Dynamic Performance Improvement of an Isolated Wind Turbine Induction Generator

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***Abstract* — A dynamic model of a variable speed stand alone wind generation unit is developed. The steady state as well as the dynamic performance of the wind system is explored. The necessary conditions for steady operation have been established. The performance of the system under variable wind gust and other disturbance conditions has been studied. It has been observed that a stand alone generator is very vulnerable to transient variations in the system. This is because of the lack of excitation to the unit. A stabilizing control scheme through a thyristor controlled variable capacitance at the generator terminal is suggested for stabilizing the system. PI controller with optimized gain settings is included in the control loop. The PI controlled variable capacitance strategy has demonstrated very good steady state and transient performance of the wind turbine-generator system.**

***Index Terms* — Wind energy system, induction generator, variable capacitor control, PI control.**

I. Introduction

As a result of increasing environmental concern, more and more electricity is generated from renewable energy. The main advantage of electricity generation from renewable sources is the absence of harmful emission and the infinite availability of the prime mover that is converted to electricity [1]. One of the best ways of generating electricity from renewable energy is to use wind turbines. A tendency to erect more and more wind turbines can be observed in power industry. Wind energy technology has developed extremely rapidly and many commercial wind turbines now on the market have capacity of 1 MW or more. Also the cost of wind-generation electricity has fallen steadily. Wind turbines in USA produce about 1 % of total generation [2]. Presently wind power meets 2 % of the total electricity demand in Europe [3]. According to [4] this development will continue to grow in coming years. It seems that in the near future wind turbines may start to influence the behavior of electrical power systems. As a result of such developments, extensive research is being carried out on the subject of wind generation.

Self-excited induction generators are good candidates for wind powered electricity generation, especially in remote areas, because they do not need an external supply to produce the excitation magnetic field. It is well known that when capacitors are connected across the stator terminals of an induction machine, driven by an external prime mover, voltage will be induced across its terminals. The induced emf and current in the stator will continue to grow until steady state condition is attained [5].

The control of a system that generates power from an unsteady input as the wind, presents a formidable problem. The wind speed varies from time to time due to gusts and is further disturbed by the effect of supporting tower shadow [6]. Under normal conditions, the stand alone generators may function perfectly well, but a little unbalance in turbine input and load may cause oscillations in frequency and voltage. This is primarily attributed to the lack of support excitation to the system.

This article investigates the dynamic aspect of the performance of wind turbine generators. It has been observed that the system oscillations or instability in the system can be overcome by introducing a variable capacitance controller at the generator terminals. A PI controller has been employed to design the 'optimum' thyristor firing angle control of the static capacitor circuit.

II. The Turbine-generator System Model

Fig. 1 shows the wind-generator system configuration. The system consists of a horizontal axis wind turbine and an induction generator connected to an isolated local load Y = G + jB. The models for the different components of the wind turbine-generator system are given in the following.

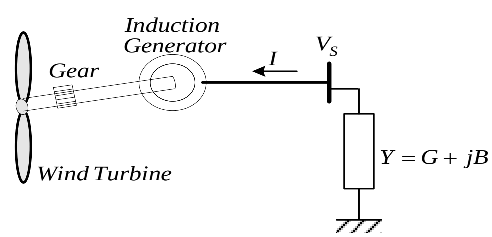

Fig.1 The wind turbine-generator system

A. Wind Turbine Model

The wind turbine is characterized by the plot of the power coefficient C_p as a function of both tip speed ratio, λ and the blade pitch angle, β. Typical C_p-λ curves for the pitch angle changing from 0 to 28° are shown in Fig. 2. The tip speed ratio λ, which is the ratio of linear speed at the tip of blades to the speed of wind, is expressed as,

$$\lambda = \frac{\Omega R}{V_w} \quad (1)$$

where R is the radius, Ω is the mechanical angular velocity, respectively, of the wind turbine rotor; V_w is the wind velocity. Expressions of C_p as a function of λ and β employed in [7] are,

$$C_p(\lambda,\beta) = 0.5176\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right)e^{\frac{-21}{\lambda_i}} + 0.0068\lambda$$
$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \quad (2)$$

The output mechanical torque and power of the wind turbine, respectively, can be calculated from the relationships [6],

$$T_m = \frac{1}{2}\rho.A.R.C_p.V_w^2/\lambda$$
$$P_m = \frac{1}{2}\rho A.C_p.V_w^3 \quad (3)$$

Here, ρ is the air density and A is the swept area by the blades. Fig. 3 shows the power-speed characteristics curves of a typical wind turbine for various wind velocities.

