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WIND POWER PLANT MODELLING AND SIMULATION

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Abstract

A mathematical simulation model for a large horizontal axis wind turbins system is presented. Examples of performed simulations are also given. The model is intended for simulation of the synchronization of the wind turbine generator against the utility grid and the operation of the wind turbine system under different wind conditions and with different control algorithms.

Particular attention has been given to the modularization. The model is divided into subsystems to make it easy to modify the model and adapt it to systems of similar type. The interactive simulation package SIMNON which allows good structuring and programming in a high level language has been used.

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Introduction

A Wind Turbine System (WTS) differs conceptually from a conventional power production unit in the sense that the power source cannot be controlled in any way. If the available power is below the rated value, the system should be operated to extract maximum energy. Normally this is achieved by letting the blade angle be a static function of the wind and rotor speed. When the wind increases further, protection from over-power is made by flapping and modulation of the blade angle.

However, as the wind is of a stochastic nature and a WTS is a dynamically soft system, excitation of poorly damped modes are probable. In order to extract the maximum energy from the fluctuating wind and to minimize the dynamic loads on the WTS, a fast and well-tuned control system is required.

The WTS designer therefore includes the dynamic performance in the construction work and a large part of the design is to simulate system behaviour under different conditions. On the other hand, simulation is also good for design-verification and functional analysis work made e.g. by the customers. The need for good dynamical models and simulation systems is thus obvious.

The goal of this work was to develop a framework for simulation of a general Wind Turbine System, based on an existing and well-proven simulation package (SIMNON). The simulation system should be good for design-verification and failure investigation in connection with faults in the plant and in the electrical network. Furthermore, the goal was also to develop a simulator for educational purposes and future design of quite new controllers, like e.g. adaptive ones.

The Wind Turbine System - WTS-3

The plant to be considered in this study is a 3 MW wind turbine system, WTS-3, which is built near the city of Trelleborg, in southern Sweden, by Karlskronavarvet AB, Sweden and Hamilton Standard, a division of United Technologies Inc, USA. A 4 MW plant (WTS-4) of the same design is built in Medicine Bow, Wyoming, USA.

The wind turbine system WTS-3 is designed to supply power in parallel with other electrical generators to a large power utility grid and to operate in wind forces of 5-26 m/s. The rated power 3 MW is reached at 14 m/s.

WTS-3 has a horizontal axis wind turbine with two teetered blades. The rotor drives a 3-phase synchronous generator through a gearbox. The power is controlled by changing the pitch angle. The blade actuators are hydraulic positioning systems.

The tower is a 78 m high and 3.8 m wide cylindrical steel shell. The nacelle and rotor can turn freely around the axis of the tower. The rotor is aligned by an active yaw mechanism of the tower against the wind, downwind of the tower. The blades lean downwind at an angle of 6° and are designed as a monolithic base structure of epoxy plastic reinforced with glass fiber. They have a length of 39 m, a maximum corda of nearly 5 m and a weight of $1.4 \cdot 10^4$ kg each.

The generator is a 3-phase, 50 Hz, 1500 r.p.m synchronous machine. The turbine rotates at 25 r.p.m. and a multi-stage planetary gearbox steps up the rotation to 1500 r.p.m. A torsionally soft mounting including hydraulic dampers of the gearbox provides a torsionally soft connection. This soft connection compensates for rapid variations in rotor speed, since the generator must operate at constant r.p.m.

The control system consists of three processors, called supervisory controller, rotor controller and interface controller. The supervisory controller supervises the system and decides mode of operation. Depending on the mode of operation, the rotor controller calculates a reference value to the hydraulic positioning system. The interface controller handles the operator communication. The three processors communicate with each other via serial communication links.

SIMNON Overview

An interactive command driven simulation package has been developed at the Department of Automatic Control, Lund Institute of Technology. The package is called SIMNON[1] (Simulation of Nonlinear Systems). SIMNON has been used extensively since 1974 for research and education as well as for industrial control and simulation problems. It is now available at most Nordic university computing centers and has been distributed to several foreign university departments. Several industrial companies have achieved SIMNON, among them two major American ones.

In SIMNON the model can be described in a special high level model language or in Fortran. The model language is simple and easy to learn. The models are defined using state variable equations. The right hand sides of the differential or difference equations are defined using simple assignment statements.

Often the system to be simulated can be divided into natural subsystems. A typical example is the process and a regulator. This should be used also in the simulation in order to simplify the programming. In SIMNON there are three different types of subsystems: continuous, discrete, and connecting. The first two types are used to define continuous time and discrete time systems respectively. The connecting subsystem defines how different continuous and/or discrete subsystems are interconnected. The connecting subsystem can be said to define the block diagram, while the continuous and discrete subsystems define the blocks.

The models can easily be modified using a special editor. When the subsystems are defined, they are compiled and error checking is done. The compiler is included in the package and is working in parallel with the editor. This enables the user to correct erroneous lines immediately. For instance it is checked that all inputs and outputs are defined, and that all parameters are given values. When the total system has been compiled, it can be simulated and the results can be displayed, stored or printed.

The interactive package SIMNON is controlled by a small number of powerful commands. There are e.g. commands to change parameters of the model, perform simulation, plot the time response of selected variables on a display and modify the model. However, the structure of each command is flexible. The commands contain arguments which may be e.g. file names, variables, numbers and options. Arguments can in some cases be omitted. Default values are then used. One common situation when running the package is that the same sequence of commands is needed several times. The user can then define a MACRO containing the commands. The MACRO can then be used as a new command several times, possibly with different values of the arguments.

Loops and jumps can be used in a MACRO. It is even possible to make a MACRO which makes the dialog look like a question and answer program when executed. This possibility can e.g. be used to introduce SIMNON to new users.

The Model

The model is developed in a modularized, structured manner. The decomposition into subsystems is shown in Figure 1.

To increase the flexibility, the inputs and outputs are chosen as unscaled, physical quantities. SI-units are used. However, to improve the model numerically, scaled quantities are used inside the subsystems. An overview of the model is given below, more detailed information can be found in Mattsson[2].

