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.

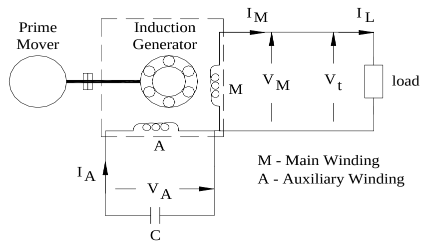

Fig. 1 Schematic diagram of capacitor excitation of two winding single phase self excited induction generator

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:

$Y_1 = 1 / [j\, F\, X_M]$;

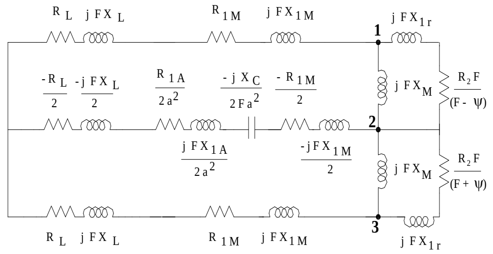

Fig. 2. Equivalent circuit of single-phase two winding self-excited induction generator.

$Y_2 = Y_1$;
$Y_3 = 1 / [R_2 F / (F - \upsilon) + j F X_{lr}]$;
$Y_4 = 1 / [R_2 F / (F + \upsilon) + j F X_{lr}]$;
$Y_5 = 1 / [R_L + j F X_L + R_{1M} + j F X_{1M}]$;
$Y_6 = Y_5$;
$Y_7 = 1 / [-R_L/2 - j F X_L/2 + R_{1A} / 2a^2 + j F X_{1A}/ 2a^2 - j X_C / 2Fa^2 - R_{1M} / 2 - j F X_{1M} /2]$;

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

$$[Y]\,[V] = [I_S] \qquad (1)$$

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

$$[Y] = \begin{pmatrix} (Y_1 + Y_3 + Y_5) & -(Y_1+Y_3) & 0 \\ -(Y_1+Y_3) & (Y_1 + Y_2 + Y_3+Y_4+Y_7) & -(Y_2+Y_4) \\ 0 & -(Y_2+Y_4) & (Y_2 + Y_4+ Y_6) \end{pmatrix} \qquad (2)$$

where

$Y_{ii} = \sum$ 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

$$[Y]\,[V] = 0 \qquad (3)$$

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.

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).

$$g\,(F, X_M \text{ or } X_C) = \text{abs}\{\text{real}(\det[Y])\} + \text{abs}\{\text{imag}(\det[Y])\} \qquad (4)$$

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 $\{(F - \upsilon)/F\}$ 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 υ 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.

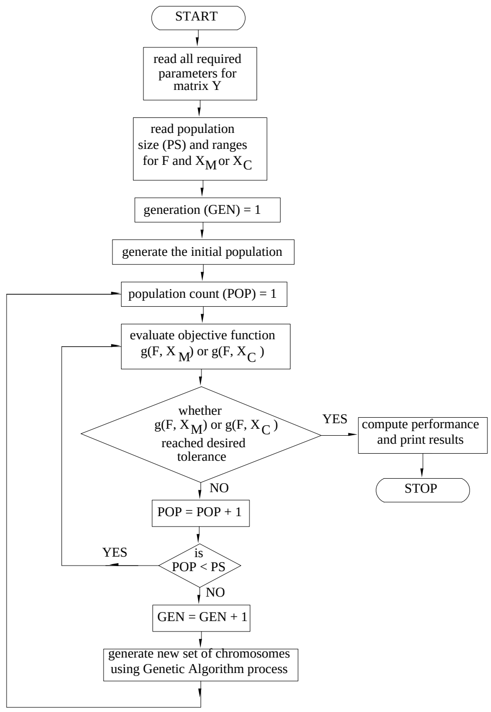

Fig. 3. Flow chart for minimization of the objective function using genetic algorithm (GA).

4. EXPERIMENTAL SETUP AND MACHINE PARAMETERS

The machine parameters of equivalent circuit have been considered for the simulated results. The details of squirrel cage induction generator is 0.75 kW, 4-pole, 50 Hz, 230 V, 6 A, 1500 rpm capacitor start. The photograph of the prototype model is shown in Fig. 4.

