STEADY-STATE ANALYSIS OF AN ISOLATED SELF-EXCITED INDUCTION GENERATOR DRIVEN BY REGULATED AND UNREGULATED TURBINE

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Abstract

This paper examines the steady-state analysis and performance of an isolated three-phase self-excited induction generator (SEIG) driven by regulated and unregulated turbine. For the case of a regulated turbine the equivalent circuit is solved with speed as a constant parameter, while for the unregulated turbine, the speed is considered as a variable which depends on the shaft torque according to the turbine characteristics. The no-load speed is considered as a constant independent parameter, which depends on wind speed which is assumed constant in this analysis. The steady-state equivalent circuit is solved using the node-admittance method, and the shaft torque is expressed in terms of the rotor current. The Newton-Raphson method is used to solve the system nonlinear equations. For the present investigation, a linear speed-torque characteristic is considered, but the method of analysis applies equally well to nonlinear characteristics. Experimental investigations on a 1-kW three-phase induction generator driven by a separately excited dc shunt motor have confirmed the accuracy of the proposed method of analysis.

Keywords: - Self-excitation, induction generators, unregulated turbines, variable speed, power generation.

1 List of Symbols:

f, ω	Per unit stator frequency, and rotor speed.
R_s, X_s, X_m	Per unit stator resistance, leakage and magnetizing reactances.
R_r, X_r	Per unit rotor resistance and reactance.
R_L, X_L, X_c	Per unit load resistance and reactance and excitaion capacitor reactance.
I_s, I_r, I_L	Per unit stator, rotor, and load currents.
V_g, V_t	Air-gap and terminal voltages.
T_e, T_{rot}, T_d	Electrical, rotational loss, and total shaft torques.
ω_0, k	No-load speed and slope of the linear speed-torque characteristics.
V_A, R_A	DC motor armature voltage, and resistance.
k_{af}, ϕ	DC motor torque constant and air-gap flux.

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2 INTRODUCTION

The soaring rates of fossil-fuel depletion over the last two decades combined with a growing concern about pollution of the environment have led to an accelerated search for renewable energy generation systems. This accelerated drive has led to a tremendous technical progress in the field of renewable energy systems over the last two decades. It has also led to a gradual tapping of the vast mini-hydro and wind energy potential available in isolated locations of the world. In most cases, these generating units have to operate at remote, unattended sites. Therefore, a maintenance-free system is desirable. The self-excited induction generator (SEIG), due to its high reliability, robustness, low cost and less maintenance requirements, etc., is highly suitable for this application. It has been increasingly used in renewable energy systems which employ wind or mini-hydro power [1-7]. These systems can be combined with other forms of renewable energy such as photovoltaics [8-9], to form an integrated renewable energy system (IRES). If properly designed, the IRES can take full advantage of the inherent diversity of wind and solar energy in most developing countries [10], to enhance the renewable power quality and minimize energy storage requirements.

The stand-alone SEIG is basically an induction machine which is driven by a prime mover, while an external capacitor is connected across its stator terminals. The capacitor provides the lagging magnetizing reactive power, required to build the air-gap flux. It also provides any lagging reactive power demand of the load. However, the amount of capacitance required for self-excitation varies with speed. Thus if a fixed value capacitor is connected across the terminals of the SEIG, the terminal voltage will vary with speed. In addition, the frequency varies, not only with varying speed, but also with varying load, even at one constant speed. Therefore, one of problem areas of stand-alone power generation systems

employing SEIG is the dynamic response of the system to a variety of disturbances such as change in the speed or load etc. The speed may vary due to external factors such as wind speed which varies randomly, or due to load variation, if the shaft speed is not regulated.

In the rigorous research on the operation of stand-alone power generation systems employing SEIG, attention is focused on the constant-speed mode of operation [1-7]. In this mode of operation, the wind speed is assumed constant and also the driving turbine is assumed to be regulated such that speed is independent of the shaft retarding torque which varies with the connected load and the excitation capacitance, etc. Therefore the speed is considered as an external control parameter which is set at one particular value for a certain wind speed. The analysis is performed in terms of circuit parameters and speed.

However, micro-hydro plants in most developing countries, sometimes use unregulated turbines due to their lower cost. The speed in this case varies not only with wind speed but also with the shaft retarding torque due to electrical load on the SEIG. Also, in the case of wind-turbines, it is desirable to allow the speed to vary according to wind speed in order to absorb maximum power from the wind. Therefore, performance analysis of the variable-speed mode of operation is useful for proper design and optimization of such systems.

