Procedure for Estimation of Equivalent Model Parameters for a Wind Farm using Post-Disturbance On-line Measurement Data

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***Abstract*—Fixed speed wind turbines (FSWT) based on induction generators (IGs) are widely used due to their simple construction and ease of operation. Proper operation and control of a wind farm composed of FSWTs requires accurate models of the main FSWT elements, including the IG. This paper presents a procedure for using on-line measurements of the post-disturbance system to estimate the equivalent model parameters of a wind farm. This procedure is the wind farm equivalent application: WFEq Application and it is suitable for use in as part of Wide Area Monitoring, Protection, and Control (WAMPAC). The performance and robustness of the WFEq are evaluated using two test systems, where the parameters of the WFEq model are estimated using the Nonlinear Least Squares method. The inputs needed to use the WFEq application are measurements of the active and reactive power after a disturbance to the system frequency. Results of the equivalent model estimation procedure demonstrate a high quality of performance in terms of both convergence and accuracy.**

***Index Terms*—Fixed speed wind turbines, generator modeling, induction machine, parameter estimation, nonlinear least squares.**

I. Introduction

FUTURE power systems face several challenges; one of them is the anticipated high penetration of intermittent generators, supported by storage, that will be connected over converters This intermittent generation will primarily consist of wind turbines of a wide variety of designs. This change in the generation mix of a system will introduce new challenges in many fields e.g. frequency control. Wind-turbine generators (WTG) provide little, or no, inertia to the system. Thus, they do not contribute to the primary frequency response of a system. The increased use of a generation technology with this property will cause a considerable reduction in the ability of an operator to ensure the security of system frequency after a disturbance. However Fixed Speed Wind Turbines (FSWT), based on single-cage induction generators (SCIG), provide natural damping of power system oscillations during a system frequency disturbance. Control of the FSWT output power during a disturbance could be used to effectively modify the system inertia. These two properties of FSWTs offer the opportunity to use them as a tool during frequency control.

Several methodologies for defining an equivalent wind farm model have been developed. These can be separated into two groups, that can be described as follows: (a) represent the entire wind farm using a single WTG as an equivalent [1], [2], [3], [4], [5], (b) divide the wind farm into several groups of WTGs based on wind speed and then aggregate their behavior into an equivalent WTG [5], [6]. A comparison of these methods can be found in [7] and they have both been found to be effective.

The data needed to form these models includes the wind distribution of the site and details regarding the wind farm layout and technologies. A procedure for determining the parameter values of the equivalent wind farm model, using on-line measurement data, is necessary if FSWTs are to be used as part of a frequency control strategy. When dealing with a FSWT accurate knowledge of the values of the machine parameters that define the behavior of the IG, a fundamental component of the FSWT, are particularly important [8].

The problem of parameter estimation for induction machines (IM) has received a great deal of attention for many years [9], [10]. These schemes use the measured response of the IM to a change in voltage to estimate the IM parameters. This problem has been solved using several optimization techniques such as: genetic algorithms (GA) [11], [12], [13] a local search algorithm (LSA), a simulated annealing (SA) approach, an evolution strategy (ES), particle swam optimization (PSO) [14], [15], improved particle swarm optimization (IPSO) [8] and Kalman filtering techniques [16]. Most of these techniques are applied to data gathered during the start-up of the machine [12], [17], [18], [19] or from direct mechanical testing [13], [14].

Applications that require the interconnection of many IMs, for example a wind farm of FSWTs, increase the complexity of the parameter estimation problem faced.

This paper presents a general procedure for the on-line estimation of the parameter values of the equivalent model of a wind farm using post-disturbance measurements of active and reactive power. Section II describes the equivalent model for the wind farm. Section III presents the procedure for the parameter estimation of the equivalent model. Section IV shows the results of simulations that confirm the validity of the proposed procedure. Finally, the advantages of this novel

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procedure are discussed in Section V.

II. Wind Farm Equivalent model

A wind farm is composed of multiple WTGs, connected to the grid through a collector system. This system starts with a the step-up transformer connected to each FSWT and includes power cables, power-factor compensation devices that eventually connect each wind turbine to the main substation. Finally, the wind farm is connected to the power network at a point of interconnection (POI).

Fig. 1 shows a schematic diagram of a grid-connected wind farm that is based on FSWT.

