Steady-State Analysis of a Self-Excited Induction Generator Self-Regulated by a Shunt Saturable Reactor

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Abstract - The terminal voltage of a self-excited isolated induction generator, supplying a fixed load, may increase considerably due to a small increase in speed, excitation capacitance or both. In most developing countries, unregulated wind-turbines are often used due to their lower cost. Under such conditions the voltage may increase to a dangerously high level which may cause machine, load or capacitor damage. This paper examines the steady-state analysis and performance characteristics of an isolated SEIG when a saturable reactor is connected across its terminals. As the reactor saturates it absorbs the excess reactive vars supplied by the excitation capacitance, and limits the increase of the terminal voltage.

I. INTRODUCTION

The increased emphasis on renewable energy sources and the rising concerns about clean environments, have accelerated research and development of suitable power generators, driven by renewable energy sources such as wind. The self-excited induction generator (SEIG) has been discussed in the literature [1]-[9] as a very good candidate for this application due to its simplicity, ruggedness, and low cost, etc. It provides a reliable and relatively inexpensive means to convert wind power to electrical power over a wide range of speed. Unless the SEIG is connected to a utility grid, its terminal voltage and frequency are free to vary with speed such that the operating slip remains small and negative. The terminal voltage of a SEIG may increase considerably due to a small increase in speed resulting in dangerously high over-voltages [4],[5]. In most developing countries, unregulated wind-turbines are often used due to their lower cost. Under such conditions the voltage may regularly increase to high levels which have been reported to cause excitation capacitor failures [6], [7].

This paper examines the steady-state analysis and performance characteristics of an isolated SEIG when a saturable reactor is connected across its terminals. As the reactor saturates it absorbs the excess reactive vars supplied by the excitation capacitance, and prevents any further increase in the terminal voltage.

It is well known that the air-gap voltage of a SEIG is limited by the saturation of the machine's magnetic circuit which makes the analysis of the SEIG circuit inherently a nonlinear problem. When a saturable reactor is connected to the SEIG's terminal, an additional nonlinearity is introduced which makes the analysis extremely difficult using the previously published conventional methods [1]-[9]. Such methods solve the SEIG equivalent circuit subject to self-excitation condition, namely the total loop impedance (or total node admittance) at the magnetizing branch be equal to zero. In this paper the resulting nonlinear complex equations are solved using a Mathcad [10] program on a personal computer. The calculated results are verified experimentally for a model system under a variety of test conditions.

II. SYSTEM MODELLING

The system consists of a 3-phase induction machine, which is being driven at speed ω in per-unit (synchronous speed = 1 per-unit). A balanced 3-phase excitation capacitor bank C is connected to its stator. A balanced resistive load (R_L) and a saturable reactor (X_L) are also connected across the stator. The steady-state equivalent circuit is shown in Fig. 1, where f and ω are the per-unit frequency and speed, and all the parameters are given in per-unit on the machine base.

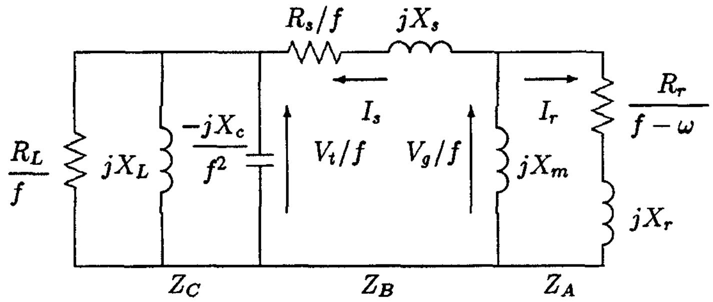

Fig. 1 Per-phase equivalent circuit of the SEIG

Generally, for specified values of ω, X_c, machine and load parameters, the circuit of Fig. 1 can be solved, such that the self-excitation condition is satisfied; namely, the total loop impedance (or total node admittance) at the magnetizing branch is zero. Therefore, at self-excitation

$$Z_A + Z_B + Z_C = 0 \tag{1}$$

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where

$$Z_A = \frac{jX_m[R_r/(f-\omega)+jX_r]}{R_r/(f-\omega)+j(X_r+jX_m)} \quad (2)$$

$$Z_B = R_s/f + jX_s \quad (3)$$

$$Z_C = 1/[\frac{1}{jX_L} + \frac{f^2}{-jX_c} + \frac{f}{R_L}] \quad (4)$$

The previously published methods [1-9] regard X_L as constant (no saturable reactor), and hence the only unknowns are f and X_m. The conventional method [1]-[9] of solution is to equate the real and imaginary parts of (1) to zero. The resulting equations are then solved using a gradient method such as the Newton-Raphson Method. Despite the simplicity of the equivalent circuit, the process of separating equation (1) into real and imaginary parts is tedious, time consuming, and the resulting equations may become too cumbersome and unmanageable for more detailed modelling of system components. Furthermore, for any change in the system configuration, such as connecting the capacitors as a short or long shunt, etc., the equations have to be derived all over again.

