STEADY-STATE ANALYSIS OF AN ISOLATED SELF-EXCITED INDUCTION GENERATOR SUPPLYING AN INDUCTION MOTOR LOAD

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ABSTRACT

This paper presents steady-state analysis of a stand-alone 3-phase self-excited induction generator supplying a 3-phase induction motor. The induction motor is driving a load with a specified speed-torque characteristics. The steady-state equivalent circuits of both machines are connected in tandom and analyzed using the node-admittance method. The techniques of this paper may be utilized to determine the optimum combination of the generator, motor, mechanical load and excitation capacitance for optimum performance and utilization efficiency.

I- INTRODUCTION

The self-excited induction generator (SEIG) is basically an induction machine which is driven by a prime mover such as a wind turbine while a capacitor is connected across its stator terminals. The capacitor in this case provides the lagging reactive power required by the magnetizing reactance of the machine, which is responsible for building magnetic flux in the air-gap. The machine in this case, is said to be self-excited and a voltage is generated across its stator terminals. The squirrel-cage induction machine due to its high reliability, robustness, brush-less rotor, low cost, and low maintenance has been increasingly used [1-6] in renewable energy systems which employ wind or mini-hydro power generation in remote unattended sites. These systems can be combined with other forms of renewable energy, such as photovoltaic systems [7-8], to form an integrated renewable energy system (IRES). The IRES can be properly designed to take full advantage of the inherent diversity of wind and solar energy in most developing countries [9].

Unless the SEIG's output is fed to a utility grid, its terminal voltage and frequency will vary with rotor speed, excitation capacitance and electrical load. With this drawback, the SEIG is more suitable for supplying loads which are not sensitive to large voltage and frequency variations, such as water-pumping systems. In such systems, the SEIG supplies an induction motor which is coupled to a mechanical load such as a water pump as shown in Fig.1. Due to the high cost of the wind turbine and equipment, the system designer is interested in maximizing the amount of pumped water.

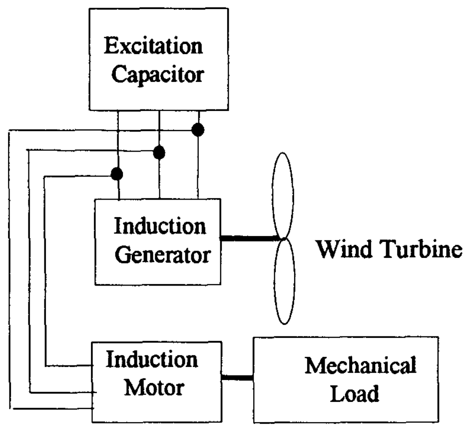

Fig. 1: System Layout

This can be achieved by proper selection and matching of the system components. Unfortunately, proper matching of the system components together is not sufficient to guarantee maximum utilization since matching is dependent on wind speed. Therefore, certain system components must be controlled according to wind speed, such that matching is achieved at every wind speed. This paper presents steady-state analysis for a control strategy to control the excitation capacitance of the induction generator such that its generated terminal voltage, which is applied to the induction motor, is kept constant regardless of rotor speed variation with wind speed.

II. SYSTEM MODELING

The steady-state equivalent circuit of the SEIG and its induction-motor load is shown in Fig. 2, in which normal-frequency reactance values are retained while the stator and rotor resistance and the capacitive reactance values are suitably modified [10]. For a stable self-excitation the machine is normally operated in the saturated state. Therefore the magnetizing reactance $X_{\phi g}$ at base frequency depends nonlinearly on the air-gap voltage V_g. The electrical load in this case is the induction motor. Therefore the load

impedance is replaced by the steady-state equivalent circuit of the induction motor after its parameters are suitably modified.

