Voltage Control of Series-Connected Synchronous Generator

Prof. A. Mohamadein,
Prof .H. Yousef
Electrical Engineering Department, College of Engineering , Alexandria University , Alexandria 21544 , Egypt

Dr. Y. G. Dessouky
Department of Electrical and Control Engineering, Arab Academy for Science and Technology, Miami, Alexandria 1029, Egypt

ABSTRACT

Series Connected Synchronous Generator (SCSG) is an induction machine (IM) with stator and rotor windings connected in series via excitation capacitors. This generator operates synchronously to produce sinusoidal output voltage with half rated frequency. This paper presents a method to control the voltage of the SCSG using series inductor. The analysis is based on a deduced phasor diagram. The effect of the series inductor on machine performance is analysed. An electronic system is proposed to achieve a closed loop voltage control system..

Keywords : Synchronous generator, variable inductor, voltage control

List of Symbols

C	excitation capacitor, μF
f	frequency of generated voltage, Hz
F_R, F_S, F_t	rotor, stator and resultant MMFs respectively
I_a, I_L	armature and load currents, A
K	effective rotor to stator turns ratio
L_x , X_x	added series inductance, H and reactance, Ω
L_{xm}	maximum limit of the series added inductance, H
N_r	SCSG rotor speed, rpm
P	number of poles
$P_{o/p}$	output power, W
R_a, R_r, R_s	armature, rotor and stator resistances respectively, Ω
R_L, X_L, Z_L	load resistance, reactance and impedance, Ω
V_{as}, V_{ar}, V	stator, rotor and load voltage per phase respectively
X_m	magnetization reactance at 50 Hz, Ω
X_s, X_r	stator and rotor leakage reactance at 50Hz, Ω
X_a, X_c	armature reactance and excitation reactance, Ω
Z_{Le}	equivalent impedance of an inductive load and excitation capacitor combination, Ω
R_{Le}, X_{Le}	real and imaginary components of Z_{Le}, Ω
Z_{eq}	equivalent impedance of armature, load and excitation capacitor combination, Ω
R_{eq}, X_{eq}	real and imaginary components of Z_{eq} ,Ω
θ, ψ, ρ	angles between (F_S & F_t) , (F_R & F_t) and (F_R & F_S) respectively, degree
ϕ_{eq}	angle between load current and voltage
α	delay angle between voltage across and current through added inductance control circuit

1 INTRODUCTION

Interest in renewable energy systems has recently increased. Therefore research work has been lately devoted to explore the different types of renewable energies.

Self-excited induction generator is suitable for converting wind energy into electrical since it can operate over a wide range of speed. This choice was prompted by the merits of this generator such as robustness, less expenditure involved. Performance study of self-excited induction generator [1]-[2] showed that the output voltage has a load dependent frequency.

Series Connected Synchronous Generator (SCSG) was proposed to produce sinusoidal output voltage whose frequency is dependent only on speed. SCSG is a slip ring induction machine whose stator and rotor windings are connected in series with sequence of two phases reversed as shown in Fig. 1. As a result, stator and rotor MMFs will rotate at the same speed but in opposite directions. Synchronous generation is possible only when stator and rotor MMFs rotate synchronously at an absolute speed equals to half rotor speed. Self-excitation process commences with the same manner as in self-excited induction generator using excitation capacitors. SCSG has been analysed using Floquet theory for solving resulting differential equations with time varying coefficients [3]-[4]. The analysis presented could not account for the effect of individual machine parameters. Another approach was presented in [5] to analyse the machine based on a deduced phasor diagram. It was concluded that stator/rotor turns ratio plays major role in defining machine performance. This approach needs iterations and is limited to predict steady-state performance only. In [6], the machine is analysed using generalised theory of electrical machines. The approach based on d-q model is suitable for predicting both transient and steady-state performances. The minimum capacitor to cause self-excitation for a particular speed is calculated. A Fixed-Capacitor Thyristor Controlled Reactor (FC-TCR) technique is implemented in [7] to control the load voltage.

The present paper introduces a method to control the voltage of the SCSG by adding a three phase inductor in series with the machine. The effect of the series inductor in the performance is illustrated. An electronic circuit to obtain a closed loop voltage control system is proposed.

