STABLE-STATE MODELING AND ANALYSIS OF THREE PHASE SELF-EXCITED INDUCTION GENERATOR WITH SERIES COMPENSATION

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ABSTRACT
This paper presents a generalized mathematical model for the analysis of three-phase self-excited induction generators (SEIG) with series compensation. Two methods of series compensation namely short-shunt and long-shunt compensation are analyzed to improve the voltage regulation of the SEIG. The proposed mathematical model is formed directly from the equivalent circuit of SEIG based on nodal admittance method by inspection. The proposed model completely eliminates the tedious work of separating real and imaginary parts of complex admittance. Also, any equivalent circuit elements can be easily included or eliminated from the model. Genetic algorithm is used to determine the performance of SEIG.

KEYWORDS: Induction Generator, Self-excitation, Voltage Variation, Genetic Algorithm & Series Compensation

I. INTRODUCTION
If an appropriate three-phase capacitor bank is connected across an externally driven induction machine, an EMF is induced in the machine windings due to the excitation provided by the capacitor. This phenomenon is termed as ‘capacitor self-excitation’, which can be used to operate the induction machine as a generator. The induced voltages and currents would continue to rise, but for magnetic saturation in the machine which results in an equilibrium state being reached. A capacitor self-excited induction generators (SEIG) offers certain advantages over a conventional synchronous generator as a source of isolated power supply. Reduced unit cost, brushless rotor, absence of a separate DC source and ease of maintenance are among the advantages [1-4]. But poor voltage regulation of SEIG even at regulated speed has been major bottleneck in its application. Steady increase in capacitor VAR with load has to be achieved to maintain good voltage regulation. Several voltage regulating schemes like switched capacitor or variable inductor or saturated core reactor based close loop schemes using relay/contractors or semiconductor switches can be incorporated to improve voltage regulation. But complex system configuration, complicated control circuit design and operational problems like harmonics and switching transients, associated with voltage regulators make ineffective the very advantages of recommending induction machine to autonomous power generation.

Inclusion of additional series capacitance to provide additional VAR with load is one of the attractive options to improve voltage regulation of SEIG. Chan proposed long-shunt compensation to examine parameter k, which is defined as the ratio of the capacitive reactance to shunt capacitive reactance, on the performance of an induction generator under different loading conditions [5]. The results shown in [5] clearly demonstrate that the long-shunt compensation can be employed to maintain load voltage under various load currents. Sridhar, et al. [6] also presented both steady-state and transient performances of both short-shunt and simple shunt compensations of an induction generator. Li Wang, et al. [7] analyzed and compared the effects of both short-shunt connections as shown in Figure 1 and long-shunt connections as shown in Figure 2 on load voltage variation of the SEIG.
Most of the methods available in literature [5-13] on steady-state performance evaluation of SEIG need separation of real and imaginary component of complex impedance. Moreover the model becomes complicated if the core loss of the machine is also accounted for. It is also observed that the mathematical model is different for each type of loads and also capacitor connections configuration at the machine terminals. Subsequently, the coefficients of mathematical model are also bound to change with change in load, capacitance configuration at the machine terminals. The author made an attempt for the first time to overcome the complication of three-phase and single-phase SEIG models [14-15] by introducing the concept of graph theory which avoids the lengthy and tedious mathematical derivations of nonlinear equations.

In the present paper, the author has developed a further simplified mathematical model of three-phase SEIG in matrix form using nodal admittance method based on inspection. In the proposed model, the nodal admittance matrix can be formed directly from the equivalent circuit of three-phase SEIG by inspection rather than deriving it from the concept of graph theory [14-15]. The proposed model completely eliminates the long and tedious manual work involved in segregating the real and imaginary parts of complex impedance or admittance. Moreover, this model is also flexible such that any equivalent circuit elements can be easily included or eliminated. Genetic algorithm (GA) is proposed to determine the steady-state performance of three-phase SEIG.

II. PROPOSED METHOD

In the analysis presented in this section, the following assumptions are made:

• Only the magnetizing reactance is assumed to be affected by magnetic saturation, and all other parameters of the equivalent circuit are assumed to be constant. Self-excitation results in the saturation of the main flux. As the value of the magnetizing reactance $X_M$ reflects the magnitude of the main flux, it is essential to incorporate in the analysis the variation of $X_M$ with the saturation level of the main flux. Passage of the leakage fluxes occurs primarily in the air and thus these fluxes are not affected to any large extent by the saturation of the main flux.