The methods of analyzing the constant-speed mode of operation are presented in various papers and textbooks [1-9]. The analysis is straightforward since speed is specified as a priori constant which is substituted in the equivalent circuit before it is solved. The self-excitation condition is then applied to the equivalent circuit. Based on this condition, the total loop impedance of the equivalent circuit, or the total node admittance at the magnetizing branch is equated to zero. For a stable self-excitation, the SEIG is normally operated in the saturated state, hence the magnetizing reactance is a nonlinear function of the air-gap voltage. The resulting complex, nonlinear equation is then solved for the operating frequency and magnetizing reactance which are then substituted in the magnetization characteristics (normally represented by a piece-wise linear function) to determine the air-gap voltage and other quantities of interest.

However, if the prime-mover speed, even at constant wind speed, depends on the shaft counter-torque, then the analysis is more complicated since the torque is not known until the equivalent circuit is solved, and the solution depends on speed. Therefore, the speed can not be considered as constant in the equivalent circuit since it depends on the torque which depends on the square of the rotor current. Only few authors have tackled this problem using a variety of very simplified models [11, 12]. Rajakaruna and Bonert [11] used an approximate equivalent circuit and a mathematical model for the B-H curve to reduce the system equations to one nonlinear equation which is solved for the operating frequency. Chan [12] used iterative techniques and the secant method to determine the intersection point of the turbine characteristics and the SEIG speed-torque characteristics.

In this paper, wind speed is assumed constant but speed dependence on the shaft torque is incorporated in the analysis. The equivalent circuit is solved with speed as function of the torque. The no-load speed is considered as an independent constant parameter which may take different values corresponding to different values of wind speed. The equivalent circuit is solved directly for the air-gap voltage instead of the magnetizing reactance. The magnetization characteristic at base frequency is used to write the magnetizing reactance as a third-order polynomial of the air-gap voltage. The steady-state equivalent circuit is used to obtain an expression for the electrical torque in terms of the air-gap voltage, frequency, speed and circuit parameters. The turbine speed-torque characteristics is used to obtain a relationship between shaft speed and the shaft retarding torque. The resulting equations are then solved using the Newton-Raphson method, which converges very fast, to give the three unknowns, namely, frequency, speed and air-gap voltage. It is assumed that all circuit parameters, including magnetization characteristic, excitation capacitance and load impedance are specified. However, it is possible to exchange some of the specified quantities with some of the unknown quantities. For example, it is possible to specify the terminal voltage as constant and solve for frequency, speed, and excitation capacitance.

For the present investigation, a linear speed-torque characteristic, which is typical for a hydro-turbine at constant water head, is considered. It is found that the steady-state performance of the SEIG is largely influenced by the slope of the speed-torque characteristics. Experimental investigations on a 1-kW three-phase induction machine driven by a shunt dc motor confirmed the accuracy of the proposed method of analysis. Although the speed-torque characteristics considered in this paper is linear, the method applies equally well to nonlinear speed-torque characteristics.

3 System Modelling

The system consists of a three-phase SEIG driven by a turbine whose speed $\omega(T_d)$ depends on the shaft torque T_d according to a given speed-torque characteristics. A three-phase balanced excitation capacitor bank is connected to the SEIG terminal. The SEIG is supplying a static three-phase balanced load. The system layout is shown in Fig. 1.

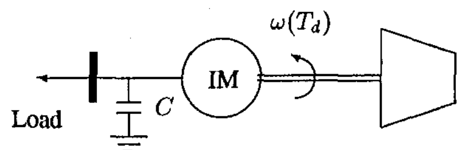

Figure 1: SEIG-turbine system.

The steady-state equivalent circuit of the SEIG 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 [13]. For a stable excitation the machine is normally operated in the saturated state.

Therefore the magnetizing reactance X_m at base frequency depends nonlinearly on the air-gap voltage V_g.

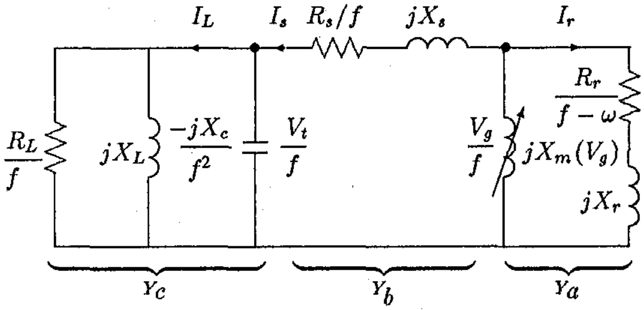

Fig. 2: Per-phase equivalent circuit of the SEIG.

