Wind Parks Equivalent Models using System Identification Techniques based on Nonlinear Model Structures

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Abstract: - In this paper models of Wind Parks (WPs) appropriate for simulation purposes of large power systems with high wind power penetration are developed. The proposed models of the WPs are developed using system identification theory with NARX model structures. Data obtained from the simulation of detailed WP models are used for system identification. The obtained models are general and they can be applied to different configurations of WPs as only system's input/output data are used and not any internal states of the model. Simulation results confirm the accuracy and the advantages of the proposed wind parks equivalent models.

Key-Words: - Wind parks, wind turbines, modeling, system identification, wind integration.

1 Introduction

Increasing of wind turbines (WTs) are connected to electrical power systems as a result of increasing environmental concern. Power produced by WPs is expected to correspond to a significant share of the overall power production in the near future and their influence to the operation of the power system will merit extra concern [1], [2].

The impact by dynamic voltage fluctuations (flicker), caused by large WP installations, becomes a major concern. In order to study similar effects suitable simulation tools should be developed [1]-[5]. The simulation of power systems with wind power generation using detailed models of WPs is a demanding and time-consuming process as the complexity of the overall model is significantly high. Therefore, the derivation of equivalent models with less computational requirements is a topic of considerable practical interest [6], [7]. For this purpose, alternatives to the traditional way of power systems modeling can be used. The advantage of such models is that they eliminate the need to develop detailed model of WPs comprising tens or hundreds of wind turbines and their interfaces.

In this paper a system identification technique [8]-[10] is applied to WPs. In more detail, a method to obtain WP equivalent models suitable for voltage quality studies of large power systems is demonstrated. General equivalent WP models are obtained using classical Nonlinear Auto Regressive with eXogenous input models (NARX) for the identification of the system. The proposed method is general and it can be applied to large WPs without regard to the type of the connected WTs. Consequently, WPs with fixed or variable speed WTs or both types of WTs can be studied.

Similar models have been proposed in [4] using classical linear ARX models together with a nonlinear transformation of the WP model inputs. The nonlinear transformation of the input data can be avoided by using nonlinear model structure as NARX models. The major problem during the identification process of a WP is to obtain reliable measurements free of noise. Due to lack of available reliable measurements, detailed models of WPs are developed in Matlab/Simulink platform [2], [11], in order to obtain the data for system identification and model validation processes.

In Section 2 of this paper the developed detailed models of the WP components are described, while in Section 3 the proposed method for the development of WP equivalent models is presented. In Section 4, a WP of general configuration is simulated and the obtained data are used for the identification of the system and the validation of the obtained equivalent model. The results obtained by the equivalent models are compared with the respective ones of the detailed WP model. Finally, general conclusions focusing on the major advantages of the proposed method are extracted.

2 Wind Park Components Modeling

A library with the models of the WP system components (WTs, power electronics, control systems, electrical lines, cables etc.) has been developed using Matlab/Simulink platform. The models described in this Section are combined together in order to obtain the WP model. The WP configuration studied in this paper corresponds to a typical WP of the Greek power system. A single line diagram of the WP is shown in Fig. 1. The WTs are connected together into groups which are connected to the MV switchgear. The power produced by the WP is fed to a 20/150kV substation through electric cables and an overhead electrical line.

The examined WP comprises variable and fixed speed WTs, pitch controlled equipped with asynchronous generators. In more detail, the models of the various components of the WP are described next.

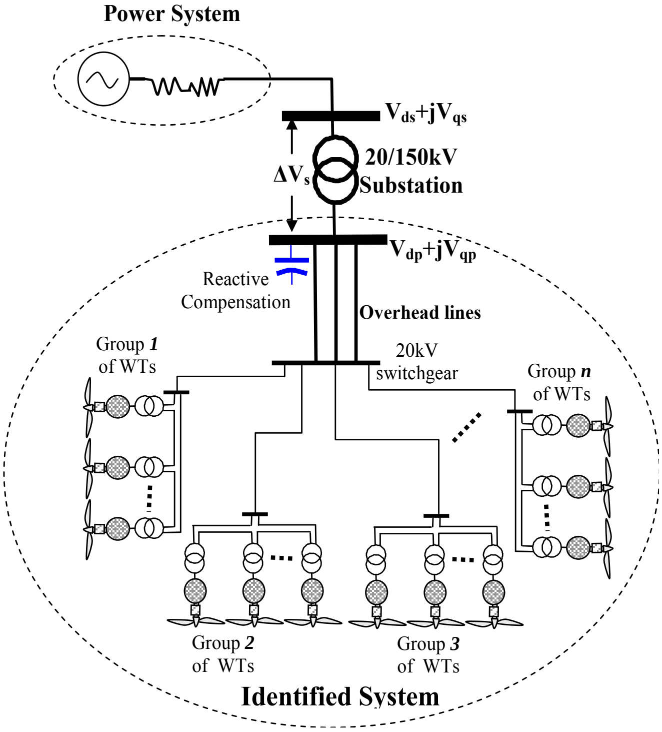


Fig. 1 General single-line diagram of a WP.

2.1 Fixed Speed Wind Turbine Model

The WT rotor aerodynamics are modeled using the well–known aerodynamic power coefficient $C_p(\lambda, \beta)$:

$$P_a = \omega_r \cdot T_a = \frac{1}{2} \cdot \rho \cdot A \cdot C_p(\lambda,\beta) \cdot V_w^3 \qquad (1)$$

P_a is the aerodynamic power, $C_p(\lambda,\beta)$ is the dimensionless aerodynamic power performance coefficient, λ is the tip speed ratio, β is the pitch angle, ρ=1.25 kg/m^3 is the air density, $A=\pi R^2$ is the rotor swept area, V_w is the wind speed, ω_r is the blade rotating speed and T_a is the aerodynamic torque.