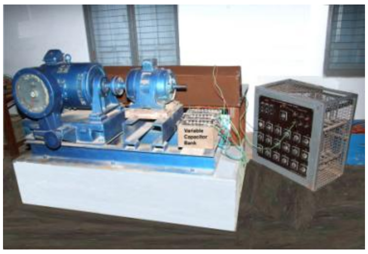

Fig.4. Photograph of the single-phase two winding SEIG.

Base values:

V_{base} = rated voltage	= 230 V
I_{base} = rated current	= 6 A
$Z_{base} = V_{base} / I_{base}$	= 38.33 ohms
Base power $P_{base} = V_{base} * I_{base}$	= 1.38 kW
Base speed N_{base}	= 1500 rpm
Base frequency f_{base}	= 50 Hz

The p.u parameters of the machine are:

$R_{1M} = 0.0734$, $R_2 = 0.1036$, $X_{lM} = X_{lr} = 0.1675$,
$R_{1A} = 0.1357$, $X_{lA} = 0.3074$, and $a=1.25$

The magnetizing reactance X_M versus air gap voltage V_g/F expressed (in p.u) by a set of piecewise linear approximations are given below.

$$V_g/F=1.689-0.2X_M \quad \text{for } X_M \le 3.2$$

$$V_g/F=2.844-0.555X_M \quad \text{for } X_M > 3.2$$

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/υ, 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_g/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, Xc, or susceptance, g_c(=1/Xc), 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 1p.u. at different constant speeds, i.e., υ=0.8, 0.9, 1.0, 1.1 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 3.0p.u to maintain the terminal voltage at 1p.u. under varying speed of 0.9 to 1.2p.u. and load ranging from 0 to 0.56p.u. (rated output power =750 W).

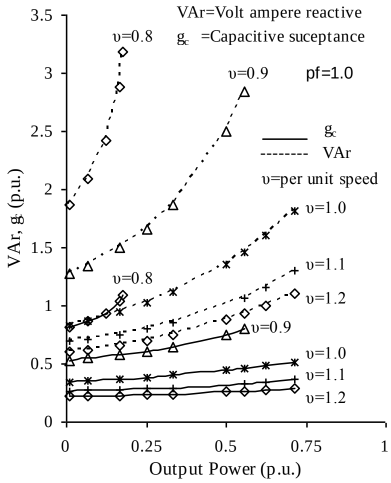

Fig. 5. VAr and g_c required at different output power to keep terminal voltage V_t constant at 1p.u.

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 0.56p.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 1.2p.u ensure safe operation of machine so far as loading is concerned.

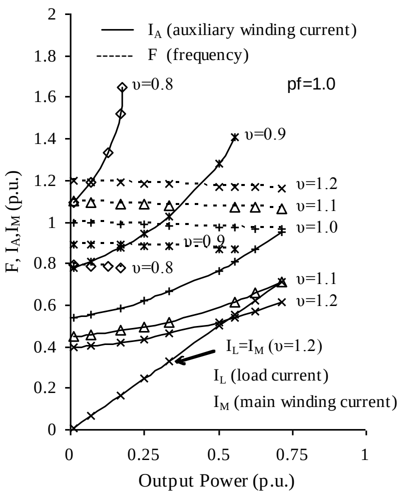

Fig. 6. Variation of F, I_A and I_M with output power to keep V_t constant at 1p.u.

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 1.8p.u for a speed of 1p.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 1.2p.u at rated output power, it does not affect the safe operation of the machine so far as loading is concerned.

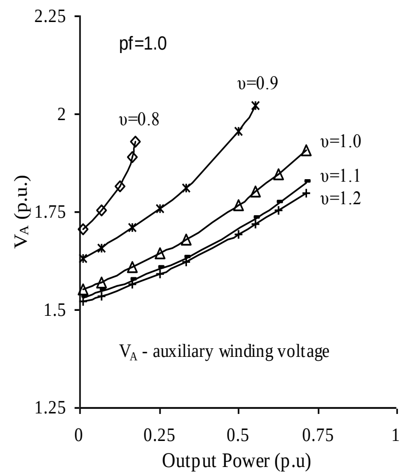

Fig. 7. Variation of V_A with output power to keep V_t constant at 1p.u.

