The Transient Models and Simulation for Analysis of WPT and WPS

Zulati Litipu, Bahman Kermanshahi, and Chi-Hung Kelvin Chu

Abstract—**This paper presents the derivation of three transient models for analysis and simulation of Wind Power Turbine (WPT) based on the theory of asynchronous induction generator. They may be used for determining the operational characteristics of WPT in normal and abnormal operation. The models are derived by using current, magnetic linkage and electromagnetic potential as variables; they are applicable to simulation of WPT and Wind Power System (WPS). The application of derived models is illustrated by using one of the models, the electromotive-force model to simulate the operation performance of a 150 kW WPT.**

The simulation results enable engineers or designers to have insight on the behavior of the WPT in operation.

Index Terms—**Result analysis, simulation, transient models, wind power turbine.**

I. Introduction

SINCE output of WPT depends on the availability of wind speed, the control and regulation of wind power is more difficult and complex than conventional power system, such as hydraulic and thermal power systems. The stability of WPS (here, WPS is denoted as the power system which contains WPT) relate to operation characteristics of each WPT. The operational quality of WPT is determined by two issues, the output characteristics and the connecting times (the numbers to cut-in and cut-off in power system). The study on the operation behaviors of WPT is important for using them in safe and economical ways.

The target of this paper is to derive a set of WPT models, covering from the wind energy input to the electrical output, for applying in different analysis. The models are in simple formation by neglecting some parameters which do not affect on the characteristics of simulation results. Each of these models is suitable for use in a particular type of study and also enables to be used in union form. As a reference way, we suggest the appropriate aspects to apply these models as follows:

- The current model is well marched for analysis of power network.
- The magnetic linkage model is convenient for analysis of WPT/generators.
- The electromagnetic potential model is suitable for analysis of synthetic power system connected to WPT.

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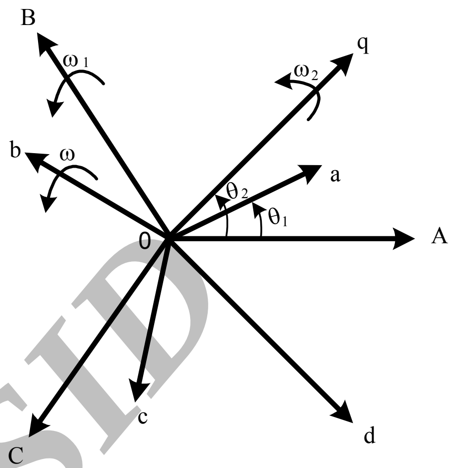

Fig. 1. The coordinate system of induction generator.

II. Derivation of WPT Models

In this paper, the target WPT is FYF450S type 150 kW asynchronous induction generator, therefore the model's derivation is based on the theory of asynchronous induction generator. In order to simplify the calculation and decouple the mutual inductances from the machine equations, Park's Law is applied to transform the reference from the ABC reference to DQO reference. Fig.1 shows the relationship between these two references [1]. In this figure uppercase and lowercase letters are respectively referred to the parameters of the rotor and stator. Angular velocities and angles are denoted by letters ω (of stator rotating magnetic field), ω_1 (of rotator in ABC system), ω_2 (of rotator in DQ system) and θ_1 (between rotator and stator in ABC system), θ_2 (of rotator between ABC and DQ system). All numerical values are assumed to be calculated in per unit system [2].

The basic equations of asynchronous generator after transformation are given in (1):

$$\begin{aligned} p\psi_d &= R_1 i_d + \omega\psi_q + V_d \\ P\psi_q &= R_1 i_q - \omega\psi_d + V_q \\ p\psi_o &= R_1 i_o + V_o \\ p\psi_D &= -R_2 i_D + (\omega-\omega_2)\psi_Q \\ p\psi_Q &= -R_2 i_Q - (\omega-\omega_2)\psi_D \\ p\psi_o &= -R_2 i_o \end{aligned} \quad (1)$$

where $p = d/dt$, i, ψ and V are the currents, flux linkages and voltages, R_1 and R_2 are the resistances of the stator and rotor, respectively.