2 ANALYSIS OF SCSG

The steady state analysis of SCSG is presented in [5] based on a deduced phasor diagram shown in Fig. 2 as derived from the

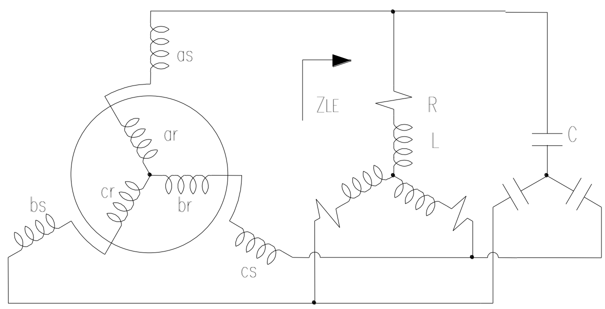

Fig. 1 Connection of SCSM

relationship between phasor currents, voltages and fluxes of the machine. It was seen that the frequency, f, of the SCSG is half the rated frequency if the machine is run as a conventional induction motor. The frequency, f, can be expressed as:

$$f = 0.5\,\frac{P N_r}{120} \tag{1}$$

then

$$X_C = \frac{1}{2\pi f C} \tag{2}$$

$$X_a = \left(X_S + X_r\right)\frac{f}{50} \tag{3}$$

$$R_a = \left(R_S + R_r\right) \tag{4}$$

Equivalent load and capacitance impedance, Z_{Le} can be expressed as:

$$R_{Le} = \frac{R_L X_c^2}{R_L^2 + \left(X_L - X_c\right)^2} \tag{5}$$

$$X_{Le} = \frac{X_c\left(R_L^2 - X_L^2 - X_L X_c\right)}{R_L^2 + \left(X_L - X_c\right)^2} \tag{6}$$

Denoting

$$\bar{Z}_{eq} = R_{eq} - jX_{eq} = Z_{eq} e^{j\phi_{eq}} \tag{7}$$

where,

$$R_{eq} = \left(R_{Le} + R_a\right) \tag{8}$$

$$X_{eq} = \left(X_{Le} + X_a\right) \tag{9}$$

Based on the phasor diagram shown in Fig. 2, it was concluded in [7] that a nonlinear function F(ψ) can be expressed as :

$$F(\psi) = K\cos\psi + \sqrt{1 - K^2\sin\psi^2} - 2K\sin\psi\tan\phi_{eq} \tag{10}$$

For each load parameters (R_L, X_L) and shaft speed, the corresponding value of ψ can be obtained by solving (10). Subsequently, the value of θ, ρ and X_m can be calculated as follows:

$$K\sin\psi = \sin\theta \tag{11}$$

$$\rho = \theta + \psi \tag{12}$$

$$X_m = \frac{R_{eq}}{2\sin\theta\sqrt{1 + K^2 + 2K\cos\rho}}\cdot\frac{50}{f} \tag{13}$$

Conventional no load test for a three phase induction motor is carried out to evaluate the relationship between air gap stator phase voltage V_{as} and magnetisation reactance X_m. Using curve fitting techniques, this relationship can be expressed mathematically as:

$$V_{as} = \begin{cases} 311.85 - 1.38X_m & X_m < 95.51 \\ 715.64 - 5.61X_m & 95.51 < X_m < 100.5 \\ 1025.29 - 8.69X_m & 100.51 < X_m \end{cases} \tag{14}$$

By knowing X_m from (13), the corresponding value of V_{as} can be obtained from (14), therefore:

$$I_a = \frac{Vas}{X_m}\frac{1}{\sqrt{1 + K^2 + 2K\cos\rho}} \tag{15}$$

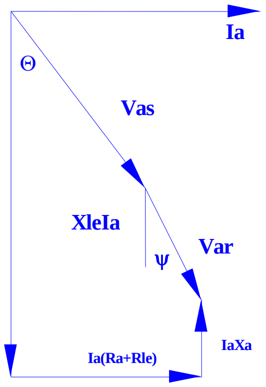

Fig. 2 Phasor Diagram

$$V = Z_{Le} I_a \tag{16}$$

$$I_L = \frac{V}{Z_L} \tag{17}$$

$$P_{o/p} = 3VI_L\cos\phi_{eq} \tag{18}$$

The experimental setup is made from a slip ring three phase induction machine whose details are given in Table 1. The parameters as has been obtained by standard tests at 50 Hz are given in Table 2. The induction machine is connected in the SCSG mode as shown in Fig. 1 and mechanically coupled to a separately excited DC machine.

Fig. 3 shows the relationship between speed versus no load voltage. The relationship between load voltage and current is shown in Fig. 4.