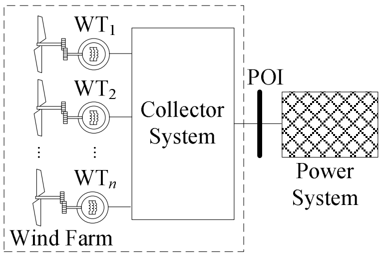


Fig. 1. Schematic diagram of a grid-connected wind farm based on FSWT.

When developing an equivalent model of the wind farm, that will be valid during a significant disturbance to the system frequency, for use by on-line applications, the following assumption are made:

- *The dynamic behavior of the wind energy capture mechanism of each WTG unit is neglected*. Consequently, the rotor is can be considered to supply constant mechanical torque. This assumption is valid for small time scales (several seconds) because changes in the wind speed are negligible during this time period.
- *The electro-mechanical behavior of the IG is considered.* The electrical part of the machine is represented by a fourth-order state-space model and the mechanical part by a second-order system. This model is represented using Park transformations of the three phase system.
- *The collector system is modeled as an equivalent series impedance.* The collection system is treated as a linear system that can be modeled using a single series impedance.

A. Induction Generator Model

The IM model described in detail in [20], [21] is a valid representation of the IGs used in FSWT applications. The use of this IM model is valid because an IG can be crudely viewed as an IM that is being driven backwards to generate electrical power [8].

This IM model uses a 4th-order state-space model of the *d-q* space flux when referred to an arbitrary angular velocity ω [21]:

$$\begin{aligned}
\dot{\psi}_{qs} &= v_{qs} - R_s i_{qs} - \omega\lambda_{ds} \\
\dot{\psi}_{ds} &= v_{ds} - R_s i_{ds} + \omega\lambda_{qs} \\
\dot{\psi}'_{qr} &= -R'_r\, i'_{qr} - \left(\omega - \omega_r\right)\lambda'_{dr} \\
\dot{\psi}'_{dr} &= -R'_r\, i'_{dr} + \left(\omega - \omega_r\right)\lambda'_{qr}
\end{aligned} \tag{1}$$

where the indices *d* and *q* indicate the *d*-axis and *q*-axis of the *d-q* reference frame, respectively. The indices *s* and *r* denote stator and rotor and the variable ω_r is the electrical angular velocity.

In the above equations, *V* denotes voltage, *i* current, *R* resistance and ψ flux linkage per second. All electrical variables and parameters are referred to the stator, as indicated by the prime notation. The flux linkage per second values (ψ) are expressed in terms of current (*i*) and the reactance (*X*) [20], [21]:

$$\begin{aligned}
\psi_{qs} &= X_{ls} i_{qs} + X_m\left(i_{qs} + i'_{qr}\right) \\
\psi_{ds} &= X_{ls} i_{ds} + X_m\left(i_{dr} + i'_{dr}\right) \\
\psi'_{qr} &= X'_{lr}\, i'_{qr} + X_m\left(i_{qs} + i'_{qr}\right) \\
\psi'_{dr} &= X'_{lr}\, i'_{dr} + X_m\left(i_{ds} + i'_{dr}\right)
\end{aligned} \tag{2}$$

The rotor angular velocity (ω_m) and its angular position (θ_m) must be included in the IM model. This is achieved in this IM model using a single differential equation for each variable.

$$\begin{aligned}
\dot{\theta}_m &= \omega_m \\
\dot{\omega}_m &= \frac{1}{2H}\left(P_m - P_e\right)
\end{aligned} \tag{3}$$

where H is the rotor inertia constant, P_m is the shaft mechanical power, and P_e is the electromechanical torque [21]:

$$P_e = v_{ds} i_{ds} + v_{qs} i_{qs} \tag{4}$$

The reactive power is calculated as follows:

$$Q_e = v_{qs} i_{ds} - v_{ds} i_{qs} \tag{5}$$

Equations (1)-(5) constitute the IM model that is used in this paper. This model is valid for a symmetrical squirrel cage induction machine. The windings of such a machine are connected using an ungrounded Y. Therefore, there is no homopolar component and only two line-to-line input voltages must be used inside the model instead of three line-to-neutral voltages. The model is defined in the *d-q* reference frame, whilst power system measurements are defined in the *abc* reference frame. The necessary transformation for the stator voltages (*abc*-to-*dq*) is defined by:

$$\begin{bmatrix} V_{qs} \\ V_{ds} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 2\cos\theta & \cos\theta + \sqrt{3}\sin\theta \\ 2\sin\theta & \sin\theta + \sqrt{3}\cos\theta \end{bmatrix}\begin{bmatrix} V_{abs} \\ V_{bcs} \end{bmatrix} \tag{6}$$