A. Magnetic Linkage Transient Model

Neglect the generator resistance R_1 and R_2, the magnetic linkage form of (1) may be written by generator current and voltage as well as the reactance of rotor, stator and excitation system as

$$\begin{aligned}
\psi_d &= -(x_1+x_m)\,i_d + x_m\,i_D = -x_{11}i_d + x_m i_D\\
\psi_q &= -(x_1+x_m)\,i_q + x_m\,i_Q = -x_{11}i_q + x_m i_Q\\
\psi_o &= -x_1\,i_o\\
\psi_D &= -x_m i_d + (x_2+x_m)\,i_D = -x_m i_d + x_{22} i_D\\
\psi_Q &= -x_m i_q + (x_2+x_m)\,i_Q = -x_m i_q + x_{22} i_Q\\
\psi_o &= -x_2\,i_o
\end{aligned} \tag{2}$$

where x_1, x_2, and x_m are the reactance of stator, rotor and excitation coils, respectively; and $x_{11} = x_1 + x_m$, $x_{22} = x_2 + x_{m.}$.

The matrix form of (2) is given as

$$\begin{bmatrix}\psi_d\\ \psi_q\\ \psi_o\\ \psi_D\\ \psi_Q\\ \psi_o\end{bmatrix} = \begin{bmatrix} -x_{11} & 0 & 0 & x_m & 0 & 0\\ 0 & -x_{11} & 0 & 0 & x_m & 0\\ 0 & 0 & -x_1 & 0 & 0 & 0\\ -x_m & 0 & 0 & x_{22} & & 0\\ 0 & -x_m & 0 & 0 & x_{22} & 0\\ 0 & 0 & 0 & 0 & 0 & x_2 \end{bmatrix} \begin{bmatrix} i_d\\ i_q\\ i_o\\ i_D\\ i_Q\\ i_o\end{bmatrix} \tag{3}$$

As the behavior of some constants in state equations does not affect the characteristics of simulation results, they may be neglected according to the relationship and influence degree on simulation target in order to simplify a complex state equation [3]. As an attempt possibility, we neglect the reactance x_m and this possibility is proved to be available in different application. Equation (3) can be expressed as $\boldsymbol{\psi} = \mathbf{X\,I}$ [4]. By neglecting the reactance x_m in (3) we have inverse matrix $\mathbf{X}^{-1}$ and

$$\begin{bmatrix} i_d\\ i_q\\ i_o\\ i_D\\ i_Q\\ i_o\end{bmatrix} = \begin{bmatrix} -\frac{1}{x_{11}} & 0 & 0 & 0 & 0 & 0\\ 0 & -\frac{1}{x_{11}} & 0 & 0 & 0 & 0\\ 0 & 0 & -\frac{1}{x_1} & 0 & 0 & 0\\ 0 & 0 & 0 & \frac{1}{x_{22}} & 0 & 0\\ 0 & 0 & 0 & 0 & \frac{1}{x_{22}} & 0\\ 0 & 0 & 0 & 0 & 0 & \frac{1}{x_2} \end{bmatrix} \begin{bmatrix}\psi_d\\ \psi_q\\ \psi_o\\ \psi_D\\ \psi_Q\\ \psi_o\end{bmatrix}. \tag{4}$$

Substituting (4) into (1), the magnetic linkage model is given by

$$p\begin{bmatrix}\psi_d\\ \psi_q\\ \psi_o\\ \psi_D\\ \psi_Q\\ \psi_o\end{bmatrix} = \begin{bmatrix} -\frac{R_1}{x_{11}} & \omega & 0 & 0 & 0 & 0\\ -\omega & -\frac{R_1}{x_{11}} & 0 & 0 & 0 & 0\\ 0 & 0 & -\frac{R_1}{x_1} & 0 & 0 & 0\\ 0 & 0 & 0 & -\frac{R_2}{x_{22}} & \omega-\omega_2 & 0\\ 0 & 0 & 0 & -(\omega-\omega_2) & -\frac{R_2}{x_{22}} & 0\\ 0 & 0 & 0 & 0 & 0 & -\frac{R_2}{x_{22}} \end{bmatrix} \times \begin{bmatrix}\psi_d\\ \psi_q\\ \psi_o\\ \psi_D\\ \psi_Q\\ \psi_o\end{bmatrix} + \begin{bmatrix} V_d\\ V_q\\ V_o\\ 0\\ 0\\ 0\end{bmatrix}, \tag{5}$$

which can be presented as $p\boldsymbol{\psi} = \mathbf{A}\boldsymbol{\psi} + \mathbf{BV}$, where $\mathbf{B}$ is unitary matrix.

