Steady-State Analysis of Self-Excited Induction Generator Using Real and Reactive Power Balances

S. M. Alghuwainem, *Senior Member, IEEE*

Department of Electrical Engineering
King Saud University
Riyadh, Saudi Arabia
Email: saadalgh@ksu.edu.sa

Abstract**—This paper presents an efficient, and flexible method of steady-state performance analysis of the three-phase self-excited induction generator. The method equates the total real and reactive power of the equivalent circuit to zero. Unlike the previous methods which equate total node admittance or total loop impedance to zero, the proposed method produces two real equations directly, without going through the lengthy, tedious, and error-prone derivations of the real and imaginary parts of the total admittance or impedance. The method is easy to formulate and flexible to include any changes in the circuit without repeating lengthy derivations to reanalyze the circuit. The method is evaluated on a laboratory-size 380-V, 750-W induction generator, and the results obtained were found to be in agreement with the published results obtained by several authors using the previous methods of analysis. Some of the results obtained using the proposed method are also verified experimentally.**

Index Terms**—Induction generator, self-excited induction generator (SEIG), steady-state analysis, wind energy.**

I. Introduction

SELF-EXCITED induction generators are increasingly being used in remote locations where renewable energy sources such as mini-hydro, wind, or other nonconventional energy sources are available. The self-excited induction generator (SEIG) is attractive for such applications since it has several features, including low cost, reduced maintenance, high reliability, rugged construction, self-protection against short-circuits, etc. However, since it is not connected to a utility grid, it has an inherently poor voltage and frequency regulations. In grid-connected mode, the terminal voltage and frequency of the induction generator are fixed by the grid, and hence its performance analysis is straightforward. On the other hand, in the stand-alone mode the terminal voltage and frequency are not fixed but they vary with speed and loading conditions, depending on the torque-speed characteristics of the driving turbine [1]-[3[. Performance analysis of the SEIG is complicated further by the presence of other nonlinearities such as magnetic saturation of the load [4] or its transformer [5], or by modeling the load as a *P*-*Q* model [6], or by the method of connecting the excitation capacitors as short or long shunt connections [7], [8]. A comprehensive overview of literature on the analysis of the SEIG under various operating conditions is listed in [9]-[11].

Steady-state analysis of the SEIG is usually based on the analysis of its simplified equivalent circuit, shown in Fig. 1, where R_s, fX_s, R_r, fX_r, R_c, fX_m, and X_c/f represent the stator resistance, stator leakage reactance, rotor resistance, rotor leakage reactance, core loss resistance, magnetizing reactance, and excitation capacitor reactance respectively, all are evaluated at per unit speed υ and per unit frequency *f*.

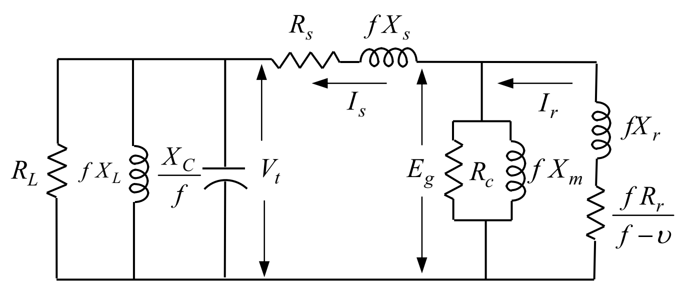

Fig. 1. Per-phase, per unit equivalent circuit of a SEIG.

All circuit parameters in Fig. 1 are assumed to be independent of voltage and current except the magnetizing reactance X_m which depends nonlinearly on E_g through the magnetization curve which can be approximated in several ways, such as an exponential function [10], a piece-wise linear function [11], or a higher order polynomial [12]-[14]. In this paper, it is represented by a third-order polynomial of the form

$$\frac{E_g}{f} = k_0 + k_1 X_m + k_2 X_m^2 + k_3 X_m^3 \tag{1}$$

The coefficients k_0 to k_3 are obtained by curve-fitting of the polynomial to the experimentally obtained magnetization curve at base frequency.

