# Selection of Capacitor for the Self-Excited Single-Phase Induction Generator

Ching-Tzong Su    Wei-Cheng Chang
**Institute of Electrical Engineering, National Chung Cheng University, Chiayi 621, TAIWAN**
**Fax:886-52752013    Email:ieects@ccunix.ccu.edu.tw**

**Abstract** The paper presents a self regulated single phase induction generator which includes shunt and series capacitances to provide self-excited and self-regulating features. A theoretical modelling is proposed in this research and suitable computer algorithms are explored for performance prediction and design improvements. Procedures have been proposed to choose appropriate values of the capacitors to attain optimum machine performance and utilization.

## 1. INTRODUCTION

### List of Symbols

F = per-unit frequency
v = per-unit speed
R1 = stator resistance
R2 = rotor resistance referred to the stator
RL = load resistance
X1 = stator leakage reactance at base frequency
X2 = rotor leakage reactance referred to the stator at base frequency
Xm = magnetizing reactance
Xsh = excitation shunt capacitive reactance
Xse = excitation series capacitive reactance
Vgf = positive-sequence air gap voltage

Recently, due to increased concern on renewable energy resources and the cost of delivering power, development of appropriate isolated power generators that driven by energy sources such as wind, biogas, small hydroelectric, etc, has been considered to be important. Because of its lower installation cost, brushless rotor construction, not needing a separate DC source for excitation, solidness and ease of maintenance, a capacitor self-excited induction generator (SEIG) has become an appealing power generator.

However, poor voltage regulating of SEIG even at regulated speeds has been a chief drawback in its application. Steady change in capacitor VAR with the variation of load has to be attained to maintain satisfactory voltage regulation. Over the years , there have been many voltage regulating methods proposed to achieve this goal Tandon et al.[1984], and Singh et al.[1990]. These methods mostly employ switched capacitor or saturable core reactor based close loop schemes using contactors or semiconductor switches. But sophisticated system configuration, complicated control circuit design and operational problems as well as switching transient, associated with voltage regulators reduce the attraction of induction generator.

Great efforts have been made, in recent years to explore the steady-state, and transient performance of three phase self-excited induction generators Malik and Hague [1986], Chan [1995] , and Shridhar et al. [1995]. However very few studies have been made on the analysis of capacitor-excited single phase induction generators.

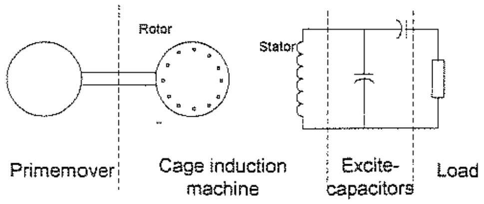

Fig. 1 System configuration

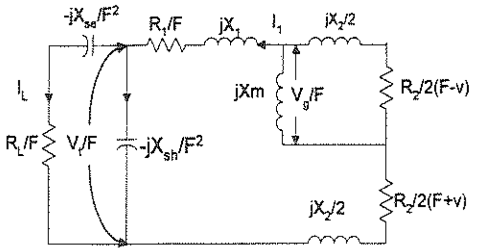

Fig.2 Equivalent circuit of single-phase SEIG

In this paper, the system consisting of both shunt and series capacitors has been analyzed (Fig. 1) . Based on the equivalent circuit, two nonlinear analytical equations are explored and resolved by using a Newton-Raphson numerical technique. Procedures have been proposed to select pertinent values of these capacitors to obtain minimum regulation. A general analysis for the prediction of the steady-state performance in this configuration is developed.

## 2. CAPACITOR SELF EXCITATION

The process of excitation in the single phase induction generator is like that in the three-phase type, but becomes intricate due to the presence of the backward rotating field. In order to initiate self-excitation, there must be residual flux in the rotor core, and if the excitation capacitance exceeds certain critical value, the resulting stator current will intensify the airgap flux, causing the stator voltage to build up. While the voltage building up, the resulting airgap flux drives the machine into saturation. Accordingly the magnetizing reactance is gradually decreased, until a balance of active and reactive power between the machine and the terminal load which comprises the load and excitation capacitance is achieved. The stable operating point is determined by the saturation characteristics, excitation capacitance, rotor speed and terminal load.

## 3. ANALYSIS

Equivalent circuit of a single phase induction machine can be employed as a basis for modelling Fitzgerald et al. [1990]. Such circuits are explored by using a double-revolving field. Fig. 2 shows the equivalent circuit of the single-phase capacitor excited induction generator with resistive load. The equivalent circuit is normalized to base frequency. Assume all parameters in the circuit are kept a constant. Besides, magnetizing reactance Xm depends on magnetizing characteristic of the machine.