In this paper, the reactance of the saturable reactor, X_L depends on the terminal voltage V_t according to the reactor magnetization characteristics. Therefore, the unknowns are f, X_m and X_L. In this case, equation (1) is insufficient to solve for the three unknowns and hence an additional equation is required. It is much more convenient to formulate the required additional equation if the unknowns are taken as f, V_g and V_t, instead of f, X_m and X_L by expressing X_m and X_L as functions of V_g and V_t respectively. Unlike X_m and X_L, the two node voltages V_g and V_t are easily related by

$$\left|\frac{Z_C}{Z_B+Z_C}\right| V_g - V_t = 0 \quad (5)$$

Unfortunately, it is very difficult, if not impossible, to separate equation (1) into real and imaginary parts in terms of V_g and V_t, since X_m and X_L are written as functions of V_g and V_t. To overcome this difficulty, this paper uses Mathcad [10] to solve equations (1) and (5) simultaneously as follows:

(a) Define all constants such as:
$R_s := 0.092 \qquad R_r := 0.064$

(b) Define machine and reactor magnetizing reactance functions:
$X_m(V_g) := 3.46 - 6.5V_g + 9.51V_g^2 - 4.77V_g^3$
$X_L(V_t) := 66.45 + 116.93V_t - 257.98V_t^2 + 98.5V_t^3$

(c) Define impedances Z_A, Z_B, and Z_C as given above.

(d) Give suitable initial guess:
$f := 0.8 \qquad V_g := 0.8 \qquad V_t := 0.8$

(e) Solve using the Mathcad's "Given..FIND" procedure:

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$Z_A(V_g, f) + Z_B(f) + Z_C(V_t, f) = 0$

$$\left|\frac{Z_C(V_t,f)}{Z_B(f)+Z_C(V_t,f)}\right| V_g - V_t = 0$$

$\mathrm{Im}(f) = 0 \qquad \mathrm{Im}(V_g) = 0 \qquad \mathrm{Im}(V_t) = 0$

FIND (f, V_g, V_t)

III. EXPERIMENTAL VERRIFICATION

A model system consisting of a 380-V, 4-pole, 60-Hz, 2.9-A, Y-connected wound rotor induction machine, coupled to a variable speed dc motor drive was tested in the laboratory. The induction machine has the following per-unit measured parameters:- $R_s = 0.092$, $R_r = 0.064$, $X_s = X_r = 0.21$, $X_r = 0.21$,

$$X_m(V_g) = 3.46 - 6.5V_g + 9.51V_g^2 - 4.77V_g^3 \quad (6)$$

A 3-phase, Y-connected, balanced excitation capacitor bank was connected across the machine terminals. The saturable reactor is represented by the following function

$$X_L(V_t) = 66.45 + 116.93V_t - 257.98V_t^2 + 98.5V_t^3 \quad (7)$$

Fig. 2 shows the calculated as well as the measured variations of the stator voltage V_s, stator current I_s and frequency f with speed ω, at no-load, for excitation capacitance $C = 25.5\mu$F. Very good agreement between measured and calculated values is clear from Fig. 2, which verify the accuracy of the proposed technique.