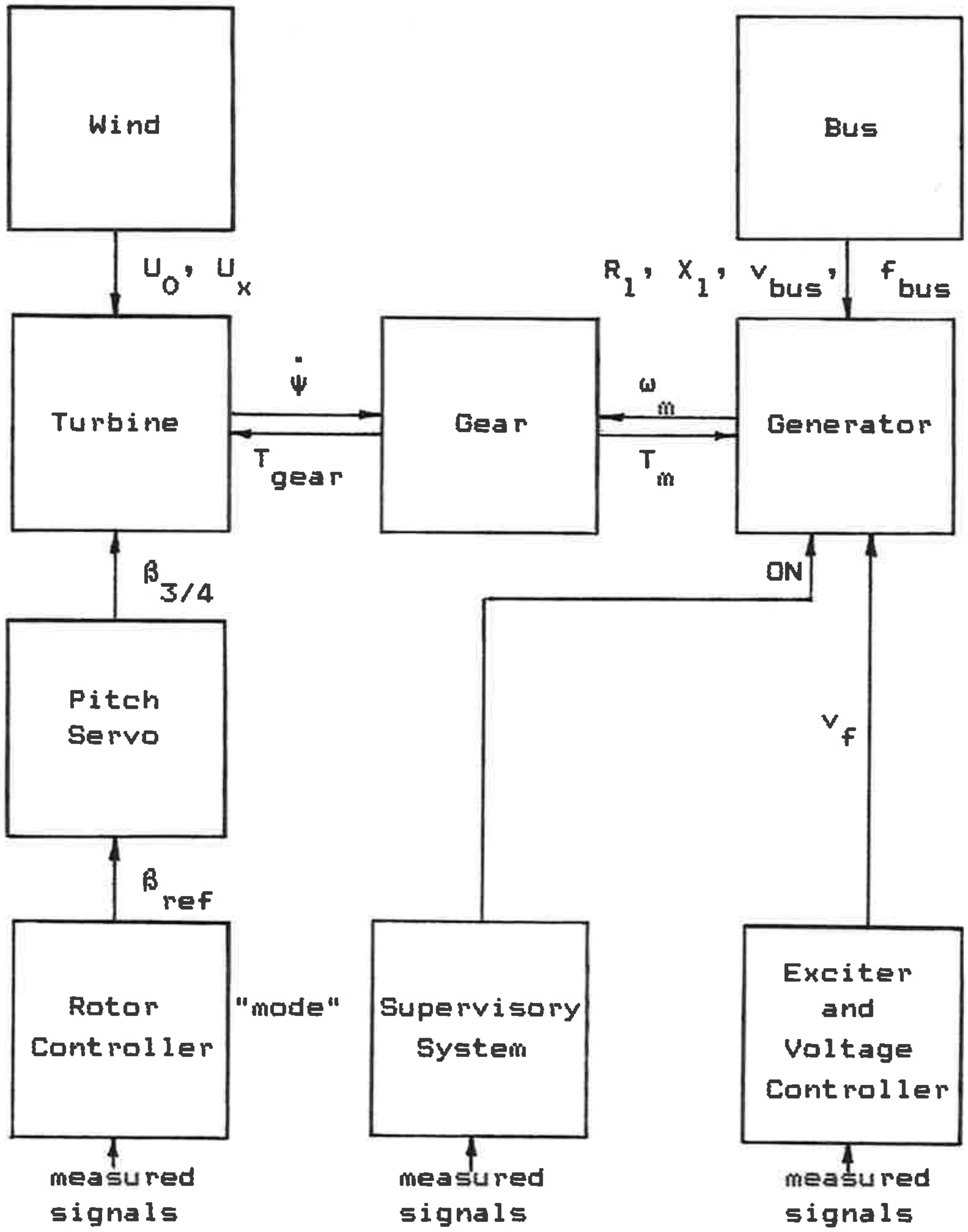


Figure 1. Model structure.

The Wind Turbine

The wind turbine is a complex mechanical construction with several degrees of freedom.

Orientation. The nacelle and turbine rotor can turn around the axis of the tower. Motion in this direction is called yawing. The turbine is designed for downwind operation and is supposed to be selfstabilizing in yaw. However, the behaviour in yaw is an open question and experience so far has not indicated any stable point. The existing methods are also deficient in their ability to predict free yaw behaviour in horizontal axis wind turbines[3]. The plant in Maglarp is a prototype and is provided with an active yaw mechanism for reasons of safety. The mechanism can turn the nacelle and rotor with a maximum speed of 1.2°/s. In the following the yawing is neglected and it is assumed that the nacelle is aligned in the direction of the wind.

Teetering. Consider Figure 2. The blades are rigidly mounted to each other and they are hinged to the main shaft by means of a teeter pin. The motion around the teeter pin (in the φ-direction) is called teetering. Since the blades are

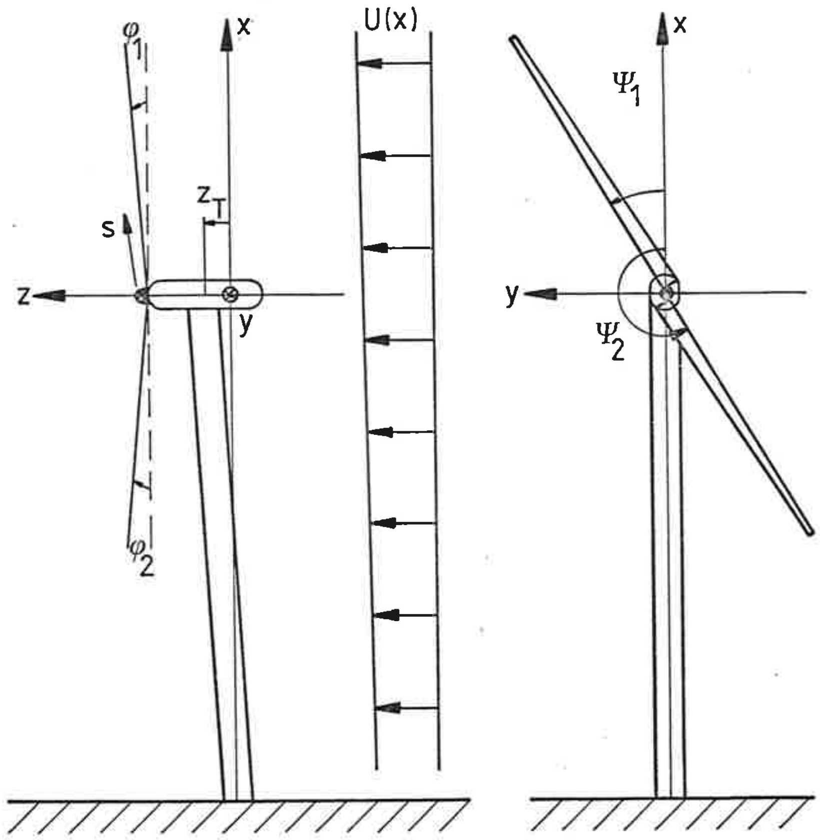


Figure 2. Wind turbine geometry.

teetered, the flapping angles satisfy:

$$\varphi_1 + \varphi_2 = 2\varphi_0 = \text{constant} \qquad (1)$$

and it is possible to describe the teetering by one variable:

$$\varphi = (\varphi_1 - \varphi_2)/2 \qquad (2)$$

Elastic blade motions. Besides the rigid body motions there are a number of elastic and vibratory motions in the tower and the blades. The bending motion out of plane of rotation is called flapping, flapwise, flatwise etc. and the bending in plane is called lead-lag, chordwise, edgewise etc. Sullivan[4] discusses blade resonance responses. He makes the following conclusions.

1. High aerodynamical damping prevents resonance in the blade flatwise direction at all frequencies.

2. Odd harmonic excitations up to and including 5 P can cause significant blade edgewise resonance response; teetering the rotor will reduce this response substantially.

The first lead-lag oscillations are modelled by viewing the turbine as a three mass system (hub and two blades) connected by springs and dampers. Values for the equivalent blade inertia J_{eB}, hub inertia J_{eH} and blade stiffness K_{eB} are chosen so that correct rigid hub first edgewise frequency ω_{er} and operational first edgewise frequency ω_{el} are achieved;

$$J_{eH} = (J_H + 2J_B)\omega_{er}^2/\omega_{el}^2 \qquad (3)$$

$$J_{eB} = \{(J_H + 2J_B) - J_{eH}\}/2 \qquad (4)$$

$$K_{eB} = J_{eB}\,\omega_{er}^2 \qquad (5)$$

Tower bendings. The WTS-3 tower has a first bending frequency of 0.84 P and for Mod-2 it is 1.3 P (1 P corresponds to the rated rotational speed). Sullivan[4] classifies towers with first bending frequencies over 2 P as "stiff" towers and those with bending frequencies between 1 P and 2 P as "firm" towers. He does not discuss towers with bending frequencies below 1 P. Hence, the tower of WTS-3 must be considered as "soft". The structural relative damping is low, typically 2%.

<u>Equations of Motion</u>. Consider Figure 2. The motion in the ψ and φ directions assuming a rigid tower is modelled by Hultgren[5]. His model, extended with the z_T-motion, will be used. Applications of Lagrange's equations yield the following equations of motion

$$(J_{eB}\cos^2\varphi_i)\,\ddot{\psi}_i - 2J_B\dot{\varphi}_i\dot{\psi}_i\sin\varphi_i\cos\varphi_i + D_{eB}(\dot{\psi}_i - \dot{\psi})$$

$$- 2gS_B\cos\varphi_i\sin\psi_i + K_{eB}(\psi_i - \psi) = T_{\psi i} \qquad i = 1, 2 \qquad (6)$$

$$J_{eH}\ddot{\psi} - D_{eB}(\dot{\psi}_1 + \dot{\psi}_2 - 2\dot{\psi}) - K_{eB}(\psi_1 + \psi_2 - 2\psi) = T_{gear} \qquad (7)$$

$$2J_B\ddot{\varphi} + S_B(\cos\varphi_1 - \cos\varphi_2)\,\ddot{z}_T + (J_B\dot{\psi}_1^2\cos\varphi_1 - gS_B\sin\psi_1)\sin\varphi_1$$

$$- (J_B\dot{\psi}_2^2\cos\varphi_2 - gS_B\sin\psi_2)\sin\varphi_2 = T_{\varphi 1} - T_{\varphi 2} \qquad (8)$$

$$S_B(\cos\varphi_1 - \cos\varphi_2)\,\ddot{\varphi} + M_T\ddot{z}_T - S_B(\dot{\varphi}_1^2\sin\varphi_1 + \dot{\varphi}_2^2\sin\varphi_2)$$

$$= F_{zT1} + F_{zT2} + F_T \qquad (9)$$

where

g	Gravitational acceleration
ψ	Azimuth angle of hub
ψ_1, ψ_2	Azimuth angles of blades
S_B	Static moment of one blade
M_T	Mass of the nacelle
$T_{\psi i}$, $T_{\varphi i}$	Aerodynamical torques
F_{zTi}	Aerodynamical thrust
T_{gear}	Driving torque to the gearbox
F_T	Reaction thrust from the tower

Aerodynamical Thrust and Torques. The aerodynamical thrust and torques can be obtained by applying static and two-dimensional airfoil theory to each cross section of the blades.