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

This criterion would keep the machine flux approximately constant. Here for each p.u. unit speed υ, capacitance and VAr have to be determined to keep the terminal voltage V_t constant at Kυ, (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.

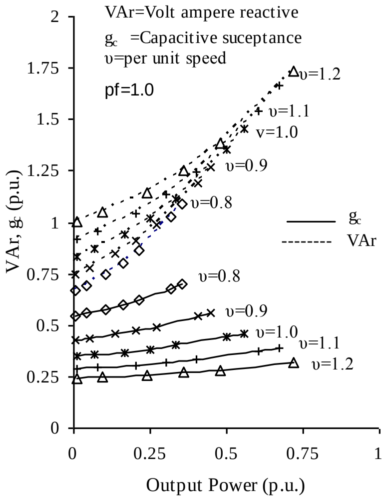

Fig. 8. VAr and g_c required at different output power to keep V_t / υ constant at 1p.u.

Variation of capacitive VAr and the capacitive susceptance g_c with output power to maintain ratio of terminal voltage to speed constant at 1p.u. under different constant speeds, i.e., υ=0.8, 0.9, 1.0, 1.1 and 1.2 are shown in Fig. 8. Though the trend of variation of g_c and output power is similar to Fig. 5 relatively smaller capacitors are required at reduced speeds due to corresponding reduction in V_t. 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.

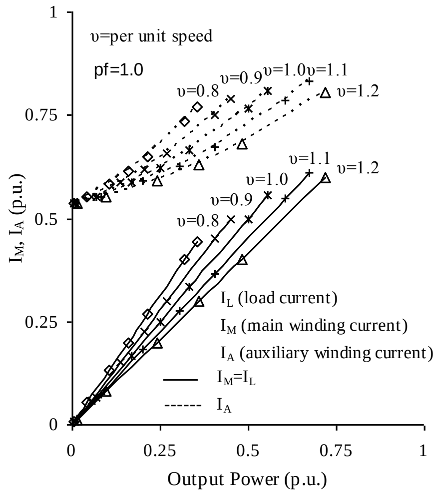

Fig. 9. Variation of I_M and I_A with output power to keep V_t/υ constant at 1p.u.

Fig. 9 shows the variation of main, auxiliary current with output power to keep V_t/υ constant at 1p.u. Here the variation of currents with speed for the same output power is considerably less than that observed in Fig. 6. In fact no-load stator current is almost constant at all speeds.

Fig. 10 shows the variation of auxiliary winding voltage with output power to keep V_t /υ constant at 1p.u. The voltage

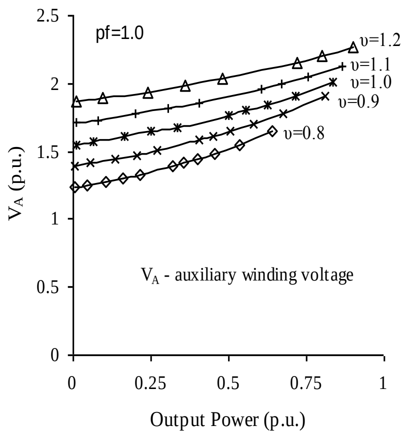

Fig. 10. Variation of V_A with output power to keep to keep V_t / υ constant at 1p.u.

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.

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_M would be constant. One may consider the situvation that both V_g and F are kept constant at particular values. It is intended to determine capacitive reactance, Xc, or susceptance, g_c(=1/Xc) and speed υ for each F to maintain V_g and F constant at all loads. Here the selected unknown variables are capacitive reactance, X_C and per unit speed, υ. The same mathamatical model developed by inspection method can be utilized irrespective of the unknown variables. Hence to obtain the unknowns X_C and υ for each F to maintain V_g and F constant at all loads, solve for det[Y] and find the unknown variables X_C and υ using genetic algorithm.