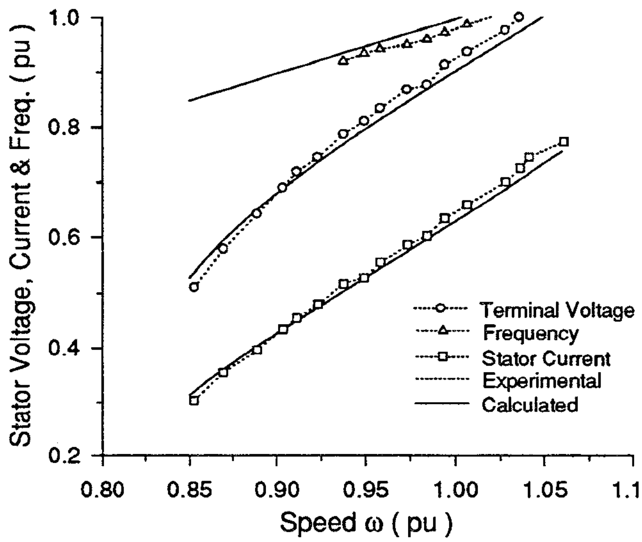

Fig. 2 Variation of stator voltage V_s, stator current I_s and frequency f with speed ω at no-load, and $C = 25.5\mu$F.

IV. EFFECT OF REACTOR SATURATION

Fig. 3 displays variation of the terminal voltage V_t with excitation capacitance, at 1 pu speed, while Fig. 4 shows variation of V_t with speed for constant capacitance, both with and without saturable reactor.

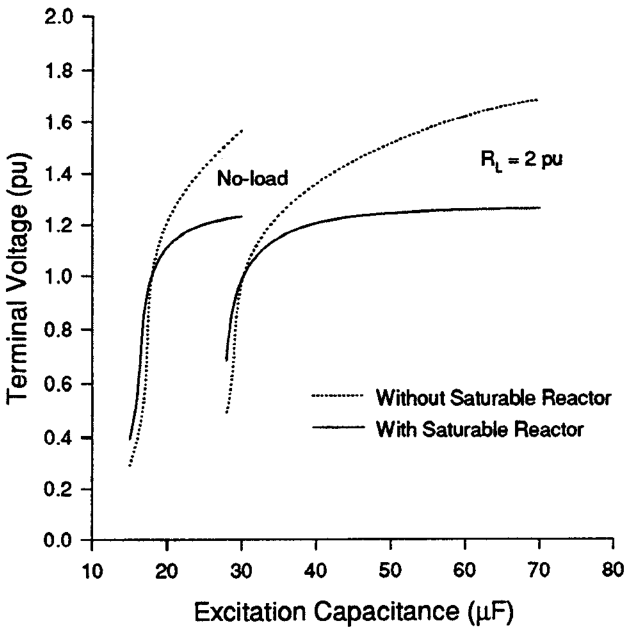

Fig. 3 Variation of the terminal voltage V_t with excitation capacitance, at 1 pu speed, with and without saturable reactor.

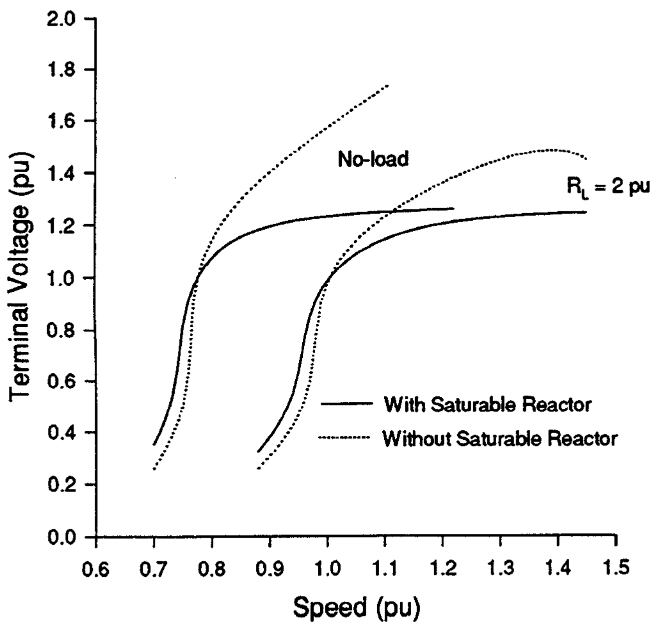

Fig. 4 Variation of the terminal voltage V_t with speed, for constant excitation capacitance $C = 30\mu F$.

V. CONCLUSIONS

In this paper, the advantages of connecting a shunt saturable reactor to the terminals of an isolated self-excited induction generator are highlighted. These advantages include self-regulation and protection against dangerously high over-voltages which result from over-excitation due to increase in capacitance or speed or both. Such overvoltages have been reported [7,8] to cause excitation capacitor failure. The additional nonlinearity introduced by the saturable reactor complicates the analysis of the SEIG considerably. A method to analyze the steady-state performance characteristics of the SEIG under these conditions is presented.

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