The following relationship describes the reference frame transformations (*dq*-to-*abc*) for the stator currents:

$$\begin{bmatrix} i_{as} \\ i_{bs} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ \dfrac{-\cos\theta + \sqrt{3}\sin\theta}{2} & \dfrac{-\cos\theta + \sqrt{3}\sin\theta}{2} \end{bmatrix}\begin{bmatrix} i_{qs} \\ i_{ds} \end{bmatrix} \tag{7}$$

where $i_{cs} = -i_{as} - i_{bs}$ due to the winding configuration. In the preceding equations, θ_m is the angular position of the arbitrary reference. A rotating reference frame with an initial angular velocity $\omega = \omega_s$, is suitable for computer simulations where the system frequency, f_s, is changing ($\omega_s = 2\pi f_s$). The use of a rotating reference frame with variable speed is vital when attempting to capture the influence of the external system frequency.

III. Wind Farm Equivalent Application

Wide Area Monitoring, Protection, and Control

(WAMPAC) systems offer a cost-effective solution for improving grid planning, operation, maintenance and energy trading [22], [23]. It can be used to provide real-time estimates of network model parameters for use in real-time applications such as System Inertia Management.

In this paper a **W**ind **F**arm **Eq**uivalent model suitable for WAMPAC application is presented: WFEq Application. The general concept behind the WFEq application is depicted in Fig. 2.

The Phasor Measurement Unit (**PMU$_i$**) is installed at the point of interconnection (POI) of the wind farm (**Bus i**), each PMU provide a data set (**S$_i$**) which represents an accurate time-stamped measurement data suitable for observing power system dynamics. Phasor measurements of voltage (**V$_i$**) and current (**I$_i$**) and frequency (**f$_i$**) are included in the data set **S$_i$**. This data is then passed to the off-site Data Concentrator (DC) through some external communication infrastructure. When a system frequency disturbance occurs, the DC sends the raw measurement data (**S$_i$**), time spam, to the WFEq application. Pre-processing is applied to the data set to deal with wrong, or missing, measurement data. Voltage and current phasors measured at the wind farm are then used to calculate the active and reactive power at the POI $\theta_i = [P_i\ Q_i]$.

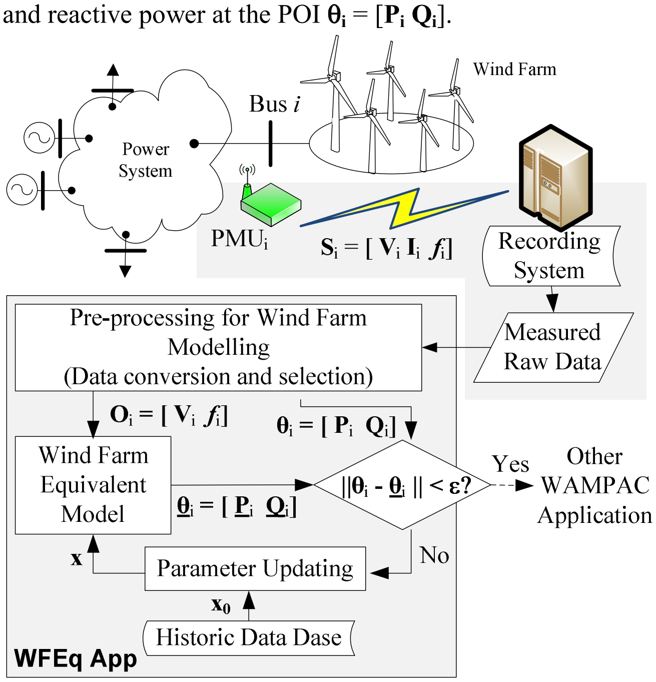


Fig. 2. Schematic representation of WFEq Application.

The procedure for executing the WFEq application is depicted in Fig. 2 and is described as follows:

- *Step 1:* Use the measurements contained in **S$_i$** to calculate **O$_i$** and **θ$_i$**.
- *Step 2:* Estimate the vector of model parameter values (**x**) using a precise and accurate suitable estimation method.
- *Step 3:* Measure the quality of the WFEq model by comparing the estimated model output $\underline{\theta}_i = [\underline{P}_i\ \underline{Q}_i]$ to the measured system behavior $\theta_i = [P_i\ Q_i]$..
- *Step 4:* If the quality of the WFEq model is acceptable, end. If it is not update **x** in some way and return to Step 3

The model used in the WFEq application must be defined by a set of electrical and mechanical parameters, these are included in the vector **x**. However, the structure of the application is independent of the model itself. Therefore, models with different levels of detail could be used within the application.

