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6-2 PERFORMANCE OF A WIND GENERATOR WITH A SUBOPTIMAL FEEDBACK EXCITATION CONTROL

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ABSTRACT

This paper deals with the application of a suboptimal excitation feedback control for the stabilization of a wind generator connected to an infinite network when operating under wind gusts. The control is proportional to a quasi-optimum combination of rotor speed variation, acceleration and torque angle of the generator. This control strategy is derived from a minimum time formulation by differentiating the electromechanical swing equation and substituting the Park's voltage and current relations into it. The control is then applied in addition to the conventional blade pitch and AVR controls. A modification of the control strategy which does not require speed control data has also been attempted. Results indicate that the quasi-optimum excitation control damps out the generator transients under various gust conditions very effectively.

1. INTRODUCTION

Recent years have seen renewed interest in the development of wind energy as an alternative to presently used and rapidly depleting resources. However the use of wind energy poses a variety of problems for the electric utilities primarily due to the uncontrollability of the power and the high degree of the variability of wind speed. Wind speed varies on a variety of time scales. In the subsecond to seconds interval the causes of the speed variations are wind gusts while the daily wind speed changes are due to the diurnal cycles.

Wind gusts will effect each wind generator and may cause them to go out of synchronism from the rest of the grid. This may occur if the rate of change of power in the wind due to the gust is greater than the capability of the machine control system to absorb the torque impulse on the generator. The performance of a wind generator under wind gusts with respect to the electric network has received less interest in the past. Conventional methods of controlling the transients following wind gusts have been reported in literature[1-3]. However, renewed interest in wind power has opened up avanues for further research in this direction.

This paper reports the application of a suboptimal excitation feedback control for the stabilization of a wind generator connected to an infinite network, in addition to the conventional blade pitch control. The control is obtained directly as a function of rotor angle variation, frequency deviation and acceleration of the wind generator with respect to the electric network.

2. SYSTEM REPRESENTATION

A wind generator feeding an infinite bus power system through a step-up transformer and transmission line, as shown in Fig. 1, is considered for this study. The electric generator is rated at 1.25 MVA, 0.8 power factor. The generator is delivering its rated load at a rated wind speed of 12.5 m/sec. The system data is given in Appendix A.

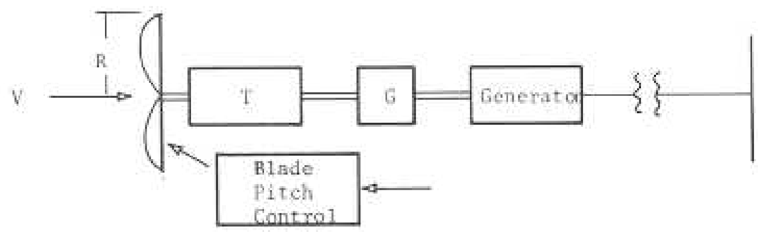

Fig. 1. Wind Turbine Generator System

There are many ways to generate constant frequency voltage. A wind turbine driving a synchronous generator is considered in this study. The wind turbine has a two-bladed propeller on a horizontal axis with stiff shaft and a step-up gearbox. It also employs a blade pitch change mechanism to control the power. A mathematical analysis of the wind turbine, blade pitch controller is given below.

2.1 Wind Turbine

The mechanical power extracted by the turbine at any time t is given by

$$P_m(t) = \tfrac{1}{2}\rho a V^3(t)\, Cp(\theta,\lambda) \qquad (1)$$

where

ρ = air density

V = wind velocity

a = The area swept by the blades

Cp = power coefficient. It is a function of both blade angle (θ) and tip speed ratio (λ).

λ = tip speed ratio = blade tip speed/wind velocity

θ = blade angle

The relationship between the power coefficient and the tip speed ratio, for a constant blade angle is non-dimensional and is normally provided by manufacturers. A least square best fit of power coefficient versus tip speed ratio curve has been mentioned[4] and a polynomial relationship has also been developed and tested. In this work a sinusoidal function is chosen since the tip speed ratio does not change much from its rated value. This means that the power coefficient remains near its maximum value. Fig. 2 shows a representative case of the power coefficient and tip speed ratio relation. The relationship is given by

$$Cp = Cp_m \operatorname{Sin} \frac{\pi}{2} \frac{\lambda}{\lambda r} \tag{2}$$

where

Cp_m = maximum value of the power coefficient.

