Probabilistic Assessment of Operational Risk Considering Different Wind Turbine Technologies

F. Gonzalez-Longatt, *Senior Member, IEEE*, J. L. Rueda, *Member, IEEE*, and D. Bogdanov

***Abstract*— This paper presents an assessment of the variability on the output power of three different types of wind turbines commercially available. The dynamic response of terminal voltage, active power and reactive power are evaluated using time-domain simulations obtained from DIgSILENT® PowerFactory™. The assessment of the variability is performed based on probability density function, Pearson correlation coefficient and scatterplots. Results of this evaluation demonstrated that variable speed wind turbines using synchronous generator exhibits the better dynamic performance considering the wind speed changes, and highlight the need of smart grid oriented control strategies aiming at coordinated management of individual wind turbine controllers to avoid adverse implications of wind speed fluctuation.**

***Index Terms*-- Monte Carlo method, probabilistic modeling, risk assessment, wind power.**

I. Introduction

WIND energy is considered as one of the most important inexhaustible sources to produce electricity [1], It mainly reduces the environmental pollution which is caused by the power plants and also can help to reduce the consumption of fossil fuels. However, the output power from *wind power plants* (WPPs) is highly variable due to intermittent and variable wind speed, which imposes a major challenge on the functionality of wind power generators, and overall wind farms costs [2], [3].

The electric output power produced by a *wind turbine* (WT) can be controlled in two ways [2]: (i) changing the aerodynamic power (pitch angle controller) and (ii) control on the generator system (including power converters). However, the wind does not blow continuously and the wind generation is often described as intermittent but this stochastic consideration regarding the wind speed, as consequence the amount of electrical power generated by a WT can vary. It is true, even for modern wind turbines that include sophisticated controllers.

The dynamic behaviour of WT is an area well developed in several publications. Special attention has received operation of WT during power system disturbances such as network voltage sags [4], [5], [6], flickers [7], symmetrical and asymmetrical faults [8], [9] and fault ride through capability [10] as well as the possibility of network voltage instability [11], [12]. Even, the small signal stability of large power system including wind power has been evaluated in some publications [13], [14]. Dynamic behaviour of wind turbines under stochastic winds [15] is that has been poorly treated in the publications. In [15], the authors evaluate the dynamic behaviour of two different technologies of WT using the variability of the mechanical torques as assessment criteria.

Based on *Monte Carlo* (MC) type simulations, this paper presents an assessment of the operational risk associated to the output power variability and the voltage support capability of three different types of wind turbines commercially available.

This paper is organized as follows: Section II presents the models that can be used to represent the current wind turbine types in power system dynamic studies. Results of time-domain simulations are shown on Section III, the model's response to a measured wind speed sequence is analyzed, and the changes in power supply are discussed. Finally, Section IV concludes the research by stating that an efficient smart grid controller must be included to mitigate the impact of wind speed fluctuations on the output power from the wind power.

II. Wind Turbine Modeling

This section presents the models that can be used to represent the current wind turbine types in power system dynamic studies. These models consider only the low frequency phenomena (fundamental frequency component of voltages and currents) and they are used for electromechanical transient simulation only.

The three most important actual wind turbine concepts are [1], [2]: (i) *Fixed speed wind turbine* (FSWT) using *squirrel cage induction generator* (SCIG) directly connected to the grid (ii) *Variable speed wind turbine* (VSWT) using *doubly fed* (wound rotor) *induction generator* (DFIG) and (iii) VSWT using direct drive *synchronous generator* (SG). These concepts are depicted on Fig. 1. The largest machines tend to operate at variable speed whereas smaller, simpler turbines are of fixed speed [2].