The simplest case for a wind farm is where the vector **x** is defined by eight parameters: $\mathbf{x} = [\ R_{eq}\ L_{eq}\ R_s\ L_{ls}\ R_r\ L_{lr}\ L_m\ H]$, where R_{eq} and L_{eq} are the electrical parameters of an equivalent series element that represents the Thevenin equivalent of the collector system and the remaining parameters correspond to the equivalent wind farm (see Fig. 3).

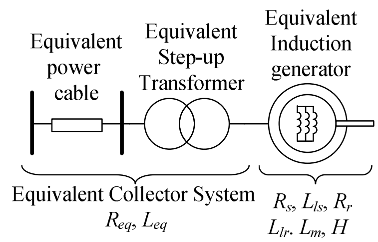


Fig. 3. Simplest representation of a WFEq Model.

More detailed models could include the effect of power factor capacitors, cable capacitances, and the active power losses associated with the magnetizing current in the transformers.

The vector **x** is represented in per unit quantities. This representation provides several advantages: all quantities are referred to one side of the transformer (POI), the results are independent of the tri-phases connections used in transformers, and per unit representations of different variable will only vary in the same narrow band allowing gross errors to be easily detected.

The last advantage only exists if the base values used in the per-unit system are intelligently selected. A convenient, and suitable, set of bases values consists simply of the active power immediately before the system frequency disturbance and the rated voltage at the POI.

An important part of the WFEq application is the parameter estimation method used for the estimation and updating of **x**. There are three main groups of estimation methods: artificial intelligence (AI) methods [24], [8], *Nonlinear Least Squares* (NLS) methods [25], hybrid methods [26]. The structure of the WFEq Application is suitable for all three methods. In this paper a NLS method is used for the parameter estimation when demonstrating the WFEq applications suitability.

Nonlinear Least Square (NLS) methods have been widely used for parameter estimation, particularly the *Levenberg-Marquardt* (L-M) version [27], [28]. This method can give a precise solution, but is very sensitive to the initial state of **x**. L-M is a damped, Gauss-Newton method, which unlike mostly other NLS methods uses a parameter μ:

$$(\mathbf{J}^T\mathbf{J} + \mu\mathbf{I})\mathbf{h}_{\mathbf{lm}} = -\mathbf{J}^T\mathbf{F} \tag{1}$$

where **J** is the Jacobian matrix, **I** is the identity matrix, **F** is the difference between the measurements and the estimate and $\mathbf{h}_{\mathbf{lm}}$ is the L-M correction [29]. The WFEq application solves the difficulties related to selecting the initial conditions of the NLS method by estimating the parameters based on the active power immediately before the system frequency disturbance.

IV. Simulation and Results

The suitability of the WFEq application is verified by applying based on the simulated response of two wind farm topologies to the typical system frequency disturbance shown in Fig. 4. The pre-disturbance frequency is 50.0 Hz, this falls to 49.35Hz during the transient with a maximum rate of change of frequency (ROCOF) of -0.87 Hz/s. This is a syntactic signal generated using DIgSILEN PowerFactory.

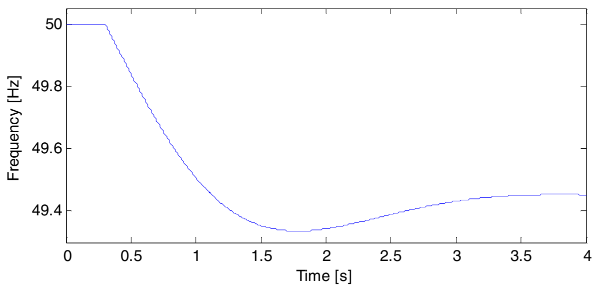


Fig. 4. Typical system frequency response power system during frequency disturbance.

The tests are performed on a wind farm consisting of nine 500kW FSWTs based on IGs. The complete set of parameters for these machines are summarized in the appendix. Two different wind farm topologies are considered in this verification, these are shown in Fig. 5 and Fig. 6.