Generally, with all machine parameters including magnetization characteristics, load and capacitance parameters at base frequency specified, it is possible to solve the circuit in Fig. 2 for f and V_g if ω is specified, or alternatively, for ω and V_g if f is specified. Applying node admittance method, the node equation at the magnetizing node may be written as

$$V_g[Y_a(f,\omega,V_g)+Y_t(f)]=0 \tag{1}$$

Hence

$$Y_a(f,\omega,V_g)+Y_t(f)=0 \tag{2}$$

since $V_g \neq 0$. Where,

$$Y_a(f,\omega,V_g)=\frac{1}{R_r/(f-\omega)+jX_r}+\frac{1}{jX_m(V_g)} \tag{3}$$

and

$$Y_t(f)=\frac{Y_b(f)Y_c(f)}{Y_b(f)+Y_c(f)} \tag{4}$$

where

$$Y_b(f)=\frac{1}{R_s/f+jX_s} \tag{5}$$

and

$$Y_c(f)=\frac{f}{R_L}+\frac{1}{jX_L}-\frac{f^2}{jX_c} \tag{6}$$

The electrical torque in per-unit is equal to the gross rotor input power, therefore

$$T_e=|I_r|^2R_r/(f-\omega) \tag{7}$$

From the equivalent circuit, the rotor current is given by

$$I_r=\frac{V_g}{f[R_r/(f-\omega)+jX_r]} \tag{8}$$

Therefore,

$$T_e=\frac{V_g^2R_r}{f^2[R_r^2/(f-\omega)+X_r^2(f-\omega)]} \tag{9}$$

The total shaft retarding torque is

$$T_d=T_e+T_{rot} \tag{10}$$

where T_{rot} is the rotational loss torque. For the present investigation, it is assumed that the SEIG is driven by a hydro-turbine at constant water head. The turbine speed-torque characteristic in this case is linear and is given by the following equation [14]:

$$\omega(T_d)=\omega_0-kT_d \tag{11}$$

where ω_0 and k are constants.

Equation (2) has complex coefficients; thus it can be separated into real and imaginary parts which are both equated to zero. Let the real part of (2) be denoted by f_1,

$$f_1=\Re e\{Y_a\}+\Re e\{Y_t\}=0 \tag{12}$$

and let its imaginary part be denoted by f_2,

$$f_2=\Im m\{Y_a\}+\Im m\{Y_t\}=0 \tag{13}$$

where $\Re e$ and $\Im m$ are the 'real part' and 'imaginary part' operator respectively. Equation (11) is real and it can be written in the form

$$f_3=\omega_0-\omega-kT_d=0 \tag{14}$$

Equations (12), (13) and (14) are solved using the Newton-Raphson method which is very suitable for solving this type of problem. The elements of the resulting Jacoubian matrix J are formed as follows:

$$J=\begin{bmatrix}\frac{\partial f_1}{\partial f} & \frac{\partial f_1}{\partial \omega} & \frac{\partial f_1}{\partial V_g}\\ \frac{\partial f_2}{\partial f} & \frac{\partial f_2}{\partial \omega} & \frac{\partial f_2}{\partial V_g}\\ \frac{\partial f_3}{\partial f} & \frac{\partial f_3}{\partial \omega} & \frac{\partial f_3}{\partial V_g}\end{bmatrix} \tag{15}$$

The above solution method can also be used if the SEIG is driven by a turbine having a nonlinear speed-torque characteristics. Equation (11), however, should be modified according to the actual turbine characteristics.