• Leakage reactance of stator and rotor, in per unit, are taken to be equal. This assumption is normally valid in induction-machine analysis.

• MMF space harmonics and time harmonics in the induced voltage and current waveforms are ignored. This assumption is valid in well-designed machines. Further, the experimental waveforms of generated voltages exhibited negligible time harmonics.

• Core loss in the machine is neglected.
Figure 3 shows the steady-state equivalent circuit of the self excited induction generator. The equivalent circuit is valid for any per unit speed $\nu$. The parameters of equivalent circuit are as follows:

$$Y_L = \frac{1}{\{R_L/F + jX_L - j X_{cb}/F^2\}}$$

$$Y_C = \frac{1}{\{-j X_C/F^2\}}$$

$$Y_S = \frac{1}{\{R_s/F + j X_{sh} - j X_{sh}/F^2\}}$$

$$Y_M = \frac{1}{\{j X_M\}}$$

$$Y_R = \frac{1}{\{R_r/(F-\nu) + j X_k\}}$$

The matrix equation based on nodal admittance method for the equivalent circuit can be expressed as

$$[Y][V] = [I_S]$$  \hspace{1cm} (1)

Where $[Y]$ is the nodal admittance matrix, $[V]$ is the node voltage matrix, and $[I_S]$ is the source current matrix.

The $[Y]$ matrix can be formulated directly from the equivalent circuit (Figure 3) using nodal admittance method based on inspection [16] as

$$[Y] = \begin{pmatrix}
Y_S + Y_M + Y_R & -Y_S \\
-Y_S & Y_S + Y_C + Y_L
\end{pmatrix}$$  \hspace{1cm} (2)

where

$Y_i = \sum$ Admittance of the branches connected to $i^{th}$ node

$Y_{ij} = -\sum$ Admittance of the branches connected between $i^{th}$ node and $j^{th}$ node

Since, the equivalent circuit does not contain any current sources, $[I_S] = [0]$ and hence Eq. (1) is reduced as

$$[Y][V] = 0$$  \hspace{1cm} (3)

For successful voltage build up, $[V] \neq 0$ and therefore from Eq. (3), $[Y]$ should be a singular matrix i.e., det $[Y] = 0$. It implies that both the real and the imaginary components of det $[Y]$ should be independently zero. Therefore to obtain required parameter which results det $[Y] = 0$, genetic algorithm based approach is implemented.

III. GENETIC ALGORITHM

Application of genetic algorithm [17] to obtain det$[Y] = 0$, which provides solution for unknown quantities, is illustrated in Figure 4. The objective function whose value is to be minimized is given by Eq. (4).

$$g\left(F, X_M \text{ or } X_C\right) = \text{abs}\{\text{real}(\text{det}[Y])\} + \text{abs}\{\text{imag}(\text{det}[Y])\}$$  \hspace{1cm} (4)
In many optimization problems to obtain initial estimates suitably, certain trials may be required. However, in the present problem of the SPSEIG, it is easy to give the range for the unknown variables $F$ and $X_M$ or $X_C$ because in well-designed self-excited induction generators, it is known that the slip $\{(F - \nu)/F\}$ is small and operation of the machine is only in the saturated region of the magnetization characteristics. So, the ranges for $F$ can be given as 0.8 to 0.999 times the value of $\nu$ and for $X_M$ as 25% to 100% of critical magnetizing reactance $X_{MO}$. Similarly for $X_C$, the same range 25% to 100% of $C_{MAX}$ can be used, where $C_{MAX}$ is the maximum capacitance required under any conditions. Thus, starting from such initial estimates, the final value of $F$ and $X_M$ or $X_C$ is obtained through GA. The air gap voltage $V_g$ can be determined from the magnetization characteristics corresponding to $X_M$, as described in Section 4. Once the air gap voltage $V_g$ is calculated, the equivalent circuit can be completely solved to determine the steady-state performance of SEIG.

**Figure 4.** Flow chart for minimization of the objective function using genetic algorithm (GA).
IV. EXPERIMENTAL SET UP AND MACHINE PARAMETERS

The parameters of the equivalent circuit (Figure 3) are obtained from experimental measurements on a laboratory model, 3.7 KW, 230 V (line voltage), 12.5 A (line current), 50 Hz, 4 poles, delta connected induction generator.