The profiles of the incoming wind at far distance before $U_\infty(t,x)$ and at the rotor disc $U_d(t,x)$ are assumed to be linear

$$U(t,x) = (U_0(t) + U_x(t)\, x)\, \hat{z} \qquad -R \le x \le R \tag{10}$$

and to be related as

$$U_d(t,x) = (1-a(t))\, U_\infty(t,x) \tag{11}$$

U_0 is the wind at the hub, U_x is a measure of the wind shear, R is the length of a blade and $a(t)$ is the interference factor.

The tower shadow has a significant impact for wind turbines downwind of the tower. Seidel[6] reports that the Mod-0 wind turbine (The ERDA-NASA 100 kW wind turbine near Sandusky, Ohio) momentarily loses more than 60 % of the rotor torque as a blade swings behind the tower. The wake depends critically on the aerodynamical properties of the tower and is difficult to model. However, the form of the wake is probably not critical for the intended use of this model. A common modification for the wind at the i:th blade is given by the factor

$$q_i(\psi_i) = \begin{cases} 1 - C\cos\left(\frac{\pi}{2}\frac{\tilde{\psi}_i - \pi}{\alpha}\right), & |\tilde{\psi}_i - \pi| < \alpha \\ 1 & \text{otherwise} \end{cases} \tag{12}$$

where

$$\tilde{\psi}_i = \psi_i \bmod 2\pi \tag{13}$$

The pitch distribution of the blades is of the form

$$\beta(s) = \beta_1 + \frac{R}{s}\beta_2 \tag{14}$$

The profile lift increment is assumed to depend linearly on the angle of attack. The profile drag increment is assumed to be independent of the angle of attack. Consequently, the stalling is not modelled. This is justified by the fact that the controller must prevent the blades from going into stalling. Introduce

$$\lambda_i = U_{dO}/(R\dot{\psi}_i) \text{ (the inflow ratio)} \tag{15}$$

$$u_s = RU_{dx}/U_{dO} \tag{16}$$

Lengthy calculations, ignoring terms of the orders: $O(\lambda_i^4)$, $O(\lambda_i^3\dot{\varphi}_i)$, $O(\dot{\varphi}_i^2)$, $O(u_s^2)$, $O(\dot{z}_T^2)$, $O(u_s\dot{\varphi}_i)$, $O(\dot{z}_T\dot{\varphi}_i)$ and $O(\dot{z}_T u_s)$ give (Hultgren[5] extended with the motion in the z_T – direction)

$$\begin{aligned} T_{\psi i} = {} & \frac{1}{2}\dot{\psi}_i^2\cos^3\varphi_i \left\{\Lambda_i\{A_1(\Lambda_i-r)-A_2\beta_1\} - \frac{1}{2}\Lambda_i^3(A_0\beta_1+A_{-1}r) - B_3\right\} \\ & - \frac{1}{2}\dot{\psi}_i\cos^2\varphi_i \left\{\{A_2(2\Lambda_i-r) - A_3\beta_1 - \frac{3}{2}\Lambda_i^2(A_1\beta_1+A_0r)\}\dot{\Phi}_i \right. \\ & \left. + \{A_1(2\Lambda_i-r) - A_2\beta_1 - \frac{3}{2}\Lambda_i^2(A_0\beta_1+A_{-1}r)\}\dot{z}_T\cos\varphi_i\right\}, \\ & i = 1, 2 \end{aligned} \tag{17}$$

$$\begin{aligned} T_{\varphi i} = {} & \frac{1}{2}\dot{\psi}_i^2\cos^2\varphi_i \left\{\frac{1}{2}\Lambda_i^2\{A_0(\frac{1}{3}\Lambda_i-r)-A_1\beta_1\} + A_2(\Lambda_i-r)-A_3\beta_1+B_2\Lambda_i\right\} \\ & - \frac{1}{2}\dot{\psi}_i\cos\varphi_i \left\{\{\Lambda_i[A_1(\frac{1}{2}\Lambda_i-r)-A_2\beta_1] + A_3 + B_3\}\dot{\Phi}_i \right. \\ & \left. + \{\Lambda_i[A_0(\frac{1}{2}\Lambda_i-r)-A_1\beta_1] + A_2 + B_2\}\dot{z}_T\cos\varphi_i\right\}, \\ & i = 1, 2 \end{aligned} \tag{18}$$

$$F_{zTi} = \frac{1}{2}\dot{\psi}_i^2\cos^3\varphi_i \left\{\frac{1}{2}\Lambda_i^2\{A_{-1}(\frac{1}{3}\Lambda_i - r) - A_0\beta_1\} + A_1(\Lambda_i - r) - A_2\beta_1 + B_1\Lambda_i\right\}$$

$$- \frac{1}{2}\dot{\psi}_i\cos^2\varphi_i \left\{\{\Lambda_i[A_0(\frac{1}{2}\Lambda_i - r) - A_1\beta_1] + A_2 + B_2\}\dot{\Phi}_i\right.$$

$$\left. + \{\Lambda_i[A_{-1}(\frac{1}{2}\Lambda_i - r) - A_0\beta_1] + A_1 + B_1\}\dot{z}_T\cos\varphi_i\right\},$$

$$i = 1, 2 \qquad (19)$$

where

$$\Lambda_i = q_i\lambda_i R \qquad (20)$$

$$r = R\beta_2 \qquad (21)$$

$$\dot{\Phi}_i = \dot{\varphi}_i - q_i U_{dx}\cos^2\varphi_i \cos\psi_i \qquad (22)$$

A_{-1}, A_0, A_1, A_2, A_3, B_1, B_2 and B_3 are blade constants.

$$A_\alpha = \varrho_a \int_0^R cas^\alpha\, ds \qquad (23)$$

$$B_\alpha = \varrho_a \int_0^R cC_D s^\alpha\, ds \qquad (24)$$

where ϱ_a is the density of air, c the local cord length, a is the lift curve slope of the blade section and C_D the profile drag coefficient of the section.

The Reaction Torque from the Tower. The influence of the tower on the nacelle is modelled as a spring with damper

$$F_T = -(K_T z_T + D_T\dot{z}_T) \qquad (25)$$

The Interference Factor. The interference factor a(t) can be calculated by using momentum theory (e.g. Shepherd[7]).

The generated power is

$$P = n_p \, 2\varrho_a \pi R^2 \, a(1-a)^2 \, U_\infty^3 \qquad (26)$$

where n_p is the degree of power efficiency of the blades.

(17), (21), (26) and the relation

$$P = \dot{\psi}_1 T_{\psi 1} + \dot{\psi}_2 T_{\psi 2} \qquad (27)$$

give (neglecting the effects of wind shear, teetering, tower motions, tower shadow and lead-lag oscillations)

$$b^3 - (1 - c_1 A_1 \frac{\dot{\psi}}{U_\infty}) b^2 - c_1 (A_2 \beta_1 + A_1 r)(\frac{\dot{\psi}}{U_\infty})^2 b - c_1 B_3 (\frac{\dot{\psi}}{U_\infty})^3 = 0 \qquad (28)$$

where

$$b = 1 - a \qquad (29)$$

$$c_1 = 1/(n_p \, 2\varrho_a \pi R^2) \qquad (30)$$

The_Pitch_Servo

A hydraulic servo system is used to vary the pitch angle. The servo is modelled as a first order system with limits on the rate. It is assumed that the blades are torsionally rigid and that the pitch servo is not affected by the wind. Friedmann[8] states that the blades in a typical wind turbine system are torsionally rigid. The first frequency of torsional mode is high (about 37 rad/s).

The_Gearbox

The shaft between the turbine rotor and the gearbox, and the shaft between the gearbox and the synchronous generator are assumed to be rigid compared to the mounting of the gearbox. This means that, disregarding the gearing, the drive train can be modelled as a nonlinear spring with a nonlinear damper.