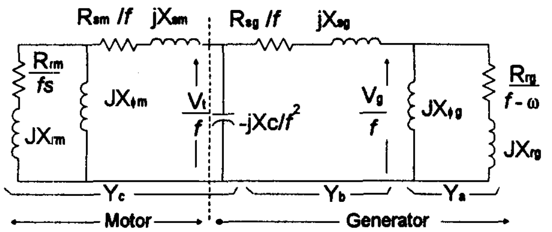

Fig. 2: Steady-State Equivalent Circuit

It is assumed that, the mechanical load speed-torque characteristics is given. For a given rotor speed of the induction generator (given wind speed), and a given load impedance, it is possible [8] to determine the required value of the excitation capacitance C such that the generated terminal voltage is equal to rated value (1 per-unit). Therefore, a relationship between C and ω can be obtained by solving the equivalent circuit of Fig. 2 for different values of ω, such that the terminal voltage which is applied to the motor is equal to rated value (1 per-unit). The techniques for analyzing the constant-speed mode of operation of the induction generator are presented in various papers and textbooks on the subject [1-10]. In this mode of operation, it is assumed that the rotor speed ω is independent of the load on the induction generator. Therefore ω is substituted in the equivalent circuit, which is solved for the remaining unknowns, namely the frequency f, the air-gap voltage V_g, excitation capacitance C, and the rotor slip of the induction motor S. The magnetization characteristics of the induction generator which can be determined experimentally is used to determine the relationship between $X_{\phi g}$ at base frequency (f = 60 Hz) and the air-gap voltage V_g. For the machine used in this study $X_{\phi g}$ is written as a third-order polynomial function of V_g.

III. SOLUTION TECHNIQUE

Generally, with all generator and motor parameters including magnetization reactances, capacitance, and pump characteristics specified, it is possible to solve the circuit of Fig. 2 for f, V_g, C and S for a given wind speed ω, subject to the condition that the terminal voltage is constant at 1 per-unit.

Applying node-admittance method to the circuit in Fig. 2, the node equation at the magnetizing node of the induction generator may be written as,

$$V_g Y_t = 0$$

Therefore $Y_t = 0$ since $V_g \neq 0$, and hence,

$$Y_a + \frac{Y_b Y_c}{Y_b + Y_c} = 0 \qquad (1)$$

$$Y_a = \frac{1}{R_{rg}/(f-\omega) + jX_{rg}} + \frac{1}{jX_{\phi g}}$$

$$Y_b = \frac{1}{R_{sg}/f + jX_{sg}}$$

$$Y_c = \frac{1}{\dfrac{(R_{rm}/fs + jX_{rm})jX_{\phi m}}{R_{rm}/fs + jX_{rm} + jX_{\phi m}} + R_{sm}/f + jX_{sm}}$$

$$-\frac{f^2}{jX_c}$$

It is important to note that the admittance Y_c depends on frequency as well as on slip S. However, the slip is determined by the motor developed torque and the pump characteristic. The developed torque can be expressed in terms of the air-gap voltage and rotor impedance which in turn depends on slip. The motor torque is calculated from rotor current and rotor resistance as follows:-

$$T_m = |Irm|^2 \frac{R_{rm}}{S.f}$$

Neglecting mechanical losses, this torque is equal to the load torque T_p. Therefore,

$$T_m - T_p = 0 \qquad (2)$$

The terminal voltage Vt can also be expressed from the equivalent circuit in terms of the air-gap voltage and the circuit impedances. Since the terminal voltage is kept constant, a third equation is formed as,

$$|V_t| - 1 = 0 \qquad (3)$$

Rotor current I_{rm} can be calculated from the circuit of Fig. 2 in terms of V_g. The water-pump counter torque T_p may be constant or speed dependent according to the type of pump used.

Equation (1) has complex coefficients, thus it can be separated into real and imaginary parts which are both equal to zero. Equations (2) and (3) have only real parts. Therefore the resulting four real equations can be solved for the four unknown variables, namely f, Vg, C and S.

IV. EXPERIMENTAL VERIFICATION

The behavior of a small size water-pumping system is investigated in the laboratory. The experimental system consists of a 1-kW, 3-phase, 380-V, 60-Hz, 4-pole, squirrel-cage induction generator driven by a shunt separately-excited dc motor. The output of the induction generator is fed to a 1-kW, 3-phase, 380-V, 60-Hz, 4-pole, squirrel-cage induction motor whose shaft is coupled to a ventilator-type water-pump. Both the induction generator and motor have the following parameters in per-unit:-
$R_{sg}=R_{sm}=0.165$, $R_{rg}=R_{rm}=0.093$, $X_{sg}=X_{sm}=0.16$, $X_{rg}=X_{rm}=0.160$. The magnetizing reactance of the induction generator $X_{\square g}$ at base frequency (60 Hz) as a function of the air-gap voltage V_g was measured by performing an open-circuit test in which the machine was driven at synchronous speed and a variable 60-Hz voltage source was applied to the stator. From the measured data of stator voltage and current, the desired relationship was obtained using regression analysis. For the test machine $X_{\phi g}$ in per-unit at base frequency is given by:

$$X_{\phi g} = 3.46 - 6.5V_g + 9.51V_g^2 - 4.77V_g^3$$

The wind-turbine was simulated by a 220-V, 6A, separately-excited dc motor.