B. Electromagnetic Potential Transient Model

From (2) we have

$$\begin{aligned} i_D &= i_d x_m/(x_2+x_m) + \psi_D/(x_2+x_m)\\ i_Q &= i_q x_m/(x_2+x_m) + \psi_Q/(x_2+x_m) \end{aligned}. \tag{6}$$

Combine (6) with q and d magnetic linkage equations of the stator and define x' as the transient reactance by

$$x' = x_1 + x_m - x_m^2/(x_2+x_m) = x_1 + x_m x_2/(x_2+x_m) \tag{7}$$

then using [5] we obtain

$$\begin{aligned} \psi_d &= -x' i_d + E'_q\\ \psi_q &= -x' i_q + E'_d \end{aligned}, \tag{8}$$

where E'_d and E'_q are the equivalent electromagnetic potential of the exciter coils on d and q axes and they may be derived as

$$\begin{aligned} E'_d &= -\psi_Q x_m/(x_2+x_m)\\ E'_q &= \psi_D x_m/(x_2+x_m) \end{aligned} \tag{9}$$

or in an alternate form

$$\begin{aligned} pE'_d &= -x_m p\psi_Q/(x_2+x_m)\\ pE'_q &= x_m p\psi_D/(x_2+x_m) \end{aligned}. \tag{10}$$

Substituting (10) into (5) and rearranging the terms we have

$$R_2 i_D + [(x_2+x_m)/x_m]pE'_q - (\omega-\omega_2)[-(x_2+x_m)E'_d/x_m] = 0.$$

Denoted $T'_{do} = (x_2+x_m)/R_2$ as time constant [6] then

$$T'_{do}pE'_q + (\omega-\omega_2)E'_d T'_{do} = -x_m i_D.$$

In the like manner we have

$$-T'_{do}pE'_d + (\omega-\omega_2)E'_q T'_{do} = -x_m i_Q.$$

The voltage equations can then be written as

$$\begin{aligned} V_d &= -R_1 i_d - \omega\psi_q\\ &= -R_1 i_d + \omega\, i_q x_{11} - \omega T'_{do} pE'_d + \omega(\omega-\omega_2)E'_q T'_{do}\\ V_q &= -R_1 i_q + \omega\psi_d\\ &= -R_1 i_q - \omega\, i_d x_{11} - \omega T'_{do} pE'_q - \omega(\omega-\omega_2)E'_d T'_{do} \end{aligned} \tag{11}$$

The stator plural equation of asynchronous generator [7] is

$$\overline{V} = -(R_1 + jx')\,\overline{I} + \overline{E'}$$

where, $\overline{V} = V_q + jV_d$, $\overline{I} = I_q + jI_d$, $\overline{E'} = E'_q + jE'_d$.

Above equation can also be written as

$$\begin{aligned} V_d &= -R_1 i_d - i_q x' + E'_d\\ V_q &= -R_1 i_q + i_d x' + E'_q \end{aligned}. \tag{12}$$

Equating (11) and (12) yields (13)

$$\begin{aligned} \omega T'_{do} pE'_d &= -E'_d + (x' + \omega\, x_{11})\, i_q + \omega\,(\omega-\omega_2)\,E'_q T'_{do}\\ \omega T'_{do} pE'_q &= -E'_q - (x' + \omega\, x_{11})\, i_d - \omega\,(\omega-\omega_2)\,E'_d T'_{do} \end{aligned} \tag{13}$$

Let x be the reactance measured at end of stator of generator; then $x = x_{11}$. When the WPT is operating in connection to a power system, the rotating magnet field of stator is synchronized with the system, therefore $\omega = 1$.

