Title	A steady-state voltage stability analysis of power systems with high penetrations of wind
Authors(s)	Vittal, Eknath; O'Malley, Mark; Keane, Andrew
Publication date	2010-02
Publication information	IEEE Transactions on Power Systems, 25 (1): 433-442
Series	Electricity Research Centre (ERC)
Publisher	IEEE
Link to online version	http://dx.doi.org/10.1109/TPWRS.2009.2031491
Item record/more information	http://hdl.handle.net/10197/2350
Publisher's version (DOI)	10.1109/TPWRS.2009.2031491

A Steady-State Voltage Stability Analysis of Power Systems With High Penetrations of Wind

Eknath Vittal, *Student Member, IEEE*, Mark O'Malley, *Fellow, IEEE*, and Andrew Keane, *Member, IEEE*

Abstract—As wind generation begins to contribute significantly to power systems, the need arises to assess the impact of this new source of variable generation on the stability of the system. This work provides a detailed methodology to assess the impact of wind generation on the voltage stability of a power system. It will also demonstrate the value of using time-series ac power flow analysis techniques in assessing the behavior of a power system. Traditional methods are insufficient in describing the nature of wind for steady-state analyses, and as such, a new methodology is presented to address this issue. Using this methodology, this paper will show how the voltage stability margin of the power system can be increased through the proper implementation of voltage control strategies in wind turbines.

Index Terms—Power flow analysis, time series, voltage control, voltage stability, wind power generation.

I. INTRODUCTION

WIND generation levels are growing in power systems around the world in response to increased pressure to reduce CO_2 levels and dependence on fossil fuels. Given the increase in wind generation and the highly variable nature of the resource, the stability of power systems will be impacted significantly. Traditional techniques are limited in capturing this variable behavior and new study techniques and methodologies will be required to properly quantify the stability of a power system.

The most common wind turbine technology installed in systems today is the doubly-fed induction generator (DFIG) machine. The older fixed speed squirrel cage induction generator (FSIG) machines are still in service, but it is uncommon for them to be utilized in new wind farm installations. Both machines contribute asynchronous power to the system, and as such, a large penetration of wind generation will impact the stability of the system, particularly the voltage stability of the system. Since the DFIG is the predominant technology installed in wind farms, this paper will focus on the changes in a power system's steady-state voltage stability in response to an increase in DFIG wind generation. The main advantage of the DFIG turbine is the ability to provide reactive power control without installing additional capacitive support. The DFIG can be operated in one of two control modes; firstly, fixed power factor (PF) control, where the turbine controls reactive power production in order to achieve a specified power factor; secondly, terminal voltage control, where the reactive power is controlled to meet a target voltage. Using these two control schemes, this paper will assess the impact of DFIG reactive power control on the system's voltage stability margin.

Various technologies and strategies have been developed in order to implement terminal voltage control. Work in [1] has shown the capabilities of reactive power control in DFIGs using combinations of grid side control and rotor side control. In [2], a case study on the Danish power system demonstrated the importance of reactive power and voltage control in maintaining system stability. In [3], PI-based control algorithm is described and implemented to manage the reactive power out of a DFIG wind farm. A coordinated voltage control strategy is applied using a DFIG wind farm in [4]. In [5], a novel algorithm for direct active and reactive power control was implemented. In [6], several generalized methods of reactive power control are provided.

Work in [7] and [8] showed that increased voltage control will improve the probability that bus voltage will lie within a specified range and improve voltage performance within the power system. Voltage performance refers to achieving desired voltages within a specified operating range, and while the improvement in voltage performance indicates increased system robustness, it is not a true measure of the power system's stability. In assessing a system's stability, a measure such as a power-voltage (PV) curve is a much better indicator of voltage stability [9].

In order to properly assess the voltage stability and in particular the voltage stability margin, a detailed ac power flow analysis of the transmission system is necessary. However, there are several issues that arise when completing power flow studies involving wind generation. As power flow studies have traditionally focused on a single operating point in the system, challenges arise in assessing the true impact of wind generation on a power system. In particular, the variable nature of wind necessitates new techniques to assess its impact.

The use of statistical techniques to analyze power systems is a well-established concept known as probabilistic load flow (PLF), and has been successfully modified to model wind. The foundation for PLFs was established in [10] and showed how transforming the input variables into random variables (RV), a resulting set of output RV can be achieved. Generally, the form of both the input and output RV is given as a probability density function (PDF), and will relay information about several operational aspects of the power system. In [11]–[13],

the focus was on the traditional operation of power systems, and required nonlinear optimization methodologies in order to achieve a solution. As a result, additional techniques must be implemented in PLFs when incorporating a variable resource such as wind.