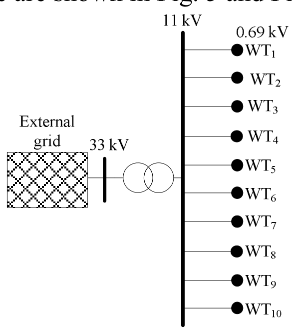
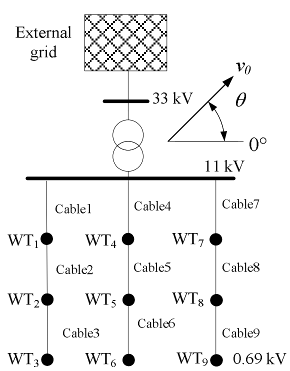


Fig. 5. Test System I – A single line of wind turbines is the simplest wind farm topology



(b) Test System II

Fig. 6. Test System II – An equally spaced grid of wind turbines is simple to plan and reduces the footprint of a wind farm, compared to a single line. The wake effect will reduce the output of this design compared to a single line.

The PMU is installed in the 11 kV side of the POI. This PMU provides measurements of voltages, currents and frequency. The signals were then exported to MATLAB® with a sampling frequency of 100Hz.

The optimization method used in these tests is NLS with a L-M algorithm, a program was coded in an m-script on MATLAB®. The NLS results were obtained using the Optimization Toolbox (Levenberg-Marquardt method) also available in MATLAB®. The parameter estimation process is performed according the set of configurations shown in Table I.

TABLE I
Stopping Configuration for the Parameter Estimation

Criteria	*Value*
Diff max changes	0.1
Diff min changes	10^{-8}
Maximum function evaluations	400
Parameter tolerance	10^{-6}
Function tolerance	10^{-6}

The wind farm in the Test System I had an active power output of 2.52MW before the system frequency disturbance occurred, this means that each WTG was operating at 56.00% of rated power. A power cable (R_c = 0.00754p.u, L_c = 0.019166 p.u) is used to connect each generator to the POI.

In Test System II the wind farm output was 4.443 MW prior to the system disturbance. In Test System II, the wake effect was applied to the wind speeds to calculate a derated, or effective, wind speed for each wind turbine.

The results of the parameters estimation for the WFEq model are presented in Table II and the evolution of the parameter estimates obtained using the procedure proposed in this paper is shown in Fig 7 and 8.

TABLE II
Summary of Estimations

	Test Case I	*Test Case II*
Parameter	*Estimated*	*Estimated*
P Error [%]	1.352	1.887
Q Error [%]	1.245	1.757
R_e [p.u]	0.0044	0.015818
L_e [p.u]	0.0172	0.013323
R_s [p.u]	0.0256	0.014882
R_r [p.u]	0.0167	0.018015
L_s [p.u]	0.0791	0.06701
L_r [p.u]	0.1025	0.08360
L_m [p.u]	2.7368	2.5895
H [s]	3.2550	3.1504

The NLS method terminated after 10 and 9 iterations for the Test System I and II respectively.

Fig. 9 and 10 show the plots of the measured and simulated response of Test System I and II respectively.

Larger discrepancies existed between the measured and modeled reactive powers than for the active powers. However, the error in active and reactive power were both below 2% for both Test Systems. These results demonstrate the high quality of performance in terms of both convergence and accuracy for the proposed WFEq Application.