λr = rated tip speed ratio

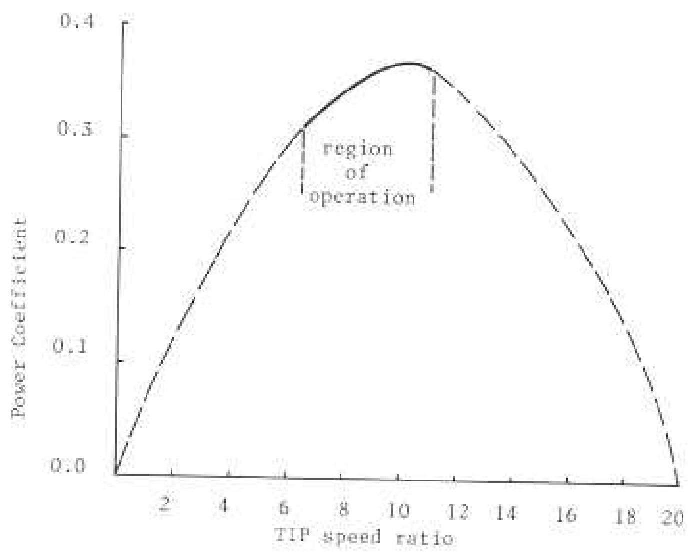

Fig. 2 Power Coefficient - Tip speed ratio relationship

The curve in Fig. 2 is valid for a reference blade angle which is defined as the angle at which maximum power coefficient occurs when the tip speed ratio is at its rated value. As the blade angle changes the curve shifts upwards or downwards along the same axis depending on the value of the blade angle with respect to the reference angle.

2.2 Wind Velocity

Wind is an uncontrollable source of power that has large fluctuations in both amplitude and direction. The torque produced is greatly influenced by the variability of the wind speed and the wind turbine generator control.

The generator rated wind speed is taken to be equal to the mean wind speed.

The machine is subjected to wind gusts of 4-6 seconds duration. The following equation for estimating the discrete longitudinal gusts are adopted.[2]

$$G\ (t,\ z) = \frac{A\ (\tau, z)}{2}\ (1 - \cos \frac{2\pi t}{\tau})\qquad 0 < t < \tau \qquad (3)$$

τ = gust period

A = gust amplitude which is a function of the gust period and the altitude z. It is given by

$$A\ (\tau,\ z) = \frac{3\ Vr}{\ln\ (Zr/Zo)}\ (\ 1 - \exp\ (\ -\ V(Za)\ \tau/1.48\ Za)\ )^{\frac{1}{2}} \qquad (4)$$

Vr = mean wind speed at a reference level Zr.

V(Za) = mean wind speed at Za.

Zo = surface roughness.

The wind speed decays exponentially toward its mean value which in this study is assumed to be the rated speed of the generator.

Fig. 3 shows a wind speed variation curve for a period of 10 seconds when the gust period is 6 seconds.

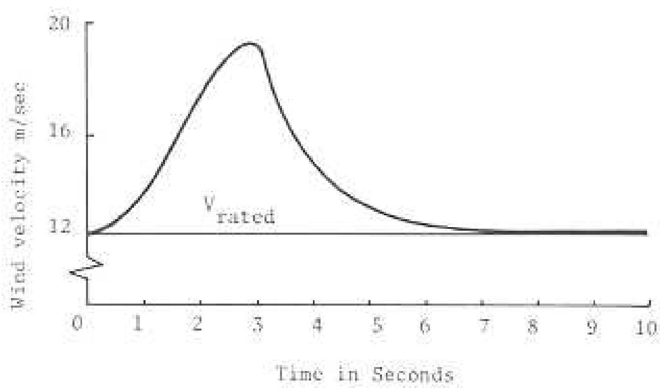

Fig. 3 Wind velocity against Time

2.3 Blade Pitch Controller

The wind turbine blade pitch control is applied according to the arrangements shown in Fig. 4. Its basic components are a pitch controller, a servo actuator and a flow limiter.[2] The input-output relations are as shown. The system is represented through the following differential equations:

$$\frac{d\ x_1}{dt} = -\ k_1\ k_2\ \Lambda_c \qquad (5)$$

$$\frac{d\,x_2}{dt} = y \qquad (6)$$

$$\frac{d\,x_3}{dt} = x_4 \qquad (7)$$

$$\frac{d\,x_4}{dt} = W_N^2\,x_2 - W_N^2\,x_3 - 2\,\xi\,W_N\,x_4 \qquad (8)$$

The power flow limiter input and output are given by

$$x = \frac{1}{\tau_p}\,(x_1 - k_1\,\Lambda_e - x_2) \qquad (9)$$

$$y = \text{Limit}\ \left(\frac{-\pi}{22.5}\,,\,\frac{\pi}{22.5}\,,\,x\right) \qquad (10)$$

The change in pitch angle is given by

$$\Delta\theta = \frac{180}{\pi}\,x_3 \quad \text{in mechanical degrees} \qquad (11)$$

where Λ_e = error in rotor speed in radians/sec.