In [14] and [15], PLFs were used to assess system reliability with large levels of wind generation, while [16] examined the transmission planning aspect of power systems by incorporating a sequential time-series along with a PLF in order to maximize the firm connection of wind generation into the system. In [17] and [18], the aspects of probabilistic load modeling and the incorporation of wind generation in power systems was examined. Since in PLF analyses, the historical data input is treated as an RV, it will include only the probability that the worst-case point will be captured during the simulation and that the system is secure for all contingencies.

In comparison to PLFs, time-series load flow simulations will deterministically model the power system and will explicitly capture the system response at the worst-case point. Studies have previously applied the time-series approach to model power systems. In [19], it was shown how time-series power flows can be applied to systems to determine overload conditions and specify non-firm connection agreements for new generators on the distribution system. In [20], a time-series analysis was implemented in modeling variable resources such as solar photovoltaic and gas-fired micro-CHP (cogeneration) in low voltage networks. Both studies examined the application of historical time-series data on the distribution level of the power system. Using a time-series data set for wind speeds and loads for multiple years, this paper will analyze the data *a priori*, and build a sequential simulation around the single worst-case point contained in those years, called a time-series power flow (TSPF) for a future power system at the transmission level.

By utilizing time-series data as the input, the worst-case point within the data set will be deterministically modeled. This allows the simulation to maintain the correlation between the wind speeds and load levels seen throughout the year. Since this is a sequential simulation that models the variability of wind generation in a power system, it is necessary to maintain the balance between the changing generation and the load in the system. This will be achieved by re-dispatching the conventional units in the system using a merit-order economic dispatch. It is also crucial that the correct units are scheduled to be online during the period of simulation. As such, a unit commitment is required to determine the online plants during the worst-case point, while taking into consideration the forced outage rates and availability of the units.

By incorporating ac power flow along with economic dispatch and unit commitment, this paper will produce a realistic simulation of a transmission system that captures the variable behavior of the wind energy resource that will provide insight into the system's steady-state voltage stability. It will be divided as follows: Section II will describe the overall methodology associated with the TSPF analysis. Section III provides an overview of the test system on which the methodology was applied. Section IV will present the results and provide a discussion about their implications, and Section V draws conclusions from the results.
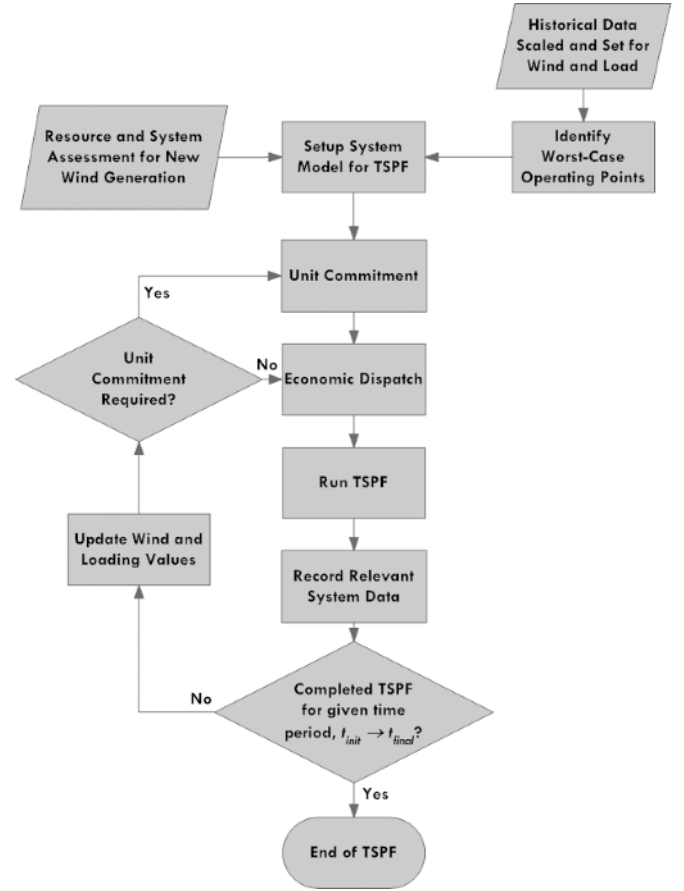

Fig. 1.   Flow chart describing the methodology used in the analysis.

II. METHODOLOGY

This section will develop a methodology for completing a TSPF analysis based on an analysis of time-series wind and loading data, and is described in the flow chart presented in Fig. 1. Each element in the flow chart represents a critical aspect of the methodology and will be described further in the following subsections.

