Capacitive Var Requirements of Single-Phase Two Winding Self-Excited Induction Generators for Desired Voltage Regulation

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ABSTRACT
This paper deals with the capacitive VAr requirements of single-phase two winding self-excited induction generators used in wind energy conversion. To predict the capacitance requirement a simple and generalized mathematical model is developed using nodal admittance method. The proposed model completely eliminates the major mathematical effort followed so far. The steady-state performance analysis of single-phase two winding self-excited induction generator for different regulating criteria such as constant terminal voltage or constant air gap flux is carried out using genetic algorithm. Results are presented in normalized form so that they are valid for a wide range of machines and would be useful for the design of voltage regulators for such generators.

Keywords
Genetic algorithm, Induction generator, and Steady-state analysis.

1. INTRODUCTION
Self-excited induction generator (SEIG) is particularly suitable for wind/hydro energy conversion in isolated application [1]. Either single-phase or three-phase self-excited induction generator can be utilized for this purpose. In case of single-phase two-winding SEIG both the main and auxiliary winding can be utilized. Therefore, capacitance can be connected across the auxiliary winding, which have better reactive power control and hence voltage regulation. In the application of a single-phase two-winding SEIG as a portable power supply, it is necessary to design the generator such that the voltage variation accompanied with load change is as small as possible. The single-phase SEIG [2-5] can have certain benefits over the single-phase synchronous generator. For example, it is virtually maintenance-free, and it has the advantage of a simple and inexpensive structure due to its squirrel-cage rotor design.

Appropriate choice of excitation capacitance is necessary in order to initiate voltage build up and to maintain a given terminal voltage when the SEIG is loaded [6-8]. Several voltage regulating schemes have been tried to achieve this objective [6-10]. This however requires that the machine operate at high flux and increased saturation levels at lower speeds/frequencies, resulting in distorted waveforms and higher losses. Therefore constant flux may be a useful criterion, which may be achieved approximately by keeping the ratio of terminal voltage to speed constant or which may be achieved exactly by keeping the ratio of air gap voltage to output frequency constant [11].

To obtain the capacitive VAr requirements of the single-phase SEIG, genetic algorithm approach is used instead of the classical Newton–Raphson method [4–11] or unconstrained nonlinear optimization method [12–15]. The major difficulty in applying the Newton–Raphson method is the need to establish the Jacobian matrix, which involves lengthy mathematical derivations, partial differentiation and inversion of the Jacobian matrix to obtain the solution. Moreover, the Newton–Raphson method needs a proper initial guess for the unknown variables for convergence. On the other hand, unconstrained nonlinear optimization techniques such as Rosenbrock’s method (gradient method) [12] and Hooke and Jeeves’ method (pattern search method) [13–15] generally involve many numbers of function evaluations, which may lie from 300 to 450 [13] and 400 to 3500 [14,15] over the practical range of load impedances. Further, these optimization techniques need proper upper and lower ranges for the unknown variables.

Therefore genetic algorithm has been proposed to carry out steady-state performance of single-phase two winding SEIG. Three criterions have been discussed which are highly useful to design a voltage regulator for the two-winding SEIG under varying speed and load. Results were presented for the three criterions for a wide range of wind speed and load.

2. MATHEMATICAL MODELING
The development of a mathematical model for single-phase two-winding SEIG for steady-state analysis using nodal admittance method is detailed below.

Fig.2 shows steady-state equivalent circuit of the single-phase two winding self-excited induction generator. The equivalent circuit is developed as discussed in the paper [12]. The equivalent circuit is valid for any per unit speed υ.

The parameters of equivalent circuit are:

\[ Y_1 = \frac{1}{|j F X_M|} \]
The matrix equation based on nodal admittance method for the equivalent circuit can be expressed as

\[ [Y] [V] = [I_s] \]

(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 (Fig. 2) using nodal admittance method based on inspection [13] as

\[ [Y] = \begin{bmatrix}
Y_1 + Y_3 + Y_5 & 0 & - (Y_1 + Y_3) \\
- (Y_1 + Y_3) & Y_1 + Y_3 + Y_5 + Y_7 & - (Y_2 + Y_4) \\
0 & - (Y_2 + Y_4) & Y_2 + Y_4 + Y_6
\end{bmatrix} \]

(2)

where

- \(Y_i\) = Σ Admittance of the branches connected to \(i^{th}\) node
- \(Y_{ij}\) = Σ 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

\[ [Y] [V] = 0 \]

(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 the \(\det [Y]\) should be independently zero. Therefore to obtain required parameter which results \(\det [Y] = 0\), genetic algorithm based approach is implemented.