4 Experimental Verification

The behavior of a 1-kW, 380-V, 60-Hz, 4-pole, Y-connected squirrel-cage induction machine driven by a separately-excited dc motor was studied in the laboratory. The induction machine has the following per-unit measured parameters:- R_s = 0.165, R_r = 0.093, X_s = X_r = 0.106. The magnetizing reactance of the machine X_m at base frequency (f=1 pu), as a function of the air-gap voltage 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 measurement data of stator voltage and current, the desired relationship was obtained using regression analysis. For the test machine X_m in per-unit at base frequency was found as:

$$X_m(V_g)=3.46-6.5V_g+9.51V_g^2-4.77V_g^3 \tag{16}$$

The unregulated turbine was simulated by a 220-V, 6-A, separately-excited dc shunt motor. Neglecting armature reaction, the speed of the motor as a function of the shaft torque

is given by

$$\begin{aligned} \omega &= \frac{V_A - R_A I_A}{k_{af}\phi} \\ &= \frac{V_A}{k_{af}\phi} - \frac{R_A}{(k_{af}\phi)^2} T_d \end{aligned} \tag{17}$$

where V_A, R_A k_{af} and ϕ are the armature voltage, armature resistance, and field flux respectively. This speed-torque relationship has the same form as the speed-torque characteristic of the hydro-turbine at a constant water head, if we let

$$\omega_0 = \frac{V_A}{k_{af}\phi} \quad \text{and} \quad k = \frac{R_A}{(k_{af}\phi)^2}$$

For constant-speed operation at $\omega_0 = 1$ pu (1800 r.p.m), the turbine is simulated by a 4-pole, 60-Hz, synchronous motor.

5 Results and Discussions

The effect of loading the SEIG is first investigated. A variable resistive load is connected to the SEIG terminals in parallel with a fixed 30 μF excitation capacitance. Figs. 3-6 show the calculated as well as the measured variations of the terminal voltage, frequency, speed and torque with load current. A very good agreement can be noticed between the calculated and the measured values. Fig. 7 shows variation of speed with torque as the load current is increased, for a unity power-factor load. It confirms the linear relationship between speed and torque according to the assumed turbine speed-torque characteristics. Figs. 8-12 show the calculated as well as the measured variations of terminal voltage, frequency, speed and torque with excitation capacitance, for a constant unity power-factor load resistance. Fig. 12 confirms the linear relationship between speed and torque according to the assumed turbine speed-torque characteristics.

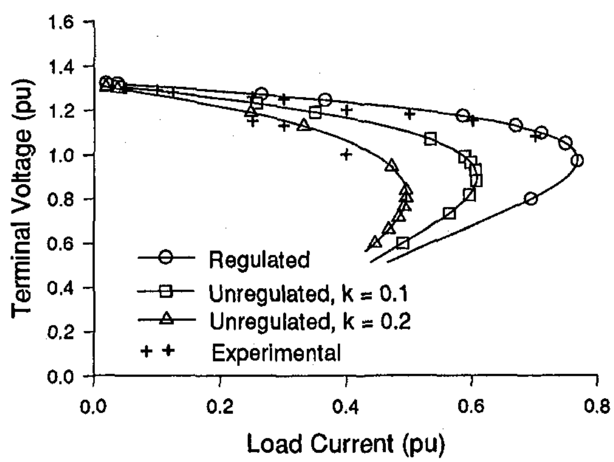

Fig. 3: Variation of the terminal voltage with load current for a unity power-factor load, no-load speed $\omega_0 = 1$ pu, and excitation capacitance $C = 30$ μF.

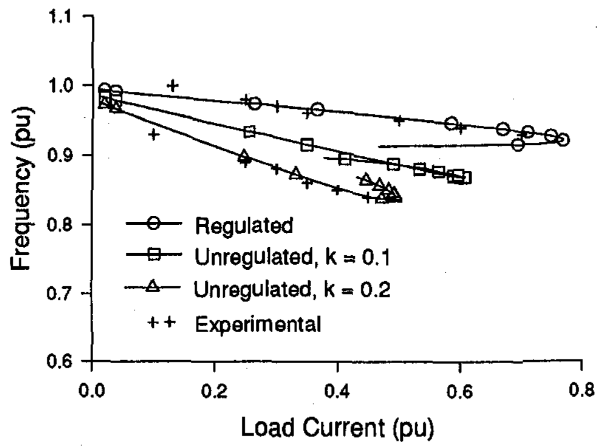

Fig. 4: Variation of frequency with load current for a unity power-factor load, no-load speed $\omega_0 = 1$ pu, and excitation capacitance $C = 30$ μF.