The analytical description of the power flow used in these simulations is given in (1) [21]. The P_i and Q_i values are updated every time-step from t_{init}, the starting time of the simulation, to t_{final}, the ending time of the simulation time-period. The values of P_i and Q_i are used to solve for voltage, V (2) and angle, θ (3). It should be noted that in (1), the initial voltage and angle value used to solve the power flow come from the previous time-step, $t - 1$. This aids in convergence and simulation time and is completed for the n buses in the system:

$$\begin{bmatrix} \Delta P_1 \\ \Delta Q_1 \\ \vdots \\ \Delta P_n \\ \Delta Q_n \end{bmatrix} = \begin{bmatrix} \frac{\partial P_1}{\partial \theta_1} & \frac{\partial P_1}{\partial |V_1|} & \cdots & \frac{\partial P_1}{\partial \theta_n} & \frac{\partial P_1}{\partial |V_n|} \\ \frac{\partial Q_1}{\partial \theta_1} & \frac{\partial Q_1}{\partial |V_1|} & \cdots & \frac{\partial Q_1}{\partial \theta_n} & \frac{\partial Q_1}{\partial |V_n|} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \frac{\partial P_n}{\partial \theta_1} & \frac{\partial P_n}{\partial |V_1|} & \cdots & \cdots & \cdots \\ \frac{\partial Q_n}{\partial \theta_1} & \frac{\partial Q_n}{\partial |V_1|} & \cdots & \cdots & \cdots \end{bmatrix} \begin{bmatrix} \Delta \theta_1 \\ \Delta V_1 \\ \vdots \\ \Delta \theta_n \\ \Delta V_n \end{bmatrix} \quad (1)$$

$$|\mathbf{V}| = \begin{bmatrix} |V_2| \\ \vdots \\ |V_n| \end{bmatrix} \quad (2)$$

$$\boldsymbol{\theta} = \begin{bmatrix} \theta_2 \\ \vdots \\ \theta_n \end{bmatrix}. \tag{3}$$

A. Importance of Time-Series Analysis and Historical Data

Traditionally, the worst-case operating point of the system generally occurs when the transmission system is most stressed (maximum load) or when generation is at a minimum and system voltages are much lower. These two scenarios are when transmission overloads and low voltage collapse are most probable. Prior to wind becoming a significant proportion of power system generation portfolios, the worst-case operating point was easily identified based on traditional weather and loading patterns.

The methodology established in this paper approaches the problem from a different perspective in comparison to PLFs. By analyzing sufficient time-series data pre-simulation, the data themselves are reduced to capture the single worst-case operating point and simulated around that point for a shorter period of time. This reduction of data reduces computation time, and allows for a robust assessment of the power system's voltage stability under high penetrations of wind generation. It is important to make sure that the loading and wind power output data are chronologically synchronized in order to ensure it captures the complex underlying relationship between wind and load. By identifying the worst-case point for multiple years of data and directly inputting that into a TSPF, a more thorough analysis is possible and a true measure of a system's stability and robustness can be realized.

In high wind penetration systems, the worst-case operating point for voltage stability studies occurs when wind generation serves the largest proportion of the system's demand, and system stability support mechanisms are at a minimum. Transmission overload studies would focus on the point where wind generation and demand were the greatest and the transmission system is the most stressed. Frequency stability studies would focus on the period when spinning reserve and inertial support is at a minimum.

B. Resource Analysis and System Model Setup

The improvement in bus voltage performance due to the addition of wind generation, in particular when utilizing the terminal voltage control capability on DFIG wind turbines, is a highly localized phenomena. This is due to the fact that the terminal voltage control will most significantly impact the region in which the wind generation is located. More significant than the locality of the control, is the power output dependence on the wind speeds of a particular region. Using the same average wind power output across an entire system will not capture the true variability of the resource as one area of the system will not see the same wind speeds as another. As a result, the use of regionally specific wind power output data for different areas of the system is required.

Using an appropriate resource assessment will aid in the placement of wind farms in the test system and provide the highest level of accuracy in the results of the simulations. A thorough assessment will be based on the transmission capacity of the system as well as the availability of high annual wind speeds. By utilizing a resource assessment in conjunction with geographically diverse wind power output data, the most realistic simulation can be achieved that captures the correlation between wind and load for any given time.

The resource analysis will provide wind power outputs and allow for the calculation of new power output levels from the farms in the system. In (4), the regional wind power output data, P^{region}, is used with the installed wind capacity, C^{wind}, to build wind power matrix, P^{wind}. This matrix is updated every time-step and represents the variability of the wind resource:

$$\begin{bmatrix} P_1^{wind} \\ \vdots \\ P_n^{wind} \end{bmatrix} = \begin{bmatrix} P^{region} \cdot C_1^{wind} \\ \vdots \\ P^{region} \cdot C_n^{wind} \end{bmatrix}. \tag{4}$$

C. Balancing Load and Variable Generation

The main difficulty in achieving a realistic simulation that incorporates significant levels of wind generation is capturing the variability of the wind resource. Using historical time-series data captures the variability of the wind; however, it presents significant challenges in an ac power flow model.

