Dynamic Performance of a Wind Generation System with Thyristor Controlled Capacitor Compensation

الأداء الدينامكي لنظامِ مولّدِ الريحِ ذوالسعةِ المتغيّرة المسيطرعليها بثايرستور

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الملخص:

طُوّرَ في هذا البحث نموذج متحرك لمولّدِ ريحِ ذو مكنة قفصِ بسرعةِ متغيّرةِ وتضمن دراسة أسلوب الريح وتوربين هوائي ومولّد حثٍّ، كما طورت في الدراسة الشبكة التي تربط الحمل المحليّ مع خَطّ التغذية. فضلا عن دراسة الأداء في الحالة الثابتة فإن الدراسة اشتملت علي دراسة الأداء الدينامكي لطاقة الرياح. وكذلك درس أداء النظامِ تحت شروط الريحِ المفاجئةِ القويةِ وحقق في كمية الحقنِ إلى الشبكة. وأستكشف أيضا مخطط متحكم الاستقرار والذي يُقلّلُ الحقنَ العابرةَ من خلال سعة متغيّرة مسيطر بثايرستور (thyristor) في أطراف المولّدَ. تضمّنت حلقة التحكم جهاز تحكم (PI) ذو أعدادات المكسب مثلى أوجدت باستخدام تقنية تحديد القطب. أظهرت إستراتيجيةُ السعةِ المتغيّرة المسيطر عليها بجهاز تحكم (PI) قدرة تثبيط جيدة جداً لنظامِ ذو مولّد الريحَ كهربائي توربيني.

كلمات المهمنة

نظام طاقة الرياح، مولّد حثّ، سيطرة مكثف متغيّرة، تحكم التكامل النسبي (PI)، تقنية تحديد قطب

ABSTRACT

A dynamic model of a variable speed cage machine wind generation unit, including wind profile, wind turbine, induction generator, local load and transmission line connecting the grid is developed. The steady state as well as the dynamic performance of the wind energy system is explored. The performance of the system under wind gust conditions has been studied and the amount of transient injection to the grid investigated. A stabilizing control scheme which minimizes the transient injection through a thyristor controlled variable capacitance at the generator terminal is explored. PI controller with optimized gain settings is included in the control loop. The 'optimal' parameters of the PI controller are obtained through a pole-placement technique. The PI controlled variable capacitance strategy has demonstrated very good damping profile for the wind turbine-generator power system.

KEY WORDS

Wind energy system, induction generator, variable capacitor control, PI control, pole-placement technique.

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I. INTRODUCTION

As a result of increasing environmental concern, more and more electricity is generated from renewable sources. 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. One way of generating electricity from renewable sources is to use wind power. A tendency to erect more and more wind turbines has been observed during recent years. As a result of this, in the near future wind turbines may start to influence the behavior of electrical power systems. Therefore adequate models to study the impact of wind turbines on electrical power systems behavior are needed.

Wind has been proven as a cost effective and reliable source of energy. Technological advancements over the last few years have placed wind energy in a firm position to compete with conventional power generation technologies. Saudi Arabia has a vast uninhabited land area as well as a long coastline, free from man made obstacles, presenting a possible wind resource [1-2]. In view of this, there is an urgent need to start research programs with the aim of studying the potential of wind energy in Saudi Arabia, site specifications and other technical needs for the wind energy assessment project. There is also a need to develop the dynamic model for effective control of the wind turbines. Though, wind and other alternative sources of energy are attractive, care has to be taken in connecting the generating plants to the existing grid because they may export their own problems as well as 'pollution' to the grid system.

Induction generators are being increasingly utilized in a wind energy conversion system since they are relatively inexpensive, rigid, and require low maintenance. However, the ever-changing nature of wind-speed and lack of inherent reactive power source of induction generator make the stability issue a very delicate matter. Many techniques have been proposed to keep the rotor speed as nearly constant as possible. The major ones are the control of blade pitch angle to control mechanical input power, and control of electrical power through the control of external VAR compensator devices [3-4].