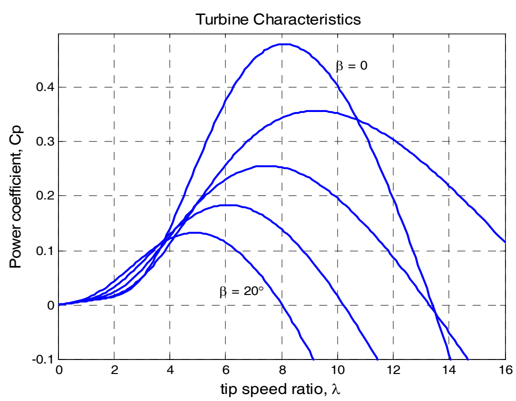

Fig.2 Typical c_p vs. λ plot

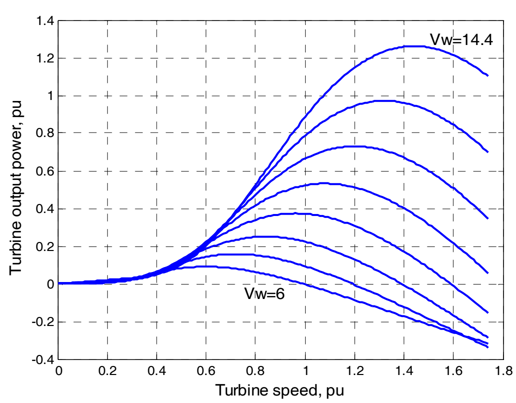

Fig. 3 Speed vs. power plot of a wind turbine

B. The Wind profile

Wind speed simulation is one of the first steps for the wind generation model. Wind speed changes continuously and its magnitude are random over any interval. For simulation of randomly changing wind speed probability distribution of the random number should be known [8]. The wind speed is usually considered constant for some intervals (say about 10 minutes). The fluctuations during such intervals can be considered to be combination of constant and sinusoidal variation. A typical formula is,

$$v = x[1 - 0.2\cos(2\pi t/20) - 0.05\cos(2\pi t/600)] \quad (4)$$

Here, x is the mean speed. The wind gust can be simulated by varying the magnitude and frequency of the sinusoidal fluctuation. A typical wind profile for mean wind speed of 14 m/s is given in Fig. 4.

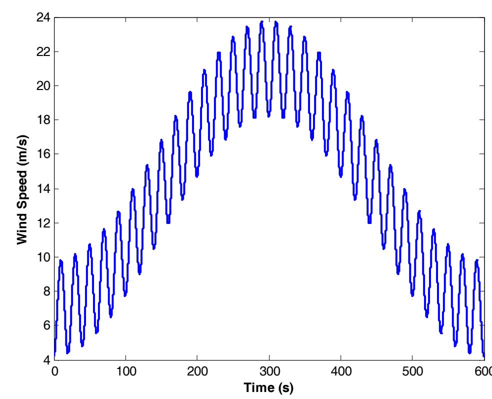

Fig. 4 Wind profile over a period of 10 minutes

C. The Induction Machine Model

The induction generator model can be derived from the generalized induction motor model of Krause [9]. The voltage current relations of the stator and rotor circuits are,

$$\frac{1}{\omega_o}\dot{\psi}_{ds} - \frac{\omega_e}{\omega_o}\psi_{qs} + R_s i_{ds} = v_{ds}$$
$$\frac{1}{\omega_o}\dot{\psi}_{qs} - \frac{\omega_e}{\omega_o}\psi_{ds} + R_s i_{qs} = v_{qs} \quad (5)$$

$$\frac{1}{\omega_o}\dot{\psi}_{dr} - s\psi_{qr} + R_r i_{dr} = v_{dr}$$
$$\frac{1}{\omega_o}\dot{\psi}_{qr} - s\psi_{dr} + R_r i_{qr} = v_{qr} \quad (6)$$