The control loop of blades pitch angle, shown in Fig. 2, is activated above WT nominal power.

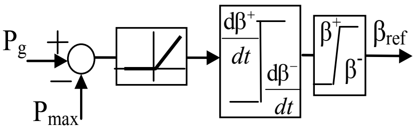


Fig. 2 Pitch angle control system.

For the reproduction of the wind speed time series a Fourier synthesis method based on the Von Karman spectral density function of the wind turbulence is used [12].

The equivalent of three elastically connected masses is used to simulate the mechanical system [11] of the WT as given in:

$$\mathbf{H}\ddot{\boldsymbol{\theta}}_m + \mathbf{D}\dot{\boldsymbol{\theta}}_m + \mathbf{C}\boldsymbol{\theta}_m = \mathbf{T} \qquad (2)$$

$\boldsymbol{\theta}_m$, $\mathbf{T}$, are the vectors of the angles of the masses and the external applied torques, respectively. **H**, **D** and **C** are the inertia, damping and elasticity matrices.

The mechanical equivalent of the three elastically connected masses is shown in Fig. 3.

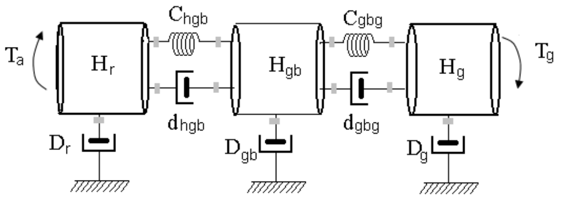


Fig. 3 Three–mass mechanical system equivalent.

Next the models of the doubly fed asynchronous generator (DFIG), the power converters and the associated control are described [13]-[16].

2.2 Variable Speed Wind Turbine model

The VSWTs examined in this paper are pitch controlled with DFIGs. This configuration is selected because it is one of the major choices among VSWTs due to its favorable operational characteristics and the reduced power converter nominal power. The electrical part of the examined type of VSWTs is shown in Fig. 4.

Generator Model

The 4th order transient model of the induction generator expressed in a reference frame rotating at the synchronous speed with the *q*-axis leading the d-axis by 90° is used. The differential equations forming the model of the generator are given in set of equations (3)-(6) [13].

$$u_{sd} = -r_s \cdot i_{sd} - \omega_s \cdot \Psi_{sq} + p\Psi_{sd} \quad (3)$$

$$u_{sq} = -r_s \cdot i_{sq} + \omega_s \cdot \Psi_{sd} + p\Psi_{sq} \quad (4)$$

$$u_{rd} = r_r \cdot i_{rd} - (\omega_s - \omega_g) \cdot \Psi_{rq} + p\Psi_{rd} \quad (5)$$

$$u_{rq} = r_r \cdot i_{rq} + (\omega_s - \omega_g) \cdot \Psi_{rd} + p\Psi_{rq} \quad (6)$$

Where, $p = \frac{1}{\omega_b}\frac{d}{dt}$, ω_b is the base cyclic frequency, ω_s is the rotating speed of the reference frame and subscripts *{d}, {q}, {s}, {r}* denote *d, q* axis, stator and rotor, respectively.

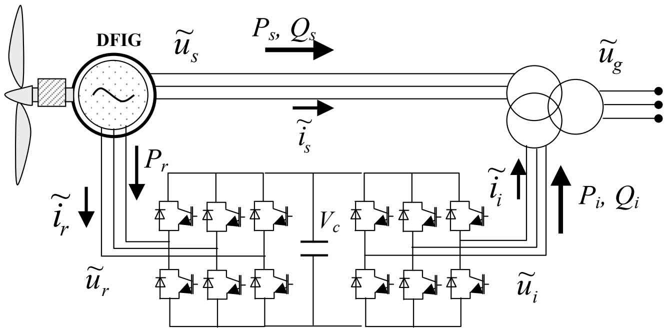


Fig. 4 Electrical part configuration of VSWT with DFIG.

Generator Control System

A four-quadrant voltage source power converter is used to decouple rotor speed from power system frequency and also to control the produced active and reactive power as shown next.

If the stator resistance, r_s, is neglected and the direct axis of the reference frame coincides with the maximum of the stator flux Ψ_s (which implies that u_{sd} equals zero and u_{sq} equals the terminal voltage) then the developed electromagnetic torque depends mainly on the rotor current quadrature component [5]. The following relation between electromagnetic torque and i_{rq} can be easily derived:

$$T_g = -\frac{L_m u_s i_{rq}}{\omega_s (L_{\sigma s} + L_m)} \quad (7)$$

u_s is generator stator terminal voltage while *{m}, {σ}* denote mutual and leakage inductances, respectively.

Again neglecting the stator resistance and assuming that the direct axis coincides with the maximum of the stator flux, it can be shown that generator stator exchanges reactive power Q_s with the network given by:

$$Q_s = -\frac{L_m u_s i_{rd}}{L_{\sigma s} + L_m} - \frac{u_s^2}{\omega_s (L_{\sigma s} + L_m)} \quad (8)$$

It is obvious from (8) that the generator stator output reactive power depends mainly on the direct component of the rotor current.

The generator control system is shown in Fig. 5. It consists of two major control loops concerning the blades rotating speed and the reactive power of generator stator.

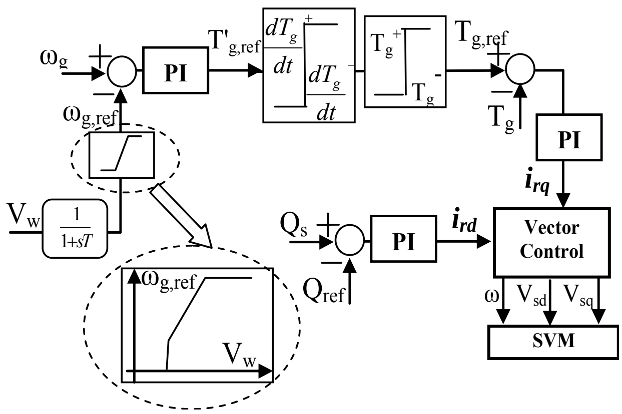


Fig. 5 Generator control system.

