Rev. Energ. Ren. : Power Engineering (2001) 9-15

Steady State Performance of Series DC Motor Powered by Wind Driven Self-Excited Induction Generator

Yaser Anagreh

Electrical Power Eng Dept. Hijjawi Faculty for Eng. Tech., Yarmouk University, Irbid JORDAN.
E-mail: anagrehy@yu.edu.jo

Abstract – *In this paper the steady-state performance of a series DC motor powered by a self-excited induction generator, through a bridge rectifier, and loaded by ventilator load is analyzed. The results help in designing an efficient integrated wind-solar energy system.*

Résumé – *Dans cet article l'etude de la performance des moteurs DC series en regime stationnaire alimentes par un generateur a induction auto-excite, a travers un pont de redressement, et charges par la charge d'un ventilateur est analyse. Les resultats aident a l'elaboration d'un systeme hybride efficace qui integre l'energie solaire et l'energie qui provient du vent.*

Keywords: DC Motor – Induction generator – Ventilator – Wind – Solar – Energy.

1. INTRODUCTION

Delivering electrical power to rural remote areas in many developing countries requires a great amount of money. Therefore, local renewable energy resources, like photovoltaic and wind, are seriously considered as alternatives for supplying energy to these locations.

A three-phase squirrel cage self-excited induction generator is usually utilized in stand-alone wind energy conversion system (WECS). This is due to the advantages of this generator type over conventional generators. This machine is rugged, self-protected against short circuit and over voltage faults, cheap and it does not require a separate source for excitation.

The steady-state performance of a wind driven self-excited generator (SEIG) has been reported [1-3]. On the other hand, the performance of a DC motor powered by a solar cell generator has been investigated in [4-6].
In this paper, the steady-state performance of a series DC motor powered by a wind driven SEIG via a rectifier bridge is analyzed. The steady state operation of the motor driving a centrifugal pump (ventilator load) is also examined.

2. SYSTEM CONFIGURATION

The block schematic diagram of the proposed wind energy conversion system (WECS) is shown in Figure 1.

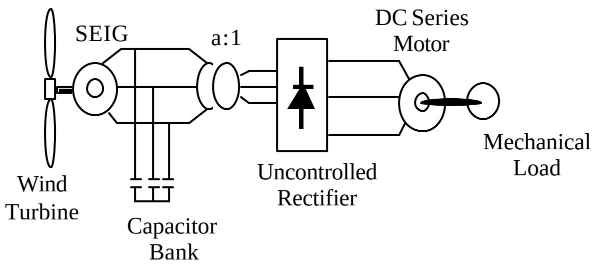

Fig. 1: Block schematic diagram of the wind energy conversion system.

The system consists of a wind turbine, a self-excited induction generator (SEIG), a diode bridge rectifier, a DC series motor and a mechanical load. Mathematical models for the system elements are given in the following sub-sections.

Wind turbine

The wind turbine (WT) acts as a prime mover to drive the SEIG. The output power of the WT is given by [7]:

$$P_{WT} = \frac{1}{2}\rho A C_p(\lambda) v_w^3 \tag{1}$$

where λ is tip speed ratio, which is expressed as:

$$\lambda = \frac{r\omega}{\nu_w} \tag{2}$$

and,

ρ Air density [kg/m^3]
A Frontal area of the wind turbine [m^2]
r radius of the wind turbine rotor [m]
$C_p(\lambda)$ power coefficient
ν_w wind speed [m/S].

Self-excited induction generator

Figure 2 shows the steady state per-phase equivalent circuit of SEIG. In this figure, core losses and the effect of the harmonics have been neglected.