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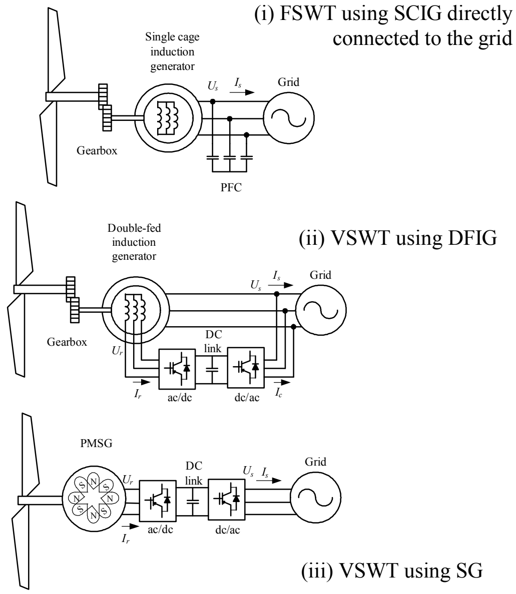

Fig. 1. Generating systems used in WT.

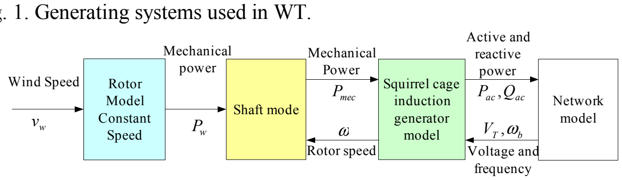

Fig. 2. General structure of tems FSWT using SCIG including the subsets and and their interactions [16].

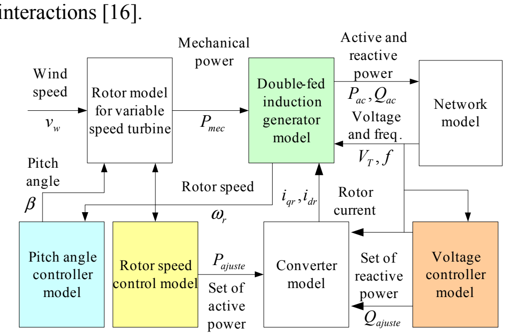

Fig. 3. General structure of tems VSWT using DFIG including the subsets and and their interactions [1].

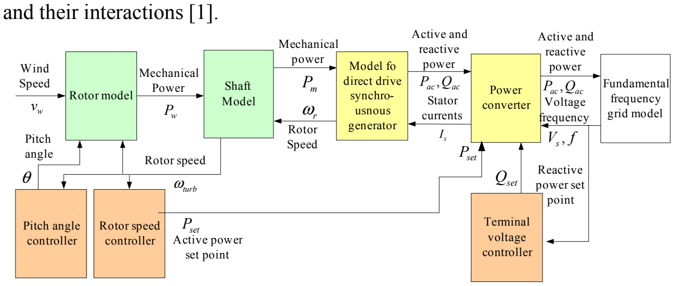

Fig. 4. General structure of typical VSWT using SG including the subsets and their interactions [1].

A. FSWT using SCIG

This WT type uses an (asynchronous) SCIG to convert the mechanical energy into electricity. The generator slip varies slightly with the amount of generated power and is therefore not entirely constant. However, because these speed variations are in the order of 1%, this wind turbine type is normally referred to as a constant-speed or FSWT.

The general structure of the FSWT model is depicted on Fig. 2, details and considerations regarding dynamic modeling, simulation and parameters for all the subsystems can be found on [1], [2], [17].

B. VSWT using DFIG

This WT type uses a DFIG instead of a SCIG. The stator winding of the *induction generator* (IG) is coupled to the grid, and the rotor winding to a power electronics converter, it is a back-to-back voltage source converter (VSC) with current control loops. Several publications deal with the dynamic modeling of this type of WT [18], [19]. Fig. 3 shows general structure of the VSWT using DFIG.

C. VSWT using SG

The direct-drive wind turbine works without a gearbox and it uses a low-speed multi-pole synchronous ring generator with the same rotational speed as the wind turbine rotor is used to convert the mechanical energy into electricity. The generator's stator is not coupled directly to the grid but to a power electronics converter. Fig. 4 depicts the general structure of a model of a VSWT with a direct-drive SG, mode details about dynamic modeling can be found on [19], [20].