The_Synchronous_Generator

When the behaviour of synchronous machines in transient conditions is studied by simulation, it is essential that the system is modelled in sufficient detail. A model on a form suitable for our purpose is given by Olive[9]. It is a

Park model and includes the stator dynamics. The rotor has one field circuit. The effects of currents in the iron parts of the rotor or in the damper windings are modelled by two circuits, one in the direct axis and the other in the quadrature axis. The generator is assumed to be connected to an infinite bus via an impedance. Symmetrical load is assumed.

The Voltage Control System

The excitation system of the generator uses an AC alternator and a rotating rectifier to produce the current needed for the generator field. The voltage control system is supplied to achieve a constant machine terminal voltage, independent of the load conditions and to distribute reactive power among the synchronous machines working in parallel at the grid. The model of the excitation system and voltage controller uses a Type 1 standard IEEE representation[10] including non-linear saturation effects (See Figure 3). The SIMNON code for this subsystem is given in Figure 4. Note, that double quote (") in the SIMNON code means a comment and is supplied for a proper documentation.

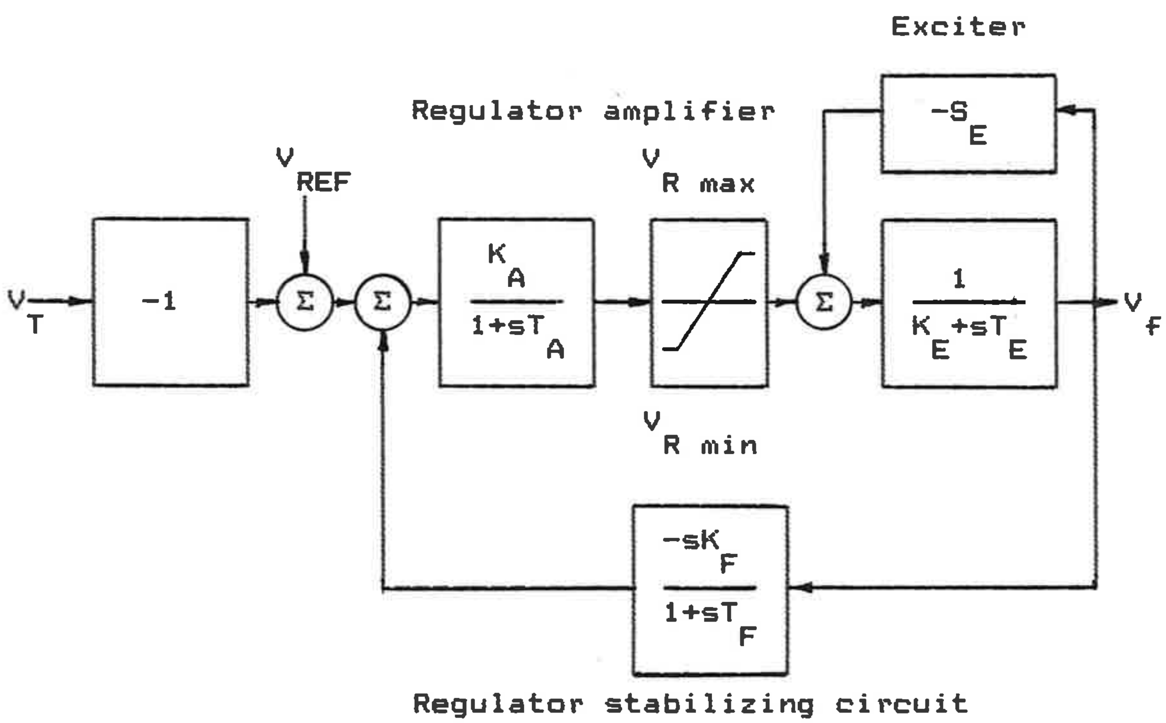


Figure 3. IEEE Type 1 excitation system representation for a continuously acting regulator and exciter without input filter.

```
CONTINUOUS SYSTEM VOLTCONT

"Description:
"  Models the excitation system and the voltage controller
"  by a Type 1 standard IEEE representation including non-
"  linear saturation effects without input filter.

INPUT vd vq
OUTPUT vf

STATE xA  xF  xE
DER  dxA dxF dxE

"Inputs:
"   vt      terminal voltage [V]
"
"Outputs:
"   vf      generator field voltage [V]
"
"States:
"   xA      rectifier voltage  [pu]
"   xF      internal state in feedback loop [pu]
"   xE      generator field voltage [pu]

Verr = (Vref-Vt)/Vnorm
dxA1 = (KA*(Verr+yF) - xA1)/TA
dxA2 = if (xA>VRmax and dxA1>0) then 0 else dxA1
dxA  = if (xA<VRmin and dxA2<0) then 0 else dxA2

SE = 0.17*xE*abs(xE)
dxE = (xA - SE - KE*xE)/TE
vf = Vnorm*vfpu

dxF = (KF/TF*xE - xF)/TF
yF = xF - KF/TF*xE

"Parameters:
Vref:  6600.      "reference voltage [V]
Vnorm: 6600.      "base voltage [V]
KA:     400.      "regulator gain
TA:       0.02    "regulator amplifier time constant [s]
VRmax:    7.3     "maximum rectifier voltage [pu]
VRmin:   -7.3     "minimum rectifier voltage [pu]
KE:       1.0     "exciter constant
TE:       0.8     "exciter time constant [s]
KF:       0.03    "regulator stabilizing circuit gain [s]
TF:       1.0     "regulator stabilizing circuit
                  " time constant [s]

END
```

Figure 4. SIMNON code for the excitation system model.

The Rotor Control System

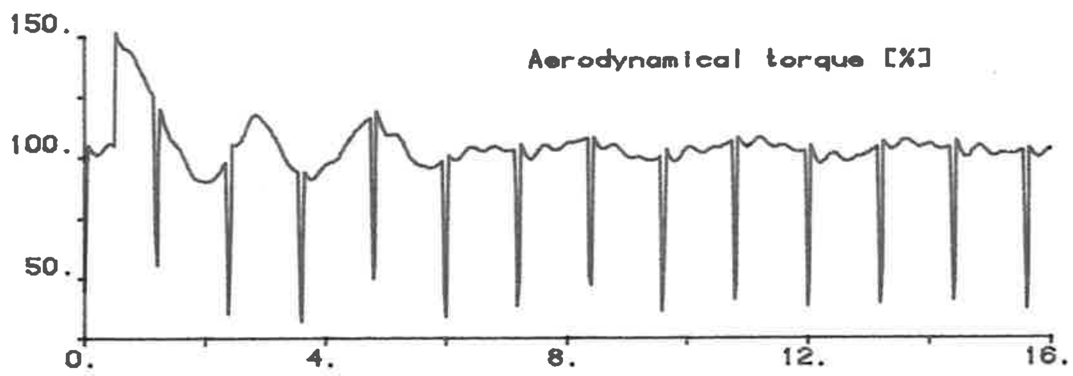
The WTS-3 Control System is a complex, microprocessor based and distributed system which has been partitioned into a number of subsystems. The rotor controller is one of these subsystems which is used to establish a blade angle reference signal to the electrohydraulical positioning system. Four modes of operation are defined: In acceleration control mode a safe start up is ensured by controlling the maximum acceleration of the rotor and by preventing excessive blade stall. In rotor speed control mode the generator speed is matched to the line frequency for a safe synchronization. In power control mode the generator is connected to the power grid and the blade angle is modulated to extract maximum power from the wind. The deceleration control mode is used for normal shutdown and controls the deceleration torque to an acceptable level.

Simulation Results

Due to the modularization each submodel could easily be tested independently of the others and when accepted, the complete WTS-3 model was formed. A number of studies with the package have been performed.

Model Validation Studies

A complex dynamical model must be validated in order to get a quality mark. During the full-scale testing period 1983-1985, system identification and model validation will be done. The only validation so far has been made by simulation comparisons from runs made by the WTS designer. For this purpose, well-defined excitations of the system from the wind were selected. The agreement with the results from Hamilton Standard is good. In Figure 5 the response to a step change in the wind from 20 m/s to 22 m/s is shown.