In the previous methods of analysis, the equivalent circuit in Fig. 1 is solved to determine the air-gap voltage, terminal voltage and frequency. The total admittance at air-gap node is equated to zero [12]-[14], or equivalently the total loop-impedance is equated to zero [15]-[18]. In both approaches, the resulting equation is in complex form, and in order to solve it by a gradient method such as the Newton-Raphson method, it has to be separated into two real equations. This separation is a lengthy, tedious, time-consuming, and error-prone task. Moreover, the derived equations are valid only for a particular machine and load model. A symbolic

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programming technique to reduce the derivations of the equations is described in [19], and a number of optimization-based techniques which minimize the required explicit algebraic expressions are developed in [20]. Despite all these improvements, the admittance and impedance methods are still inflexible and need considerable amount of algebraic manipulations.

The method proposed in this paper is simple, flexible, and efficient. It is based on formulating two real equations, one for real power balance, and the other for reactive power balance. The equations can be easily modified to reflect any changes in the load model or excitation capacitor connections without repeating lengthy derivations.

The proposed method is evaluated on a laboratory-size 750-W, 380-V, induction generator operating under various conditions. The results obtained are compared with experimentally obtained results.

II. Problem Formulation

Real power balance requires that power generated is equal to the sum of power delivered to the load plus real power losses. Referring to Fig. 1, this relationship can be written as,

$$\frac{|V_t|^2}{R_L}+\frac{|E_g|^2}{R_c}+|I_s|^2 R_s+|I_r|^2\frac{fR_r}{f-v}=0 \quad (2)$$

Similarly, reactive power balance requires that the reactive power generated by the excitation capacitor is equal to the sum of reactive power delivered to the load plus reactive power losses. Referring to Fig. 1, this relationship can be written as,

$$\frac{|V_t|^2}{fX_L}+\frac{|E_g|^2}{fX_m}+|I_s|^2 fX_s+|I_r|^2 fX_r+\frac{f|V_t|^2}{X_C}=0 \quad (3)$$

where,

$$I_s=\frac{E_g-V_t}{\sqrt{R_s^2+f^2X_s^2}},\; I_r=\frac{E_g}{f\sqrt{R_r^2/(f-v)^2+X_r^2}},\text{ and }\; X_C=\frac{-1}{2\pi(60)C},$$

where C is the excitation capacitance. Equations (1), (2), and (3) can be solved for f, E_g, and V_t, using a numerical calculation software package such as MATLAB [21] and/or MATHCAD [22].

III. Performance Analysis

Performance analysis of the generator whose parameters are given in Appendix A, is calculated under various operating using the proposed method. The effect of excitation capacitance on the terminal voltage and frequency at constant speed is shown in Figs. 2 and 3, whereas the effect of speed on the terminal voltage and frequency is shown in Fig. 4. The effect of load power on the terminal voltage and frequency is shown in Figs. 5 and 6. Performance without any constraints except constant speed is the most basic mode of operation. In this case, for each constant speed there is a minimum value of excitation capacitance to achieve self-excitation. For the same speed, the minimum capacitance to achieve self-excitation increases with load power. Increasing the excitation capacitance further increases the terminal voltage as shown in Fig. 2. Increasing the excitation capacitance beyond the minimum capacitance decreases the frequency as shown in Fig. 3, however the higher the speed and the lower the load, the higher the frequency as expected. The effect of speed on terminal voltage and frequency for a constant excitation capacitance is to increase terminal voltage in a way similar to increasing capacitance at constant speed, and to increase frequency linearly as shown in Fig. 4.

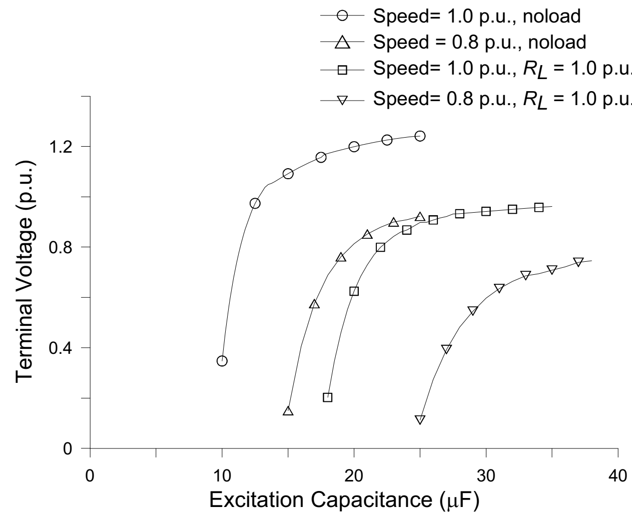

Fig. 2. Effect of excitation capacitance on terminal voltage.