In this study, dynamic model of a variable speed cage machine wind generation unit feeding a grid system, along with a local load, is developed. Improvement of the damping properties of the system through a PI controlled variable capacitance stabilizer is investigated.

II. WIND TURBINE-GENERATOR SYSTEM MODELING

Fig. 1 shows the wind-generator system configuration. The system consists of a horizontal axis wind turbine and an induction generator (IG) interfaced to the utility grid through a transmission line. The models for the different components of the wind turbine-generator system are given in the following.

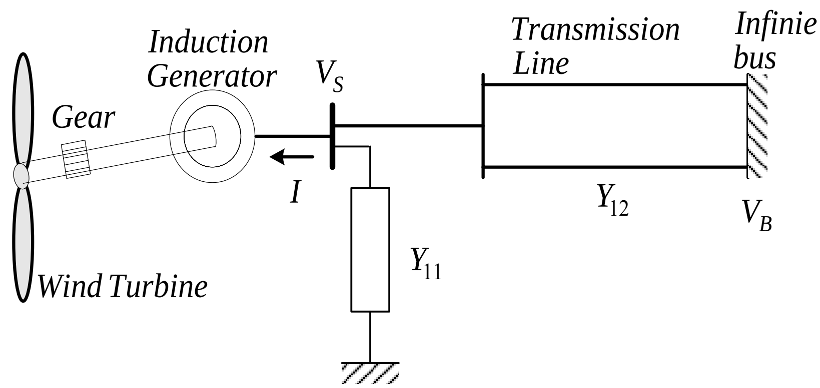


Fig.1. Wind-generator system

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 20° 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 the wind, is expressed as,

$$\lambda = \frac{\Omega R}{V_w} \tag{1}$$

Where R is the radius of the turbine blades, Ω is the mechanical angular velocity of the wind turbine rotor, V_w is the wind velocity. Expressions of C_p as a function of λ and β, as employed in reference [5], are

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

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

$$\begin{aligned} T_m &= \frac{1}{2}\rho.A.R.C_p.V_w^2 / \lambda \\ P_m &= \frac{1}{2}\rho.A.C_p.V_w^3 \end{aligned} \tag{3}$$

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.

B. *The Induction Machine Model*

The induction generator model can be derived from the generalized induction motor model of Krause [7]. The voltage current relations of the stator and rotor circuits are,