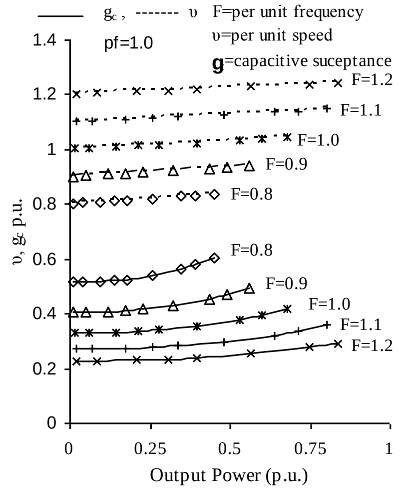

Fig. 11. Variation of υ and g_c with output power to keep air gap flux constant i.e., Vg/F constant at 1p.u. (for different constant value of F).

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.

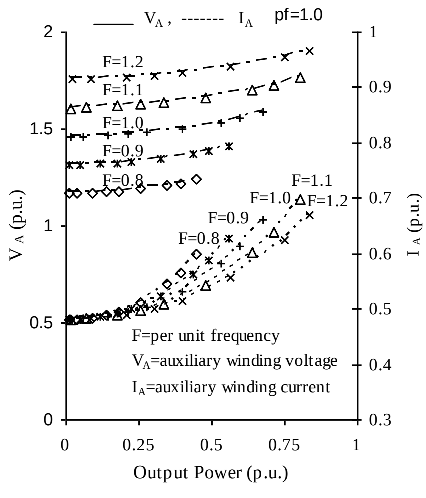

Fig. 12. Variation of V_A and I_A with output power to keep constant air gap flux (V_g/F=1.0) for different values of F.

Fig. 12 shows the variation of V_A and I_A with output power to keep constant air gap flux for different values of F. The auxiliary winding voltage V_A raises 1.82p.u. at an output power of 0.56p.u. The variation of auxiliary winding current is similar to that in Fig. 9, due to similar operating conditions.

Variation of V_t and I_L with output power is shown in Fig. 13. The variation of load current is similar to that in Fig. 9, due to similar operating conditions. Comparing the results of

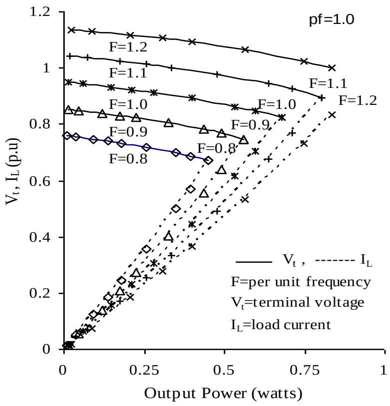

Fig. 13. Variation of V_t and I_L with output power to keep constant air gap flux (V_g/F=1.0) for different values of F.

criterion II and criterion III it can be concluded that keeping V_t / υ constant is sufficient to obtain the performance similar to a constant flux condition.

6. CONCLUSION

The range of terminal capacitance and the capacitive VAr required for a single-phase two winding self-excited induction generator to be operated under varying speeds and loads is determined in order to obtain desired voltage regulation. A mathematical model using nodal admittance method based on inspection and a genetic algorithm based computation of steady-state performance of single-phase SEIG for different operating criteria have been proposed. The proposed model avoids extensive efforts in separating real and imaginary components of the impedance of the machine for deriving the specific model in different operating modes. The matrix Y developed by inspection method is used for all criterions without any modifications, whatever the combinations of unknowns may be. The variation of capacitive VAr, machine current and output frequency, with output power are presented graphically in p.u and discussed so that the results are general and would be relevant for a range of machines. The range of terminal capacitance and the capacitive VAr required for a self-excited generator to be operated under varying speeds and loads is determined in order to obtain desired voltage regulation. The variation of capacitive VAr, machine current and output frequency with output power are presented. Results are presented for speed variation from 0.8 to 1.2p.u. Satisfactory operation with a practicable range of capacitance could be observed in the speed range from 1.0 to 1.2p.u at constant terminal voltage. A constant flux operation needs reduced range of capacitors and also results in better performance due to the absence of higher saturation level, but the terminal voltage will have to be varied with speed

7. ACKNOWLEDGMENTS

The authors gratefully acknowledge the support and facilities provided by the authorities of the Annamalai University, Annamalainagar, Tamilnadu, India to carry out this research work.

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