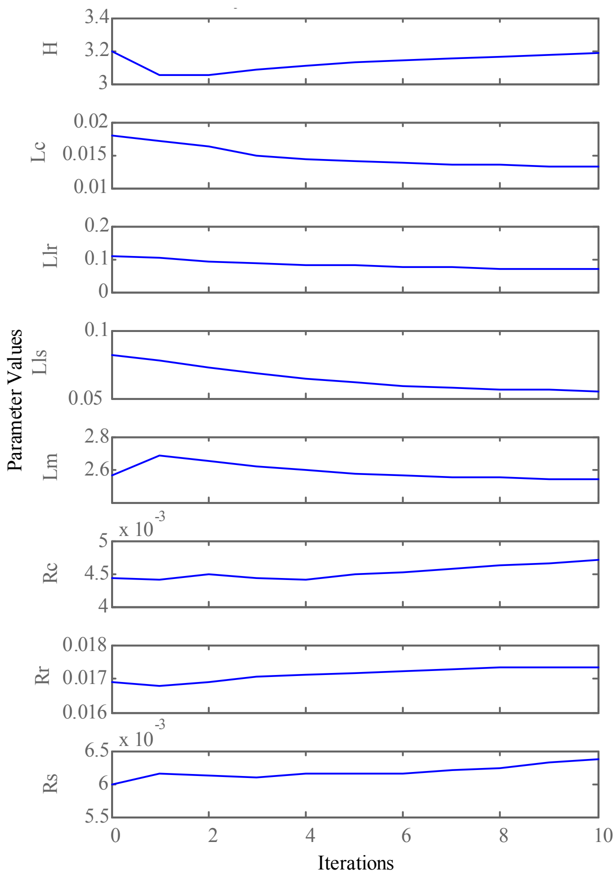


Fig. 7. Trajectories of Estimated parameters: Test System I

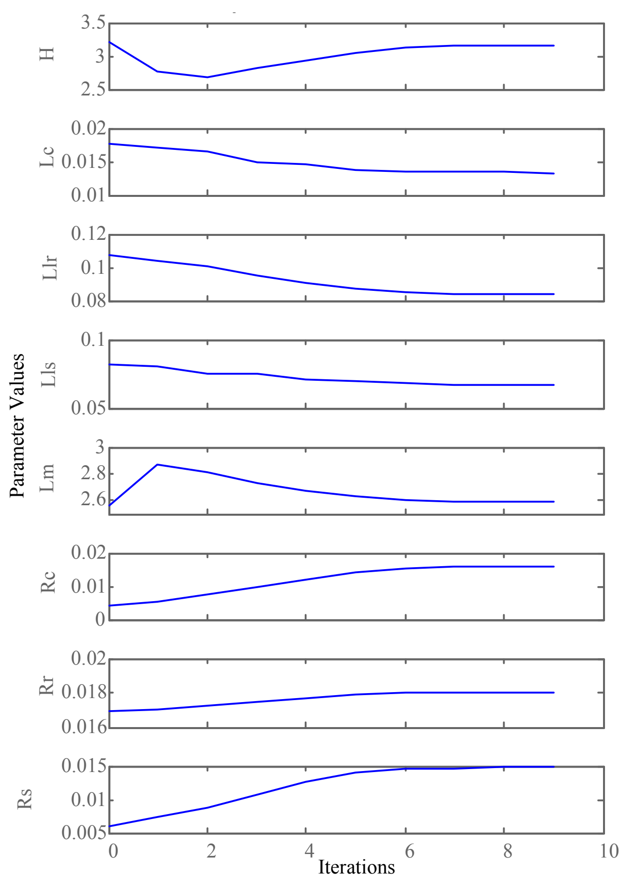


Fig. 8. Trajectories of Estimated parameters: Test System II

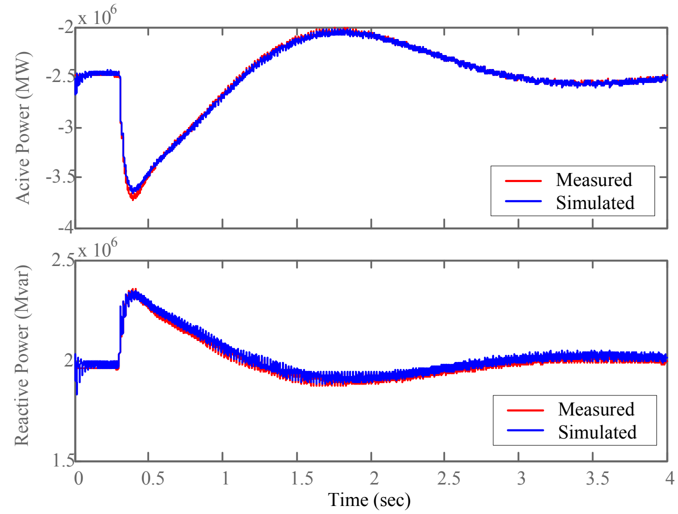


Fig. 9. Results of the WFEq model estimation: Test System I

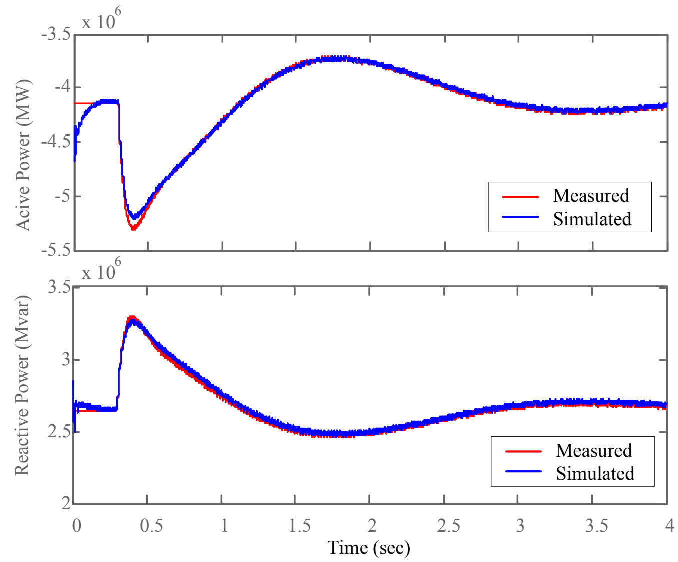


Fig. 10. Results of the WFEq model estimation: Test System II

A second test was performed with Test System II, in this case the impact of the wake effect on the output of the wind farm was included. An asymmetrical distribution of the wind turbines is assumed in the wind farm and also the wake effect. Consequently the active power generated by each wind turbine is different: 0.50, 0.35, 0.10, 0.35, 0.15, 0.1, 0.1, 0.25, 0.35 MW for WT_1 to WT_9. The reactive compensation is located at the low voltage (0.69 kV) terminal of each WTG (Q_c = 160 kVAr).