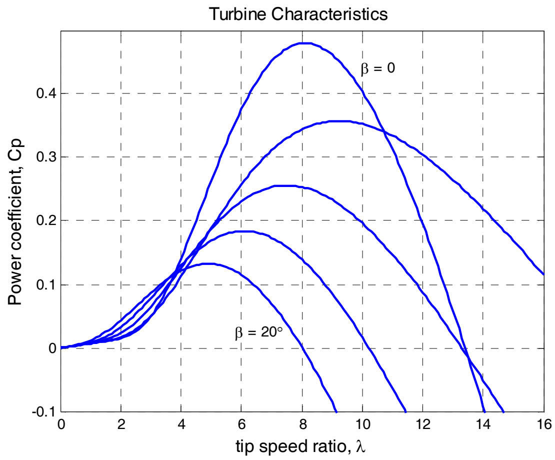


Fig.2. Typical C_p vs. λ plot

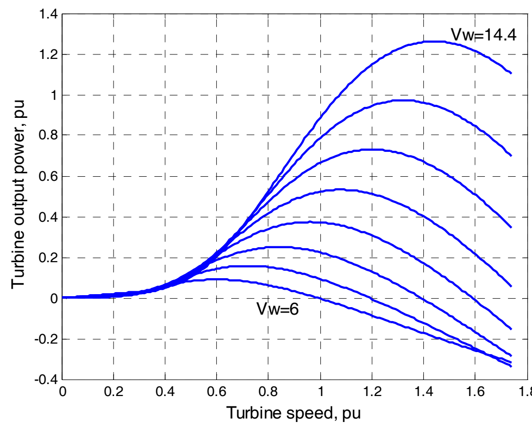


Fig. 3. Typical power vs. speed plots for a wind turbine

$$\frac{1}{\omega_o}\dot{\psi}_{ds} - \frac{\omega_e}{\omega_o}\psi_{qs} + R_s i_{ds} = v_{ds}$$
$$\frac{1}{\omega_o}\dot{\psi}_{qs} + \frac{\omega_e}{\omega_o}\psi_{ds} + R_s i_{qs} = v_{qs} \tag{4}$$

$$\frac{1}{\omega_o}\dot{\psi}_{dr} - s\psi_{qr} + R_r i_{dr} = v_{dr}$$
$$\frac{1}{\omega_o}\dot{\psi}_{qr} + s\psi_{dr} + R_r i_{qr} = v_{qr} \tag{5}$$

The flux linkages and currents are related through,

$$\psi_{ds} = x_s i_{ds} + x_m i_{dr}$$
$$\psi_{qs} = x_s i_{qs} + x_m i_{qr} \tag{6}$$
$$\psi_{dr} = x_r i_{dr} + x_m i_{ds}$$
$$\psi_{qr} = x_r i_{qr} + x_m i_{qs} \tag{7}$$

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

$$s = \frac{\omega_o - \omega}{\omega_o} \tag{8}$$

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,

$$(2H)\dot{s} = P_e - P_m - Ds \tag{9}$$

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

$$\begin{aligned} P_e &= \psi_{qr} i_{dr} - \psi_{dr} i_{qr} = (x_r i_{qr} + x_m i_{qs}) i_{dr} - (x_r i_{dr} + x_m i_{ds}) i_{qr} \\ &= -x_m i_{qr} i_{ds} + x_m i_{dr} i_{qs} \end{aligned} \tag{10}$$

C. The Wind Profile

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

$$v = x[1 - 0.2\cos(2\pi t / 20) - 0.05\cos(2\pi t / 600)] \qquad (11)$$

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.

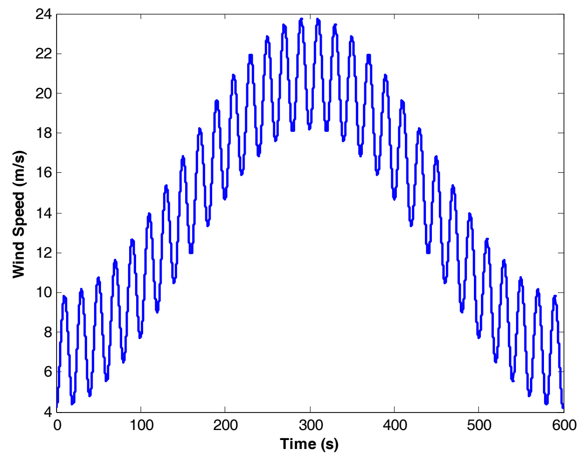


Fig. 4. Wind profile over a period of 10 minutes

D. Transmission Line and Load Model

Retaining the notation for induction motor operation, the transmission line-load equation from Fig. 1 can be written as,

$$I = (V_b - V_s)Y_{12} - V_s Y_{11} \qquad (12)$$

where, I is the induction generator current (negative), $Y_{12} = g_{12}+jb_{12}$ is the transmission line admittance, $Y_{11} = g_{11}+jb_{11}$ is the local load admittance, V_s is the generator terminal voltage, and V_b is the grid voltage. Writing $I = i_{ds} + ji_{qs}$ and $V_s = v_{ds} + jv_{qs}$, (12) can be expressed in the form:

$$\begin{aligned} v_{ds}(g_{11} + g_{12}) - v_{qs}(b_{12} + b_{11}) &= -i_{ds} + V_b g_{12} \\ v_{ds}(b_{12} + b_{11}) + v_{qs}(g_{11} + g_{12}) &= -i_{qs} + V_b b_{12} \end{aligned} \qquad (13)$$

E. The Composite Dynamic Model

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 power output is obtained as,

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

Here, the rotor speed n is in rpm. From the set of equations (4-6), 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 (9) are combined to give the closed form state equations,

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

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 (4-5) and solving simultaneously with (13).