The flux linkages and currents are related through,

$$\psi_{ds} = x_s i_{ds} + x_m i_{dr}$$
$$\psi_{qs} = x_s i_{qs} + x_m i_{qr} \quad (7)$$

$$\psi_{dr} = x_r i_{dr} + x_m i_{ds}$$
$$\psi_{qr} = x_r i_{qr} + x_m i_{qs} \quad (8)$$

The slip s used in the above equations is defined as,

$$s = \frac{\omega_o - \omega}{\omega_o} \quad (9)$$

In the generation mode the slip will be negative and the stator currents will reverse their directions. The rotor motion of the machine is expressed through the following slip equation,

$$(2H)\dot{s} = P_e - P_m - Ds \qquad (10)$$

Where, the electrical torque (or power) in pu is written as,

$$\begin{aligned} P_e &= \psi_{qr} i_{dr} - \psi_{dr} i_{qr} \\ &= -x_m i_{qr} i_{ds} + x_m i_{dr} i_{qs} \end{aligned} \qquad (11)$$

D. The Load model

A simple load model for the induction generator shown in Fig. 1 is considered. Retaining the original current directions of the induction motor operation, we write,

$$I = -V_s Y \qquad (12)$$

Here, Y = G +jB is the load admittance and V_s is the generator terminal voltage. Writing, I = i_{ds} + ji_{qs} and V_s = v_{ds} + jv_{qs} , (12) can be expressed in the form,

$$\begin{aligned} Gv_{ds} - Bv_{qs} &= -i_{ds} \\ Bv_{ds} + Gv_{qs} &= -i_{qs} \end{aligned} \qquad (13)$$

For dynamic simulation, the turbine power output given in Fig. 3 has to be expressed as an analytic function of the generator rotor speed or slip. For a certain wind velocity, a polynomial function has been generated through curve fitting methods using MATLAB functions. For example, for a wind velocity of 14 m/sec, the expression for the turbine output power is obtained as,

$$\begin{aligned} P_m &= -5.5848\times10^{-14} n^5 + 5.397\times10^{-10} n^4 - 1.9059\times10^{-6} n^3 \\ &+ 0.0029\times n^2 - 1.6024n + 346.86 \end{aligned} \qquad (14)$$

The speed n is in rpm.

From the set of equations (5-7), the derivatives of the generator currents i_{ds}, i_{qs}, i_{dr}, and i_{qr} are obtained in terms of v_{ds}, v_{qs}, v_{dr}, and v_{qr} . Equation (13) is solved for v_{ds} and v_{qs} are then substituted into it. These four differential equations along with slip derivative equation (10) are combined to give the closed form state equations,

$$\dot{x} = f[x] \qquad (15)$$

where, x is the vector of states $[i_{ds}\ i_{qs}\ i_{dr}\ i_{qr}\ s]$. The steady state values of the currents are solved by dropping the derivative terms in (5-6) and solving simultaneously with (13).

For certain residual voltage v_{dr} and v_{qr} the excitation is adjusted by adjusting the capacitive component of the load admittance, Y. Under normal conditions perfect power or torque balances can be obtained. The system however is very sensitive to input power variations requiring continuous adjustment of the excitation. In the event of fixed excitation, even a small gust can lead to unacceptable transient performance. The following section describes the introduction of a capacitive injection circuit for transient performance improvement.

III. THE PROPOSED CONTROL STRATEGY

The transient under performance can normally be compensated for by blade pitch control on the turbine side. However, this is slow. Alternatives proposed in the literature are voltage, current and power control on the generator side. This article looks into the possibility of transient enhancement through the introduction of a variable capacitance/reactance at the generator terminal [10]. The variable reactance can be obtained by controlling a static var system through the firing angle control of the thyristors. The controller is connected to the generator terminal as shown in Fig. 5. The functional block diagram for the control circuit is given in Fig.6.