The base values are:

\[ V_b (\text{base voltage}) = 230 \text{ V}, \]
\[ I_b (\text{base current}) = 12.5 / \sqrt{3} = 7.22 \text{ A}, \]
\[ Z_b (\text{base impedance}) = 31.86 \Omega, \]
\[ N_b (\text{base rotor speed}) = 1500 \text{ rpm}, \]
\[ F_b (\text{base frequency}) = 50 \text{ Hz}. \]

The per-unit parameters of this machine are: \( R_S = 0.0678, R_r = 0.0769, X_{ls} = X_{lr} = 0.1204 \). The magnetizing reactance \( X_M \) (p.u) versus air gap voltage \( V_g/F \) (p.u) expressed by a set of piecewise linear approximations as follows:

- \( 1.7315 - 0.2492 \times X_M, \quad X_M \leq 3.26 \)
- \( 1.9854 - 0.3262 \times X_M, \quad 3.26 < X_M \leq 3.74 \)
- \( 4.2633 - 0.9328 \times X_M, \quad 3.74 < X_M \leq 4.1 \)
- \( 0, \quad 4.1 < X_M \)

V. RESULTS AND DISCUSSION

5.1. Steady-State Performance Analysis of Short-shunt SEIG

The selected unknown variables are magnetizing reactance \( X_M \) and frequency \( F \) for obtaining performance characteristics of the machine. To find the steady-state performance of short-shunt SEIG, the long-shunt component \( X_{clo} \) in the term \( Y_S \) can be assigned as zero in Eq. (2). For obtaining steady-state performance characteristics of short-shunt connections, solve the determinant of the matrix shown in Eq. (2) and find the unknown variables \( X_M \) and \( F \) using genetic algorithm (Figure 4).

The Characteristics of the short-shunt SEIG feeding pure resistive load are shown in Figure 5. Capacitance \( C \) is selected to be \( 31.5 \mu \text{F} \) as it results in a no-load terminal voltage of 1.0pu (base voltage is 230V). It is observed from Figure 5 that the variation of the load voltage with output power is marginal. Further the inclusion of series capacitance \( (C_{sh} = 105 \mu \text{F}) \) results in higher overload capability of the system.
Figure 6 shows the effect of series capacitance on the characteristics of the short-shunt SEIG under the same self excitation capacitance of \( C = 31.5 \mu\text{F} \) and rotor speed of 1pu. Three series capacitance values, 90\( \mu\text{F} \), 105\( \mu\text{F} \) and 120\( \mu\text{F} \) for short-shunt connections were employed to study the steady-state performance of the short-shunt SEIG. Figure 6(a) shows the terminal voltage versus output real power for short-shunt connections. The terminal voltage decreases under lower output real powers and increases under higher output real powers. It is also observed that, under higher output real powers, the lower the series capacitance values, the higher are the terminal voltages. Figure 6(b) shows the load voltage versus output real power for short-shunt connections. Load voltage variations are less from no load to rated load conditions. When the output real power is below 1.8p.u, the smaller the short-shunt capacitance value, the larger the load voltage is. When the output real power is greater than 1.8p.u, the smaller the short-shunt capacitance value, the lower the load voltage is. Figure 6(c) shows the characteristics of stator current versus output real power for short-shunt connections. Stator winding current are well below the rated value at rated output real power.

Figure 7 shows the predicted characteristics of the short-shunt SEIG with an inductive load power factor of 0.9. The system observes voltage sag at light load as shown in Figure 7 nevertheless, the system displays self-regulation when loaded to higher load. Figure 8 shows the steady-state characteristics of maximum voltage variation versus short-shunt capacitance at unity and 0.9 lagging power factor loads at rated speed. The short-shunt connection has the voltage variation of zero percent as observed at rated output power and speed with self excitation capacitance \( C=27 \mu\text{F} \) (\( V_{\text{NL}}=1\text{pu} \)), series capacitance \( C_{\text{s1}}=83.44\mu\text{F} \) at unity power factor load. For 0.9 lagging power factor load, the short-shunt connection has the voltage variation of zero percent as observed at rated output power and speed with self excitation capacitance \( C=27 \mu\text{F} \) (\( V_{\text{NL}}=1\text{pu} \)), series capacitance \( C_{\text{s1}}=117.25\mu\text{F} \).
5.2. Performance Analysis of Long-shunt SEIG

The same matrix as shown in Eq. (2) can be used to find the unknown variables \( X_M \) and \( F \) for long-shunt connections. Since short-shunt connections is not considered, the \( X_{csh} \) value in the term \( Y_L \) can be assigned as zero in Eq. (2). For obtaining steady-state performance characteristics of long-shunt connection, solve the determinant of the matrix shown in Eq. (2) and find the unknown variables \( X_M \) and \( F \) using genetic algorithm (Figure 4).