If WPT is working as a generator, we have $(\omega-\omega_2)/\omega=-s$. Substituting this into (13) yields the electromotive-force transient model

$$\begin{aligned} T'_{do} pE'_d &= -E'_d + (x'+x)\, i_q - sE'_q T'_{do} \\ T'_{do} pE'_q &= -E'_q - (x'+x)\, i_d + sE'_d T'_{do} \end{aligned} \qquad (14)$$

or in the matrix form as

$$p\begin{bmatrix} E'_d \\ E'_q \end{bmatrix} = \begin{bmatrix} \frac{-1}{T'_{do}} & -s \\ s & \frac{-1}{T'_{do}} \end{bmatrix} \begin{bmatrix} E'_d \\ E'_q \end{bmatrix} + \begin{bmatrix} \frac{(x'+x)}{T'_{do}} & 0 \\ 0 & \frac{-(x'+x)}{T'_{do}} \end{bmatrix} \begin{bmatrix} i_q \\ i_d \end{bmatrix}.$$

The matrix one is the standard matrix form of application: $p\mathbf{E} = \mathbf{AE} + \mathbf{BI}$.

C. Current Transient Model

Substituting (2) into (1) and considering the simplified matrix $\mathbf{X}^{-1}$, the current transient model is given by (15):

$$p\begin{bmatrix} i_d \\ i_q \\ i_o \\ i_D \\ i_Q \\ i_o \end{bmatrix} = \begin{bmatrix} -\frac{R_1}{x_{11}} & \omega & 0 & 0 & -\frac{\omega x_m}{x_{11}} & 0 \\ -\omega & -\frac{R_1}{x_{11}} & 0 & \frac{\omega x_m}{x_{11}} & 0 & 0 \\ 0 & 0 & -\frac{R_1}{x_1} & 0 & 0 & 0 \\ 0 & -\frac{(\omega-\omega_2)x_m}{x_{22}} & 0 & -\frac{R_2}{x_{22}} & \omega-\omega_2 & 0 \\ \frac{(\omega-\omega_2)x_m}{x_{22}} & 0 & 0 & -(\omega-\omega_2) & -\frac{R_2}{x_{22}} & 0 \\ 0 & 0 & 0 & 0 & 0 & -\frac{R_2}{x_{22}} \end{bmatrix}$$

$$\begin{bmatrix} i_d \\ i_q \\ i_o \\ i_D \\ i_Q \\ i_o \end{bmatrix} + \begin{bmatrix} -\frac{1}{x_{11}} & 0 & 0 & 0 & 0 & 0 \\ 0 & -\frac{1}{x_{11}} & 0 & 0 & 0 & 0 \\ 0 & 0 & -\frac{1}{x_1} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{x_{22}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{x_{22}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{x_2} \end{bmatrix} \begin{bmatrix} V_d \\ V_q \\ V_o \\ 0 \\ 0 \\ 0 \end{bmatrix}, \qquad (15)$$

where, $p=d/dt$. This model is also the standard matrix form as $p\mathbf{I} = \mathbf{AI} + \mathbf{BV}$.

D. Relationship between WPT Input and Output in Energy Conversation

WPT blades receive wind energy to drive generator axes by the torque of wind blades:

$$T_w = (\pi\rho c_p R^3 v_w \omega_2)/T_h \lambda P_N . \qquad (16)$$

Specify T_T as input torque to generator, then

$$dT_T/dt = (T_w - T_T)/T_H \qquad (17)$$

Conversed magnetic-electric torque is $T_E = \psi_d i_q - \psi_q i_d$.

Take s as slip of generator, and then the operation characteristic may be expressed as

$$\begin{aligned} ds/dt &= (T_T - T_E)/T_J \\ d\theta/dt &= \omega_2 \end{aligned}, \qquad (18)$$

where

T_H =Inertia time constant of WPT,
c_p & λ =Power ratio and high speed ratio of WPT,
P_N & R =Rated power and radium of WPT,
ρ & V_w =Air density and wind speed,
T_J =Inertia time constant of generator.

III. Application Results

Like the items suggested previously, the models are suitable for different studies, since this study deals with the impact of stability and output characteristic of WPT, the electromagnetic potential model as well as slip and torque equations are therefore selected.

SIMULNK® in MATLAB® software proposes many standard simulation models for control system, and the state space problem can be expressed by mathematic way. In this paper SIMULINK® is selected to perform the simulation.