This second test also allows a demonstration of the ability of the procedure to create an accurate WFEq model when the reactive power consumptions are different and locally compensated.

The parameter estimation algorithm terminated after 21 iterations. Fig 11 shows the evolution of the estimated parameters and comparison to Fig. 8 demonstrates a significant increase in variation during this evolution. The large changes are specially observed in the reactive compensation Q_c and the stator inductance (L_{ls}). The plots of the measured and simulated response are depicted in Fig. 12, the error in the reactive power was once more higher than the active power but both were still below 5%.

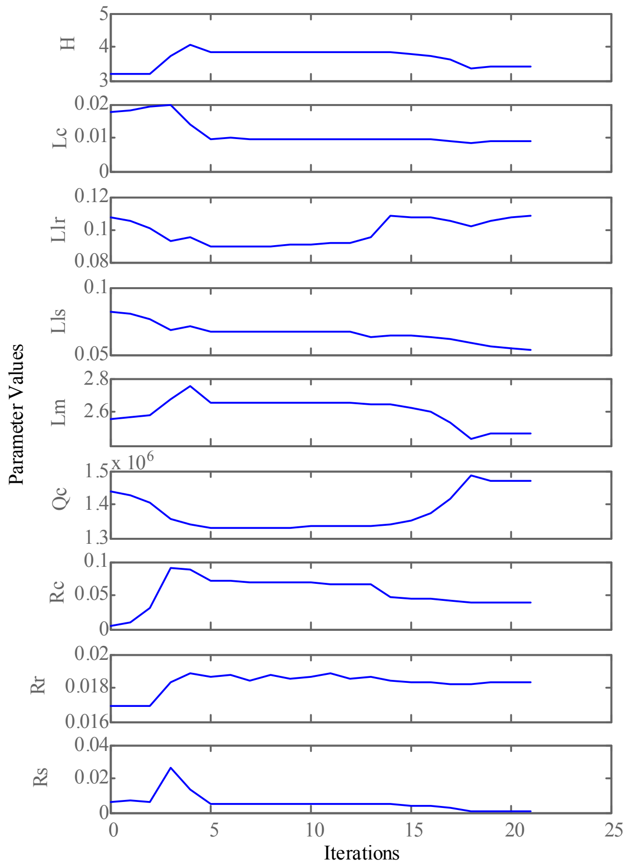


Fig. 11. Trajectories of Estimated parameters, for highly different level of generation and reactive power locally compensated.