TABLE 1. IM DETAILS
220/380V , 6.3/3.6A,.
2.2 kW, 1440 rpm
50 Hz, 4 pole

TABLE 2. IM PARAMETERS
R_s = 2.08 Ω , R_r = 1.96 Ω,
X_s = 5.28 Ω , X_r = 3.92 Ω,
K = 0.86 and

3 SCSG WITH SERIES INDUCTOR

The effect of adding a three phase inductor in series between the machine and the equivalent impedance Z_{Le} on machine performance can be studied using the same procedure explained in section (2) except for equation (9) which is changed to:

$$X_{eq} = X_{Le} - X_a - X_x \tag{19}$$

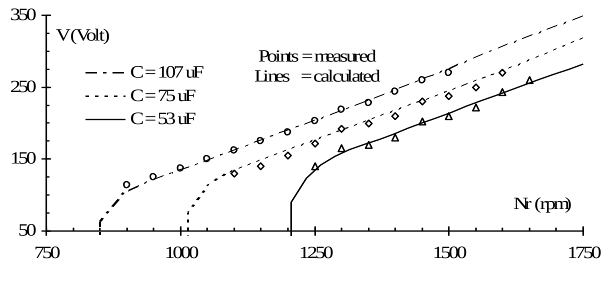

Fig. 3 Relation of no-load voltage and speed for different excitation capacitors

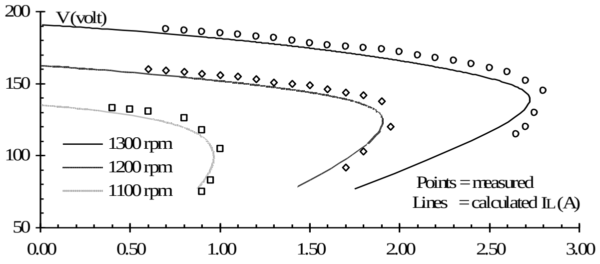

Fig. 4 Relation of load voltage and current at different speeds

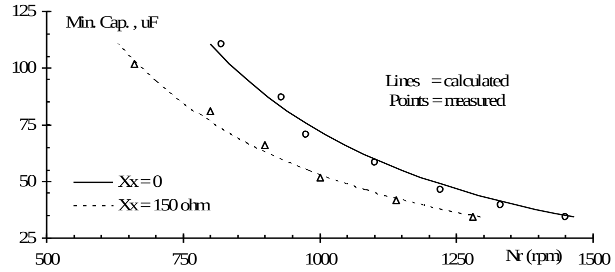

Fig. 7 Relation of minimum excitation capacitor and speed for different added series reactance

The relation between no load voltage and speed for different inductor values is shown in Fig. 5. It is seen that no load voltage increases as the series inductor increases. This means that the terminal voltage can be controlled by controlling the series inductor. Fig. 6 shows the relation between load voltage and current for different inductor values. If the cut off voltage is defined as the voltage corresponding to that load after which self excitation process will fail, it is seen from Fig. 6 that the cut off voltage increases as the series inductor increases. It can also be seen that the maximum current obtained without series inductor is higher than that obtained with series inductor. If the reflex voltage is defined as the voltage corresponding to maximum load current, it is seen that the reflex voltage increases as the series inductor increases.

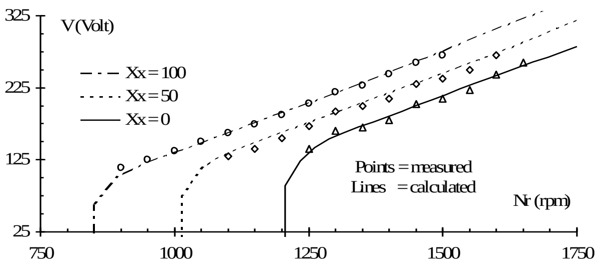

Fig. 5 Relation of no-load voltage and speed for different added series reactance

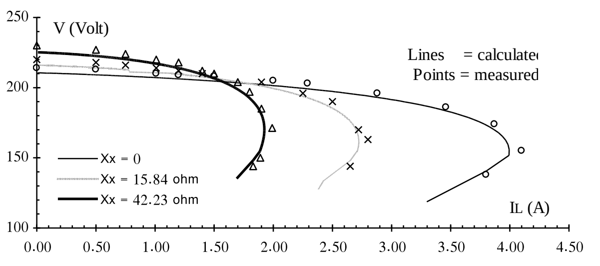

Fig. 6 Relation of load voltage and current for different series reactance

In SCSG, there is a minimum capacitor corresponding to each rotor speed to commence process of self excitation. This value can be evaluated by substituting (X_m) by unsaturated value in (13). Fig. 7 shows the relation between minimum capacitance requirement to cause self excitation versus rotor speed. One advantage of adding series inductor can be seen from Fig. 7 as the minimum capacitor requirement decreases with increasing inductor value.

4 VOLTAGE CONTROL

Like most generators, the voltage level of SCSG decreases up on resistive or inductive loading. With reference to Fig. 3, it is seen that the no load voltage increases as the excitation capacitor increases. Therefore, voltage can be controlled by controlling the excitation capacitor. This scheme was applied in [9] using Fixed Capacitor-Thyristor Controlled Reactor (FC-TCR) technique to control the voltage level of SCSG.

Another way of controlling voltage level can be achieved by adding a three phase inductor in series as shown in section 3 such that the value of the series inductor is increased upon loading to compensate for the voltage drop resulted from this loading.