A. Models Rearrangement

As mentioned above, we can write

$$\begin{aligned} T'_{do} pE'_d &= -E'_d + (x'+x) i_q - sE'_q T'_{do} \\ T'_{do} pE'_q &= -E'_q - (x'+x) i_d + sE'_d T'_{do} \\ ds/dt &= (T_T - T_E)/T_J \\ dT_T/dt &= (T_w - T_T)/T_H \end{aligned} . \qquad (19)$$

WPT is a kind of asynchrony-induction generator; the state denoted by (19) is nonlinear one with multi-input, output and variables, the standard state models proposed by SIMULINK® are difficult to be directly applied into it. To linearize (19), problem is to find out an equivalent-linear state and represent it with same output. Write (19) as vector $p\mathbf{X}$ and define $\mathbf{Y}$ as an output vector of $p\mathbf{X}$, then express them in the form of

$$\begin{aligned} p\mathbf{X} &= \mathbf{AX} + \mathbf{BU} = \mathbf{f(X,U)} \\ \mathbf{Y} &= \mathbf{CX} + \mathbf{DU} = \mathbf{F(X,U)} \end{aligned} . \qquad (20)$$

Considering the operation time point t_0 is one of the state intersections of $p\mathbf{X}$ and $\mathbf{Y}$, then in very small increment Δt near t_0, the new state $\mathbf{Y}$ must satisfy $p\mathbf{X}$. By taking subscript 0 as simple of initial values in accordance with t_0 and adding increment Δ to variables in accordance with the Δt, then (20) can be expressed as

$$\begin{aligned} p\mathbf{X} &= p\mathbf{X}_0 + \Delta p\mathbf{X} = \mathbf{f}[(\mathbf{X}_0 + \Delta\mathbf{X}), (\mathbf{U}_0 + \Delta\mathbf{U})] \\ \mathbf{Y} &= \mathbf{Y}_0 + \Delta\mathbf{Y} = \mathbf{f}[(\mathbf{X}_0 + \Delta\mathbf{X}), (\mathbf{U}_0 + \Delta\mathbf{U})] \end{aligned} . \qquad (21)$$

As Δt is assumed to be small enough, the above equation can be expressed by Taylor Law series. By neglecting second and higher power of $\Delta\mathbf{X}$ and $\Delta\mathbf{U}$, expanding (21) at time t_0, then we have:

$$\begin{aligned} \Delta pX_i &= \frac{\partial f_i}{\partial X_1}\Delta x_1 + \ldots + \frac{\partial f_i}{\partial X_n}\Delta x_n + \frac{\partial f_i}{\partial U_1}\Delta u_1 + \ldots + \frac{\partial f_i}{\partial U_r}\Delta u_r \\ \Delta Y_j &= \frac{\partial F_j}{\partial X_1}\Delta x_1 + \ldots + \frac{\partial F_j}{\partial X_n}\Delta x_n + \frac{\partial F_j}{\partial U_1}\Delta u_1 + \ldots + \frac{\partial F_j}{\partial U_r}\Delta u_r \end{aligned}$$

where n is the order of system and r is the number of input.

Above equation can be written as:

$$\begin{aligned} \Delta p\mathbf{X} &= \mathbf{A}\Delta\mathbf{X} + \mathbf{B}\Delta\mathbf{U} \\ \Delta\mathbf{Y} &= \mathbf{C}\Delta\mathbf{X} + \mathbf{D}\Delta\mathbf{U} \end{aligned} \qquad (22)$$

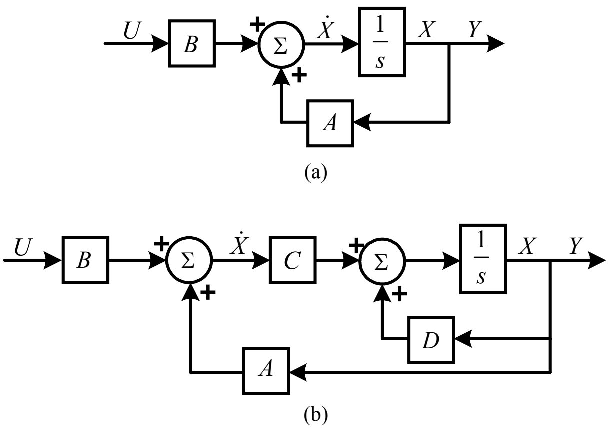

Fig. 2. Block diagram of states (a) before linearization, and (b) after linearization.

in which **C** is output constant matrix; **D** is constant matrix related to input.