Rotating speed is maintained close to its reference by regulating the developed electromagnetic torque. Electromagnetic torque and generator stator reactive power are regulated by controlling the quadratic and direct rotor current components, respectively. Limiters are applied to the reference of the electromagnetic torque and its rate of change in order to avoid mechanical stresses. The rotating speed reference is the filtered output of the wind speed–optimal rotating speed characteristic. At low wind speed, the optimal rotating speed is applied as reference, while at high wind speed a constant rotating speed is imposed according to the V_w-$\omega_{g,ref}$ characteristic of Fig. 5.

Grid-side Converter Control System

The active power injected to the grid, P_{grid}, is controlled by regulating the grid-side inverter voltage phase angle, while the voltage magnitude is adjusted in order to control the output reactive power [17]. Phase angle δ, voltage magnitude Vinv and system frequency are led to the Pulse Width Modulator to produce the firing pulses for the IGBTs [15], [18]. The reference of the output reactive power is limited according to the P-Q characteristic of Fig. 6.

If grid voltage decreases below 0.8 (p.u.) then the P-Q characteristic shown in Fig. 6 is varied according to the measured voltage in order to maintain the output current below its nominal value.

This operating feature is critical for the grid-side power converter protection and it is also a requirement for the low voltage fault-ride through capability.

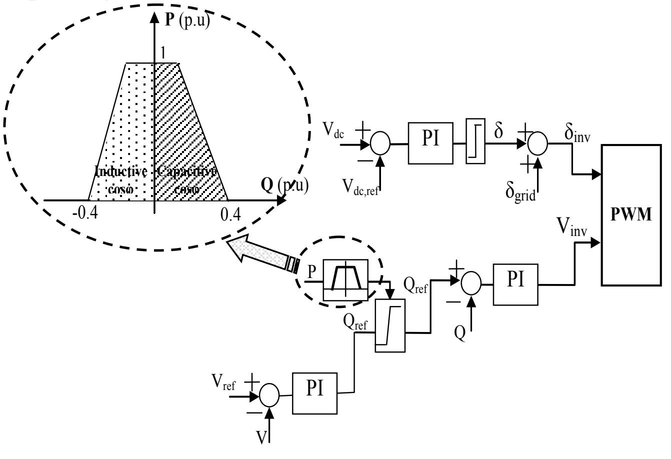


Fig. 6 Control system of grid-side inverter.

2.3 Models of overhead electrical lines and power cables

The overhead lines used for the connection of the WP to the power system are modeled as an equivalent RL branch [13]:

$$\begin{bmatrix}\Delta V_d\\ \Delta V_q\\ \Delta V_0\end{bmatrix}=\begin{bmatrix}R_s-R_g & -\omega(X_s-X_m) & 0\\ \omega(X_s-X_m) & R_s-R_g & 0\\ 0 & 0 & R_s+2R_g\end{bmatrix}\begin{bmatrix}i_d\\ i_q\\ i_0\end{bmatrix}+ \quad (9)$$

$$\begin{bmatrix}-(X_s-X_m) & 0 & 0\\ 0 & -(X_s-X_m) & 0\\ 0 & 0 & X_s+2X_m\end{bmatrix}p\begin{bmatrix}i_d\\ i_q\\ i_0\end{bmatrix}$$

ΔV_d, ΔV_q, ΔV_0, i_d, i_q, i_0 are the dq0-axis voltage drop and the current components referred to the synchronous rotating frame, R_s is the series resistance, R_g is the resistance of the neutral wire, X_s, X_m are the series and the mutual inductance between stator and rotor windings, respectively.

For the modeling of the cables used for the interconnection of the WTs inside the groups and also the groups of the WTs the capacitances of the cables are also taken into account. Π-equivalent is assumed where the cable capacitance is divided into two equal shunt-capacitances at the ends of the cable.

3 Wind Park Equivalent Model

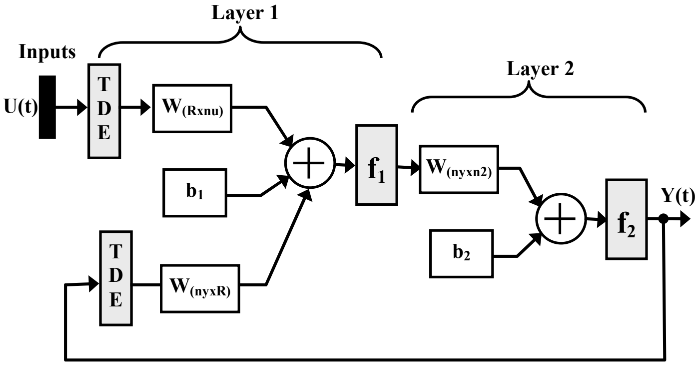
3.1 General

In this paper classical NARX models, are used for system identification [8]-[10]. The NARX model is based on the linear ARX model, which is commonly used in time-series modeling. The output of an NARX model, **Y**(t), is related to a finite number of past outputs and inputs as shown in (10) :

$$\mathbf{Y}(t)=f(\mathbf{Y}(t-1),\mathbf{Y}(t-2),...,\mathbf{Y}(t-n_Y),\mathbf{U}(t-1),\mathbf{U}(t-2),...,\mathbf{U}(t-n_U)) \quad (10)$$

Where, **U** is the input vector of the model, Y is the output vector of the system and ***f*** is a nonlinear function.