3. PERFORMANCE OF SEIG BY GENETIC ALGORITHM

Application of genetic algorithm [14] to obtain \(\det[Y] = 0\), which provides solution for unknown quantities, is illustrated in Fig. 3. The objective function whose value is to be minimized is given by Eq. (4).

\[ g(F, X_M \text{ or } X_C) = \text{abs}\{\text{real}[Y]\} + \text{abs}\{\text{imag}[Y]\} \]

(4)

In many optimization problems to obtain initial estimates suitably, certain trials may be required. However, in the present problem of the SEIG, 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 \(X_{g0}\). 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.
Fig. 4. Photograph of the single-phase two winding SEIG.

Base values:
\[ V_{\text{base}} = \text{rated voltage} = 230 \text{ V} \]
\[ I_{\text{base}} = \text{rated current} = 6 \text{ A} \]
\[ Z_{\text{base}} = V_{\text{base}} / I_{\text{base}} = 38.33 \text{ ohms} \]
Base power \[ P_{\text{base}} = V_{\text{base}} * I_{\text{base}} \]
Base speed \[ N_{\text{base}} = 1500 \text{ rpm} \]
Base frequency \[ f_{\text{base}} = 50 \text{ Hz} \]

The p.u. parameters of the machine are:
\[ R_{\text{IM}} = 0.0734, \quad R_{\text{a}} = 0.1036, \quad X_{\text{IM}} = X_{\text{a}} = 0.1675, \quad R_{\text{IA}} = 0.3074, \quad \text{and } a=1.25 \]

The magnetizing reactance \( X_M \) versus air gap voltage \( V/F \) expressed (in p.u.) by a set of piecewise linear approximations are given below.
\[ V/F=1.689-0.2X_M \quad \text{for } X_M \leq 3.2 \]
\[ V/F=2.844-0.555X_M \quad \text{for } X_M > 3.2 \]

5. RESULTS AND DISCUSSION

It is necessary to determine the VAr requirements under different performance criteria [11]. The three criteria considered are as follows:

i) Criterion I: Terminal voltage \( V_t \), constant at all loads and speeds.

ii) Criterion II: Ratio of terminal voltage to speed \( V_t/\omega \), constant at all loads and speeds. This would keep the machine flux approximately constant.

iii) Criterion III: Ratio of airgap voltage to output frequency, \( V/F \), constant. This would keep the air gap flux exactly constant.

5.1 Criterion I: Terminal Voltage \( V_t \) Constant at All Loads and Speeds

Here it is required to determine the capacitive reactance, \( X_c \), or susceptance, \( g_c = 1/X_c \), for a given speed and load to obtain the required constant terminal voltage. Here the selected unknown variables are capacitive reactance, \( X_c \) and frequency, \( F \). For obtaining steady-state performance characteristics, solve for det\( [Y] \) (Eq. (2)) and find the unknown variables \( X_c \) and \( F \) using the genetic algorithm discussed in Section 3.

Variation of capacitive VAr and the capacitive susceptance \( g_c \) with output power to maintain the terminal voltage constant at 1 p.u. at different constant speeds, i.e., \( u=0.8, 0.9, 1.0, 1.1 \text{ and } 1.2 \) are shown in Fig. 5. The capacitive VAr requirements increase as the speed decreases and VAr needed increases also with output power. From the Fig. 5, it can be concluded that a voltage regulator should be capable of providing a range of VAr from 1.27 to about 3.0 p.u. to maintain the terminal voltage at 1 p.u. under varying speed of 0.9 to 1.2 p.u. and load ranging from 0 to 0.56 p.u. (rated output power = 750 W).

The corresponding variation of auxiliary, main winding current and output frequency with output power at constant terminal voltage is shown in Fig. 6. At a constant speed, the output frequency is almost constant reducing by about 5% from no load to 0.56 p.u. load. Thus additional frequency regulating systems need not be required. The auxiliary and main winding currents are well below the rated current at rated output power for a speed ranging from 1.0 to 1.2 p.u. ensure safe operation of the machine so far as loading is concerned.