Equation (22) is linearized state of (20), and it enable, in defined time range, to represents the states denoted by (20), or these two states are equivalent states. Equation (22) can be linked to SIMULINK® program and calculated by numeral method.

Apply (22) to target state denoted by (19) based on proposed variables and parameters. Let $\Delta\, p\mathbf{X} = \dot{\mathbf{X}} = [\dot{E}'_d, \dot{E}'_q, \dot{s}, \dot{T}_T]$, $\Delta\,\mathbf{X} = \mathbf{X} = [E'_d, E'_q, s, T_T]$ and $\Delta\mathbf{U} = \mathbf{U} = [I_d, I_q, v_w]$, we have

$$\begin{bmatrix} \dot{E}'_d \\ \dot{E}'_q \\ \dot{s} \\ \dot{T}_T \end{bmatrix} = \begin{bmatrix} -\frac{1}{T'_{do}} & -\omega_2 s & -\omega_2 E'_{qo} & 0 \\ \omega_2 s & -\frac{1}{T'_{do}} & \omega_2 E'_{do} & 0 \\ -\frac{I_{do}}{T_J} & -\frac{I_{qo}}{T_J} & 0 & \frac{1}{T_J} \\ 0 & 0 & 0 & -\frac{1}{T_H} \end{bmatrix} \begin{bmatrix} E'_d \\ E'_q \\ s \\ T_T \end{bmatrix} + \begin{bmatrix} 0 & \frac{x+x'}{T'_{do}} & 0 \\ -\frac{x+x'}{T'_{do}} & 0 & 0 \\ -\frac{E'_{do}}{T_J} & -\frac{E'_{qo}}{T_J} & 0 \\ 0 & 0 & \frac{\pi\rho c_p R^3 v_0 \omega_2}{T_h \lambda P_N} \end{bmatrix} \begin{bmatrix} I_d \\ I_q \\ v_w \end{bmatrix}. \quad (23)$$

The linearization form of (23) can be realized by

$$\begin{aligned} \dot{\mathbf{X}} &= \mathbf{AX} + \mathbf{BU} \\ \mathbf{Y} &= \mathbf{CX} + \mathbf{DU} \end{aligned}. \quad (24)$$

By taking the Laplace transform of (24), the principle of linearization before and after linearization can be shown by Fig. 2 [8], [9].

B. Construction of the Appropriate Model

Since the interest in this study is to examine the changes of the WPT electromagnetic potential, the electromotive-force transient model is therefore selected. For normal WPT operation, the change in the range of the difference in rotation speed should be as wide as possible. However, the change in the range during transient process should be as narrow as possible to reduce the change to the range of the magnitude of the magnetic field. Literalizing all variables near their normal operation point (I_{qo}, I_{do}, E'_{qo} and E'_{do}) at

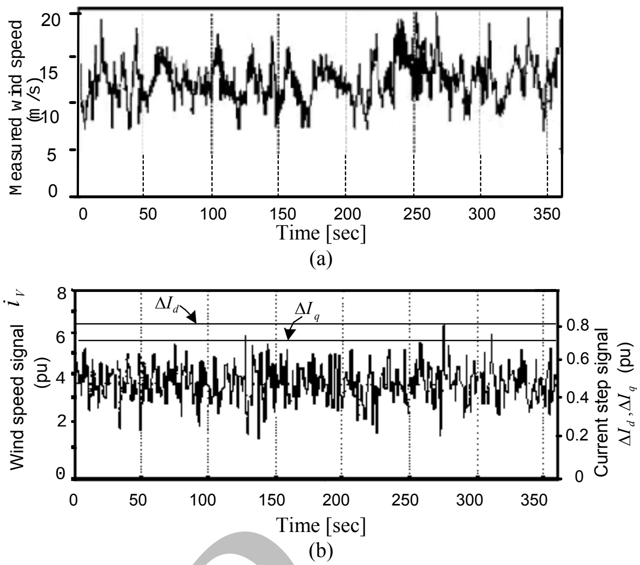

Fig. 3. (a) Measured wind speed, (b) wind speed signal i_v and ΔI_d, ΔI_q.