Fig.3 shows the magnetization characteristic of the machine, which relates the airgap voltage Vg/F to the magnetizing reactance Xm and may be stated as

$$\frac{V_g}{F} = K_1 - K_2 X_m \dots\dots\dots\dots\dots\dots\dots (1)$$

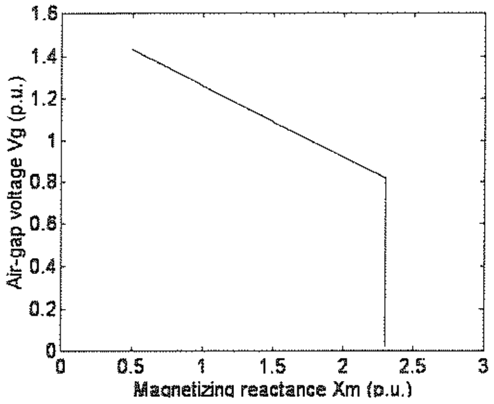

Fig.3 Variation of Vg/F with magnetizing reactance

Where K1 and K2 depend upon the material and design of the machine. As explained in [3], Newton Raphson method can be employed by network simplification of Fig. 2 by equating appropriate loop impedance to zero. It can be seen that direct application of Fig. 2 leads to complicated equations. Great simplification could be attained Murthy [1993] by substituting F by v except in the term F-v. Consequently, a simplified circuit of Fig.1 can be approximated as Fig. 4.

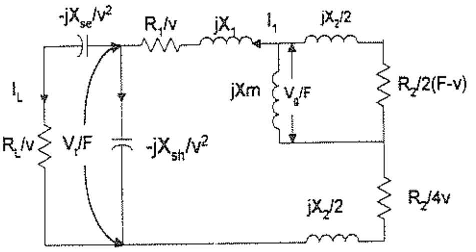

Fig. 4. Approximate equivalent circuit of single-phase SEIG

From Fig. 2 and employing Kirchhoff's law, we have:

$$\boldsymbol{Z_S I_S = 0}$$

Under steady state self excitation, because the stator current will not be zero, the Zs will be zero. This implies that the real and imaginary parts of Zs should be zero. Therefore, we can rearrange into the following two nonlinear equations which are functions of Xm and F;

$$f(X_m,F) = (C_1 X_m + C_2) +$$

$$(C_3 X_m + C_4) = 0 \text{..........................}(2)$$

$$g(X_m,F) = (D_1 X_m + D_2) +$$

$$(D_3 X_m + D_4) = 0 \text{..........................}(3)$$

*where*

$$C_1 = -X_{eq} - \frac{X_2}{2}$$

$$C_2 = -X_{eq} X_2$$

$$C_3 = (X_{eq} + \frac{X_2}{2})v$$

$$C_4 = R_{eq} R_2 + X_{eq} X_2 v$$

$$D_1 = R_{eq}$$

$$D_2 = R_{eq} X_2$$

$$D_3 = \frac{R_2}{2} - R_{eq} v$$

$$D_4 = X_{eq} R_2 - R_{eq} X_2 v$$

and

$$R_{eq} = \frac{1}{v}(R_1 + \frac{R_2}{4} + \frac{R_L X_{sh}^2}{R_L^2 v^2 + (X_{sh} + X_{se})^2})$$

$$X_{eq} = X_1 + \frac{X_2}{2} - \frac{R_L X_{sh}^2 + \frac{1}{v^2}(X_{se} X_{sh}^2 + X_{sh} X_{se}^2)}{R_L^2 v^2 + (X_{sh} + X_{se})^2}$$

The Newton-Raphson method was applied to solve these nonlinear equations for Xm and F. This method requires an initial guess for the unknown variable, say Xm0 and F0. At the end of the 1st iteration of the method, Xm and F will become Xm = Xm0 + h and F = F0 + k . to satisfy eq. (2) and (3)., the increments h and k are given as follows :

$$\begin{bmatrix} h \\ k \end{bmatrix} = \begin{bmatrix} \frac{\partial f}{\partial X_m} & \frac{\partial f}{\partial F} \\ \frac{\partial g}{\partial X_m} & \frac{\partial g}{\partial F} \end{bmatrix}^{-1} \begin{bmatrix} -f_0 \\ -g_0 \end{bmatrix} \text{..............}(4)$$

where f0 and g0 are the values of f(Xm,F) and g(Xm,F) for the initial values Xm = Xm0 and F = F0.

The iterative process is continued until specified accuracy is satisfied, that is

$$|f(X_m,F)| < \in \quad \text{and} \quad |g(X_m,F)| < \in$$

where $\in$ is a small quantity (e.g., $\in$=10e-05).