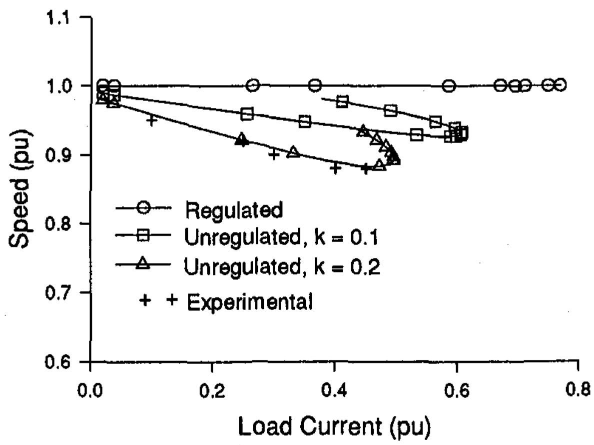

Fig. 5: Variation of speed with load current for a unity power-factor load, no-load speed $\omega_0 = 1$ pu, and excitation capacitance $C = 30$ μF.

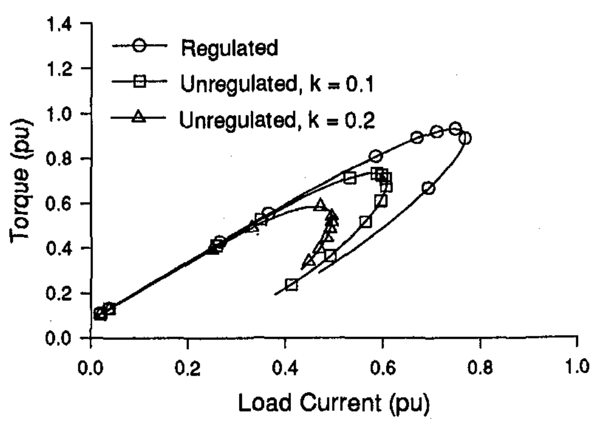

Fig. 6: Variation of torque with load current for a unity power-factor load, no-load $\omega_0 = 1$ pu, and excitation capacitance $C = 30$ μF.

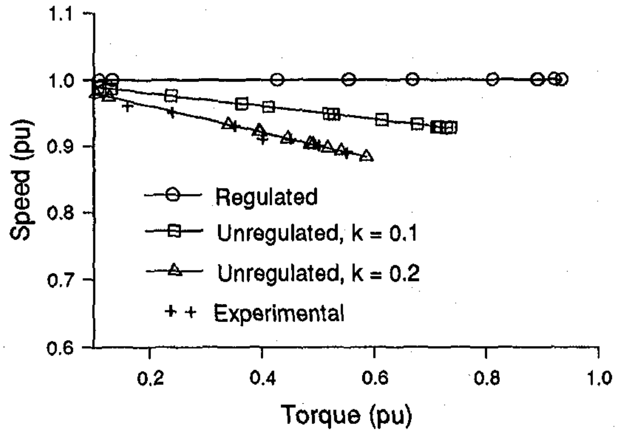

Fig. 7: Variation of speed with torque for a unity power-factor load, no-load speed ω_0 = 1 pu, and excitation capacitance $C = 30\ \mu F$.

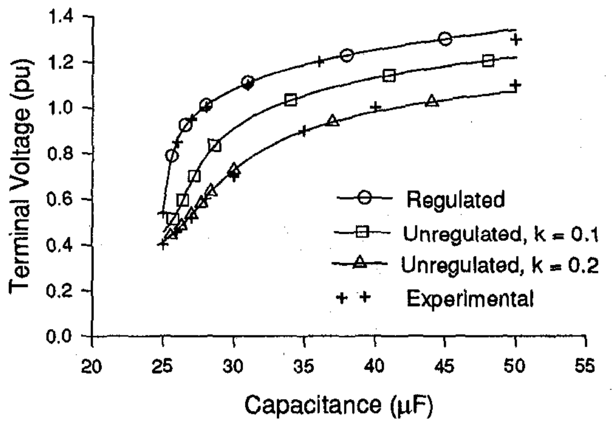

Fig. 8: Variation of terminal voltage with capacitance for constant unity power-factor load resistance, R_L = 1.5 pu, and no-load speed ω_0 = 1 pu.

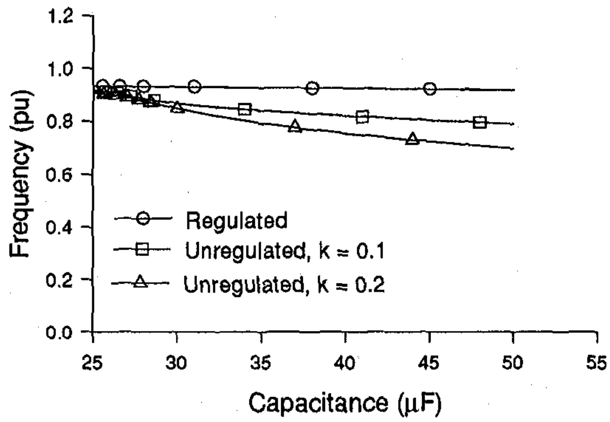

Fig. 9: Variation of frequency with capacitance for constant unity power-factor load resistance, R_L = 1.5 pu, and no-load speed ω_0 = 1 pu.