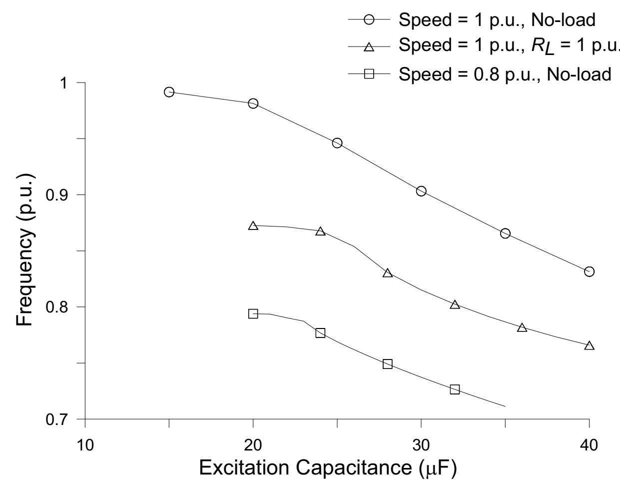

Fig. 3. Effect of excitation capacitance on frequency.

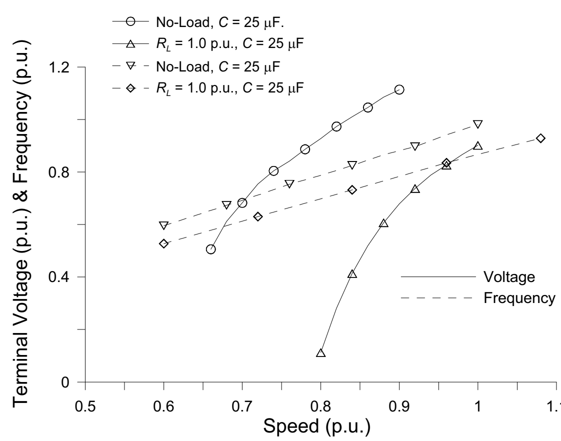

Fig. 4. Effect of speed on the terminal voltage and frequency.

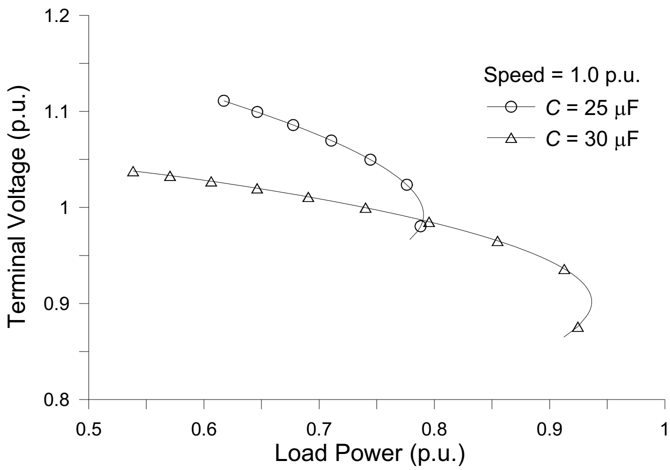

Fig. 5. Effect of load power on the terminal voltage.

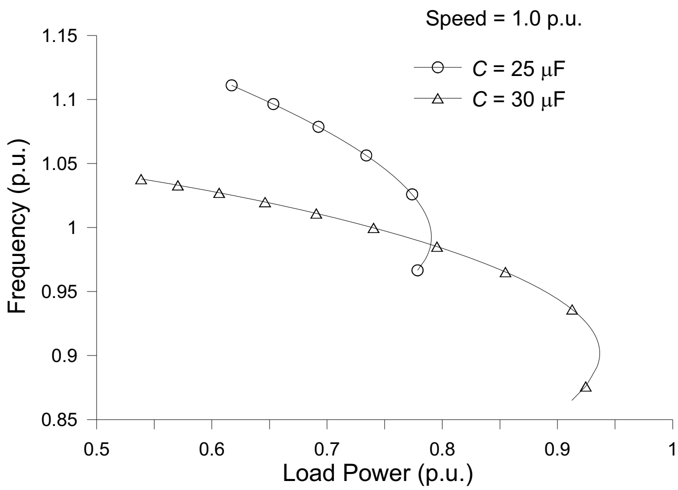

Fig. 6. Effect of load power on frequency.