= $\Lambda - \Lambda_N$

Λ_N = reference rotor speed in radians/sec.

Λ = rotor speed in radians/sec.

W_N = angular frequency in radians/sec.

k_1, k_2, ξ, τ_p as defined in the list of variables.

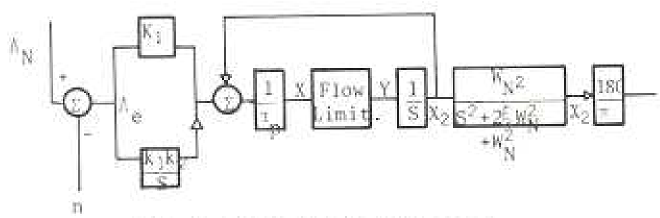

Fig. 4. Blade Pitch Controller

3. SYNCHRONOUS GENERATOR EXCITER SYSTEM

The current-flux-voltage relationships of a synchronous generator can be expressed through the well known Park's equation which are summarized in Appendix B. The exciter system considered in this study is given in Fig. 5.

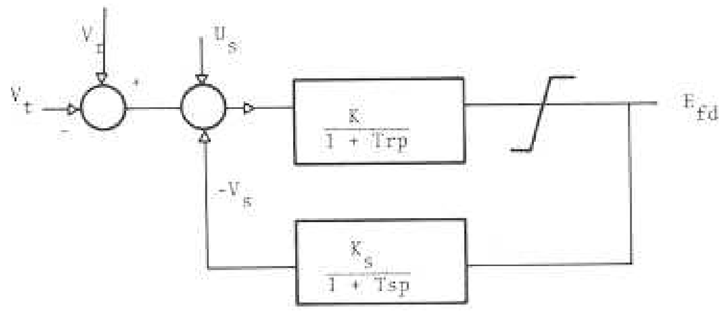

Fig. 5 IEEE Exciter Model

In addition to the normal terminal voltage feedback the exciter has a stabilizing signal V_s with a provision of an extra signal U_s.

The equations of the generator with the excitation system can be written as a set of state equations

$$\dot{X} = f(X, Y, U) \tag{12}$$

$$G(x,y) = 0 \tag{13}$$

Equation (12) includes the generator and its exciter dynamics while equation (13) includes the system and generator algebraic relationships. X is the state vector, Y includes all the other variables and the control U is solely the excitation voltage E_{fd} in this study.

4. THE EXCITATION CONTROL STRATEGY

Following a fault or disturbance in the power system, it can be effectively controlled by the control of excitation voltage[5]. A minimum time excitation control strategy which requires feedback of rotor angle signal (δ), frequency variation $n(p\delta/\omega_o)$ and acceleration $\alpha(pn)$ is discussed below.

Differentiate swing equation (B-8) in the appendix to give

$$T_m\, p^3(\delta/\omega_o) = \dot{T}_i - \dot{T}_e \tag{14}$$

Expressing the derivatives of T_i, and T_e as functions of speed control system parameters and generator current voltages etc, (14) can be written as

$$p^3(\delta/\omega_o) = L_1(y) + L_2(y) + b\,(y)\,u\,(t) \tag{15}$$

$$= L(t) + b(t)\,u(t)$$

The field voltage u(t) is constrained by the maximum and minimum values. At any instant of time r.h.s. of (15) has two possible values U_{max} or U_{min} (call it β) depending on whether u(t) is maximum or minimum (say +1 or -1).