a defined wind speed for (8), (10) and (11) yields:

$$p\Delta E'_d = -\frac{1}{T'_{do}}\Delta E'_d + \frac{x+x'}{T'_{do}}\Delta I_q + \omega_2 s \Delta E'_q - \omega_2 s E'_{qo}$$

$$p\Delta E'_q = -\frac{1}{T'_{do}}\Delta E'_q - \frac{x+x'}{T'_{do}}\Delta I_d + \omega_2 s \Delta E'_d + \omega_2 s E'_{do}$$

$$ps = \frac{1}{T_J}\Delta T_T - \frac{E'_{qo}}{T_J}\Delta I_q + \frac{E'_{do}}{T_J}\Delta I_d - \frac{I_{qo}}{T_J}\Delta E'_q + \frac{I_{do}}{T_J}\Delta E'_d$$

$$p\Delta T_T = \frac{1}{T_H}(\Delta T_w - \Delta T_T)$$

The above equations can be rewritten in matrix form as:

$$\begin{bmatrix} \Delta\dot{E}'_d \\ \Delta\dot{E}'_q \\ \dot{s} \\ \Delta\dot{T}_T \end{bmatrix} = \begin{bmatrix} -\frac{1}{T'_{do}} & \omega_2 s & -\omega_2 E'_{qo} & 0 \\ \omega_2 s & -\frac{1}{T'_{do}} & \omega_2 E'_{do} & 0 \\ \frac{I_{do}}{T_J} & -\frac{I_{qo}}{T_J} & 0 & \frac{1}{T_J} \\ 0 & 0 & 0 & -\frac{1}{T_H} \end{bmatrix} \begin{bmatrix} \Delta E'_d \\ \Delta E'_q \\ s \\ \Delta T_T \end{bmatrix} + \begin{bmatrix} 0 & \frac{x+x'}{T'_{do}} & 0 \\ -\frac{x+x'}{T'_{do}} & 0 & 0 \\ \frac{E'_{do}}{T_J} & -\frac{E'_{qo}}{T_J} & 0 \\ 0 & 0 & \frac{\pi\rho c_p R^3 V_0 \omega_2}{T_h \lambda P_N} \end{bmatrix} \begin{bmatrix} \Delta I_d \\ \Delta I_q \\ \Delta V_w \end{bmatrix}. (25)$$

C. Transient Simulation

This model is applied to a WPT with the following characteristics: Rated power, $P_N = 150$ kW, frequency $f = 50$ Hz, rated voltage $V_N = 400$ V. Based on the generator parameters under rated wind speed, 12m/s, the coefficients of matrices **A** and **B** for the WPT are as follows:

$$\mathbf{A} = \begin{pmatrix} -0.5 & 0.011 & -0.64 & 0 \\ 0.011 & -0.5 & 0.77 & 0 \\ 0.25 & -0.433 & 0 & 0.375 \\ 0 & 0 & 0 & -0.33 \end{pmatrix}$$

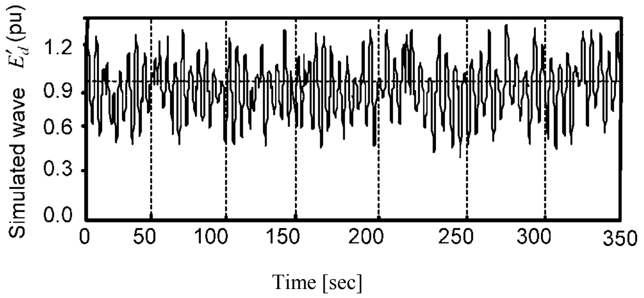

Fig. 4. Response signal of simulated E'_d.

$$\mathbf{B}=\begin{pmatrix}0 & 1.348 & 0\\ -1.348 & 0 & 0\\ 0.3 & -0.24 & 0\\ 0 & 0 & 1.19\end{pmatrix}$$

ΔI_d, ΔI_q and ΔV_w are inputs to the simulation model shown in Fig. 2. Currents, ΔI_d and ΔI_q, are inserted in the form of unit step function. Wind speed signal, ΔV_w, is inserted in the form of a random current, i_v. Fig. 3(a) shows the measured wind speed (14.8 m/s) in average; and Fig. 3(b) shows the input wind speed signal i_v and ΔI_d, ΔI_q. Figs. 4-6 show the simulated responses of the WPT to the input.