III. Simulations and Results

In this section, the dynamic response of the three different types of wind turbines described on the previous sections is evaluated using time-domain simulations. All models are developed using *DIgSILENT Simulation Language* (DSL) and the dynamic response calculated using DIgSILENT® PowerFactory™ v14.0.525.1 [21]. The post-processing assessment is performed with MATLAB® [22] program developed by the authors. All simulations are performed using a personal computer based on Intel®, Core™ i7 CPU 2.0GHz, 8 GB RAM with Windows® 7 Home Edition 64-bit operating system.

To determine power fluctuations of one single wind turbine, one wind speed time series data set is sufficient. A 60.0 seconds time series of measured wind speed sequence is used for the assessment of the variability on the output power of WT, it is shown Fig 5. The wind speed time-series is selected because provides highly changing values around the nominal wind speed for the WT used for simulation.

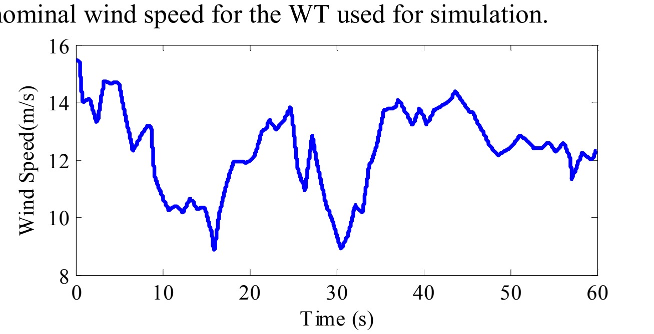

Fig. 5. Wind speed (v_w = 12.5258 m/s mean value) time series used in the simulation [17].

The wind speed time-series depicted on Fig. 5 is applied to a cluster of 33×2MW WT which is connected to a transmission system considered weak (see Fig 6), three cases has been simulated, one per each WT technology. The time-domain response for the terminal voltage (V_T), active power (P_T) and reactive power (Q_T) are plotted on Fig. 7.

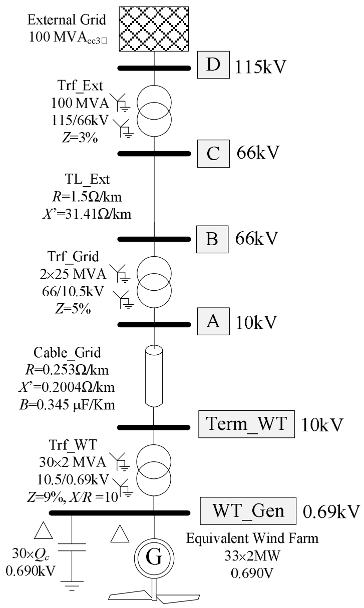

Fig. 6. Single-line diagram for the representative test system. Data of all components is depicted in the diagram. Qc: variable reactive power compensation.

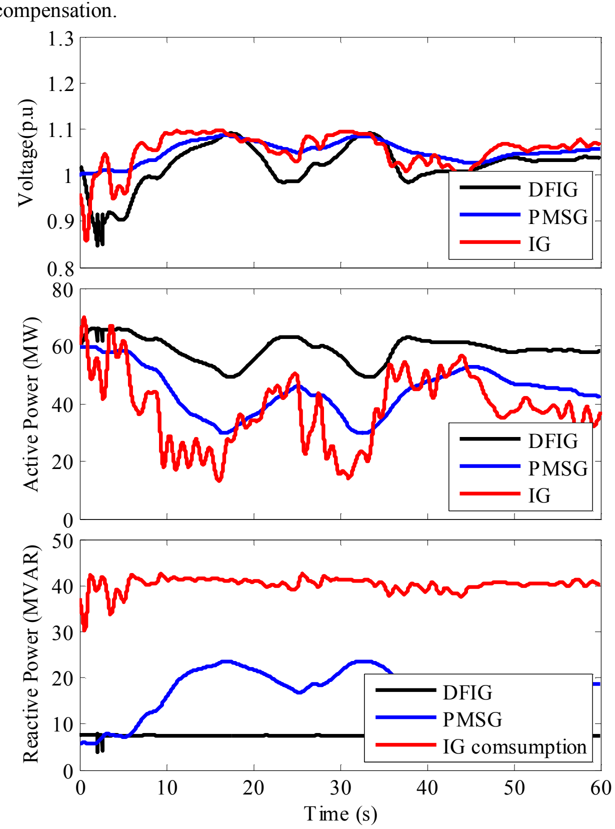

Fig. 7. Simulated responses to a measured wind speed. Starting from above: Terminal voltage, Active power output and reactive power output.The meaning of the curves is indicated in the graphs.