IV. Performance with Constant Terminal Voltage

Performance analysis with constant terminal voltage is investigated by solving (1), (2), and (3) in addition to the equation representing constant terminal voltage, namely

$$|V_t| = 1.0 \quad (4)$$

Fig. 7 shows the capacitance needed as the speed varies at constant terminal voltage and constant power. Fig. 8 shows the capacitance needed as the load power varies at constant terminal voltage and constant speed.

V. Discussion of Results

Performance without any constraints except constant speed is the most basic mode of operation. In this case, for each constant speed there is a minimum value of excitation capacitance to achieve self-excitation. For the same speed, the minimum capacitance to achieve self-excitation increases with load power. Increasing the excitation capacitance further increases the terminal voltage as shown in Fig. 2. Increasing the excitation capacitance beyond the minimum capacitance decreases frequency as shown in Fig. 3, however the higher the speed and the lower the load, the higher the frequency as expected. The effect of speed on terminal voltage and frequency for a constant excitation capacitance is to increase terminal voltage in a way similar to increasing capacitance at constant speed, and to increase frequency linearly as shown in Fig. 4. The effect of load power on the terminal voltage and frequency is to decrease both until certain maximum load power is reached at which the machine becomes unstable and the terminal voltage and frequency collapse as shown in Figs. 5 and 6. For operation with constraints such that the terminal voltage as well as the load power are constant requires variation of excitation capacitance with speed as depicted in Fig. 7 theoretically as well as experimentally. More excitation capacitance is required at lower speeds whereas less capacitance is required at the higher speeds. For operation with the constraint that the terminal voltage as well as speed are constant, the excitation capacitance must vary with load power as depicted in Fig. 8.

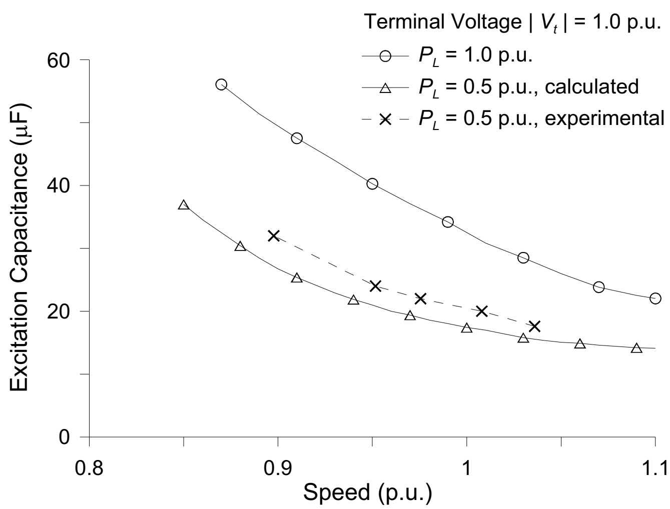

Fig. 7. Excitation capacitance versus speed for constant

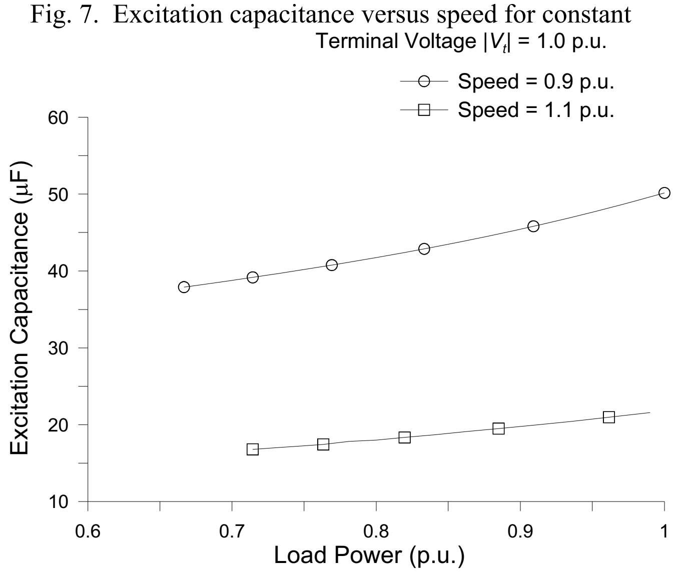

Fig. 8. Excitation capacitance versus load power for constant terminal voltage.

VI. Conclusion

A novel method of steady-state performance analysis of three-phase self-excited induction generator is presented in this paper. The method is more flexible in allowing different operation scenarios without repeating lengthy derivations. The results obtained using this method are in full agreement with results obtained by previous methods. Some of the results obtained by this method were verified experimentally.

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