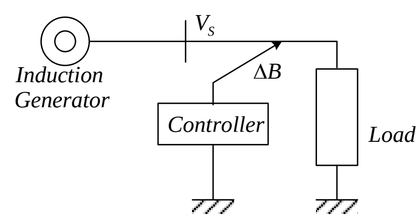

Fig. 5 Auxiliary stabilizing static capacitor

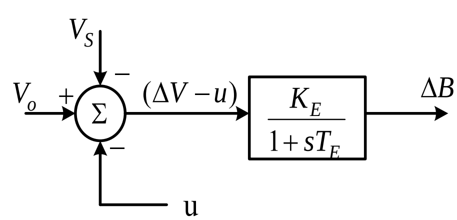

Fig. 6 Block diagram for the capacitance/reactance control

The dynamic equations for the control block can be written as,

$$\frac{d\Delta B}{dt} = -\frac{1}{T_E}\left[K_E \Delta V + \Delta B\right] + \frac{K_E u}{T_E} \qquad (16)$$

The control signal u for the wind turbine-generator system has been constructed through a PI controller. The 'optimal' parameters of the PI controller are obtained through a pole-placement technique.

The PI controller is normally installed in the feedback path as shown in Fig. 7. An additional washout blocks the unwanted signal in the steady-state. The steps involved in the design process are,

- Considering the extended nonlinear model including the controller equation (16), and selecting the proper output variable, the linearized system equations are written as,

$$\dot{x} = Ax + Bu \qquad y = Cx \tag{17}$$

- For a specific location of eigenvalue λ it can be shown that,

$$\frac{\lambda T_w}{1+\lambda T_w}\left[K_p + \frac{K_i}{\lambda}\right] = \frac{1}{C(\lambda I - A)^{-1}B} \tag{18}$$

Placing a complex pair of eigenvalues $\lambda = \alpha \pm j\beta$ at desired locations to provide adequate damping to the system, (18) can be solved for K_p and K_i.

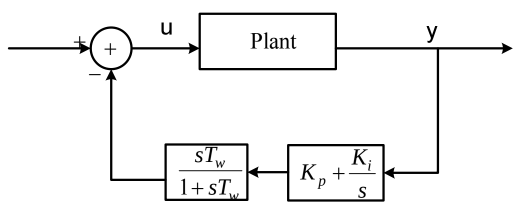

Fig.7. PI controller block diagram

V. Simulation Results

The wind turbine-generator system given in Fig.1 was simulated along with thyristor controlled capacitor control. As indicated earlier, the wind turbine-stand alone induction generator is very sensitive to input changes. The following simulation results are presented for a sample disturbance condition of 15% step torque decrement. The uncontrolled responses are all oscillatory and growing. Insertion of automatic feedback stabilizing capacitor at the terminal of the generator itself has enough stabilizing effect. Properly adjusted PI controller provides extremely good damping behavior.

The eigenvalues of the linearized system with the stabilizing circuit dynamics included are: -1185.9 ± j4651.8, -7.2 ± j15, -2332.5, and -5.2. PI controller gains for closed loop pole locations at λ= -12.83 ± j15 gave K_P = -37.8819 and K_i = 410.49. Figures 8, 10, and 12 show the induction generator shaft speed, machine power output, terminal voltage, respectively, without any control. The corresponding responses with the proposed PI control of exciting capacitance are given in figures 9, 11 and 13, respectively. Fig. 14 shows the stator current in phase 'a' of the three phase machine with the proposed PI control. It can be observed that proposed PI controller with the optimized gain settings controls the transient oscillations of the virtually unstable system very quickly.

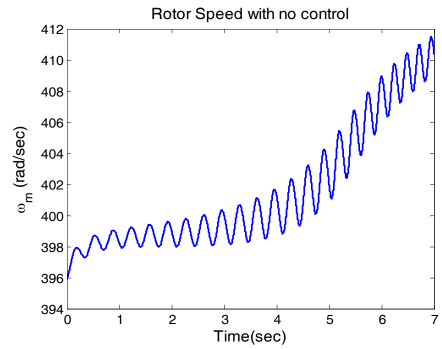

Fig. 8 Angular speed of the induction generator rotor for 15% torque step without control

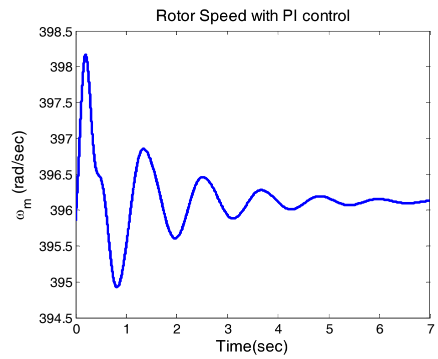

Fig. 9 Angular speed of the generator for 15% torque step corresponding to Fig. 8 with control