The variability of the electrical output on each technology is evident. FSWT exhibits a clear correlation between the wind sped and the all-electrical variables. The most important negative effect of low wind speed is the increase on the terminal voltage. It reaches potentially high levels that are out the regulation band (±5%). Reactive power consumption results the higher of all technologies evaluated, it is consequence of the operational requirements from the SCIG. VSWT exhibit a better performance in terms of all electrical variables than FSWT. Differences between DFIG and PMSG on the active power response are due different operation modes on the terminal voltage controller and its effect on the reactive power support. DFIG is operated at unitary power factor as consequence the reactive power generation is nearly to zero at the terminal voltage can change as consequence of active power production and its flow thorough the weak transmission system. The converter used on DFIG is set to produce only active power, as consequence, all the power produce by the Wt is converted in active power and fed into the AC grid. The converter used by the PMSG is providing voltage support that means the power produced by the WT is partially converted into active power and reactive power. The difference between PMSG and DFIG becomes larger at lower average wind speeds and becomes less significant at higher average wind speeds. This is due to better performance of the PMSG at partial power. The VSWT using PMSG exhibits the better dynamic performance considering the wind speed changes.

The changes on the short term wind speed on variability of the output WT variables is studied considering the *probabilistic density function* (PDF) on each electrical variable. Fig. 8, 9 and 10 show the PDF of terminal voltage, active power and reactive power respectively.

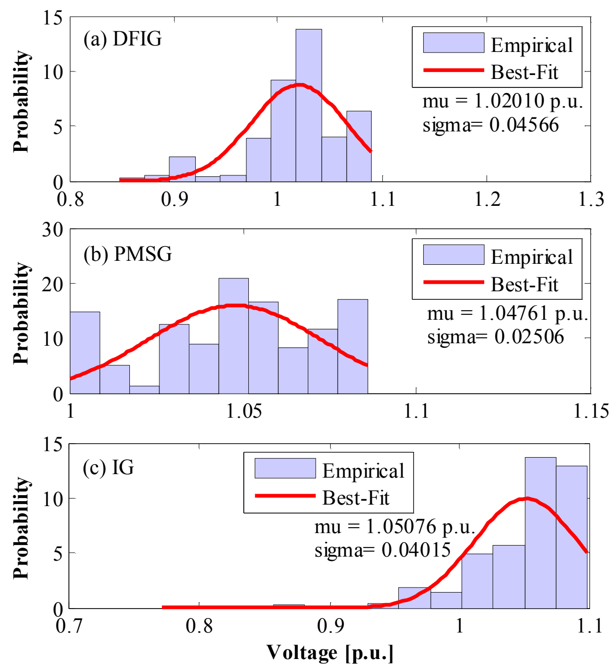

Fig. 8. PDF of the terminal voltage for the considered WT.

The empirical and normal PDF are plotter for each one of the considered. It is not a primary objective of this paper discuss about the fit goodness, otherwise conclusions about the variability on the electrical variables is the main concern.

The higher voltage levels and more changing voltage profile is found on the FSWT using SCIG, on the other hand the smallest variability is found on the VSWT using PMSG. The variability on the active power output on VSWT using DFIG is the smallest of all technologies evaluated and the SCIG exhibits the higher changes on the active power output. DFIG is operated at unitary power factor as consequence the variability on the reactive power generation is nearly to zero.

PMSG shows the larger variability of the reactive power output, it is consequence it is operating on variable power factor to compensate changes on terminal voltage during modification on the power flow on the weak transmission system. PDF of reactive power output on SCIG shows a relatively small value, it is consequence the reactive power consumption is directly related to the changes on the rotational speed as consequence of the wind speed changes.