The time optimal control u(t) can be determined from the following three functions

$$\Sigma_1 = \delta/\omega_o - \frac{\pi}{2\omega_o} - \frac{n \cdot pn}{\beta} + \frac{}{3\beta^2}(pn)^3 \quad (16)$$

$$\Sigma_\alpha = \Sigma_1 + \pi/2\omega_o \quad (17)$$

$$\Sigma = n - \frac{pn^2}{2\ L(t) + b(t)\ \ Sgn\ \{pn\}} \quad b(t) < 0$$

The control is $u^* = 1$ if $\Sigma > 0$, $u^* = -1$ if $\Sigma < 0$ and $u = Sgn\ \Sigma$ if $\Sigma_1 \leq 0$ and $\Sigma_2 \geq 0$. Here, we assume b(t) to be negative.

The control obtained is bang bang in nature. The additional stabilizing control U_s should be such as to drive E_{fd} according to the scheme proposed. This would be possible only if the exciter forward time constant Tr is zero. For a finite time constant Tr, the stabilizing control which is found to be suitable is expressed as

$$U_s = K\ \gamma \quad (19)$$

where γ is either Σ_1, Σ_2 or Σ depending on the location of the state trajectory. The details of the derivation are given in reference (6).

5. SYSTEM STUDIES

The system shown in Fig. 1 is modelled on a digital computer using a transient stability program containing Park's equation for the synchronous machine, its electromechanical swing equation, the blade pitch controller and the dynamics of the simplified IEEE exciter. The differential and algebraic equations are solved by a technique employing the trapezoidal integration method.

Results are obtained in the form of plots of the internal machine angle, the machine terminal voltage and field voltage as well as frequency change over a time interval of 10 seconds.

Following a wind gust of 6 seconds duration the machine internal angle is shown in Fig. 6. Curve 'a' in Fig. 6 shows the internal angle variation with time when only the blade pitch control and the normal AVR control are applied. Although the machine is stable with respect to the infinite system the generator exhibits slowly growing oscillatory response. The generator response is then recorded, for the same wind conditions with the excitation control strategy discussed in section 4. This strategy is used in addition to the conventional blade pitch and the AVR controls. The generator response with the control proportional to a combination of rotor speed deviation, acceleration and torque angle is shown in curve 'b' of Fig. 6. This response is much superior over that with normal AVR control. The suboptimal controller stabilizes the system in a fairly short time. The response is oscillation free and the first peak is also lower than that of Fig. 6-a. Fig. 6 curve 'c' shows the generator response with a simple frequency feedback. The response is better than with a conventional control but still shows oscillations.

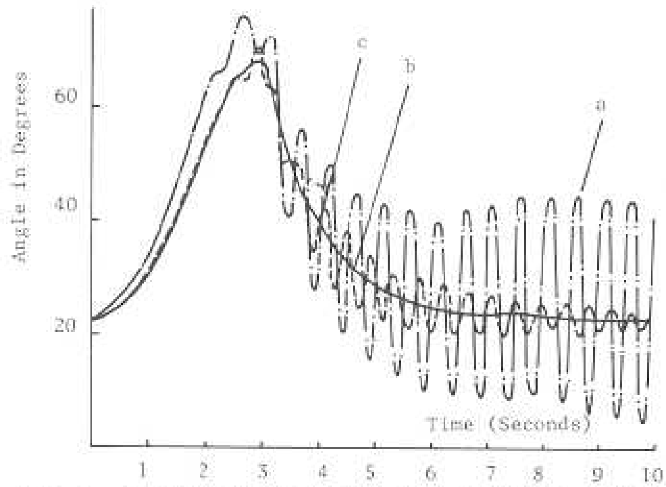

Fig. 6. Internal Angle against Time following a gust of 6 seconds. a) conventional control. b) suboptimal control. c) velocity feedback only.

The suboptimal controller used requires the derivative of the input torque and hence involves the parameters of the speed control system. The derivative of the input torque may be difficult to measure. An approximation of the parameters of the suboptimal controller, whereby the input torque variation is neglected, has been considered. Fig. 7 shows the plot of the machine internal angle against time, for the previous wind conditions, with and without neglecting the contribution of the input torque derivative $L_1(y)$. Curve 'a' which is the machine response with $L_1(y) = 0$ is seen to be oscillation free but the machine settles at a slightly higher angle than that of curve 'b'.