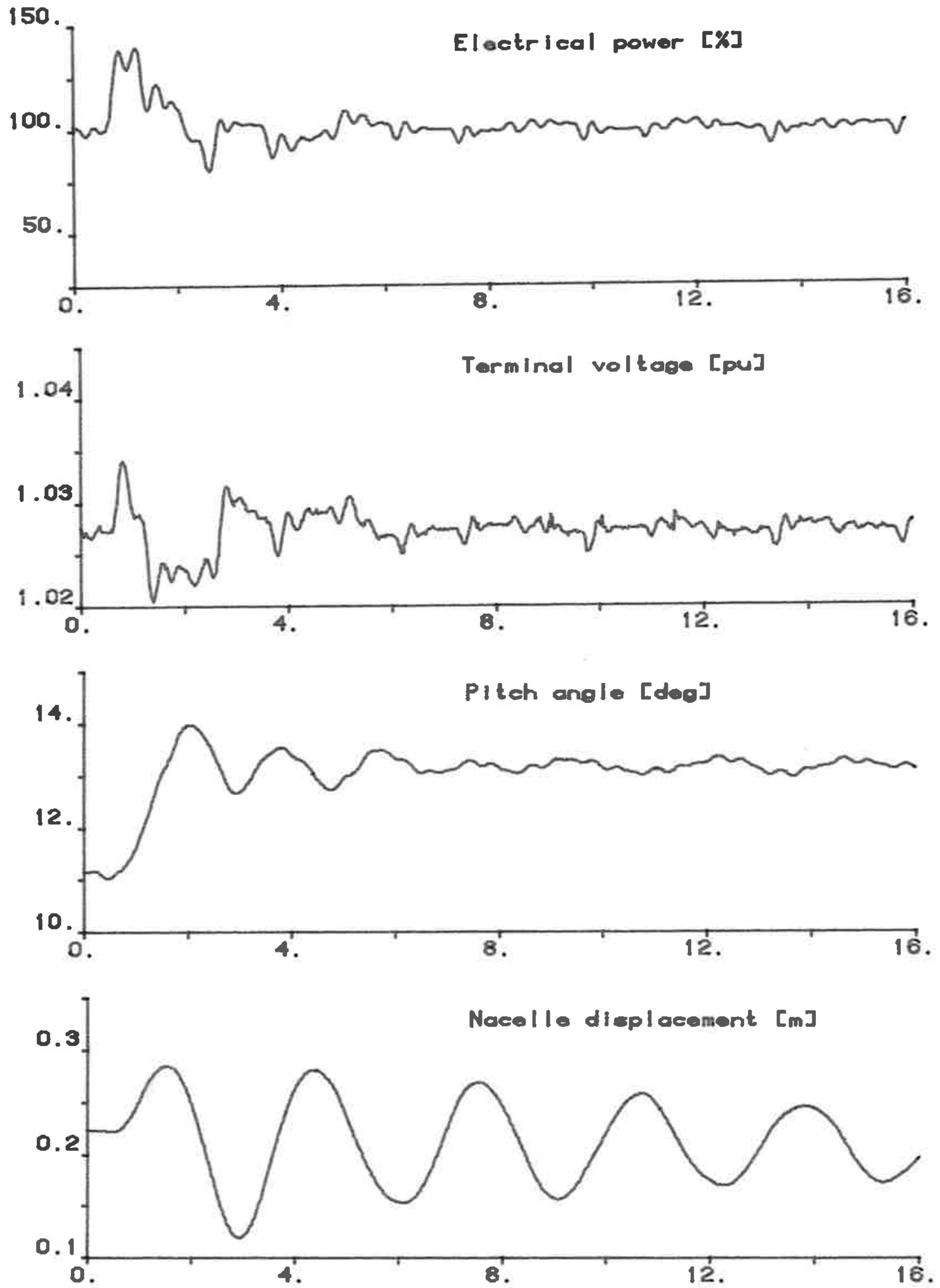
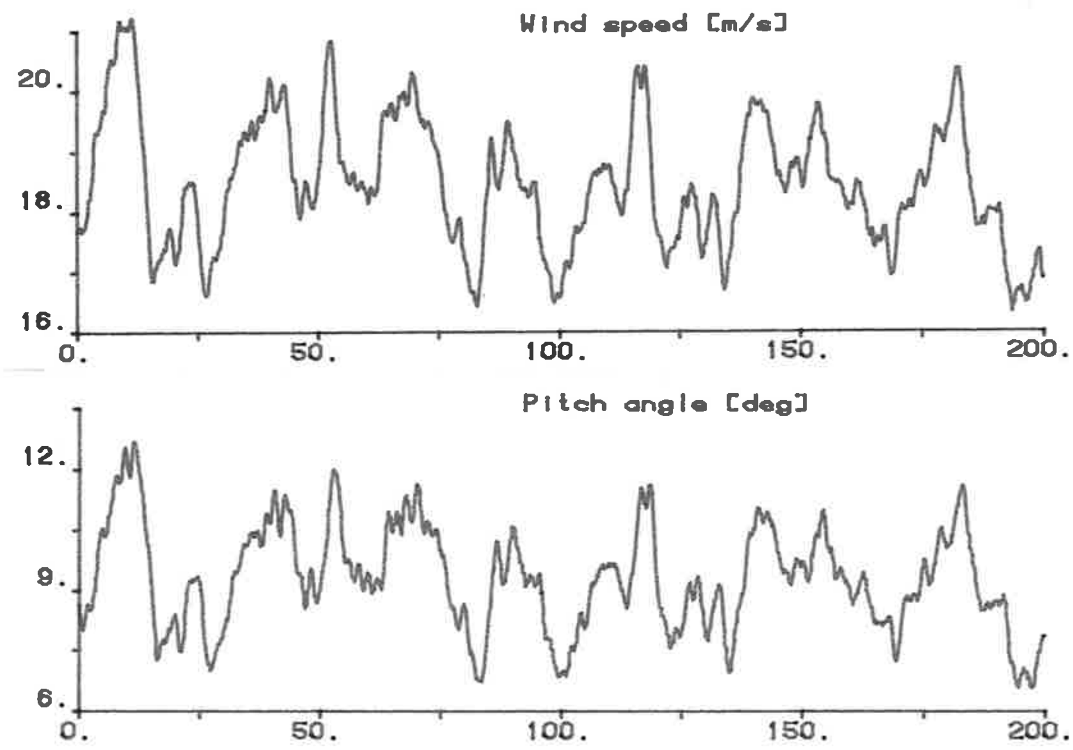


Figure 5. The response to a step change in the wind from 20 m/s to 22 m/s at t = 0.5 s.

Stochastic Wind Studies

The wind can be modelled in different ways. A model for discrete longitudinal wind gusts is given in Hwang and Gilbert[11]. The framework of stochastic processes can be used to model turbulence. SIMNON provides noise generators. It is in SIMNON also possible to use measured wind data.

Normal operation in on-line and off-line mode has been studied using a simple stochastic wind model. A pseudo random wind disturbance was generated and the spectral property of the longitudinal wind velocity was approximated by a first order model (The Dryden spectrum)[12]. However, to account for the spatial filtering effect due to averaging over a large area in space, typical for large scale wind turbines, a first order spatial filter was also introduced. A simulation with this wind model is shown in Figure 6.



