p.u. frequency with X_m at different Speed (at unity power factor and Load Impedance = 1.0 p.u.)

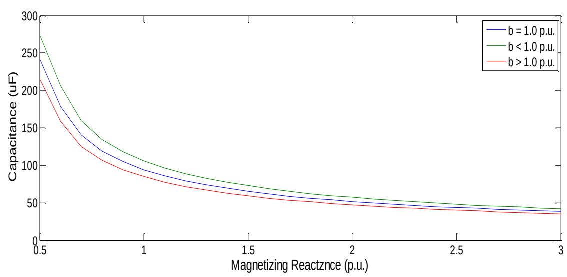

Fig. 10 Variation in Capacitance with X_m at different Speed (at unity power factor and Load Impedance = 1.0 p.u.)

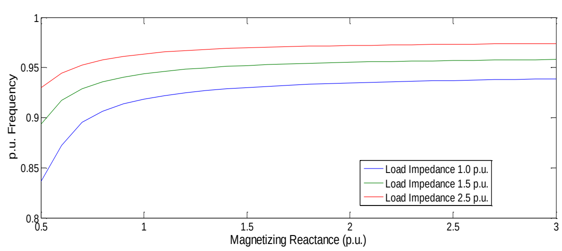

Fig. 11 Variation in p.u. frequency with X_m at different Load Impedance (at unity power factor and b = 1.0 p.u.)

The effect of Load impedance on the variation of p.u. frequency and required excitation capacitance with magnetizing reactance at rated speed and unity power factor is shown in Fig. 11 and Fig. 12. It is observed that there is a significant increment in p.u. frequency and decrement in excitation capacitance as the Load impedance increases for the same value of magnetizing reactance.

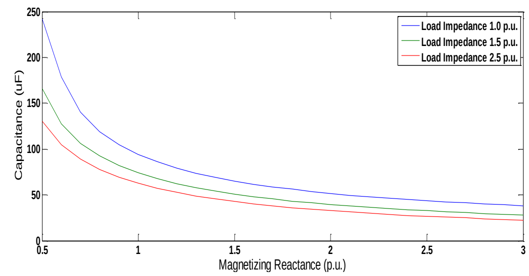

Fig. 12 Variation in Capacitance with X_m at different Load Impedance (at unity power factor and b = 1.0 p.u.)

V. CONCLUSION

Nodal admittance method for computing the minimum value of capacitance to initiate self-excitation in SEIG has been described. This method is based on steady state equivalent circuit, in which load and excitation branches are separate to each other. The value of p.u. frequency and corresponding value of excitation capacitance is determined by solving a 6th degree polynomial. Estimation of capacitance requirement for maintaining constant terminal voltage when SEIG on Load is also discussed. On the basis of different characteristics, it is observed that p.u. frequency is increasing with load and magnetizing reactance up to a range near to the rated values, after that the p.u. frequency is increasing slightly. It is also concluded that the value of excitation capacitance is reduced very fast up to rated speed and load, after that the decrement is very small and seems almost constant.

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APPENDIX

Machine Parameters

The rating of induction machine and different parameters are;

Rated Power	:	2 kW
Base Voltage	:	380 V
Base Current	:	5.4 A
Rated Frequency	:	50 Hz
Rated Speed	:	1500 rpm
Rs (per-unit)	:	0.0982
Xs (per-unit)	:	0.112
Rr (per-unit)	:	0.0621
Xr (per-unit)	:	0.0952
Xm (per-unit)	:	2.58.