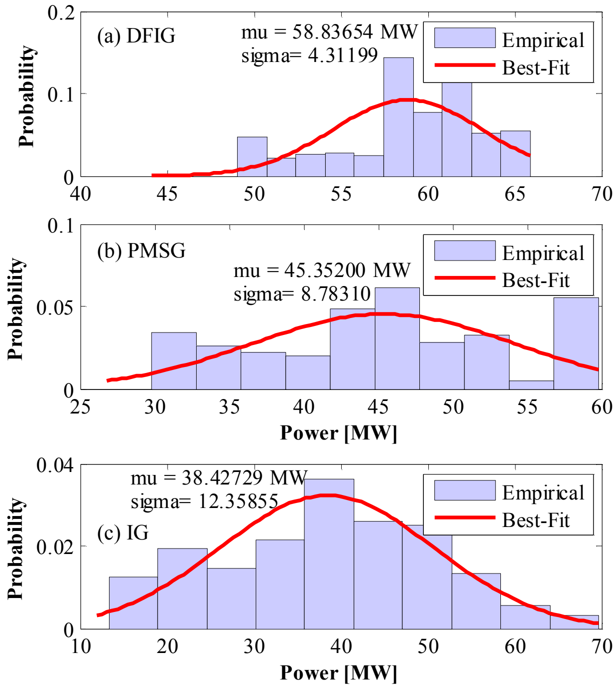

Fig. 8. PDF of the active power output for the considered WT.

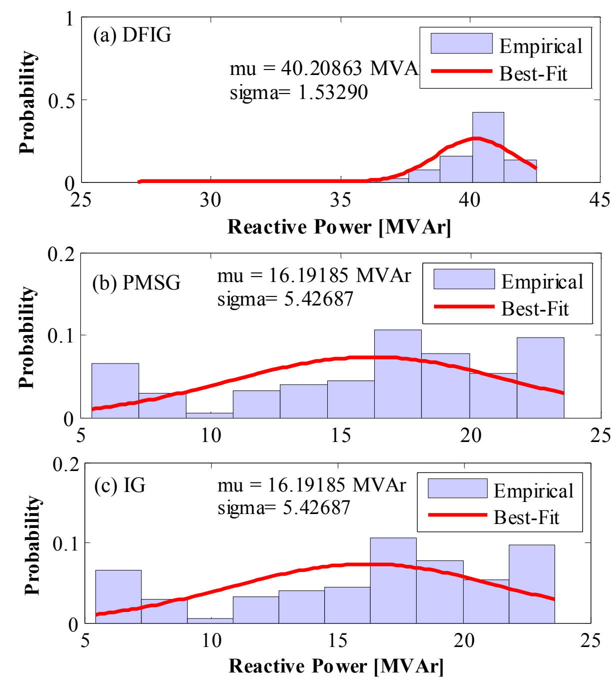

Fig. 9. PDF of the reactive power output for the considered WT.

The correlation coefficients are calculated for all electrical variables and the wind speed, the idea is to establish if there is a linear relationship between two variables while controlling for the effects of one or more additional variables. Correlation is a technique for investigating the relationship between two quantitative, variables and measures a linear association between them. The *Pearson correlation* coefficient is used measures the linear association between the variables analyzed in this paper. Table I, II, and III show the results of correlation analysis for voltage, active power, and reactive power.

TABLE I
CORRELATION ANALYSIS BETWEEN WIND SPEED AND THE TERMINAL VOLTAGES

		Wind Speed	SCIG	DFIG	PMSG
Wind Speed	Pearson Correlation	1	-0.601**	-0.711**	-0.778**
	Sig. (2-tailed)		0.000	0.000	0.000
	N	6447	6134	6127	6447
SCIG	Pearson Correlation	**-0.601****	1	0.600**	0.453**
	Sig. (2-tailed)	0.000		0.000	0.000
	N	6134	6134	6127	6134
DFIG	Pearson Correlation	**-0.711****	0.600**	1	0.620**
	Sig. (2-tailed)	0.000	0.000		0.000
	N	6127	6127	6127	6127
PMSG	Pearson Correlation	**-0.778****	.453**	0.620**	1
	Sig. (2-tailed)	0.000	0.000	0.000	
	N	6447	6134	6127	6447