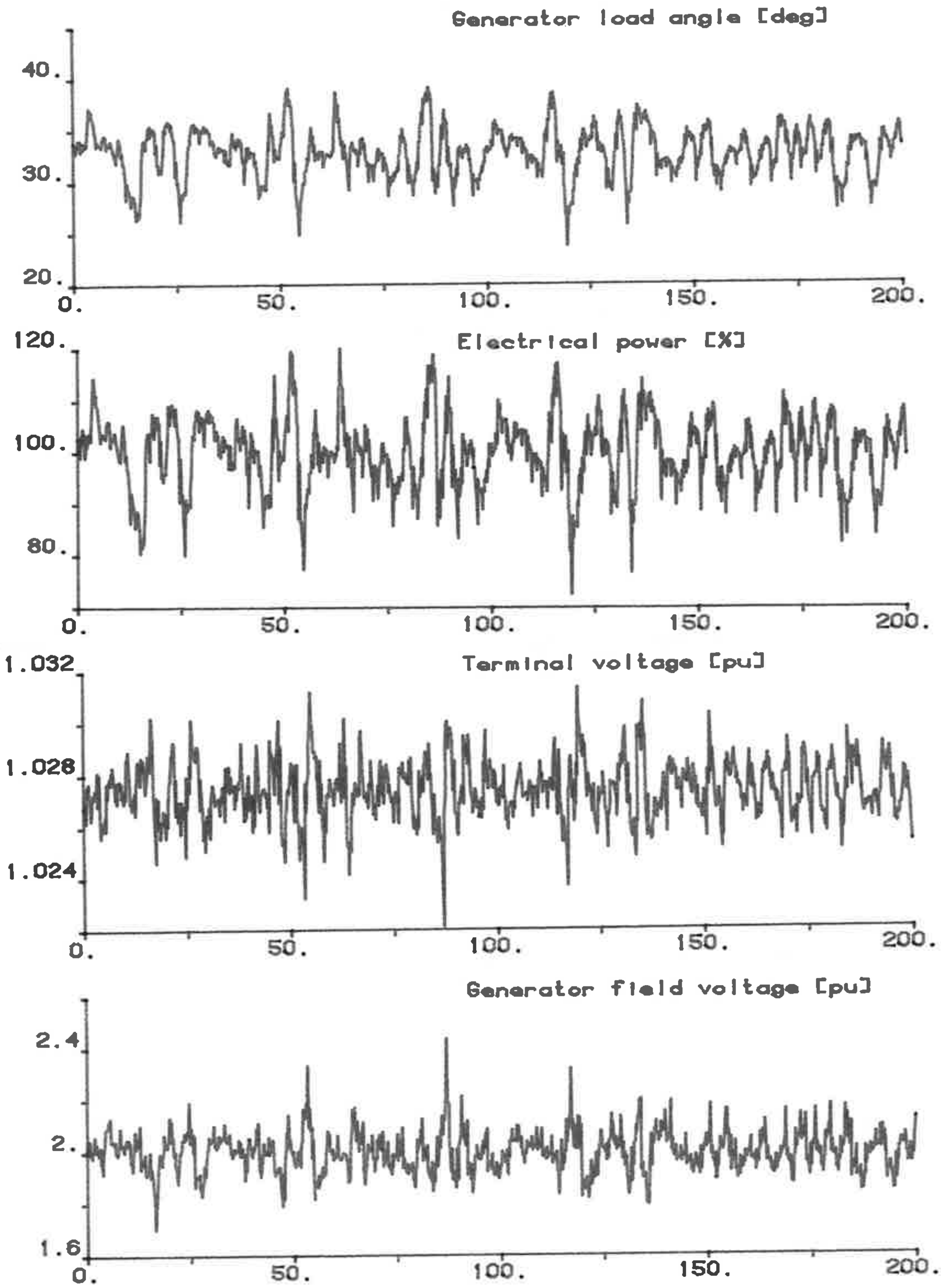


Figure 6. The response to a turbulent wind with a mean wind speed of 18 m/s and standard deviation of 1.8 m/s.

Synchronization Studies

The problem of synchronizing the generator against an infinite bus under gusting wind conditions is discussed by Hwang and Gilbert[11].

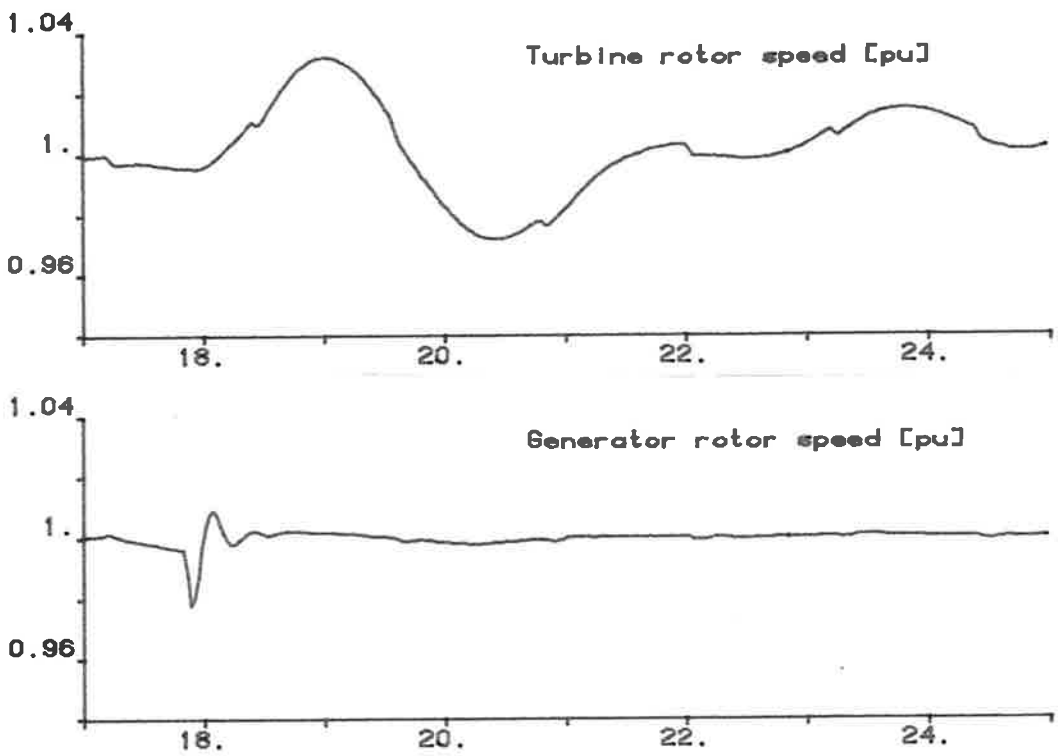
Before the generator in WTS-3 can be connected to the utility grid, a number of conditions must be fulfilled:

1. The difference between the bus voltage and the terminal voltage must be less than 100 V.

2. The phase difference between the bus and the generator must be less than 30°.

3. The turbine must not be more than 1% from sychronous speed.

Synchronization in both low and constant wind and in high and turbulent wind were simulated. During the startup, the rotor speed is held constant at 40% (10 rpm) while the teeterlocks are disengaged. The simulations were started from this point. The reference value of the turbine speed to the rotor controller was set to 100.26%. A simulation of synchronization in high and turbulent wind is shown in Figure 7.



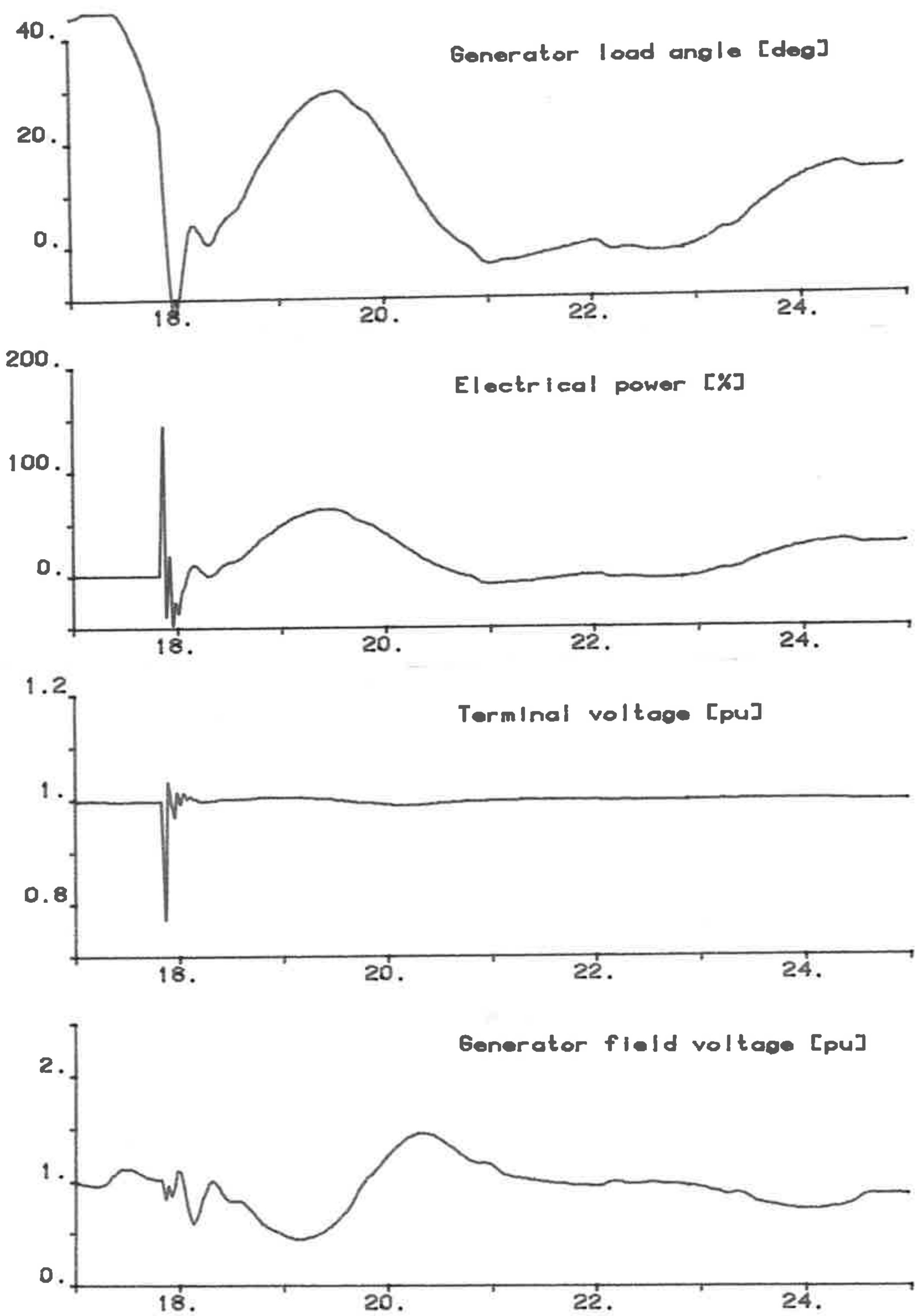


Figure 7. Synchronization against the grid. The mean wind speed was 22 m/s and the standard deviation was 4.4 m/s.