The NARX model can be implemented by using a feed-forward neural network to approximate the function, ***f***, where the next value of the dependent output signal **Y**(t) is regressed on previous values of the output signal and previous values of an exogenous input signal. A diagram of the resulting network is shown in Fig. 7, where a two-layer network is used for the approximation. This implementation also allows for a vector ARX model, where the input and output can be multidimensional.



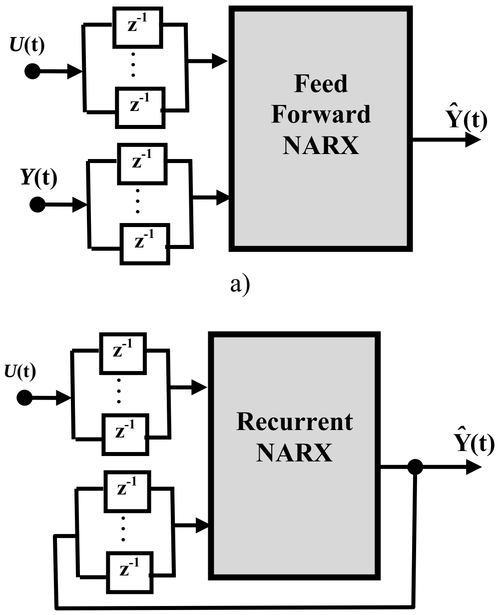
W: Weight matrices, **b:** Bias matrices, **f:** Activation function
TDE: Time delay element

Fig. 7 NARX model structure.

There are many applications for the NARX network. It can be used as a predictor of the next value of the input signal, for nonlinear filtering, in which the target output is a noise-free version of the input signal. The use of the NARX network is also used for the modeling of nonlinear dynamic systems.

An important configuration of NARX network that is useful in training is based on the series-parallel architecture shown in Fig. 8.a. Because the true output is available during the training of the network, a series-parallel architecture, in which the true output is used instead of feeding back the estimated output, can be used. This has two advantages. The first is that the input to the feedforward network is more accurate. The second is that the resulting network has a purely feedforward architecture, and static back-propagation can be used for training.

In real applications the output of the NARX network is the estimation of the output of a nonlinear dynamic system. In this case, the output is fed back to the input of the feed-forward neural network as part of the standard NARX architecture– parallel architecture- , as shown in the Fig. 8.b. In this paper the NARX model in series – parallel architecture is derived from training process and then it is transformed to an equivalent network of parallel architecture.



a)

b)

Fig. 8 a) NARX series-parallel architecture, b) NARX parallel architecture.

3.2 Data used for system identification and model validation

The inputs of the WP detailed model are the dq-axis voltage components, referred to the synchronous rotating frame, at the WP connection bus together with the wind speed at the sites of the WTs.

The input vector of the NARX model is given by,

$$\mathbf{U}(t)=\begin{bmatrix} V_p \\ --- \\ \mathbf{u}_W \end{bmatrix},\quad \mathbf{u}_W=\begin{bmatrix} V_{w1} \\ \vdots \\ V_{wn} \end{bmatrix} \tag{11}$$

Input vector **U**(t) comprises the rms voltage $V_p=(V_{dp}^2+V_{qp}^2)^{1/2}$ at the WP common coupling point, as shown in Fig. 1, and the vector $\mathbf{u}_W$ that contains the processed wind speed signals. In more detail, the wind speed at the sites of the WTs are filtered and normalized in [-1:1] interval. Also, the voltage is normalized in [-1:1] interval.

The output vector **Y**(t) of the WP equivalent model comprises the active power P_{wp} and the reactive power Q_{wp}, produced by the WP:

$$\mathbf{Y}(t)=\begin{bmatrix} P_{wp} \\ Q_{wp} \end{bmatrix} \tag{12}$$

3.3 Data creation for System Identification and Model Validation

The detailed model of a WP is simulated using different random wind speed time series. The active and reactive powers injected to the system compose the output vector of the model. The WP system is simulated twice using in each case different wind speed time series in order to reproduce the identification and validation data sets. The obtained data are processed as described in the next paragraph.

3.4 Process of data used for Training and Validation of NARX network

The inherent elasticity at low and high speed sides of the drive train, the slip speed of the asynchronous generators and the variable rotating speed in case of VSWTs conduce to the low-pass characteristics of the system. Consequently, WTs operate as low-pass filters and as a result the produced power is free of fast wind speed variations.

For the above reasons the wind speeds are filtered in order to increase the accuracy of the equivalent model. First order transfer functions, $\frac{1}{1+sT}$, are used for wind speed filtering. Different time constants are used for variable and fixed speed wind turbines. The active power produced is limited due to stall characteristics of the blades or pitch control feature. This characteristic is reproduced by the use of inverse tangent activation function for the hidden layer of the NARX network.

Finally, all the input and the output variables of the NARX network, are normalized in the [-1, 1] interval.

3.5 System Identification and Model Validation Methods

Generally, there are two ways to validate the model:

- Use of plots
- Use of statistical tests on the prediction errors **e**(t)

It is useful to plot the output of the model excited only by the input with no disturbances added and estimate how well the model fits to the validation data. Concerning the second approach statistical tests based on some assumptions concerning model residuals **e(t)** are applied. These assumptions rely on the following hypotheses [8]:

- **e**(t) is zero mean white noise
- **e**(t) has symmetrical distribution
- **e**(t) is independent of past inputs.

4 Simulation Results

4.1 Case study

A library with the models of the WP system components (WTs, power electronics, control systems, electrical lines, compensating capacitors *etc*.) has been developed using *Simulink* and *Matlab* code. The models described in Section 3 are combined in order to develop the model of the examined WP.

The nominal power of the examined WP is 27MW and it consists of three groups of WTs each comprising three WTs. Two of the groups consist of VSWTs while the third one comprises CSWTs. The nominal output power of the assumed VSWTs and CSWTs is 3 MW.