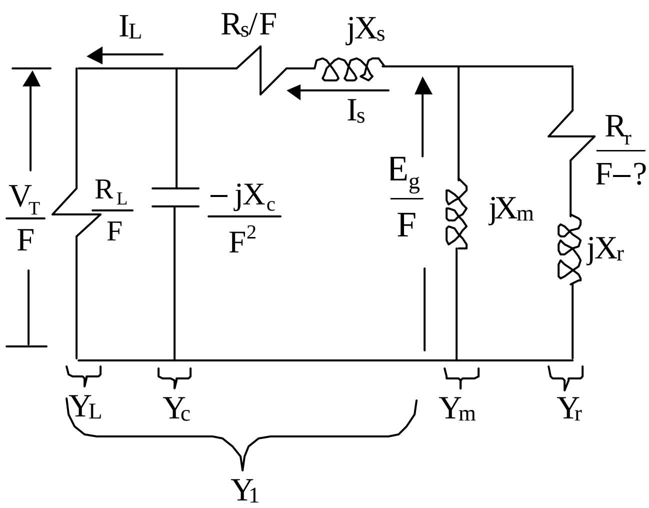

Fig. 2: Per phase equivalent circuit of a self excited induction generator.

In addition, all circuit parameters are assumed to be constants and independent of saturation level except the magnetizing reactance X_m. For successful steady-state self-excitation, the total admittance must be zero [1, 8]:

$$Y_1 + Y_m + Y_r = 0 \tag{3}$$

where

$$Y_1 = \frac{(Y_c + Y_L)(Y_s)}{Y_c + Y_L + Y_s}$$

$$Y_L = \frac{1}{(R_L/F)}$$

$$Y_r = \frac{1}{\frac{R_r}{F-?} + jX_r}$$

$$Y_c = \frac{1}{-(jX_c/F^2)}$$

$$Y_s = \frac{1}{(R_s/F) + jX_s}$$

$$Y_m = \frac{1}{jX_m}$$

and,

F per unit frequency

ν per unit speed of the WT rotor

The other circuit parameters are defined in Appendix-II.

Equating the real part and imaginary part of Equation 3 to zero, the following Equations are obtained:

$$\frac{R_{ab} + (R_s/F)}{(X_s - X_{ab})^2 + (R_{ab} + (R_s/F))^2} + \frac{R_r/(F - ?)}{X_r^2 + (R_r/(F - ?))^2} = 0 \tag{4}$$

$$\frac{1}{X_m} = -\{\frac{X_r}{X_r^2 + (R_r/(F - ?))^2} + \frac{X_s - X_{ab}}{(X_s - X_{ab})^2 + (R_{ab} + (R_s/F))^2}\} \tag{5}$$

where

$$R_{ab} = R_L X_c^2/[F(F^2 R_L^2 + X_c^2)] \tag{6}$$

$$X_{ab} = R_L^2 X_c/(F^2 R_L^2 + X_c^2) \tag{7}$$

Equation 4 can be rewritten as a fifth order polynomial in F:

$$A_5F^5 + A_4F^4 + A_3F^3 + A_2F^2 + A_1F + A_0 = 0 \tag{8}$$

The coefficients A_0 … A_5, are functions of the equivalent circuit parameters that are given in Appendix I. For the given pu values of ν, R_L and X_c, the pu value of F can be determined by solving Equation 8. The pu value of X_m can then be computed from Equation 5.

Having determined the values of X_m and F, the steady-state performance of the generator can be obtained using the circuit of Figure 2 with the help of the generator's magnetization curve.

Uncontrolled bridge rectifier

The output DC voltage (V_{DC}) of three- phase bridge rectifier can be expressed in terms of the generator's phase voltage (V_T) and the transformer turns ratio (a) as:

$$V_{DC} = (\frac{3\sqrt{3}}{\pi})(\frac{\sqrt{2}}{a})V_T \tag{9}$$

Assuming that the bridge rectifier is ideal, the real power on the AC side will equal the DC power on the DC side. This yields:

$$3V_T I_L = V_{DC} I_{DC} \tag{10}$$

Substitution of Equation 10 in Equation 9 gives:

$$I_{DC} = \frac{\pi a}{\sqrt{6}} I_L \tag{11}$$

where

I_L the phase current of the generator

I_{DC} DC current of the bridge rectifier

Series DC motor and mechanical load

The voltage and torque Equations of the DC series motor under steady-state operation are given by [4]:

$$V_m = RI_m + E_m \tag{12}$$

$$T_m = A + Bw_m + T_L \tag{13}$$

where

$$E_m = M_{af} I_m w_m \tag{14}$$

$$T_m = M_{af} I_m^{\,2} \tag{15}$$

$$R = R_a + R_f \tag{16}$$

Substitution of Equations 14 and 15 in Equations 12 and 13 yields:

$$V_m = RI_m + M_{af} I_m w_m \tag{17}$$

$$M_{af} I_m^{\,2} = A + Bw_m + T_L \tag{18}$$

The torque T_L is a ventilator load torque, which is varying with ω_m. By connecting the motor terminals to the terminals of the SEIG, via the bridge rectifier, it is possible to write:

$$\begin{cases} V_m = V_{DC} \\ I_m = I_{DC} \end{cases} \tag{19}$$

V_{DC} and I_{DC} are given in Equations 9 and 11, respectively.

The motor speed-torque Equation can be expressed as:

$$?_m = \frac{V_{DC} - R\sqrt{T_m / M_{af}}}{M_{af}\sqrt{T_m / M_{af}}} \tag{20}$$

3. RESULTS AND DISCUSSION

Matlab software package is implemented to simulate the mathematical models of the system elements given in the previous section. The parameters of the generator, the motor and the load are given in appendix II.

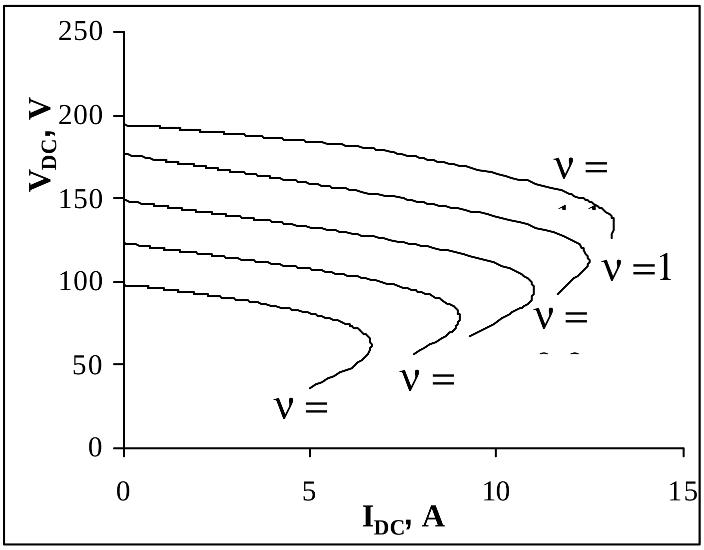

Fig. 3: The V-I characteristics of SEIG for five prime mover speeds.

Figure 3 shows a family of $V_{DC} - I_{DC}$ characteristics, which represent the converted Volt-Ampere characteristics of SEIG (see Equations 9 and 11), for five prime mover speeds; ν = 0.7: 0.1: 1.1 pu. At any prime mover speed, the DC voltage drops with load. On the other hand, V_{DC} almost increases linearly with prim mover speed for each load; e.g. at load of 4 A, V_{DC} almost double if ν is increased from 0.7 pu to 1.1 pu. This part of the present work helps in designing a suitable voltage regulator for the WECS.

Figure 4 gives the motor speed-torque characteristics for five wind turbine speeds. The ventilator load torque T_v and the characteristic of the motor, which is supplied by constant voltage of 180 V, are also shown in the Figure. As expected, the characteristics of the motor powered by SEIG are different from the characteristic when constant voltage supply is used, especially at low prime mover speed and at low motor speed. The system operating points at different prime mover speeds are at the intersection points of the load lines and the motor characteristics. As can be seen, with T_v load type the system can operate for the whole chosen range of ν.

For better system utilization, the extra DC power obtained at higher prime mover speeds, e.g. ν>0.9 pu, can be used for other applications.