Overspeed Simulation Studies

To avoid damage, the system must be protected against overpower. If the power exceeds 140% of rated power the emergency system is activated. It disconnects the generator and brakes the turbine to avoid high rotor speeds. The turbine must also be braked when the load is lost for other reasons. The only way to brake the turbine is to change the pitch angle so that an aerodynamical breaking torque is achieved. Simulations were performed to determine minimum blade servo speed needed to avoid high rotor speeds. With a given servo speed during emergency the maximum rotor speed decreases with increasing wind speed. An electrical power of 140% can be achieved at a wind speed of 15 m/s. In Figure 8 a critical case is simulated with different blade servo speeds during emergency. It is assumed that the wind speed is 15 m/s and that the system is in stationarity and producing rated power. At t = 1 s the blade servo starts going with maximum speed (4°/s) giving increasing power. When the power exceeds 140% the generator is disconnected and the emergency system is activated.

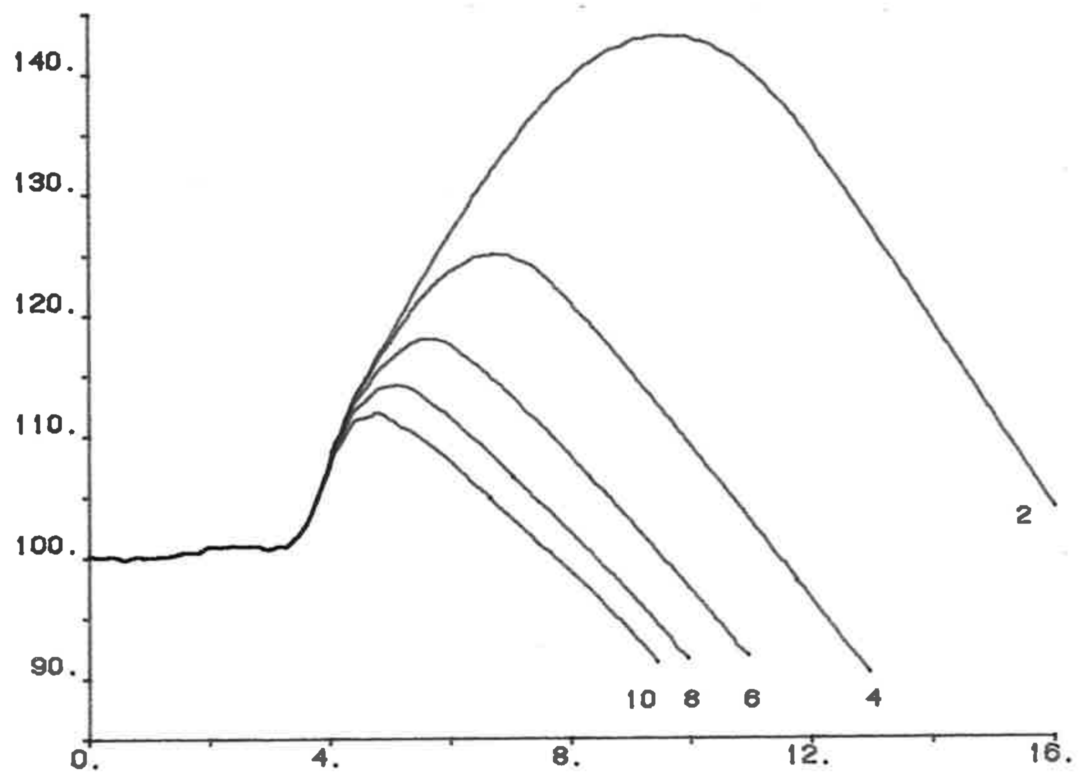


Figure 8. Rotor speed simulation at different emergency pitch rates (2 - 10 deg/s).

Transient Stability Studies

The integration of the WTS-3 prototype into the local electrical grid in southern Sweden is an area of a great interest. A simplified bus model was developed for the grid. With the model shown in Figure 9 the transient behaviour of the wind turbine generator during electrical disturbances was investigated. With the system initially operating at rated condition, 3 MW, a 3-phase fault was applied at the bus at different locations (a-g). After a given time the fault was cleared by breaker action in the line where the fault was applied. However, for simulations the connection between the generator and the infinite bus is assumed to be modelled as a serial impedance. The bus voltage, bus frequency and the impedance may be time varying. For example stochastic disturbances in the bus frequency can be modelled so that the standard deviation and spectral properties are conform with normal operating records. The model in Figure 9, must be transformed to serial form. The response to a fault during 100 ms at c) is shown in Figure 10. The wind speed was 15 m/s.

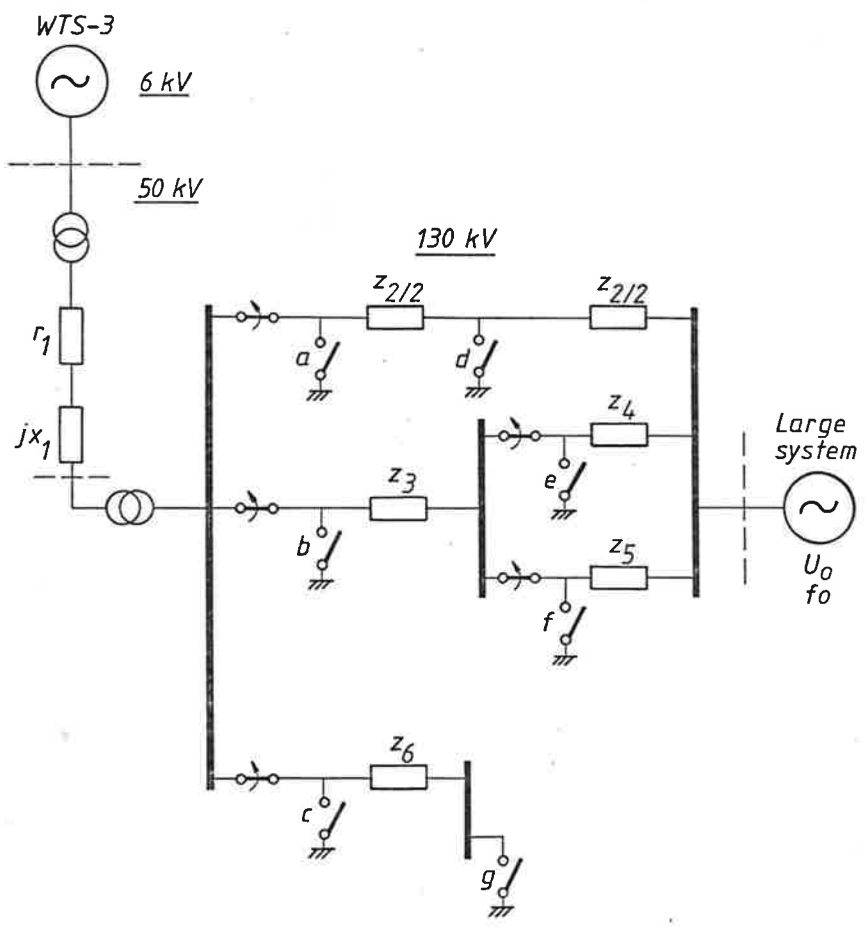
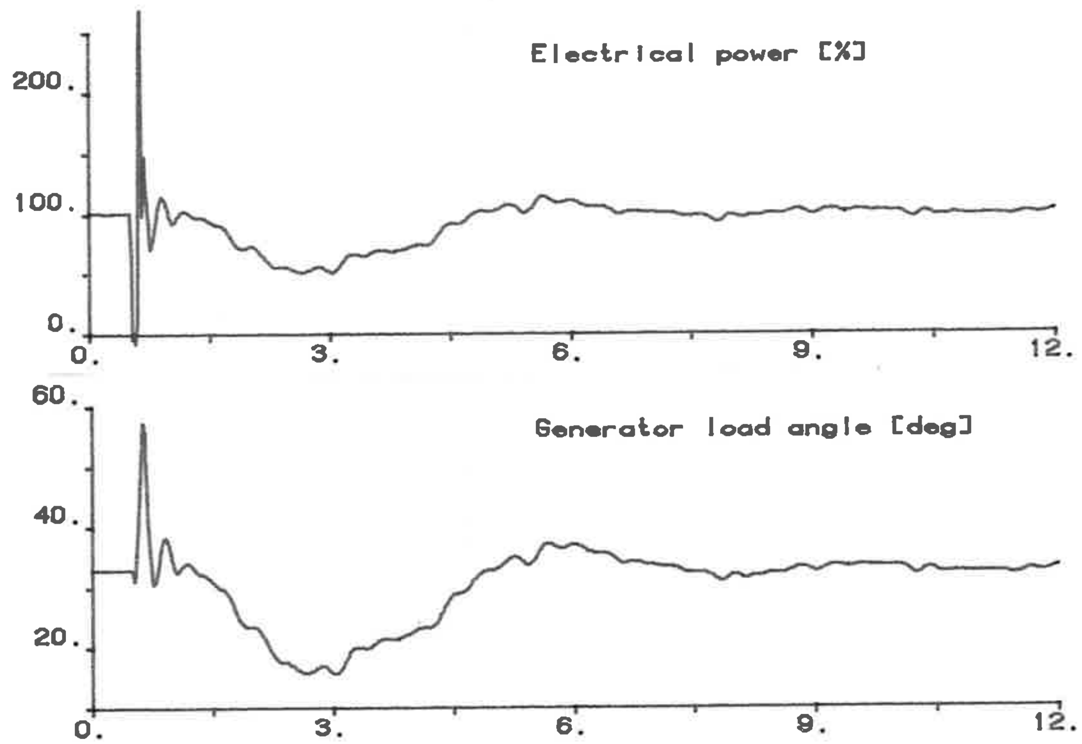