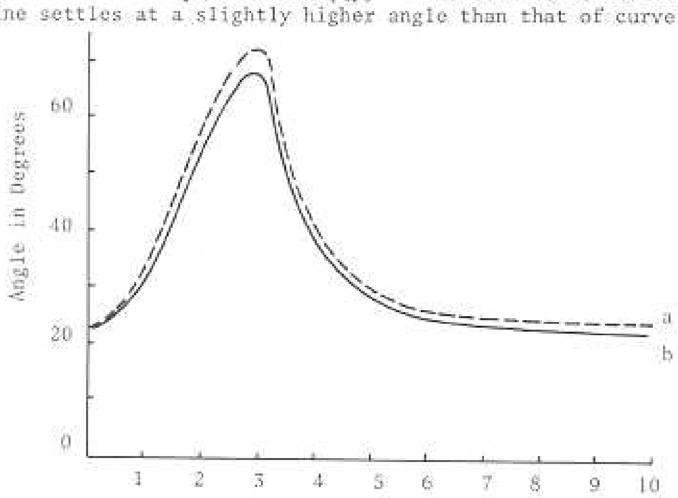

Fig. 7. Angle-Time Relationship

a- with torque variations neglected
b- with torque variations considered

Fig. 8 illustrates the variations of the machine terminal voltage following the wind gust. It can be seen from curve 'a' that the terminal voltage exhibits oscillatory response if only the blade pitch and normal AVR controls are applied. Curve 'b' on the other hand shows that the terminal voltage is brought to its pre-gust value in a short time if the excitation control strategy of section 4 is applied in addition to the normal controls.

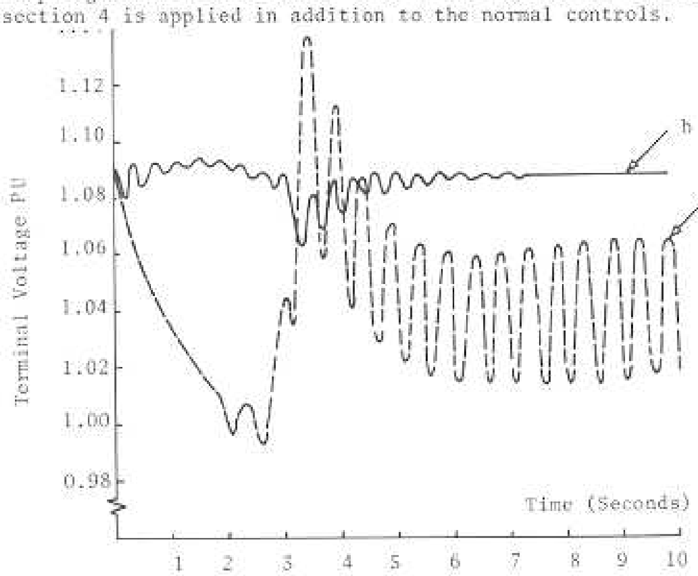

Fig. 8. Terminal Voltage-Time Relationship
a) Normal control. b) Suboptimal control.

Figs. 9 & 10 show the field voltage and the frequency error of the machine for the same wind conditions.