To find the change of the series inductor with load current that keeps zero voltage regulation or keeps constant terminal voltage that equals no load voltage (V_o) corresponding to a given operating speed and excitation capacitor, the same set of the non-linear simultaneous equations (5) to (8), equations (10) to (17) and equation (19) are rearranged and solved for each current value at a given voltage level (V_o) resulting in the value of the series inductor.

With reference to Fig. 6 , it should be noted that this technique is limited to a certain value of a series inductor (L_{mx}) at which the reflex voltage equals to the required voltage level (V_o). This is because if the inductor is increased beyond L_{mx}, the required voltage level (V_o) will be met at a load current less than that obtained at L_{mx}.. Fig. 8 shows the relation between load current and inductor needed to keep constant voltage.

5. EXPERIMENTAL CONTROL CIRCUIT

A variable inductor can be experimentally obtained using the circuit shown in Fig. 9 where a series triac and inductor (L_m) is paralleled to another inductor (L_c). The effective inductance as a function of the delay angle (α) between the voltage across and current through the circuit is given by [2]:

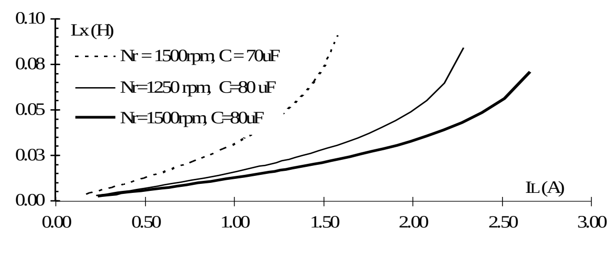

Fig. 8 Relation between load current and inductor needed to keep constant voltage.

$$L_x(\alpha) = \frac{L_m}{\frac{L_m}{L_c} + 1 - \frac{2}{\pi} - \frac{\sin(2\alpha)}{\pi}} \quad (20)$$

Therefore, the inductance can be increasingly varied from ($\frac{L_m}{\frac{L_m}{L_c}+1}$)to ($L_c$) if (α) varies from zero to 90°. This circuit is used to control the voltage of SCSG. The closed loop voltage control circuit can be realised by the circuit shown in Fig. 10 where a reference saw tooth signal synchronised with the voltage across the added inductor circuit is generated and compared with the mean value of load voltage. The compactor output is inputted to a positive edge trigging circuit whose output is applied to the gate drive circuit of the triac.

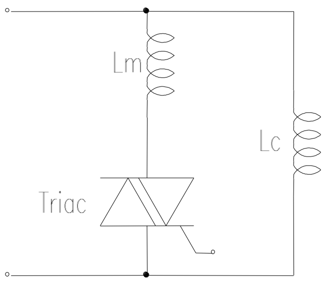

Fig. 9 Variable inductor circuit

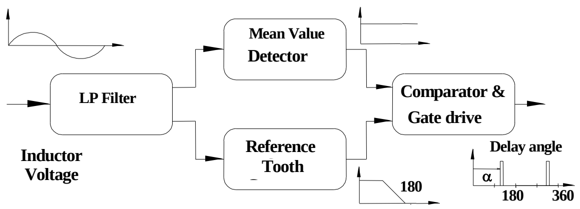

Fig. 10. The closed loop voltage control circuit

REFERENCES

[1] C.F. Wagner, 'Self excitation of induction motors', AIEE Trans. , Vol. 58, pp 47-51, Feb. 1939.

[2] N.H. Malik and S.E. Haque,' Steady state analysis and performance of an isolated self excited induction generator', IEEE Trans. on EC, Vol. 1, No. 3, 1986, pp 134-139.

[3] A. Mostafa, A.L. Mohamadein and E.M. Rashad, 'Analysis of series connected wound rotor self excited induction generator', IEE Proc., Pt. B., Vol. 140, No. 5, Sept. 1993.

[4] A. Mostafa, A.L. Mohamadein and E.M. Rashad, 'Application of Floquet's theory to the analysis of series-connected wound-rotor self-excited synchronous generator', IEEE Trans. on EC., Vol. 8, No. 3, Sept. 1993.

[5] A.L. Mohamadein and E.A. Shehata, 'Theory and performance of series connected self excited synchronous generator', IEEE Trans. on EC, Vol. 10, No. 3, Sept. 1995, pp. 508-515.

[6] A.L. Mohamadein, H.A. Yousef and Y.G. Dessouky, 'Series connected self excited synchronous generator: steady state and transient behaviours', IEEE Trans. on EC, Vol. 14, No. 4, Dec. 1999, pp1108-1114.

[7] Y.G. Dessouky, 'Voltage control of series connected synchronous generator', M.Sc. Thesis, Oct. 1993, Alexandria University, Egypt