Dynamic model (15) was simulated for a number of disturbance conditions for representing the wind variations. For smaller input changes or wind gusts, excursions of the system variables are within tolerable limits. However, if the size of the disturbance grows, the system voltage and frequency variations may be unacceptable.

III. THE PROPOSED CONTROL STATEGY FOR STABILITY

The transient performance can be compensated 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. The variable reactance can be obtained by controlling a static VAR system through the firing angle control of the thyristors. An equivalent circuit diagram of the system shown in Fig. 1 along with the controller is shown in Fig.5a.

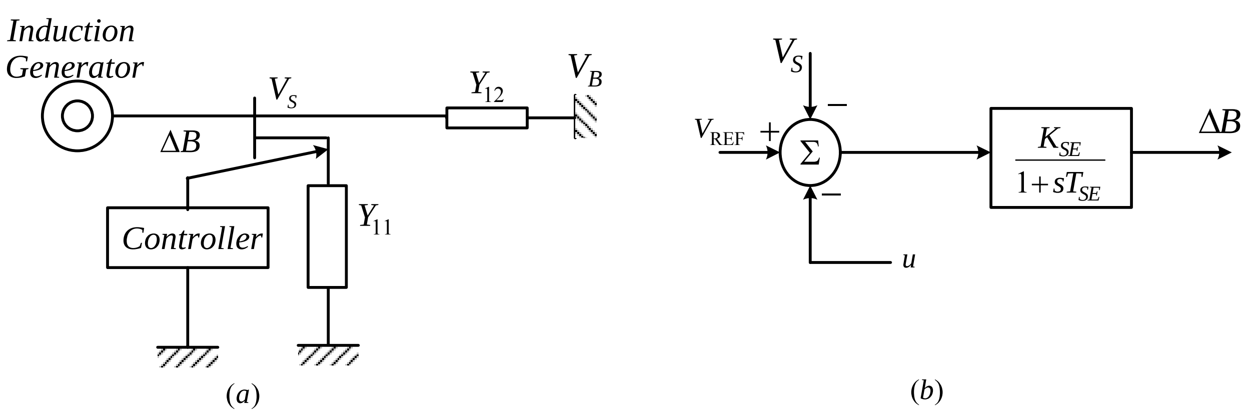


Fig. 5. Block diagram for the capacitance/reactance control

The dynamic equation for the controller block is given by [9],

$$\frac{d\Delta B}{dt} = -\frac{1}{T_{SE}}\left[K_{SE}\Delta V_s + \Delta B\right] + \frac{K_{SE}u}{T_{SE}} \qquad (16)$$

where, $\Delta V_S = V_{REF} - V_S$ and ΔB is the change in susceptance b_{11} [$Y_{11}=g_{11}+jb_{11}$]. Equation (16) can be represented by the functional block diagram of Fig. 5b.

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. 6. An additional washout blocks the unwanted signal in the steady-state. The steps involved in the design process are,

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

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx \end{aligned} \qquad (17)$$

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

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

  Placing two eigenvalues λ_1 and λ_2 at desired locations to provide adequate damping to the system, (18) can be solved for K_p and K_i.