In the examined WP, the WTs are connected with XLPE cables (Z_{XLPE}=0.244+j·0.1304Ohm/km). The connection cables used inside the groups are assumed of equal length, 200m, while the ones used for the connection of the groups of WTs, are considered of length equal to 500m. An ACSR-95, double-circuit, 20km, overhead electrical line (Z_{ACSR}=0.1075+ j·0.1670 Ohm/km) is used in order to connect the WP to the 20kV bus of the MV/HV substation. The impedance of the voltage transformer is considered equal to 15%. Also, a 12 MVAR compensation capacitor is installed at the 20kV bus of the MV/HV substation. The above configuration corresponds to one typical, medium capacity WP system of the Greek power system.

The base values used in this study are 50 MVA for power, 20 kV for voltage at medium voltage level and 690V at low voltage level (WT generator output).

4.2 WP system identification

Nine different random wind speed time series are used as inputs to the WTs models, as shown in Figs. 9-11. The duration of the wind speed time series used for the training of the NARX network is 330 sec. The above data are used for the identification of the WP system. After several trials a NARX model with 10 hidden neurons and two output neurons was selected as it ensures minimum model error together with the least complexity. Inverse tangent activation function is used for the neurons of the hidden layer while linear activation function is used for the output neurons of the NARX network. The squared error of the output of the model converges to a minimum after almost 200 training epochs as shown in Fig. 12. WP active power and reactive power obtained by the detailed model and those estimated by the NARX model are compared in Fig. 13.

4.3 WP equivalent model validation

Nine wind speed time series different than the ones used for the identification of the system are used for the validation of the NARX model, as shown in Figs. 14-16. The duration of the wind speed time series used for model validation is 90 sec. It is considered that the examined WP is located in the southeastern part of Greece where excellent wind capacity occurs. The WP is connected to MV/HV substation of the Greek transmission system located in this area. Thevenin equivalent impedance of the power system estimated at the 150kV busbar of the MV/HV substation is $0.039\angle 75.45$ (p.u.) for Greek power system maximum load conditions.

The comparison of the results obtained using the detailed and the equivalent WP model is done in Figs. 17-18. It is obvious from the plots that the results obtained using the equivalent and the detailed WP models almost coincide. In Fig.18 the voltage drop at MV/HV substation obtained with detailed and equivalent WP model is shown. The estimated short-term flicker index, P_{st}, is 0.46 using either the detailed or the equivalent WP model.

Finally, it should be mentioned that the simulation of the detailed model requires approximately only 5% of the respective simulation time required by the detailed WP model.

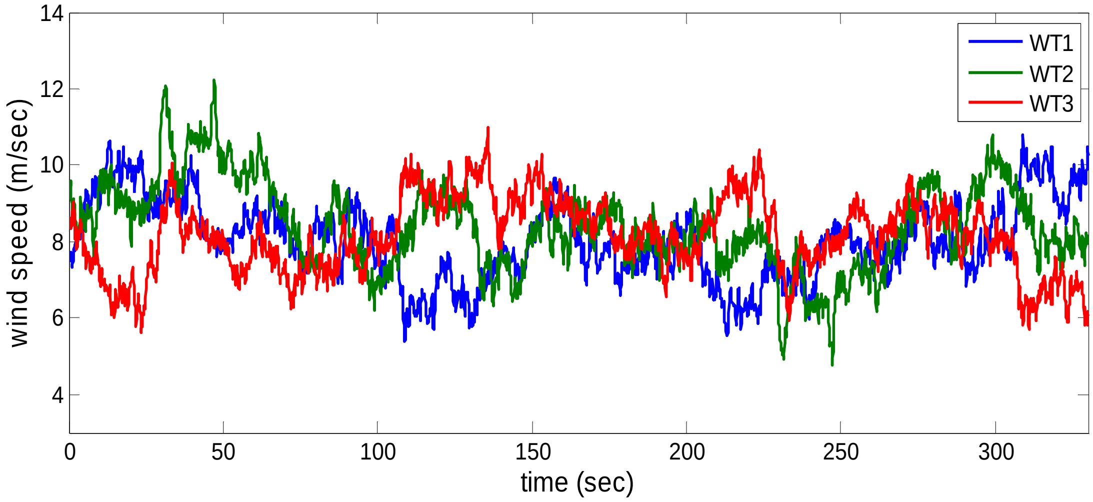


Fig. 9 Wind speeds (group1 of VSWTs).

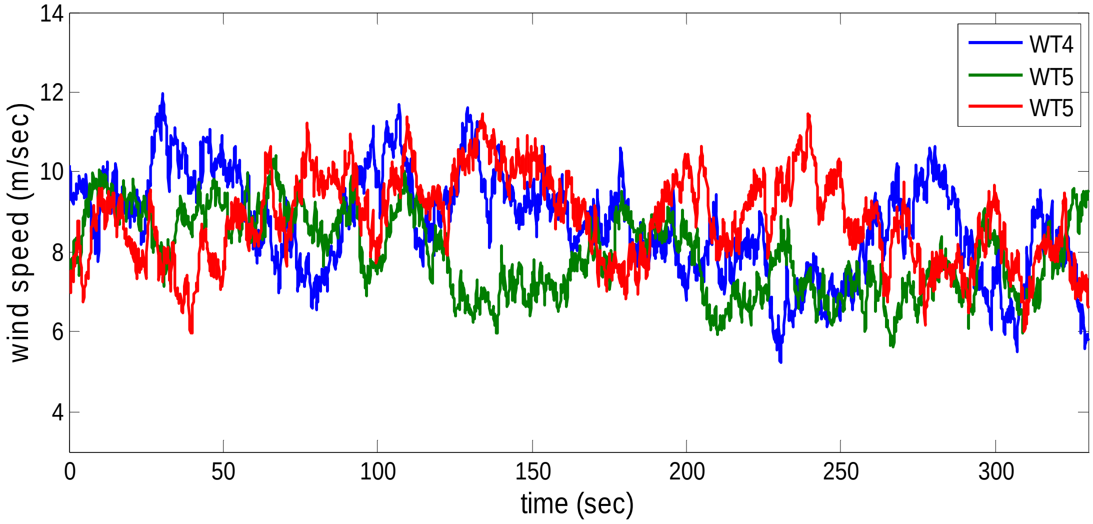


Fig. 10 Wind speeds (grou2 of VSWTs).

