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# Capacitive VAr requirements for wind driven self-excited induction generators

S. Singaravelu *, S. Velusami

*Department of Electrical Engineering, Annamalai University, Annamalainagar, Chidambaram 608 002, Tamilnadu, India*

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**Abstract**

This paper presents the capacitive VAr requirements of a three phase pole changing self-excited induction generator and a single phase self-excited induction generator, used as isolated power sources by a constant speed or a variable speed prime mover, to obtain the desired voltage regulation at various values of load and speed. Different performance criteria such as constant terminal voltage or constant air gap flux have been considered. The developed mathematical model using nodal analysis based on graph theory is quite general in nature and can be used for any combination of the unknown variables such as magnetizing reactance ($X_M$) and frequency ($F$) or capacitive reactance ($X_C$) and frequency ($F$) or capacitive reactance ($X_C$) and speed ($v$). The proposed model completely avoids the tedious and erroneous manual work of segregating the real and imaginary components of the complex impedance of the machine for deriving the specific model for each operating modes. Moreover, any element, like the core loss component, can be included or excluded from the model if required. Next, to obtain the capacitive VAr requirements of a three phase pole changing self-excited induction generator and a single phase self-excited induction generator, a fuzzy logic approach is used for the first time to find the unknown variables using the above model. The results are presented in a 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:* Graph theory; Induction generator; Pole changing; Self-excitation; Steady state analysis

## 1. Introduction

There has been a huge increase in energy demand during the last few decades, which has accelerated the depletion of the world fossil fuel supplies. Environmental concerns and international policies are supporting new interests and developments for small scale power generation. Therefore, the study of both three phase and single phase self-excited induction generators (SEIG) has regained importance, as they are particularly suitable for wind and small hydro power plants [1]. It is well known that for the operation of an induction generator in the stand alone mode, capacitive excitation is necessary to maintain the voltage across the machine terminals. The terminal voltage of the machine depends on the values of capacitance, speed and load connected across its terminals. The voltage of the machine decreases with an increase in the load connected across its terminals. The voltage of the machine also decreases or increases with a decrease or increase in prime mover speed. Therefore, a steady increase in capacitor VAr with load or under varying speed has to be achieved to maintain good voltage regulation. Several voltage regulating schemes have been attempted to achieve this objective [2,3]. This, however, requires that the machine operate at high flux and increased saturation levels at the lower speeds/frequencies, resulting in distorted waveforms and higher losses. Therefore, constant flux may be a useful criterion [4], which may be achieved approximately by keeping the ratio of the terminal voltage to speed constant or which may be achieved exactly by keeping the ratio of the air gap voltage to output frequency constant.

Most of the mathematical models available in the literature [2–9] on the capacitive VAr requirements of three

* Corresponding author. Tel.: +91 4144 238735; fax: +91 4144 238275.
*E-mail address:* ganapss@yahoo.com (S. Singaravelu).

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**Nomenclature**

| | |
|---|---|
| $R_S$, $R_r$ | per phase stator and rotor (referred to stator) resistance |
| $R_C$ | per phase equivalent loss resistance (core loss) |
| $X_{ls}$, $X_{lr}$ | per phase stator and rotor (referred to stator) leakage reactance |
| $X_M$ | per phase magnetizing reactance |
| $X_{MO}$ | per phase unsaturated magnetizing reactance |
| $X_C$ | per phase capacitive reactance of terminal capacitor $C$ |
| $R_L$, $X_L$ | load resistance and reactance per phase (all reactances referred to above relate to base frequency $F$) |
| $F$, $\upsilon$ | per unit frequency and speed |
| $I_S$, $I_r$, $I_L$ | stator, rotor (referred to stator) and load current per phase |
| $V_g$, $V_t$ | air gap and terminal voltage per phase |
| $G$ | real or imaginary value of det[$Y$] |
| $H$ | correction value of unknown variables |
| $G_{max}$ | maximum real or imaginary value of det[$Y$] |
| $H_{max}$ | maximum correction value of unknown variables |
| $G_{fuz}$ | fuzzy signal of $G$ |
| $H_{fuz}$ | fuzzy signal of $H$ |
| $\Delta F$ | frequency correction value |
| $\Delta X_M$ | magnetizing reactance correction value |
| $\Delta X_C$ | capacitive reactance correction value |

phase and single phase SEIGs need manual separation of the real and imaginary components of the complex impedance of the equivalent circuits to derive specific models. In this paper, a new mathematical model is developed for both three phase pole changing SEIGs and single phase SEIGs using a nodal admittance method based on graph theory. The mathematical models developed using graph theory completely avoid the tedious manual work involved in segregating the real and imaginary components of the complex impedance of the equivalent circuit. Also, the same model can be implemented for any type of load and any combination of the unknown variables, such as magnetizing reactance ($X_M$) and frequency ($F$) or capacitive reactance ($X_C$) and frequency ($F$) or capacitive reactance ($X_C$) and p.u. speed ($\upsilon$). Since the model developed using graph theory results in a matrix form, any element, like the core loss component, can be easily included or eliminated. Further, the added advantage of this model is that the leakage reactance of the stator ($X_{ls}$) and rotor ($X_{lr}$) can be handled separately, if needed, by avoiding the assumption $X_{ls} = X_{lr}$ without any modification in the model.

Next, to obtain the capacitive VAr requirements of the three phase pole changing SEIG and the single phase SEIG, a fuzzy logic approach is used instead of the classical Newton–Raphson method [4–9] or unconstrained nonlinear optimization method [10–14]. 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) [10,11] and Hooke and Jeeves' method (pattern search method) [12–14] generally involve many numbers of function evaluations, which may lie from 300 to 450 [12] and 400 to 3500 [13,14] over the practical range of load impedences. Further, these optimization techniques need proper upper and lower ranges for the unknown variables.

In this paper, the capacitive VAr requirements of the three phase pole changing SEIG and the single phase SEIG are found using a fuzzy logic process with a simple rule base, and it is relatively very simple for programming. Though the fuzzy rules are simple, their performances are found to be sufficiently robust [15]. Further, the merit of applying the fuzzy logic process is that it provides a fruitful direction with good prospects for having global solutions even when it starts with bad initial conditions. The developed fuzzy logic approach has been applied to the three phase pole changing SEIG and the single phase SEIG to compute the lagging reactive power requirements of the machines for different performance criteria such as constant terminal voltage or constant air gap flux at various values of load and speed. To validate the simulated results of the three phase pole changing SEIG and the single phase SEIG, they are compared with the classical Newton–Raphson method [4–9] based results with the same tolerance.

## 2. Development of mathematical model for a three phase SEIG using graph theory

Fig. 1 shows the per phase steady state equivalent circuit of the pole changing SEIG. The equivalent circuit is valid for any per unit speed $\upsilon$.

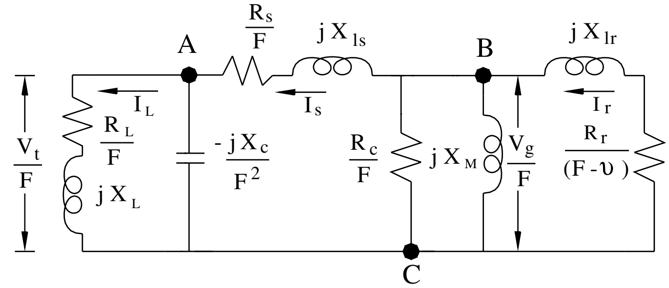


Fig. 1. Equivalent circuit of the induction generator with load.