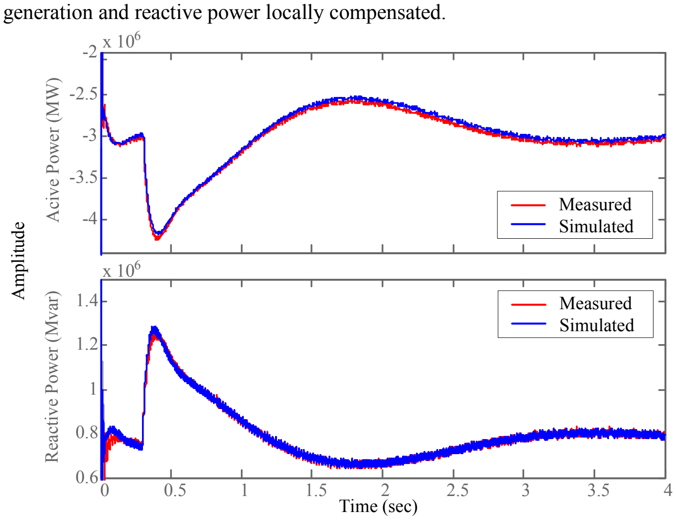


Fig. 12. Results of the WFEq model estimation: Measured versus simulated response.

V. Conclusions

In this paper, a novel procedure for the estimation of the parameter values of an equivalent wind farm model is presented. This procedure is based on post-disturbance measurements of the active and reactive power, at the POI of the wind farm during a frequency deviation.

The increasing deployment of wide area monitoring devices, such as PMUs, means that data of this nature will be increasingly available in the future. The frequency deviation used to stimulate the response from the wind farm, necessary during the validation, is the typical frequency response of a power system to a large active power disturbance. This deviation was chosen to demonstrate that the proposed procedure can operate successfully for the realistic frequency fluctuations that will occur in real power systems.

The procedure presented in this paper can be used with any parameter estimation method. However, for demonstration purposes a NLS method was used and the results demonstrate a high quality of performance in terms of both convergence and accuracy. In all cases the method was capable of converging to a global minimum with an acceptable precision.

VI. Appendix

TABLE A
Parameter Valued for the WTG

Parameter	*Variable*	*Value*
Stator resistance	R_s [p.u]	0.00599
Rotor resistance	R_r [p.u]	0.01691
Stator inductance	L_s [p.u]	0.08213
Rotor inductance	L_r [p.u]	0.10723
Magnetizing reactance	L_m [p.u]	2.55619
Inertia constant	H [s]	3.2000

TABLE B
Mechanical Power inputs for FSWT used in the Test System II

WTG	P_{sh} [MW]
1, 4, 7	0.500
2, 5, 8	0.494
3, 6, 9	0.486

TABLE C
Parameters Values for the Cables used in the Test System II

Cable	R_c	L_c
1, 4, 7	0.0211	0.01137
2, 5, 8	0.0219	0.01237
3, 6, 9	0.0399	0.015937

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VIII. Biographies

Francisco M. González-Longatt (S'01, M'03, SM' 2009) was born in Cagua-Venezuela, on July 30, 1972. He graduated on Electrical Engineering of Instituto Universitario Politécnico de la Fuerza Armada Nacional, Venezuela (1994), and Master of Business Administration of Universidad Bicentenaria de Aragua, Venezuela (1999) and PhD of Universidad Central de Venezuela (2008). His main area of interest is integration of intermittent renewable energy resources into power grid with special interest on dynamic behavior. He is former associate professor on Electrical engineering Department of Universidad Nacional Politécnico de la Fuerza Armada Nacional, Venezuela and He is vice-president of the Venezuelan Wind Energy Association. He is currently a Post Doctoral Associate Research School of Electrical and Electronic Engineering, The University of Manchester.

Pawel Regulski obtained the MSc degree in Electrical Engineering from the Wroclaw University of Technology (Poland) in 2008. Currently he is a PhD student at the University of Manchester working on load modeling and voltage stability. His main research interests include development of new estimation techniques and implementation of artificial intelligence techniques in power system applications.

Peter Wall graduated from the University of Manchester with a Bachelors degree in Electrical and Electronic Engineering (2008) and with a Masters degree in Power Systems (2009). His main area of interest is power system dynamics and frequency stability. He is currently a PhD student at The University of Manchester.

Vladimir Terzija (M'95, SM'2000) is the EPSRC Chair Professor in Power System Engineering in the School of Electrical and Electronic Engineering, The University of Manchester, where he has been since 2006. From 1997 to 1999, he was an Assistant Professor at the University of Belgrade, Serbia. From 2000 to 2006, he was with ABB AG, Germany, working as an expert for switchgear and distribution automation. Dr. Terzija is a convenor of the Cigre WGB5.14 "Wide area protection and control technologies" and a member of several IEEE working groups and task forces. His main research interests are Smart Grid, application of intelligent methods to power system monitoring, control, and protection, switchgear and fast transient processes, as well as DSP applications in power systems.