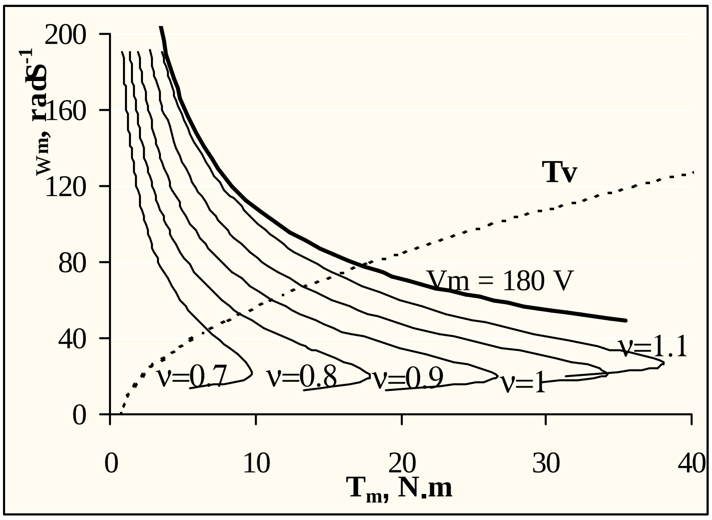

Fig. 4: Speed-torque characteristics of the DC series motor.

4. CONCLUSION

The paper presented the analysis of steady-state operation characteristics of a DC series motor powered by SEIG via bridge rectifier, and loaded by a ventilator load. The simulation results were obtained using Matlab software package. The system with ventilator load can operate for a wide wind turbine speed range. A further work will be directed into the practical implementation of the proposed WECS.

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APPENDICES

APPENDIX-I: Polynomial's Coefficients

The coefficients of the fifth order polynomial (Equation 8) are obtained by simplifying Equation 4, rearranging its terms and dividing by $(R_L X_c)^2$. The coefficients are given by:

$$A_0 = -?R_r(\frac{R_3}{R_L})^2$$

$$A_1 = R_r(\frac{R_3}{R_L})^2 + R_3(\frac{R_r}{R_L})^2 + ?^2 R_3(\frac{X_r}{R_L})^2$$

$$A_2 = -2?R_3(\frac{X_r}{R_L})^2 - ?R_r\{(\frac{R_s}{X_c})^2 + (\frac{X_s}{R_L})^2 - 2(\frac{X_s}{X_c})\}$$

$$A_3 = R_r[(\frac{X_s}{R_L})^2 + (\frac{R_s}{X_c})^2 - 2(\frac{X_s}{X_c})] + R_3(\frac{X_r}{R_L})^2 + R_s(\frac{R_r}{X_c})^2 + ?^2 R_s(\frac{X_r}{X_c})^2$$

$$A_4 = -?[R_r(\frac{X_s}{X_c})^2 + 2R_s(\frac{X_r}{X_c})^2]$$

$$A_5 = R_r(\frac{X_s}{X_c})^2 + R_s(\frac{X_r}{X_c})^2$$

where $R_3 = R_s + R_L$

APPENDIX-II. Parametrs of the WECS

A. Self-Ecxited Induction Generator

The SEIG used in the present work is 3-phase, 4-pole, 60 Hz, 1 kW, 380 V, 2.27 A, Y-connected squirrel cage induction machine whose per phase equivalent circuit parameters in pu are:

Stator resistance	$R_s = 0.1$
Stator reactance	$X_s = 0.2$
Rotor resistance	$R_r = 0.06$
Rotor reactance	$X_r = 0.2$

The relationship between the magnetizing reactance X_m and the air-gap voltage E_g/F is given as:

$$\frac{E_g}{F} = 1.12 + 0.078 X_m - 0.146 X_m^2 \qquad 0<X_m<3$$

B. Series DC Motor and Mechanical Loads

Terminal voltage	$V_m = 180$ V,
Armature current	$I_m = 8.6$ A
Shaft speed	$\omega_m = 75.92$ rad/S
Armature resistance	$R_a = 2.55\ \Omega$,
Field resistance	$R_f = 1.714\ \Omega$
Mutual inductance	$M_{af} = 0.22$ H
Torque constant	A = 0.3 N.m

Viscous torque constant	$B = 0.004$ N.m/rad/S
Ventilator load torque	$T_v = 0.4 + 0.0063\omega_m^{1.8}$
Electromagnetic torque	$T_m = A + B\omega_m + T_v$