V. RESULTS AND DISCUSSION

For a constant shaft speed and full-load developed torque of the induction motor at rated speed, the required excitation capacitance, frequency and slip are calculated. The calculated values are compared with the experimentally obtained values. Fig. 3 shows variation of the excitation capacitance C with shaft speed ω.
It is clear from Fig. 3 that, in order to maintain the rated terminal voltage applied to the motor, the terminal excitation capacitance must be decreased as the speed increases and vice-versa.

VI. CONCLUSIONS

This paper analyses a self-excited induction generator which supplies an induction motor driving a water-pump. It is possible to specify a constant applied terminal voltage to the induction motor so that it is capable of driving the water-pump at full rated speed. This is achieved by controlling the excitation capacitance connected to the terminal of the induction generator by using, for example, a thyristor-controlled reactor in parallel with a fixed capacitance. The experimentally obtained capacitance values for a laboratory model agreed very closely with the calculated values obtained using theoretical analysis.

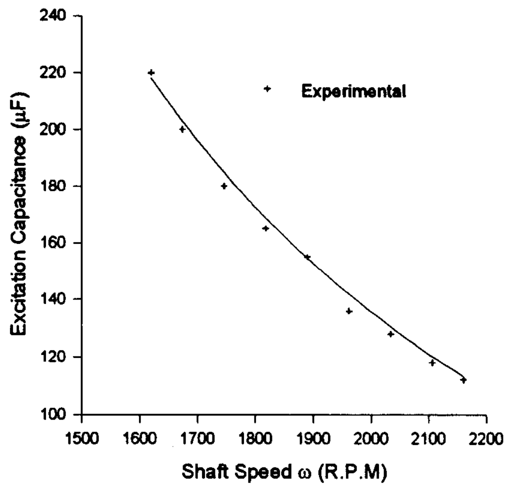

Fig. 3: Capacitance Variation with Rotor Speed

REFERENCES

[1] D. B. Watson, J. Arrillaga and T. Densem, "Controllable dc Power Supply from Wind-Driven Self-Excited Induction Machines," *Proc. IEE*, Vol. 126, No. 12, 1979, pp. 1245-1248.

[2] G. Raina and O. P. Malik, "Wind Energy Conversion Using a Self-Excited Induction Generator," *IEEE Trans. on Power App. & Sys.*, Vol. 102, No. 12, 1983, pp. 3933-3936.

[3] N. H. Malik and A. H. Al-Bahrani, "Influence of the Terminal Capacitor on the Performance Characteristics of a Self-Excited Induction Generator," *IEE Proceedings-C*, Vol. 137, No. 2, 1990.

[4] S. S. Murthy, O. P. Malik, and A. K. Tandon, "Analysis of Self-Excited Induction Generators," *IEE Proceedings-C*, Vol. 129, No. 6, 1982, pp. 260-265.

[5] L. Ouazene and G. McPherson, Jr., "Analysis of the Isolated Induction Generator," *IEEE Trans. on Power App. & Sys.*, Vol. 102, No. 8, 1983, pp. 2793-2798.

[6] A. K. Al Jabri and A. I. Alolah, "Limits on the Performance of Three-Phase Self-Excited Induction Generators," *IEEE Trans. on Energy Conversion*, Vol. 5, No. 2, 1990, pp. 350-356.

[7] S. M. Alghuwainem, "Performance Analysis of a PV Powered DC Motor Driving a 3-phase Self-Excited Induction Generator," *IEEE Trans. on Energy Conversion*, Vol. 11, no. 1, pp. 155-161, March 1996.

[8] S. M. Alghuwainem, "Speed Control of a PV Powered DC Motor Driving a Self-Excited 3-Phase Induction Generator for Maximum Utilization Efficiency," *IEEE Trans. on Energy Conversion*, Vol. 11, No. 4, pp. 768-773, December 1996.

[9] R. Ramakumar, "Renewable Energy Sources and Developing Countries," *IEEE Trans. on Energy Conversion*, Vol. PAS-102, No. 2, pp. 502-510, February 1983.

[10] M. G. Say, *Alternating Current Machines*, London: Pitman, 5th Ed., 1983, pp. 333-336.