** Correlation is significant at the 0.01 level (2-tailed).

TABLE II
CORRELATION ANALYSIS BETWEEN WIND SPEED AND THE ACTIVE POWERS

		Wind Speed	SCIG	DFIG	PMSG
Wind Speed	Pearson Correlation	1	0.813**	0.813**	0.769**
	Sig. (2-tailed)		0.000	0.000	0.000
	N	6447	6127	6127	6447
SCIG	Pearson Correlation	**0.813****	1	1.000**	.561**
	Sig. (2-tailed)	0.000		0.000	0.000
	N	6127	6127	6127	6127
DFIG	Pearson Correlation	**0.813****	1.000**	1	0.561**
	Sig. (2-tailed)	0.000	0.000		0.000
	N	6127	6127	6127	6127
PMSG	Pearson Correlation	**0.769****	0.561**	0.561**	1
	Sig. (2-tailed)	0.000	0.000	0.000	
	N	6447	6127	6127	6447

**. Correlation is significant at the 0.01 level (2-tailed).

TABLE III
CORRELATION ANALYSIS BETWEEN WIND SPEED AND THE REACTIVE POWERS

		Wind Speed	SCIG	DFIG	PMSG
Wind Speed	Pearson Correlation	1	0.330**	-0.010	-0.742**
	Sig. (2-tailed)		0.000	0.451	0.000
	N	6447	6134	6127	6447
SCIG	Pearson Correlation	**0.330****	1	0.041**	-0.212**
	Sig. (2-tailed)	.000		.001	.000
	N	6134	6134	6127	6134
DFIG	Pearson Correlation	**-0.010**	0.041**	1	.001
	Sig. (2-tailed)	.451	0.001		0.946
	N	6127	6127	6127	6127
PMSG	Pearson Correlation	**-0.742****	-.212**	0.001	1
	Sig. (2-tailed)	0.000	0.000	0.946	
	N	6447	6134	6127	6447

**. Correlation is significant at the 0.01 level (2-tailed).

The correlation coefficients based on Pearson presented on Table I demonstrated a significant negative correlation between the terminal voltage and the wind speed. Pearson's correlation coefficients for voltage and wind speed (SCIG: -0.601, DFIG: -0.711, PMSG: -0.778) are significant at the 0.01 level. It means there is a strong relationship between wind speed and voltage. Specifically, increases on the wind speed produce decrease on the terminal voltage and vice versa. The weak transmission system explains this effect, when the wind speed increases the output power increase (see Table II, SCIG: 0.813, DFIG: 0.813, PMSG: 0.769 significant at the 0.01 level, see Fig. 11) and the voltage drop across the transmission line decreases the terminal voltage at the WT. Table III demonstrates there is no relationship between wind speed and reactive power in the case of DFIG (correlation coefficient -0.010 is not significant at the 0.01 level). It is because the DFIG is operated at unitary power factor as consequence the reactive power generation is independent of the wind speed.