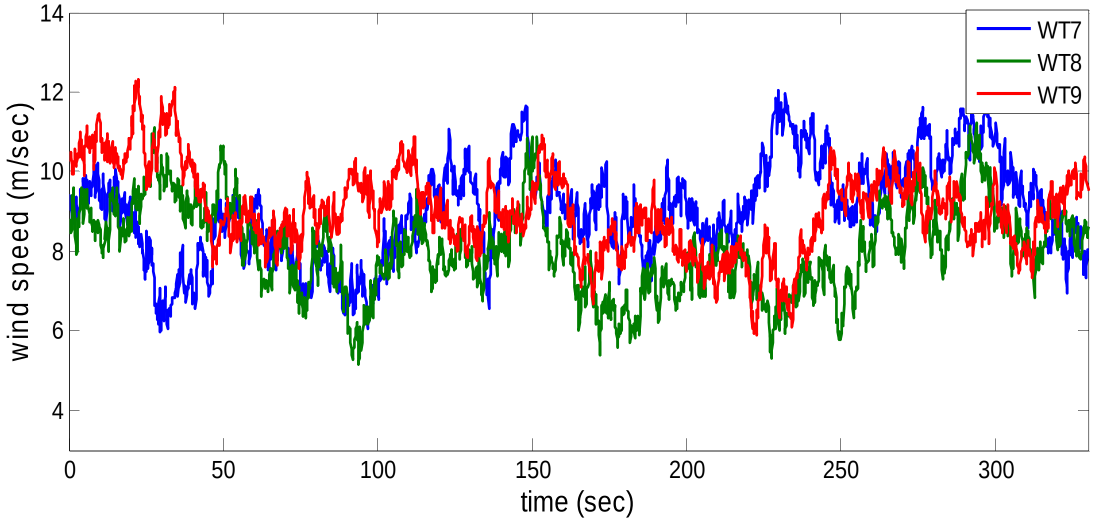


Fig. 11 Wind speeds (group3 of CSWTs).

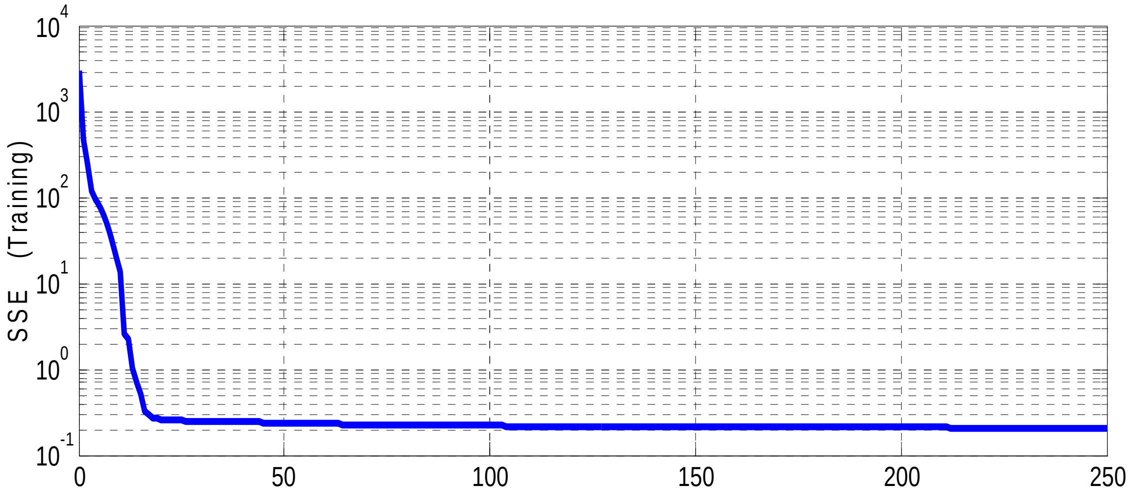


Fig. 12 Summed squared error (training).

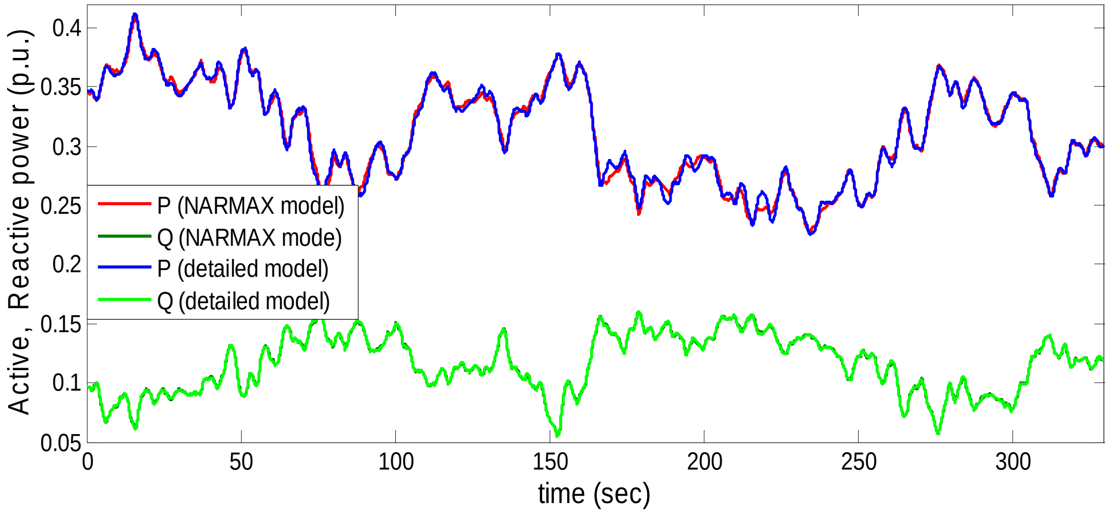


Fig. 13 WP output active, reactive power estimated with detailed and equivalent model (training).