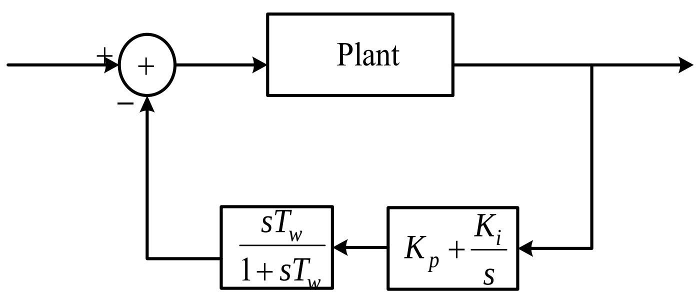


Fig.6. PI controller block diagram

IV. SIMULATION RESULTS

The wind turbine-generator system given in Fig.1 was simulated along with thyristor controlled capacitor control. The eigenvalues of the linearized system including the capacitive injection block (16) are [-1138.4± j5047.5, -2249.6,-8.9, -5.9 ± j6.9]. The response of the system with an equivalent wind gust for 0.1s duration causing 20% power imbalance are exhibited in Figs. 7-10.

The uncontrolled responses of the rotor speed, generator power output, stator terminal voltage variation and stator current are shown in part (a) of these figures when no control action is taken.

The responses of the wind turbine-induction generator system with the proposed PI control are shown in part (b) of Figs. 7-10. The gain settings of the PI controller are, K_P= -150 and K_I= -200, respectively. These gains are determined by relocating the corresponding eigenvalues of the rotor transients to -9 ± j13, approximately. It can be observed that the uncontrolled system is quite poorly damped, while the PI controller provides extremely smooth transition to normal operation. Simulations carried out for other disturbance conditions and also for other operating conditions demonstrate that the PI controller gives reasonably robust performance.

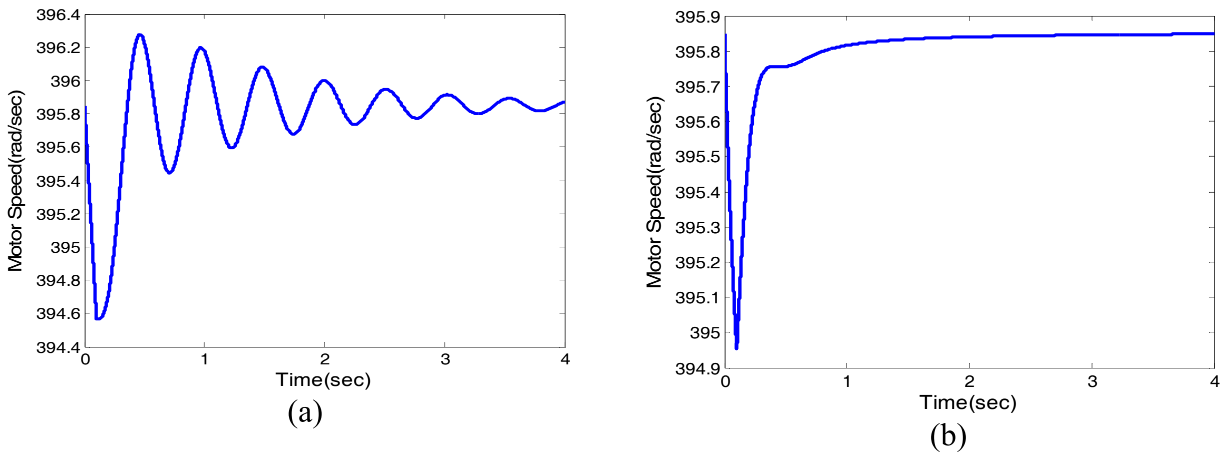


Fig. 7. Induction generator rotor angular speed following a wind gust for 0.1s duration causing 20% power imbalance a) with no control, and b) with proposed PI control.