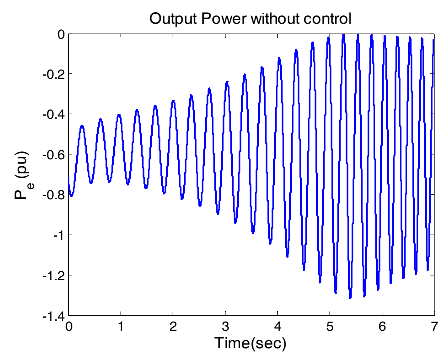

Fig. 10 Power output of the induction generator for 15% torque step without control

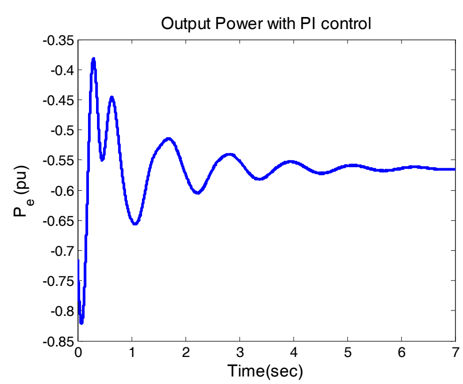

Fig. 11 Power output of the generator for 15% torque step corresponding to Fig. 10 with control

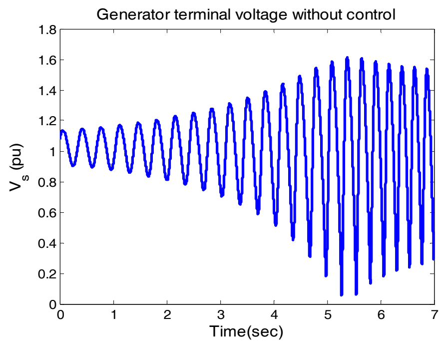

Fig. 12 Terminal voltage of generator for 15% torque step without control

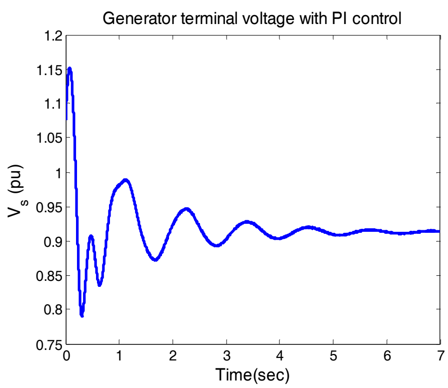

Fig. 13 Terminal voltage of generator for 15% torque step corresponding to Fig. 12 with control

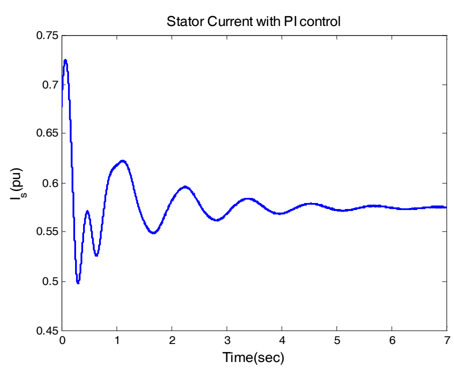

Fig. 14 Stator current of the generator for 15% torque step with PI control

VII. Conclusion

Improvement of damping performance of a stand alone wind turbine driven induction generator system is investigated through insertion of variable capacitance at the generator terminal. The capacitive injection is controlled through PI control of the thyristor firing angle. The gains of the PI controllers are tuned optimally through a pole-placement technique. It has been observed that the stand alone generator is very sensitive to input power changes in terms of its dynamic behavior. This is attributed to the lack of self excitation to the system. For satisfactory dynamic performance a well designed additional variable excitation controller is essential. The PI control of the thyristor firing angle to generate variable capacitance has been observed to provide good damping to the system. The controller design is generally robust for acceptable ranges of operation. However, for very large operating regions, fine tuning of the controllers will be needed.

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