Dynamic Response of Wound Rotor Induction Generator for Wind Energy Application

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ABSTRACT

The magnitude and frequency of the output voltage can be controlled by varying the effective rotor resistance of a wound rotor induction generator (WRIG), over a wide speed range. For a given stator load impedance, both the frequency and the voltage can be maintained constant as the speed is varied, without changing the excitation capacitance. When the stator load is variable, simultaneous voltage and frequency control requires the excitation capacitance to be changed as the rotor resistance is varied. Simulations performed on a 1.8-kW wound rotor induction machine confirm the feasibility of the method of control. Simulated implementation of a closed-loop control scheme for a WRIG using chopper-controlled rotor resistance is also discussed. With a properly tuned proportional-plus-integral (PI) controller, satisfactory dynamic performance of the WRIG is obtained. The implemented scheme may be used in a low-cost variable-speed wind energy system for providing good-quality electric power to remote regions.

Index Terms—Induction generators, slip-ring machines, voltage and frequency control.

1. INTRODUCTION

In this paper unlike induction generators connected to the power utility grid, both the frequency and the terminal voltage of the SEIG vary with load even when the rotor speed is maintained constant. An increase in the rotor speed will result in a proportionate increase in frequency, often accompanied by severe over voltage and excessive current. Recently, there has been rigorous research on the voltage and frequency control of squirrel-cage type SEIGs [1]–[5], but relatively little research efforts have been devoted to the use of the slip-ring induction machine for generator applications. Although the slip-ring machine is more expensive and requires more maintenance, it permits rotor slip-power control when driven by a variable-speed turbine. When a grid connection is permissible, the slip-ring machine may be operated as a double-output induction generator (DOIG) using the slip-energy recovery technique [6]. In the case of a wound rootor induction generator (WRIG), the system cost can be further reduced by the use of a simple rotor resistance controller [7], [8]. Since only a capacitor bank needs to be connected to the stator terminals. Another advantageous feature of the WRIG is that independent control of the voltage and frequency can be achieved easily. The rating of the rotor resistance controller is small compared with the generator rating; hence, the cost saving is quite significant. Fig.1shows the circuit arrangement of a three-phase WRIG. The excitation capacitance C is required for initiating voltage buildup and maintaining the output voltage.

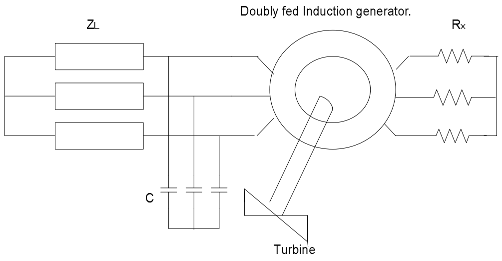

Fig.1 wound rotor induction generator.

2. PERFORMANCE AND ANALYSIS OF WRIG

Fig.2 shows the per-phase equivalent circuit of the WRIG, where the rotor resistance R_2 is the sum of the rotor winding resistance and the external rotor resistance, both referred to the stator side. The circuit has been normalized to the base (rated) frequency through the introduction of the per-unit frequency “a” and the per-unit speed “b” [9].

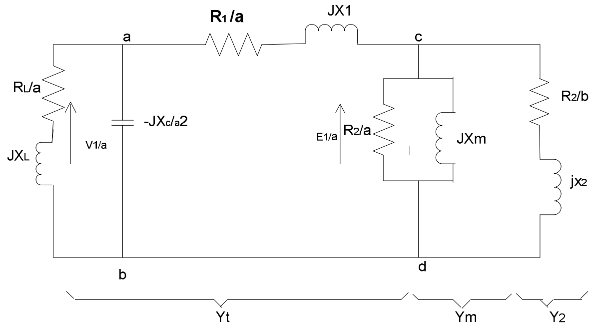

Fig.2 Per-phase equivalent circuit of the WRIG

Various methods have been developed for solution of the SEIG equivalent circuit. Adopting the nodal admittance method [10], the following relationship may be established for successful voltage build-up:

$$Yt+Ym+Y_2=0 \qquad (1)$$

Where

$$Yt = \frac{1}{Zt} = \frac{1}{Zac+Zab} = Gt + jBt \qquad (2)$$

$$Ym = \frac{a}{Rc} - j.\frac{1}{Xm} = Gm - jBm \qquad (3)$$

$$Y_2 = \frac{1}{\frac{R_2}{a-b} + jX_2} = G_2\text{-}jB_2 \qquad (4)$$

Equating the real and imaginary parts in (1) to zero, respectively, the fallowing equations in real numbers are obtained:

$$G_t+G_m+G_2=0 \qquad (5)$$

$$B_t\text{-}B_m\text{-}B_2=0 \qquad (6)$$

For a given rotor speed, load impedance and excitation capacitance, (5) is a nonlinear equation in the variable only. Numerical solution of (5) using an iterative method [10] enables a to be determined, and (6) can subsequently be used to calculate Xm.

Performance analysis and experiments for variable-speed operation were conducted on a three phase,four-pole,50-Hz,380-V,4.5-A,1.8-kW, star/star connected WRIG whose per-unit equivalent circuit constants are R_1=0.0597,X_1=0.118,R_2=0.0982,X_2=0.118. The magnetization curve (plot of E_1 versus Xm) was represented by the following set of describing equations:

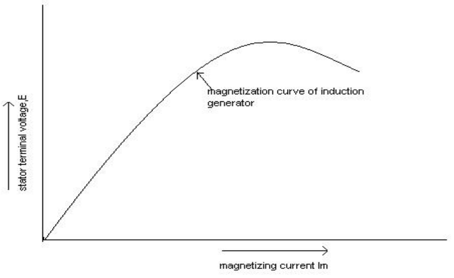

Fig.3 Magnetization Curve

Xm (pu)	E (pu)	Im (pu)
0.2	1.393	6.967
0.6	1.2603	2.10
1	1.1286	1.1286
1.7728	0.8714	0.4915

Table 1-Magnetization curve parameter

To achieve higher system efficiency, it is important that the power dissipated in Rx be fully utilized. The total power output of the WRIG is then the sum of the stator load power and the power consumed by Rx. The operating speed range of the WRIG depends upon the maximum value of Rx available, the rated voltage of the rotor winding, as well as the mechanical constraints of the turbine generator system.

3. FREQUENCY AND VOLTAGE CONTROL:

It is assumed that both the excitation capacitance and stator load resistance remain constant, while Rx is varied with b in order to maintain a constant output frequency. For convenience, the conductance Ge= Gt+Gm and the slip parameter γ = a-b are introduced. From (4) and (5), the following equation may be written:

$$Ge+\gamma R_2/R_2^2+\gamma^2X_2^2=0 \quad (7)$$

It should be noted that for a specified value of a, Ge is a constant when the excitation capacitance and load resistance are both constant.

Solving (7) for γ, one obtains

$$\mathrm{R}_{\frac{2}{\gamma}} = \mathrm{R}_{\frac{2}{a-b}} = \frac{-1\pm\sqrt{1-4G_e^2X_2^2}}{2G_e} \quad (8)$$

For practical induction generators, the term R2/(a-b) usually assumes a large negative value; hence, the negative sign in the numerator of (8) should be chosen. Therefore Equation (9)

$$\mathrm{R}_{\frac{2}{a-b}} = \frac{-1-\sqrt{1-4G_e^2X_2^2}}{2G_e} \quad (9)$$

Shows that the total rotor circuit resistance should be varied linearly with the per-unit speed b in order to control the frequency at a given value. Substituting (10) into (6)

$$\frac{1}{Xm} = Bt - 2X_2G_e^2/-1+\sqrt{1-4G_e^2X_2^2} \quad (10)$$

Equation (10) implies that for a given per-unit frequency a, excitation capacitance and load resistance, the magnetizing reactance Xm of the WRIG, and hence, the air gap voltage is independent of the rotor speed.