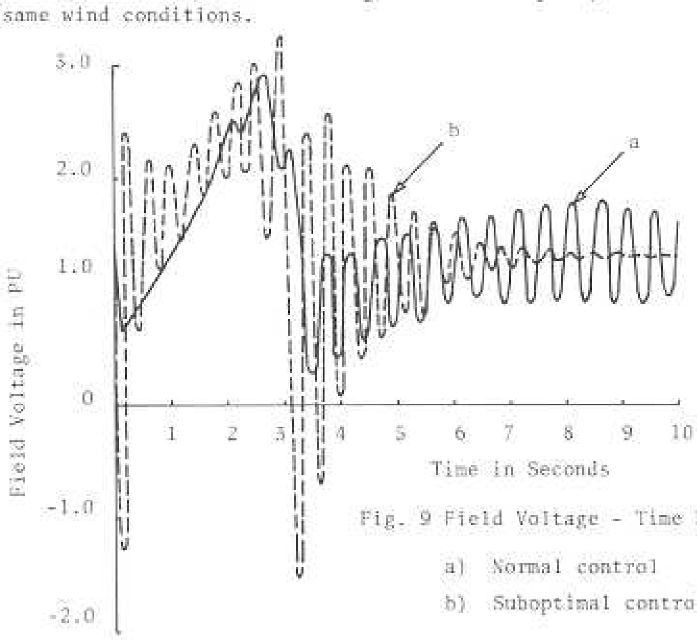

Fig. 9 Field Voltage - Time Relationship
a) Normal control
b) Suboptimal control

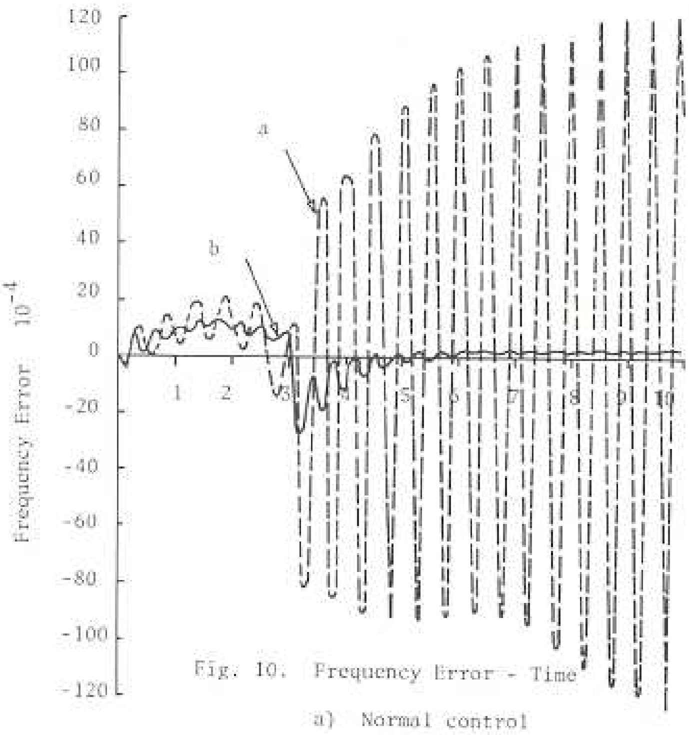

Fig. 10. Frequency Error - Time

a) Normal control

b) Suboptimal control

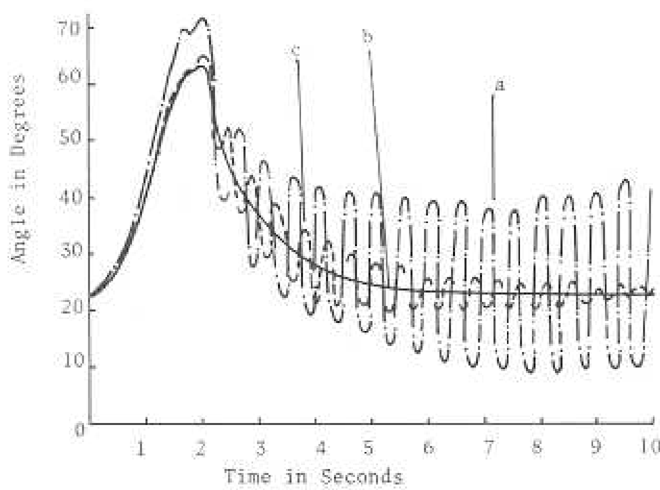

Fig.11. Angle-Time for 4-second gust

a- normal control
b- suboptimal control
c- velocity feedback

Fig. 11 depicts the generator response for a wind gust of 4 seconds with conventional control, excitation control strategy and a simple frequency feedback. The generator response is identical to that of Fig. 6. Regardless of the wind gust duration the suboptimal controller still shows a superior response compared to that of the blade pitch control and the normal AVR control.

6. CONCLUSIONS

A wind generator feeding an infinite bus electric power system is simulated on a digital computer. The performance of the wind generator, following wind gusts, was studied with a suboptimal excitation control strategy which is proportional to a quasi-optimum combination of rotor speed variation, acceleration and torque angle. The control is found to provide an almost oscillation free transition of different states to their terminal values when compared with the conventional controls of the blade pitch and AVRs. A modification of the control strategy which does not require speed control data was attempted and was found to provide a response not as good as the original optimum scheme but much superior compared to a velocity feedback.

List of Variables

V	=	wind velocity m/sec
a	=	area swept by blades
ρ	=	air density Kg/m^3
C_p	=	power coefficient
θ	=	blade angle in mech. radians
θ_N	=	reference blade angle in mech. radians
λ	=	tip speed ratio
Λ	=	turbine speed in radians/sec.
Λ_N	=	reference turbine speed
A	=	gust amplitude
τ	=	gust period
V_r	=	mean wind speed at a reference level
G	=	gearbox ratio
k_1	=	controller proportional gain in seconds
k_2	=	controller integral gain per second
ζ	=	damping ratio
τ_p	=	control hydraulic actuator time constant in seconds
W_N	=	undamped natural angular frequency in radians/sec.