D. Analysis of the Simulation Results

The followings can be observed from the results of simulation for a WPT shown in Figs. 4-6.

(1) From the curve in Figs. 4 and 5, electromagnetic potential E'_d and E'_q respond very quickly to the change in wind speed. The range of changes is relatively large. This indicates that during transient state, the stability of the WPT is relatively low. There are two reasons for this: (1) The WPT (150 kW) may be too small, i.e. not enough inertia, and (2) the lack of a blade control system in the WPT. During operation, it is necessary to monitor the wind speed very closely and be ready to stop the operation of the WPT when there is a large change of wind speed. This situation can be alleviated very simply by adding inertia to the rotor of the WPT.

(2) Fig. 6 shows that when wind speed changes, the WPT may be working as an electric generator or as an electric motor. The change of the function of a WPT from electric generator to electric motor or vice versa cannot be done instantaneously, as this change is too fast for the WPT to follow. WPT, because of its inertia, will tend to stay at its previous working state, and this figure shows that it only follows the wind speed changes slowly. The sign of s is determined by the wind speed. WPT works as an electric generator when s is positive (at high wind speed), and works as an electric motor when s is negative (at low wind speed). It is obvious that the s value of small and middle size WPT generally changes much faster under sudden change of wind speed [10]. But because of it smaller size, it will not have significant impact on the power system it is connected to.

(3) The change of wind speed signal, i_v affects the electromagnetic potential significantly. This means that the change in wind speed is the main source of interference for the WPT.

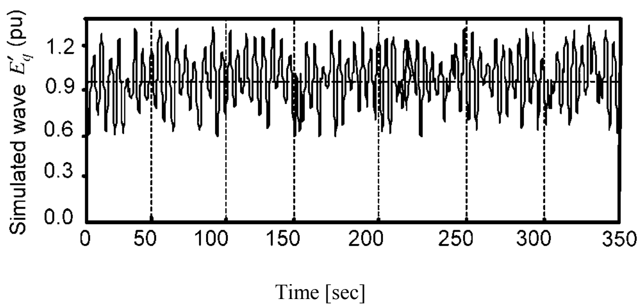

Fig. 5. Response signal of simulated E'_q

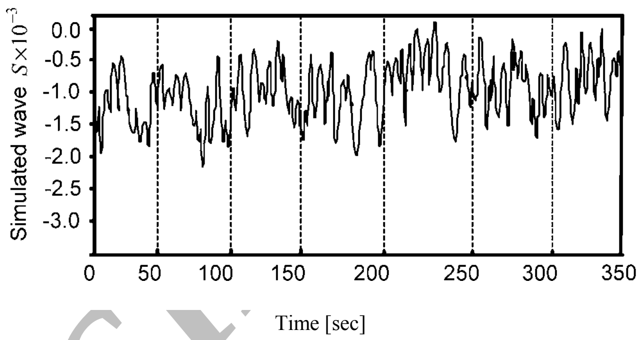

Fig. 6. Response signal of simulated s.

(4) Due to the small capacity of the WPT, the influence on the turning moment, T_T would be insignificant and therefore is omitted in this study.

(5) Studies have shown that the wind condition of most wind plant site usually changes in a wide range. This suggests the WPT should be deployed with stable frequency control or with blade shape change control.

IV. CONCLUSIONS

In conclusion, each transient model derived in this paper provides different advantages in the study of wind power turbines and generators. The followings can be concluded from this study:

(1) Depending on the target of the research, different WPT models can be derived and used in the simulation.

(2) In order to provide more accurate and precise results, the Δ value used in the linearization should be as small as possible.

(3) ΔV_w is injected into the model in the form of random-pulse current signal. The range of this signal should be determined based on the actual wind intensity and variation at the operation site. The WPT studied in this paper has a rated wind speed of 12 m/s. It may be necessary to define in more detail the relationship between signal range and wind speed to obtain a more accurate simulation result.

(4) ΔI_d and ΔI_q are put in the form of a unit step current signal. The type and range of these signals should be determined and selected according to objective of the calculation and simulation.

(5) Results of this simulation can be used in analyzing the operating characteristics of WPT and can also be used to study its impact on the operation and stability of the power system it is connected to.

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