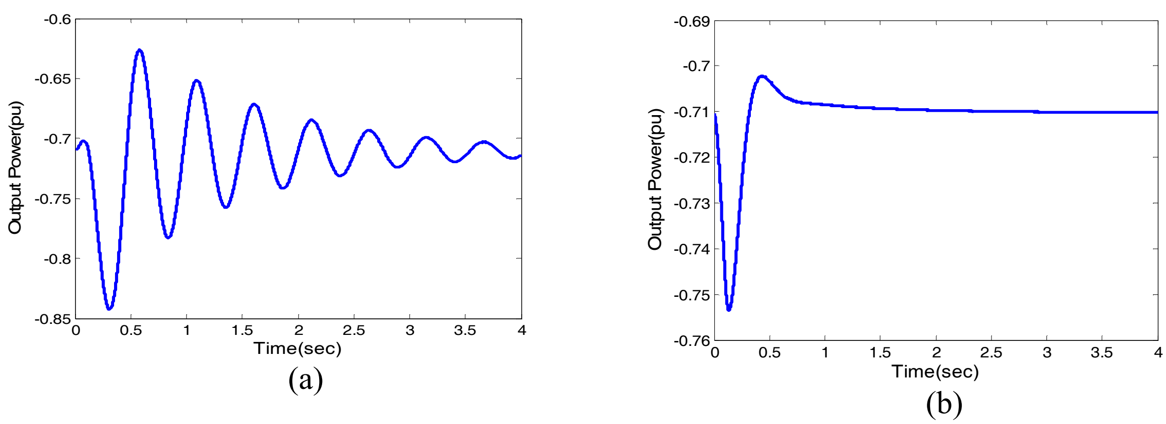
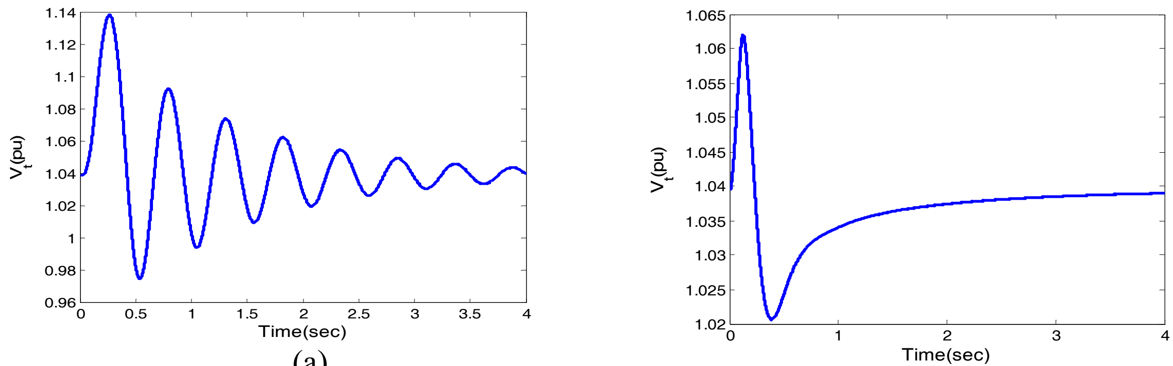
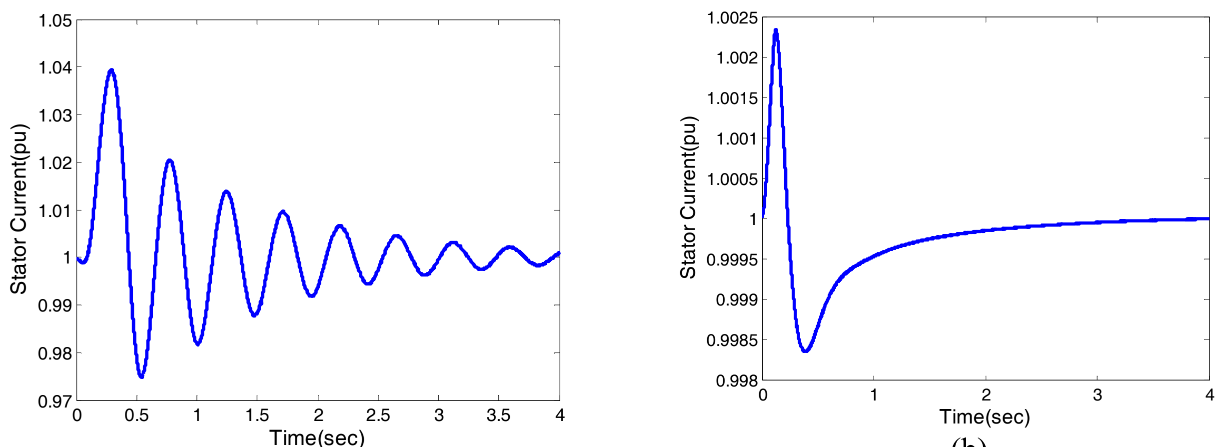