The predicted characteristics of the long-shunt SEIG feeding pure resistive load are shown in Figure 9. Shunt capacitance \( C \) and long-shunt capacitance \( C_{sh} \) are selected as 50\( \mu \)F and 300\( \mu \)F as it results in a no-load terminal voltage of 1.06pu (base voltage is 230V). It is observed from Figure 9 that the variation of the load voltage with output power is marginal. Further the inclusion of series capacitance results in higher overload capability of the system.
Figure 10 shows the predicted characteristics of long-shunt connections under the same shunt capacitance $C$ of 50\,$\mu$F and rotor speed of 1pu. Three capacitance values, 260\,$\mu$F, 300\,$\mu$F and 340\,$\mu$F for long-shunt connections were employed to study the steady-state performance of the long-shunt SEIG.

Figure 10(a) shows the terminal voltage versus output real power for long-shunt connections. When the output real power is below 1.4\,p.u, the smaller the long-shunt capacitance value, the lower the terminal voltage.

Figure 10(b) shows the load voltage versus output real power for long-shunt connections. The load voltage decreases as the output real power increases for all capacitance values.

Figure 10(c) shows the stator current versus output real power for long-shunt connections. The stator current increases as the output real power increases for all capacitance values.

Figure 10. Effect of series capacitance on the characteristics of the long-shunt SEIG (UPF)

Figure 10 shows the predicted characteristics of long-shunt connections under the same shunt capacitance $C$ of 50\,$\mu$F and rotor speed of 1pu. Three capacitance values, 260\,$\mu$F, 300\,$\mu$F and 340\,$\mu$F for long-shunt connections were employed to study the steady-state performance of the long-shunt SEIG.

Figure 10(a) shows the terminal voltage versus output real power for long-shunt connections. When the output real power is below 1.4\,p.u, the smaller the long-shunt capacitance value, the lower the terminal voltage. For a given value of output real power, the terminal voltage is highest for the lowest capacitance value and lowest for the highest capacitance value.

Figure 10(b) shows the load voltage versus output real power for long-shunt connections. The load voltage decreases as the output real power increases for all capacitance values. The load voltage is lowest for the highest capacitance value and highest for the lowest capacitance value for a given value of output real power.

Figure 10(c) shows the stator current versus output real power for long-shunt connections. The stator current increases as the output real power increases for all capacitance values. The stator current is highest for the highest capacitance value and lowest for the lowest capacitance value for a given value of output real power.
terminal voltage is. When the output real power is greater than 1.4p.u, the smaller the long-shunt capacitance value, the higher is the terminal voltage.

Figure 10(b) shows the load voltage versus output real power for long-shunt connections. It is observed that the voltage variations are low for different values of series capacitance at rated load conditions. Figure 10(c) shows the characteristics of stator current versus output real power for short-shunt connections. The stator winding current is well below the rated value at rated output real power. Figure 11 shows the steady-state characteristics of maximum voltage variations versus long-shunt capacitance at unity and 0.9 lagging power factor loads. The long-shunt connections has the voltage variation of zero per cent is observed at rated output power and speed with shunt capacitance $C=54\,\mu\text{F}$, series capacitance $C_{lo}=270\,\mu\text{F}$, no-load load voltage $V_{NL}=1\,\text{pu}$ at unity power factor load. For 0.9 lagging power factor load the long-shunt connections has the voltage variation of zero percent is observed at rated output power and speed with shunt capacitance $C=90\,\mu\text{F}$, series capacitance $C_{lo}=270\,\mu\text{F}$, no-load load voltage $V_{NL}=1\,\text{pu}$.

![Figure 11. Maximum voltage variation of long-shunt connection](image)

VI. CONCLUSIONS

Genetic Algorithm is proposed to determine the steady-state performance of a self-excited induction generator with series compensation. The possibility of improving voltage regulation of the SEIG by using an additional capacitance in series with the load (short-shunt) or generator terminals (long-shunt) has been investigated. Higher values of capacitances are required for long-shunt connection when compared to short-shunt connection. It is also observed that it is possible to obtain almost flat load voltage characteristics of the SEIG with short-shunt connection. Therefore, short-shunt connection can be used to improve the voltage regulation of the three-phase self-excited induction generator.

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