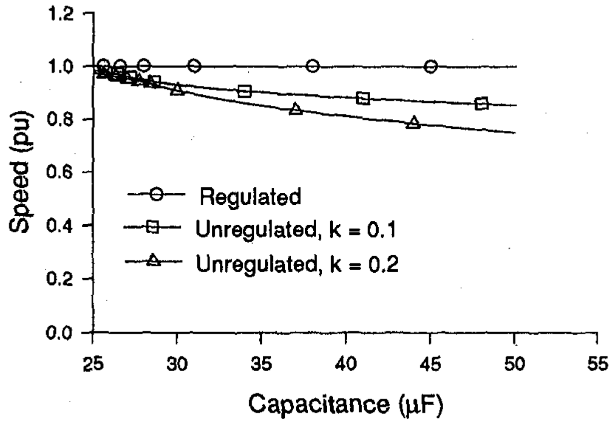

Fig. 10: Variation of speed with capacitance for a constant unity power-factor load resistance, R_L = 1.5 pu, and no-load speed ω_0 = 1 pu.

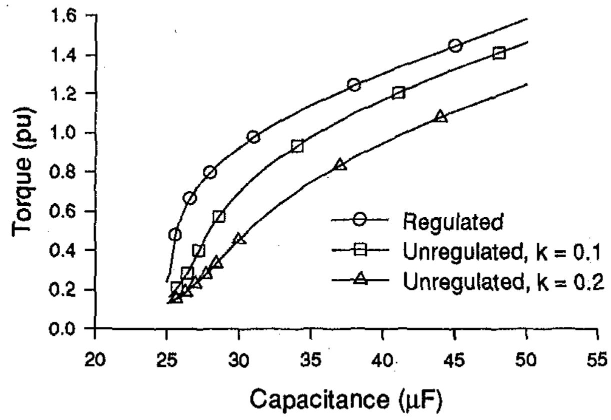

Fig. 11: Variation of torque with capacitance for constant unity power-factor load resistance, R_L = 1.5 pu, and no-load speed ω_0 = 1 pu.

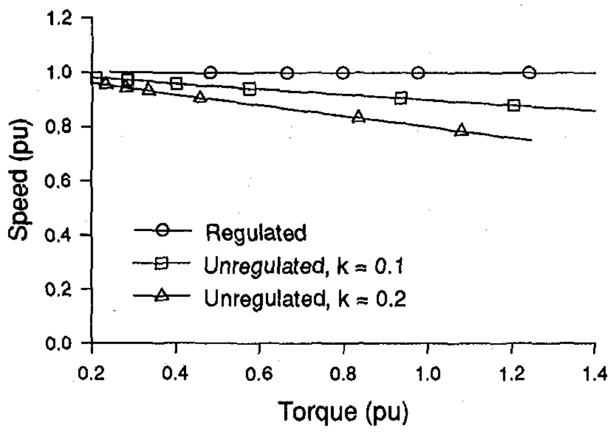

Fig. 12: Variation of speed with torque for a constant unity power-factor load resistance R_L = 1.5 pu, and no-load speed ω_0 = 1 pu.

6 CONCLUSIONS

In this paper, steady-state analysis and performance of an isolated self-excited induction generator driven by regulated and unregulated prime-mover is presented. It is well known that steady-state performance of the isolated SEIG is very sensitive to speed variations. Therefore, if speed decreases with increased shaft torque due to increased electrical load, even at constant wind speed, its effect must be incorporated for accurate performance analysis. A method to incorporate speed-torque dependence in the SEIG analysis is presented in this paper. It is found that a small percentage of speed regulation has a significant influence on the isolated SEIG performance. The techniques and results of this paper are useful for the analysis of the variable-speed mode of operation of the isolated SEIG, whether speed variation is caused by wind speed variation or due to loading of the turbine. However, wind speed varies randomly from time to time and from season to season, which makes it difficult to incorporate in the analysis.

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