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APPENDICES

Appendix A: System Parameters

The 1.25 MVA wind turbine generator parameters are as shown:

Turbine rated power	1.25 MVA	
Generator power factor	0.8	
Rated wind velocity m/sec	12.5	
Turbine rotor radius R m	28.57	
Gear ratio G	21.543	
Rated tip speed ratio	10	
Rated speed Λ radians/sec	4.375	
No. of Blades	2	
No. of poles	8	
Air density Kg/m^3	1.085	
Rated power coefficient	0.368	
Inertia constant KW-sec/KVA	2.0	
$x_{d'}$ in pu of machine rating	0.2	
$x_{q'}$	0.3	
x_d	0.5	
x_q	0.3	
$x_{d''}$	0.2	
$x_{q''}$	0.3	
Step transformer + Line	pu of machine ratings	0.3
AVR gain		200
Regulator limits		+ 6 & -4.0

Blade pitch controller parameters

$k_1 = 1.0$

$k_2 = 1.5$

$W_N = 100$

$\xi = 0.02$

$\tau_p = 0.01$

Velocity function parameters

$Z_a = 30.0$ m

$Z_R = 30.0$ m

$Z_o = 0.2$ m

$\tau = 6$ seconds

$V(Z_a) = 12.5$ m/sec.

Appendix B: Synchronous generator equations

Park's equations relating the voltages, currents etc. for the development of the control strategy are given here. The notation and symbols are those of Kimbark. Subscripts d, q and f refer to armature direct, quadrature axes and field quantities respectively. The flux, voltage and current relations of the different circuits in the normalized form are:

$$\begin{aligned}
\psi_d &= x_f i_f - x_d i_d \\
\psi_q &= x_g i_g - x_q i_q \\
\psi_f &= x_{ff} i_f - x_f i_d \\
\psi_g &= x_{gg} i_g - x_g i_q
\end{aligned} \qquad \text{B-1}$$

$$\begin{aligned}
\upsilon_d &= -ri_d - \frac{\omega}{\omega_0}\psi_q + \frac{1}{\omega_0}p\psi_d \\
\upsilon_q &= -ri_q + \frac{\omega}{\omega_0}\psi_d + \frac{1}{\omega_0}p\psi_q
\end{aligned} \qquad \text{B-2}$$

$$\begin{aligned}
\upsilon_{fd} &= r_f i_f + \frac{1}{\omega_0}p\psi_f \\
0 &= r_g i_g + \frac{1}{\omega_0}p\psi_g
\end{aligned} \qquad \text{B-3}$$

Neglecting the transformer voltage (i.e. setting $p\psi_d$, $p\psi_q$ terms to zero) and considering the fact that the variation of frequency has little effect on voltages ($\omega/\omega_o = 1$), they can be expressed as

$$v_d = -ri_d + x_q i_q + e_d \qquad \text{B-4}$$

$$v_q = -ri_q - x_q i_q + e_q$$

where

$$e_d = e_d' - (x_q - x_q')\, i_q$$

$$e_q = e_q' - (x_d - x_d')\, i_d \qquad \text{B-5}$$

and

$$\frac{de_q'}{dt} = \frac{E_{fd} - e_i}{T_{do}'}$$

$$\frac{de_d'}{dt} = \frac{e_d}{T_{qo}'} \qquad \text{B-6}$$

$$e_i = x_f i_f$$

Combining equations B-4 and B-5 or writing the transient condition equations directly gives

$$v_d = x_q' i_q + e_d'$$

$$v_q = -x_d' i_d + e_q' \qquad \text{B-7}$$

The electromechanical swing equation can be broken up into two differential equations

$$p\delta = \omega_o\, n$$

$$pn = T_i/T_m - T_e/T_m \qquad \text{B-8}$$

T_i, T_e and T_m are the input torque, airgap torque and inertia constant of the generator respectively, n is the p.u. angular frequency deviation and is expressed as

$$n = \frac{\omega - \omega_o}{\omega_o} \qquad \text{B-9}$$

Ignoring armature copper loss, the airgap torque can be expressed as

$$T_e = \upsilon_d i_d + \upsilon_q i_q \qquad \text{B-10}$$

A combination of equations (B-6 - B-10) to give overall equations of each synchronous generator can be written in terms of a set of four differential equations of the state vector e'_d, e'_q, n and δ and few other algebraic relationships in the form equations (12) and (13).

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