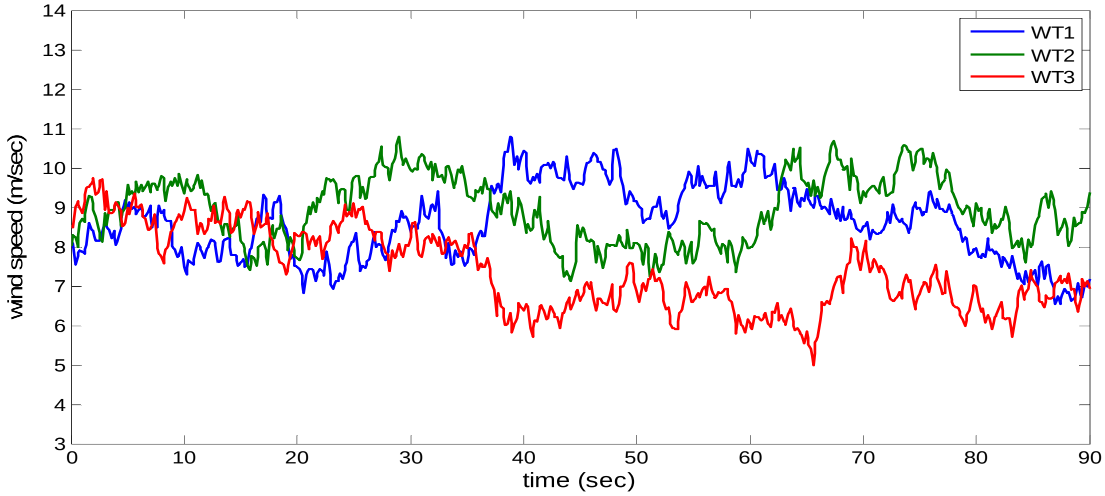


Fig. 14 Wind speeds for NARX model validation (group1 of VSWTs).

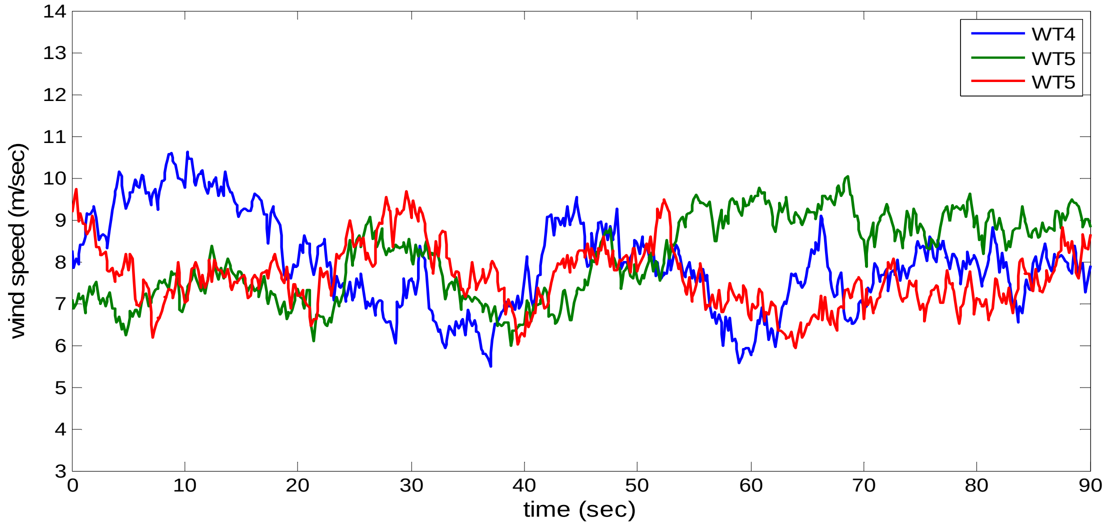


Fig. 15 Wind speeds for NARX model validation (grou2 of VSWTs).

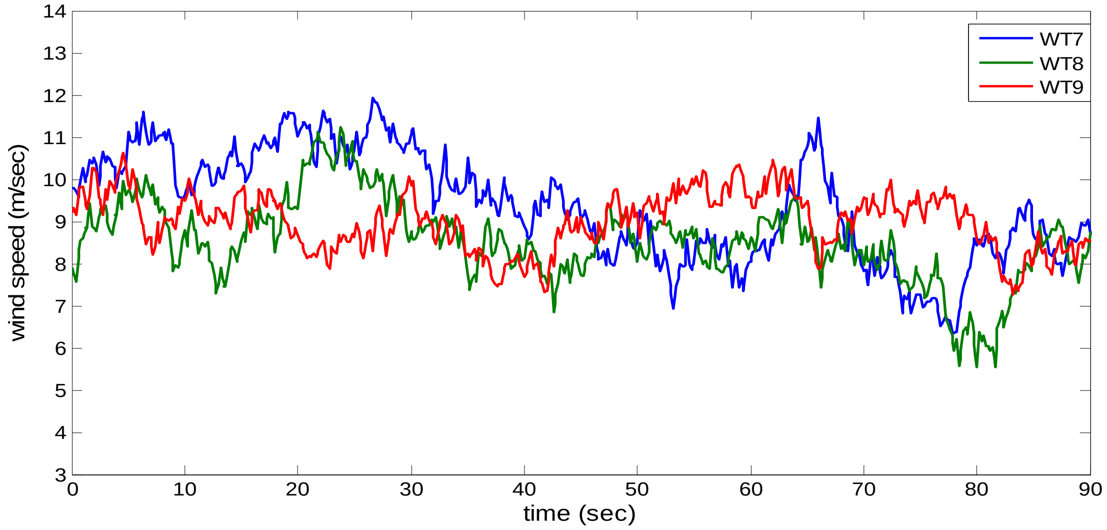


Fig. 16 Wind speeds for NARX model validation (group3 of CSWTs).