After obtaining Xm and F , Vg can be attained from Eg. (1). Then performance may be determined using the following equations obtained from the equivalent circuit of Fig. 2.

$$\overline{V}_t = \overline{V}_{gf} \frac{R_p - j X_p}{R_{eq} + j X_{eq}}$$

$$\overline{V}_L = \overline{V}_t \frac{R_L v}{R_L v - j X_{se}}$$

$$\overline{I}_L = \frac{\overline{V}_L}{R_L}$$

$$P_{out} = |\overline{I}_L|^2 R_L$$

## 4. COMPUTATION AND EXAMPLE

A single phase cage induction motor is selected as an example for illustration. The electrical details and parameters of the machine are as below.

Rated voltage = 425 V

Rated current = 4.5 A
Pole = 4
Frequency = 60 Hz
Stator resistance, R1=0.053 p.u.
Rotor resistance, R2=0.06 p.u.
Leakage reactance, X1=X2=0.087 p.u.

In order to determine the magnetizing reactance at different airgap voltage Vg, the machine can be driven at base speed(v=1) by the D.C. motor, and the input impedance measured at different input voltage. Because we need the variation of Xm with the air gap flux, to beproportional to Vg/F, it is necessary to compute the airgap voltage by subtracting the voltage drop in the stator leakage impedance from the input voltage. Xm at each voltage is obtained by substracting the stator leakage impedance from the measured input impedance. The variation of Vg/F with Xm is nonlinear due to magnetic saturation. To simplify the analysis, the variation under saturation region is linearized using appropriate curve shown in Fig. 2 which may be expressed as:

$$V_g = 1.6 - 0.34X_m$$

or

$$X_m = 4.7 - 2.94V_g$$

### Selection of Shunt Capacitance

Fig. 5 shows the no load characteristic of the machine. It is observable that the terminal voltage of the machine increases with increase in shunt capacitance (Csh) and the rise of terminal voltage is limited by the saturation of magnetic circuit of the machine. Pertinent value of shunt capacitance can be chosen depending on the maximum permissible voltage across the machine terminals and loads requirements. Fig. 6 shows the variation of terminal voltage with respect to output power when the generator is only excited by shunt capacitance. Fig. 7. shows the variation of stator current with respect to output power for different shunt capacitance. It can be seen that for lower shunt capacitance the power capability of SEIG increases. But insufficient shunt capacitance results in low terminal voltage. The value of Csh (30uF) corresponding to no load terminal voltage close to rated value (1.0 p.u.)has been determined.

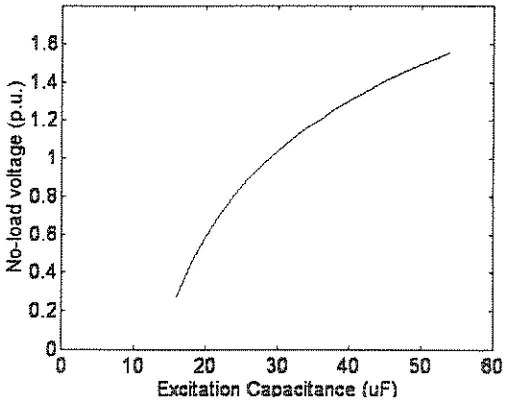

Fig. 5 Variation of no-load voltage with excitation capacitance

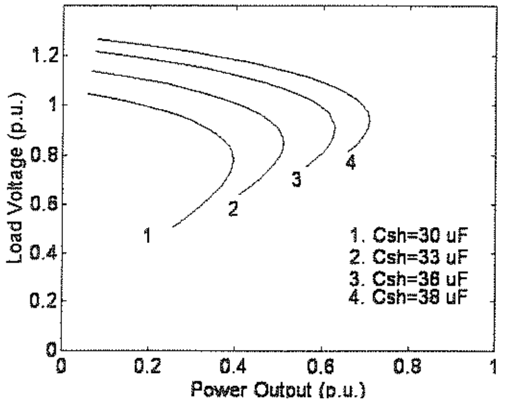

Fig. 6 Variation of load voltage with output power (Cse = 0)

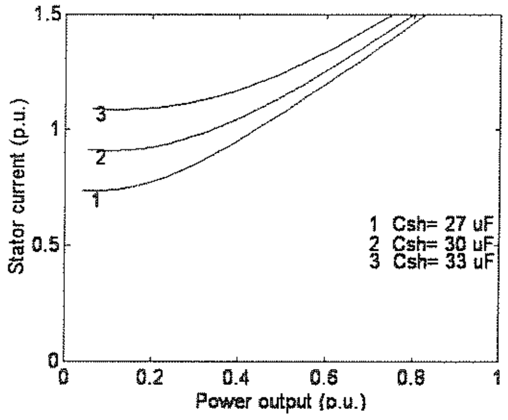

Fig. 7 Variation of stator winding current with output power

### Selection of Series Capacitance

Fig. 8 shows the variation of voltage regulation with series capacitance (Cse) at constant speed.