Fig. 6(b) shows the variation of external rotor resistance and the resultant output voltage when the per-unit frequency of the WRIG is maintained at 1.0 p.u. and the stator load is 1800w. Over a wide range of speed, the stator voltage remains constant at 530v when C= 30µf.

4. CONTROL WITH VARIABLE STATOR LOAD:

When the stator load impedance is changed, it is also possible to maintain the output frequency constant by varying Rx, but the stator terminal voltage will differ from the nominal value. In order to control the stator terminal voltage at the desired value, it is necessary to control the excitation capacitance C simultaneously Rx as is varied. The analysis can now be formulated as the following problem. For a given value of load impedance Z_L and per-unit speed b,to determine the values of C and Rx that result in operation of the WRIG at the specified voltageV1* and per-unit frequency. at a specific rotor speed, has to be increased when the output power increases, while has to be reduced. There is thus a value of output power at which is reduced to zero, which corresponds to operation with the slip-rings short-circuited. At b=1.56 p.u. for example, this condition prevails when the machine is delivering an output power of 530v.

[A] External Rotor Resistance Controller using Chopper:

It is desirable to have automatic control of the voltage and frequency when either the stator loads Impedance or the rotor speed changes. Instead of a variable three-phase rotor resistance, a Chopper-controlled external resistance may be employed, as illustrated in Fig. 4. Assuming that the diodes in the rotor bridge rectifier are ideal and the choke is lossless, the effective external resistance per phase in the rotor circuit, referred to the stator winding, is given by [12]

$$R_x = 0.5a_t^2(1-\alpha)R_{dc} \tag{11}$$

Rx= 430Ω

Where Rdc = dc resistance across the chopper, α = duty cycle of the chopper

αt = stator/rotor turns ratio.

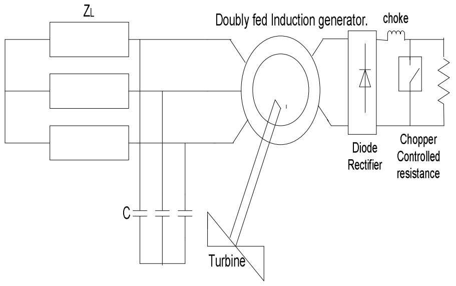

Fig.4 WRIG with chopper controlled ext .rotor resistance

A reduction in the duty cycle of the chopper results in an increase in the effective rotor resistance of the WRIG. A variable external resistance is thus presented to the rotor circuit.

[B] Closed-Loop Control:

Fig.5 shows the block diagram for closed-loop control of voltage and frequency of the WRIG.The stator terminal voltage is conveniently chosen as the feedback variable since any change in speed and stator load impedance will result in a corresponding change in the terminal voltage. Referring to fig.5, the stator terminal voltage signal, derived from the step-down isolation transformer and signal conditioning circuit, is compared with the reference signal that corresponds to the set-point voltage. The error signal is fed to a proportional- plus-integral (PI) controller that outputs a signal for controlling the duty cycle of the chopper via pulse-width modulation (PWM), opto isolation. In the prototype controller implemented, the chopper main switch was a power metal-oxide semiconductor field-effect transistor (MOSFET) controlled by a PWM circuit.

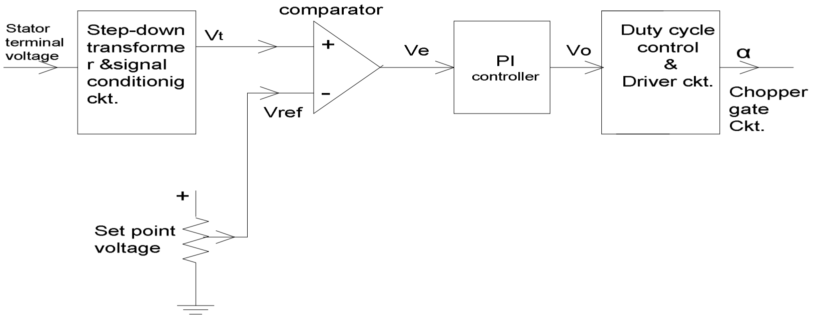

Fig. 5 Feedback circuit for voltage control of WRIG

Proper tuning of the PI controller is required in order to give satisfactory dynamic performance. For this purpose, the WRIG may be approximated as a first-order system with the following transfer function:

The parameters of the transfer function may be determined using the open-loop step response method [13]. With the transfer function identified, the gain of the proportional controller Kp and the gain of the integral controller Ki can be determined using the Ziegler–Nichols open-loop tuning method [13].

[C] Dynamic Response:

To study the dynamic response of the WRIG with closed-loop control, the machine was driven by a separately-excited dc motor that emulated an unregulated, variable-speed turbine while a resistive load was being supplied. It was found that with an excitation capacitance of 30µf per phase, the terminal voltage could be maintained at the rated value over a wide speed range, the maximum rotor speed attained being limited primarily by the rated current of the dc motor. The PI controller took effect as soon as the speed started to change, outputting a corresponding PWM control signal. The stator voltage was restored to the set-point value in approximately 2s when the speed was increased from 1.56 to 1.86p.u. (Fig. 6 c& d), and 3.2 s when the speed was decreased from 2 to 1.75 p.u. (fig. 6 c& d) at no load. The dynamic response characteristics displayed very little overshoot, showing that the controller had been properly designed, with minimal overshoot and small steady-state error.

TABLE 2

Simulation Result in MATLAB Full load to No-load

Load (W)	**O/P Voltage (V)**	**O/P Current (A)**	**Stator voltage (pu)**	**Stator current (pu)**	**Torque (pu)**
1800	**510**	**4**	**1**	**1**	**-1.3**
1500	**520**	**3.3**	**1**	**1**	**-1.2**
500	**530**	**0.9**	**1**	**1**	**-1**
100	**550**	**0.3**	**1**	**1**	**-0.5**

Stator output voltage in no load (100w)

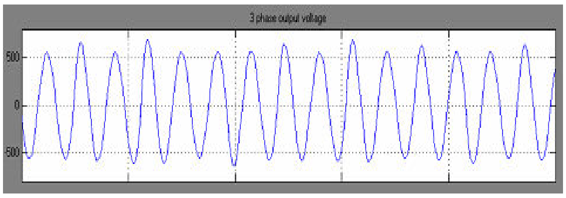

Fig.6 (a)

Stator output voltage full load (1800w)

Fig.6 (b)

Rotor speed (pm) in no load(100w)

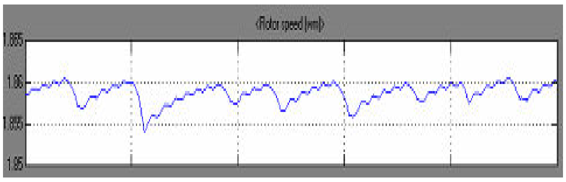

Fig.6(c)

Rotor speed (rpm) in full load (1800w)

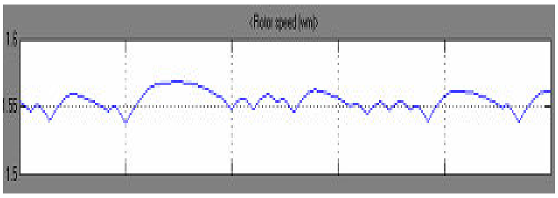

Fig. 6(d)

5. CONCLUSION

This paper has presented the voltage and frequency control for a self-excited slip-ring induction generator by varying the external rotor resistance. Steady-state performance and the control characteristics of the WRIG have been obtained from an equivalent circuit analysis. It is shown that with a constant load Impedance and excitation capacitance, both the frequency and the output voltage of the WRIG can be maintained constant by rotor resistance control over a wide range of speeds without exceeding the stator current limit. A properly tuned PI controller enables good steady-state accuracy and satisfactory dynamic response to be obtained on the generator system.

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