Fig. 5. VAr and \( g_c \) required at different output power to keep terminal voltage \( V_t \) constant at 1 p.u.

Variation of auxiliary winding voltage with output power at constant terminal voltage is shown in Fig. 7. The voltage in the auxiliary winding increases up to 1.8 p.u. for a speed of 1 p.u. at rated output power. Since the current in both windings (Fig. 6) are still less than the rated current for a speed ranging from 1.0 to 1.2 p.u. at rated output power, it does not affect the safe operation of the machine so far as loading is concerned.
Variation of capacitive VAr and the capacitive susceptance, \( g_c \), with output power to maintain ratio of terminal voltage to speed constant at 1.2p.u. Here the trend of variation of \( g_c \) with output power is similar to Fig. 5 relatively smaller capacitors are required at reduced speeds due to corresponding reduction in \( V_s \). It was also observed that capacitive VAr requirement at any load differs very little with speed in contrast to Fig. 5. Thus a constant flux criterion would be a desirable feature if the terminal voltage variation with speed is acceptable.

5.2 Criterion II: Ratio of Terminal Voltage to Speed (\( V_t/\upsilon \)) Constant at all Loads and Speeds

This criterion would keep the machine flux approximately constant. Here for each p.u. unit speed \( \upsilon \), capacitance and VAr have to be determined to keep the terminal voltage \( V_t \) constant at \( K \upsilon \), (\( K=1 \)). Here again the selected unknown variables are capacitive reactance, \( X_c \), and frequency, \( F \). Thus det of \( Y \) is solved and the unknown variables \( X_c \) and \( F \) are computed using the genetic algorithm discussed in Section 3.

5.3 Criterion III: Ratio of Air gap Voltage to Output Frequency (\( V_g/F \)) Constant at all Loads and Speeds

This criterion would keep the machine flux exactly constant. Here the airgap flux which is proportional to \( V_g/F \) is maintained constant. At constant flux, \( X_s \) would be constant. One may consider the situation that both \( V_g \) and \( F \) are kept constant at particular values. It is intended to determine capacitive reactance, \( X_c \), or susceptance, \( g_c =1/X_c \) and speed \( \upsilon \) for each \( F \) to maintain \( V_g \) and \( F \) constant at all loads. Here in the auxiliary winding raises up to 2.1p.u. for a speed of 1.2p.u at rated output power. Since the current in both windings (Fig. 9) are still less than rated current for a speed ranging of 0.8 to 1.2p.u at rated output power it does not affect the safe operation of the machine so far as loading is concerned.
the selected unknown variables are capacitive reactance, \( X_c \) and per unit speed, \( \nu \). The same mathematical model developed by inspection method can be utilized irrespective of the unknown variables. Hence to obtain the unknowns \( X_c \) and \( \nu \) for each \( F \) to maintain \( V_g \) and \( F \) constant at all loads, solve for \( \text{det}[Y] \) and find the unknown variables \( X_c \) and \( \nu \) using genetic algorithm.

Fig. 11 shows the VAr requirements to maintain ratio of air gap voltage to frequency constant at different constant value of \( F \) at load ranging from 0 to 0.56p.u. The range of capacitor required is less than that with criterion I. Variation of \( g_c \) with output power is more pronounced at lower speeds. These results are similar to those of Fig. 8.

Fig. 12 shows the variation of \( V_A \) and \( I_A \) with output power to keep constant air gap flux \((V_g/F=1.0)\) for different values of \( F \).

Fig. 13 shows the VAr requirements to maintain ratio of air gap voltage to frequency constant at different constant value of \( F \) at load ranging from 0 to 0.56p.u. The range of capacitor required is less than that with criterion I. Variation of \( g_c \) with output power is more pronounced at lower speeds. These results are similar to those of Fig. 8.

**Fig. 11.** Variation of \( \nu \) and \( g_c \) with output power to keep air gap flux constant \( i.e., V_g/F=1.0 \) (for different constant value of \( F \)).

**Fig. 12.** Variation of \( V_A \) and \( I_A \) with output power to keep constant air gap flux \((V_g/F=1.0)\) for different values of \( F \).

**Fig. 13.** Variation of \( V_c \) and \( I_c \) with output power to keep constant air gap flux \((V_g/F=1.0)\) for different values of \( F \).