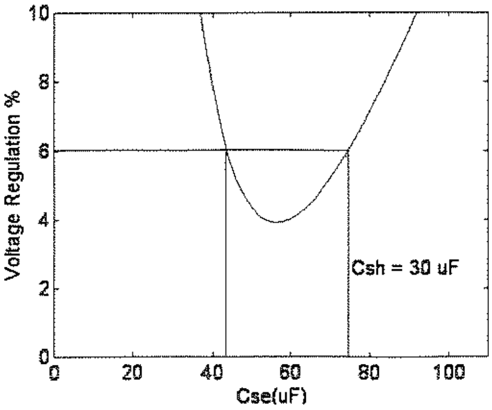

FIG. 8 Variation of voltage regulation with series capacitance

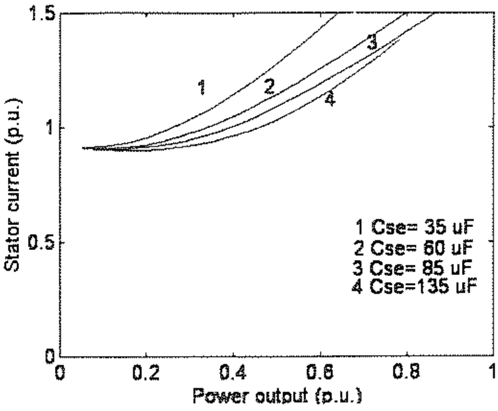

Fig. 9 Variation of stator winding current with output power

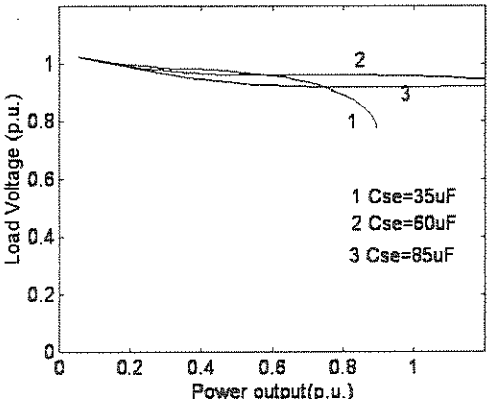

Fig. 10 Variation of load voltage with output power

From this figure , it reveals that there is a minimum value of voltage regulation. Fig. 9 also shows a group of stator winding currents for different series capacitance with output power. It can be seen that for higher Cse the power capability of SEIG increases, because at rated stator winding current it can deliver much more output power. Even if the higher Cse can enhance the power capability of the SEIG, we will acquire poor voltage regulation. Fortunately terminal voltage is permitted to vary within a specified range. Taking the permissible voltage regulation of 6%, a range of Cse ( 44 - 74uF) is available for the selection. Fig. 10 shows the variation of load voltage with output power.

From the above analysis , appropriate values of these capacitances can be chosen by first studying the variation of no load terminal voltage with shunt capacitance and the effect of Csh on stator winding current. We can choose an appropriate value for Csh from these curves. Then we studied the influence of Cse on voltage regulation. A pertinent value of Cse can be chosen from the range of value determined by considering the desired regulation and other operation constraints. Fig. 11 shows the various characteristics of the SEIG for the chosen values of the shunt (Csh=30 uF) and series capacitor (Cse=60 uF). It is observable that the curve of the load voltage is very smooth. For the selected capacitors it is seen that the full load voltage regulation is as low as 5%.

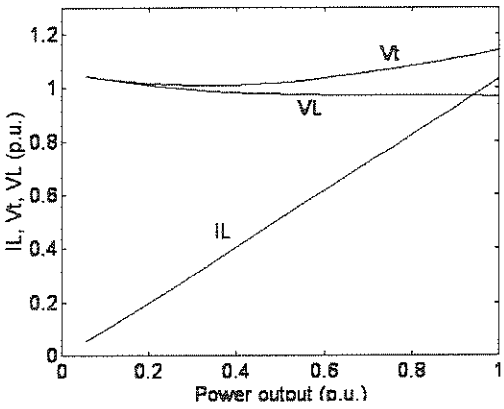

Fig. 11 Characteristics of SEIG

## 5.CONCLUSIONS

A self regulated induction generator has been proposed. The capacitances including shunt and series provide self-exciting and self-regulating features. A theoretical modeling is proposed in the paper and proper computer algorithms can be explored for performance prediction and design improvements. The analysis presented in this research should be helpful to select the appropriate capacitance pairs for attaining optimum machine performance and utilization.

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