Figure 9. Simplified bus model for transient stability simulations.

Under full load the gearbox mounting of WTS-3 is twisted about 1000 electrical degrees. If the load is lost due to for example a short circuit near the generator, the untwisting of the spring will accelerate the rotor of the generator (the inertia of the turbine rotor is about ten times the inertia of the generator rotor). Simulations show that synchronism is lost if the load is lost more than 0.16 s. This is also a typical value for conventional turbine generators. It is not possible to prevent loss of synchronism at electrical faults by controlling the blade angle. The torque driving the generator is given by the twisting of the gearbox mounting. Since the generator should remain in synchronism, it means that the turbine should be slowed down or in other words the aerodynamical torque should be negative. However, the blade angle must be changed more than ten degrees to achieve a braking torque and it is limited to 0.6 - 0.8 of rated torque.

If the bus voltage is greater than zero, it is possible to increase the electrical torque by increasing the excitation voltage and in this way restore the electrical torque. The success depends critically on the product of the new bus voltage and the maximum excitation voltage that can be achieved. If the product is greater then one, it is possible to maintain synchronism. The dynamics of the excitation system seems to be fast enough and it should not to cause any problems.



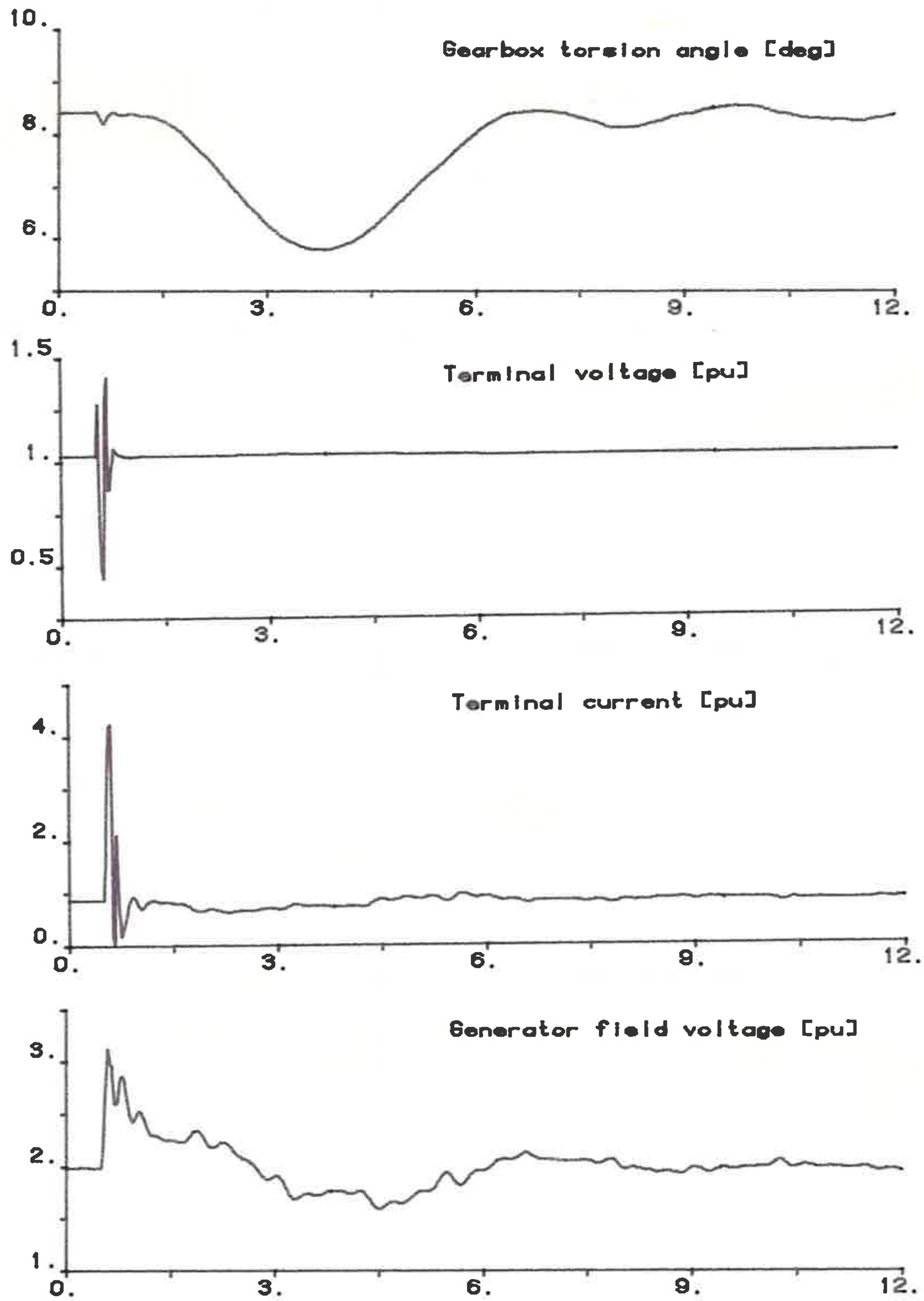


Figure 10. Transient stability simulation. 3-phase fault applied at c) at t=0.5 s and cleared at t=0.6 s.

Conclusions

By the modularization and use of a high level simulation language a Wind Turbine Simulation package was developed.

The flexible model structure has pointed out the advantage of "step-by-step" model-building and implementation procedures. Increasing submodel complexity and changing complete parts are easy to handle and normally affect only the connecting system. The use of the MACRO facility for system setup, state-initialization, data storage plotting etc. has shown the advantage of using a well-designed simulation package (SIMNON) and reduces preparation time to a minimum.

The package described here was adapted to the design of the WTS-3. However, incorporation of submodels for asynchronous generators, up-wind turbines etc. will expand the simulation package further and is planned as a forthcoming phase.

The submodel validation procedure for the WTS-3 package was made by comparisons with runs from the designer. Only minor discrepancies were found, mainly in the aerodynamical part. The results from stochastic wind simulation show significant dynamical properties of the different components and the response in the quality of control was investigated. The results from the transient stability studies show the system behaviour during faults in the network and will be used for further investigations and a selective design of the generator protection system.

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