Fig.8. Induction generator power output a) with no control, and b) with PI control. The disturbance is as in Fig. 7.



(a) (b)

Fig.9. Induction generator terminal voltage following a wind gust for 0.1s duration causing 20% power imbalance a) with no control, and b) with PI control.



(a) (b)

Fig.10. Stator phase current (a) without control (b) with control corresponding to the disturbance condition of Fig. 9.

V. CONCLUSIONS

Improvement of damping performance of a wind turbine-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 normal system damping is inadequate, and under conditions of variable wind gusts, unacceptable transients may arise. The design of wind turbine-generator system should have enough safeguards in this respect. 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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APPENDIX

Generator and transmission line data (values are in pu except stated otherwise)

r_s=0.04373, r_r=0.024, x_s=3.418, x_r=3.418, x_m=3.289, D=0.002, H=3, g_{11}=0.2, b_{11}=0.6, R=0.8, X=1, synchronous speed=1800 rpm.

Turbine Data
A=577 m^2, ρ=1.225 kg/m^3, R=13.5m, gear-ratio =1:23, β=0.

REFERENCES

[1]. Rehman, S, 2005, "Prospects of Wind Farm Development in Saudi Arabia", *Journal, Renewable Energy*, Vol. 30, pp. 447–463.

[2]. Rehman, S, El-Amin, I.M, Ahmad, F, Shaahid, S.M., Al-Shehri, A.M.,and Bakhashwain, J.M., 2007, "Wind Power Resource Assessment for Rafha, Saudi Arabia", *Journal, Renewable and Sustainable Energy Reviews*, Vol. 11, pp. 937-950.

[3].Chen, W.L., and Hsu, L.L, 2006, "Controller Design for an Induction Generator Driven by a Variable-speed Wind Turbine", *IEEE Trans. on Energy Conversion*, Vol. 21, no. 3, pp. 625-635.

[4]. Saad-Saoud, Z, Lisboa, M. L. Ekanayake, J. B., Jenkins, N. and Strbac, G, 1998, "Application of STATCOMs to Wind Farms", *Proc. IEE – Gener, Transm, Distrib,* Vol. 145, No. 5, pp. 511-516.

[5]. Ted, K., and Brekken, A., 2005, "A Novel Control Scheme for a Doubly-fed Induction Wind Generator under Unbalanced Grid Voltage Conditions", *Ph. D. Thesis, University of Minnesota,.*

[6]. Abdin, E.S. and Xu, W., 2000, "Control Design and Dynamic Performance Analysis of a Wind Turbine-induction Generator Unit", *IEEE Trans on Energy Conversion*, Vol. 15, No. 1, pp. 91- 96.

[7]. Krause, P.C., 1986, *Analysis Electric Machinery*, McGraw-Hill, New York.

[8]. Karari, M., Rosehart W. and Malik O.P., 2005, "Comprehensive control strategy for a variable speed cage machine wind generator unit", *IEEE Transactions on Energy Conversion*, vol. 20, No. 2, pp. 415-423.

[9]. Munda, J.L., and Miyagi, H., 2002, "Stability Analysis and Control of a Wind Turbine Driven Induction Generator", *Electric Power Components and Systems,* Vol. 30, pp. 1223-1233.