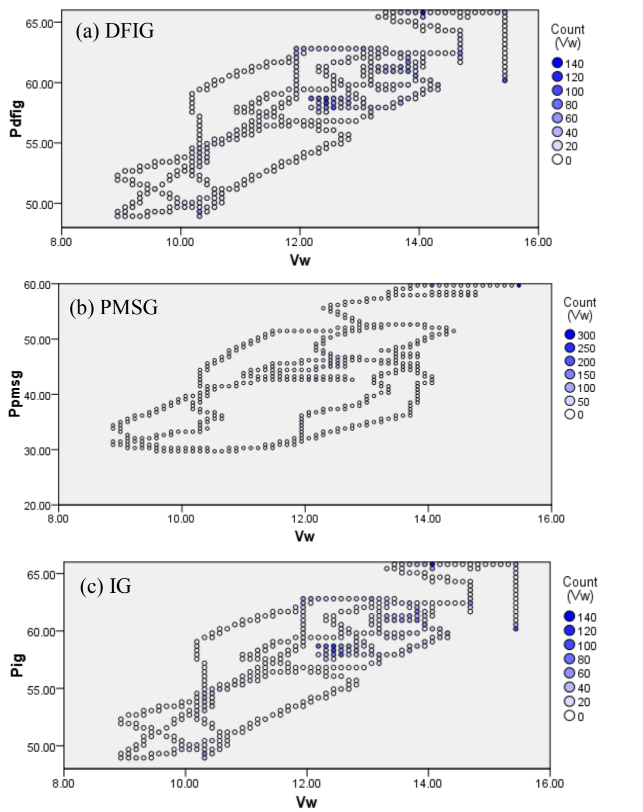

Fig. 11. Scatter-plots of active power output versus wind speed for the considered WT.

IV. Conclusions

This paper presents an assessment of the variability on the output power of wind three different types of wind turbines commercially available. Time-domain simulations obtained from DIgSILENT® Power Factory™ are used to evaluate the dynamic response of terminal voltage, active power and reactive power on the wind turbines technologies considered. The assessment of the variability is performed using Monte Carlo type simulations and statistical analysis: probability density function, Pearson correlation coefficient and scatter plots.

Results of this assessment demonstrated: (i) a significant negative correlation between the terminal voltage and the wind speed, increases on the wind speed produce decreases on the terminal voltage and vice versa, (ii) the weak transmission system has a booster effect on this correlation, (iii) strong positive correlation is found between wind speed and the output power, and (iv) terminal voltage controller can change the correlation coefficient, in this paper DFIG operating at unity factor produce no significant correlation between wind speed and reactive power.

In addition, these remarks highlight the need of global coordinated the reactive power control for wind power plants. Such a scheme would receive commands from the transmission or distribution system operators, as well as measurements from PMU devices (i.e. voltages and currents) and should adaptively controls the turbines by setting the corresponding VQ reference values.

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VI. Biographies

Francisco M. Gonzalez-Longatt (S'02, M'05, SM'08) was born in Cagua, Venezuela, on July 30, 1972. is currently a Lecturer in Electrical Engineering in the Faculty of Engineering and Computing, University of Coventry and he is Vice-President of Venezuelan Wind Energy Association. His academic qualifications include first Class Electrical Engineering of Instituto Universitario Politécnico de la Fuerza Armada Nacional, Venezuela (1994), Master of Business Administration (Honors) of Universidad Bicentenaria de Aragua, Venezuela (1999) and PhD in Electrical Power Engineering from the Universidad Central de Venezuela (2008). He is former associate professor on Electrical engineering Department of Universidad Nacional Politécnico de la Fuerza Armada Nacional, Venezuela (1995-2009). He was formerly with the School of Electrical and Electronic Engineering, The University of Manchester as Postdoctoral Research Associate (2009-2011). His main area of interest is integration of intermittent renewable energy resources into future power system and smart grids.

José L. Rueda (M’10) was born in 1980. He received the Electrical Engineer diploma from the Escuela Politécnica Nacional (EPN), Quito, Ecuador, in 2004 and the Ph.D. degree in electrical engineering from the Universidad Nacional de San Juan, San Juan, Argentina, in 2009. From September 2003 until February 2005, he worked in Ecuador, in the fields of industrial control systems and electrical distribution networks operation and planning. Currently, he is a research associate at the Institute of Electrical Power Systems, University of Duisburg-Essen. His current research interests include power system stability and control, system identification, power system planning, probabilistic and artificial intelligence methods, smart grids, heuristic optimization, FACTS devices and wind power.

Dimitar Bogdanov was born in Sofia, Bulgaria, on June 11, 1974. He graduated from the Technical University - Sofia, and received Master degree from the same university in 1998. He has received a PhD degree from the same university in 2009 in Electrical Power Engineering. His field of interest includes electrical relay protections and automation, electrical networks, nuclear power plants (electrical and technological aspects), renewable energy sources (electrical aspects). Currently he is assistant professor in the Faculty of Electrical Engineering of the Technical University – Sofia. He works on studies related to improvement of the protection schemes for connection of renewable sources of energy to the grid.