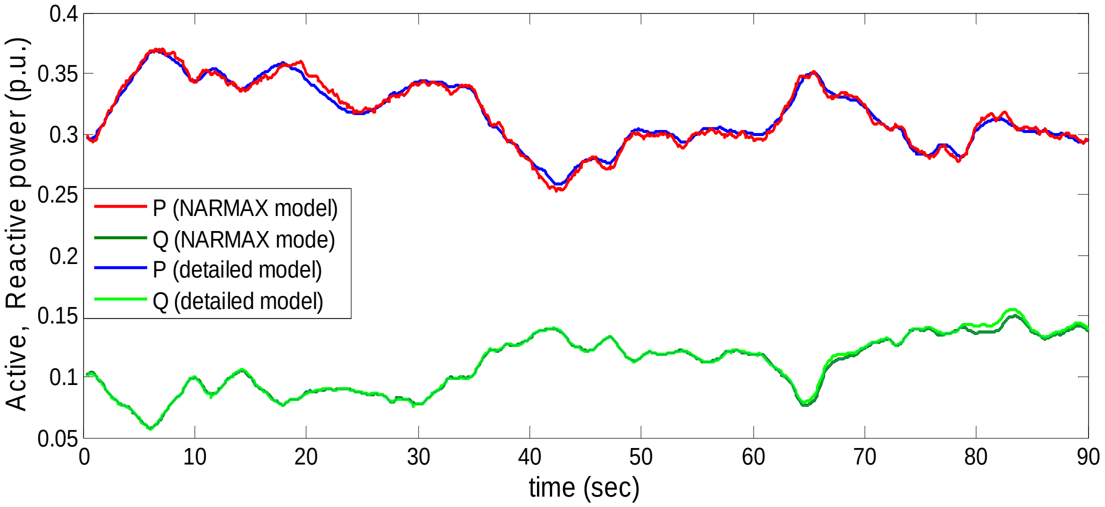


Fig. 17 WP output active, reactive power estimated with detailed and equivalent model (validation).

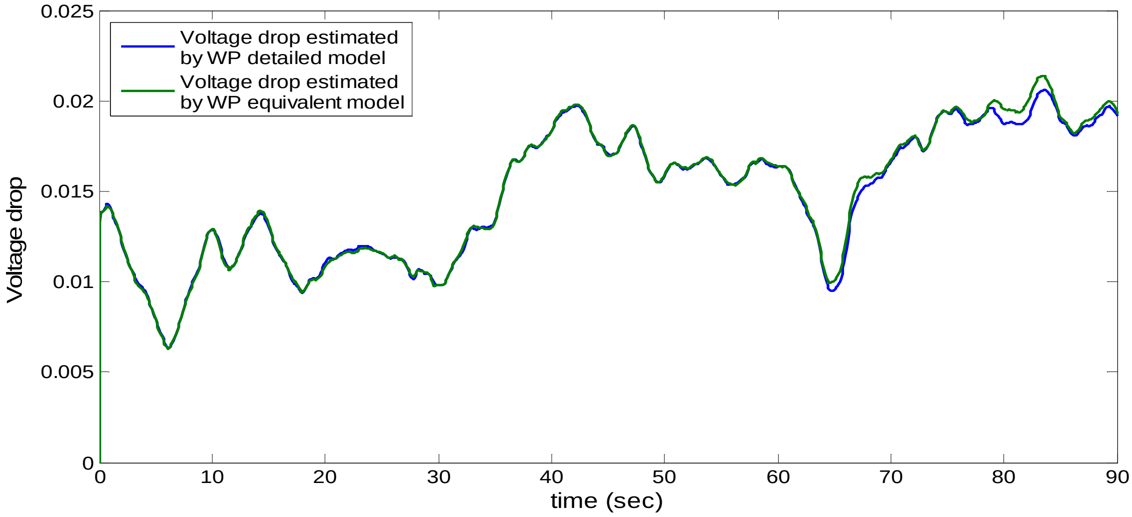


Fig. 18 Voltage drop at MV/HV substation.

5 Conclusions

In this paper equivalent models for WPs are derived. These models are suitable for simulation of large power systems with high wind power penetration. The detailed model of a WP comprising fixed and variable speed WTs is developed and the obtained simulation results are used for the identification of the WP system. Simulation results confirm the accuracy and the advantages of the proposed equivalent models.

Provided that the computational capacity required for the simulation of a power system with high wind power penetration is extremely higher if detailed models are used, the proposed equivalent models present several advantages like:

1. The obtained WP models require significantly less simulation time while they present excellent accuracy as demonstrated by the respective simulation results.
2. The proposed equivalents become more advantageous in case of large WPs comprising tens or even hundreds of WTs.
3. They are general and they can be applied to different WPs configurations independent from the type of the WTs used. Also, they can be easily introduced to several commercial network analysis software platforms without significant modifications.
4. Inputs and outputs of the WP model providing the necessary information for WP identification are only used.
5. The power system model could be further simplified if the proposed method is applied to sections of the system with high wind power penetration.

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