As wind farm power output and system loading changes at each time-step in the simulation, action must be taken in order to maintain system-wide load/generation balance. In a TSPF, the commitment and power output of the conventional generation units are inter-temporally dependent, i.e., the past state of the unit will impact any future state. However, there are two distinct levels of this inter-temporal dependence; the first is between each individual time-step. As wind generation and system loading are updated continuously, load/generation balance will need to be maintained using an economic dispatch algorithm [21]. This allows the online conventional generation to ramp up or ramp down output levels in order to achieve a system balance.

The second issue arises in the determination of which conventional units are online and available to ramp their output levels. This is dealt with by using the wind power output and loading data in conjunction with a unit commitment algorithm to determine a commitment schedule [22]. This takes into account the minimum start-up times and up and down times of the generating units and makes sure that a generator does not start-up or shut-down outside of its operating limitations. A unit commitment can be completed as often as necessary based on the make-up of the system's generation portfolio. Using economic dispatch and unit commitment together will facilitate load/generation balance within the system as wind generation varies across the system.

By using (4), in conjunction with an economic dispatch, (ED), and unit commitment algorithm, (UC), the power output from the conventional units in the system is determined (5). In (5), f represents a function of the UC, ED, and P^{wind}. Next, by combining the power outputs from P^{conv} and P^{wind},

a matrix containing the power generated at all units in the system is achieved (6):

$$\begin{bmatrix} P_1^{conv} \\ \vdots \\ P_n^{conv} \end{bmatrix} = f \left(UC, ED, \begin{bmatrix} P_1^{wind} \\ \vdots \\ P_n^{wind} \end{bmatrix} \right) \qquad (5)$$

$$\begin{bmatrix} P_1 \\ \vdots \\ P_n \end{bmatrix} = \begin{bmatrix} P_1^{wind} \\ \vdots \\ P_n^{wind} \end{bmatrix} + \begin{bmatrix} P_1^{conv} \\ \vdots \\ P_n^{conv} \end{bmatrix}. \qquad (6)$$

Utilizing (6) and the desired terminal voltage set-points for the voltage controlled buses in the system, V^{term}, the reactive power levels at all the machines in the system can be determined (7). V^{term} will vary based on the type of voltage control algorithm implemented. If the operator desires to achieve secondary or tertiary voltage control a broader area-wide or regional control scheme must be implemented [23], [24]. In (7), g represents a voltage control algorithm that behaves similar to a simple excitation system [25] found in conventional synchronous machines. Voltage is controlled to a specified control level, and implemented locally to achieve a specific target voltage at a particular bus. Finally, the determination of the active power (6) and the reactive power (7) allows for the solution of (1), and the determination of the voltage levels (2) and angles (3) for all the buses in the system:

$$\begin{bmatrix} Q_1 \\ \vdots \\ Q_n \end{bmatrix} = g \left(\begin{bmatrix} P_1 \\ \vdots \\ P_n \end{bmatrix}, \quad \begin{bmatrix} V_1^{term} \\ \vdots \\ V_n^{term} \end{bmatrix} \right). \qquad (7)$$

D. Data Analysis and PV Curves

Voltage stability is a crucial component of system stability and will be impacted with the addition of a variable generation resource such as wind generation. PV curves are an indication of a system's voltage stability as active power injection increases in the system [9].

In the case of this analysis, the active power injection is given by the wind generation produced at each bus and the voltage stability is reflected in the bus voltages at the varying voltage levels. As the control strategy shifts from fixed PF to terminal voltage control, the bus voltages will vary greatly as the wind power output changes. The use of the TSPF analysis allows the PV curves to represent the changes in wind power output and the resulting voltages that occur due to the variance in the power generation.

The behavior of PV curves and the relationship to voltage stability is a well-established concept [9], [26]. The PV curve is influenced by the PF of the system. More inductive PFs limit the power transfer capability of the bus, and lower the value at which the critical voltage is reached. The opposite is true for capacitive PFs, where the critical voltage or the point of voltage collapse is extended and allows for increased power transfer in the system. This extension of the critical voltage point is known as the voltage stability margin, and is a measure that directly reflects an increase in voltage stability in the power system and indicates that the system is more secure. Since the maximum

power transfer for a particular bus is limited to the size of the connected wind farm, the voltage value reached at maximum power will indicate an increase or decrease in the voltage stability margin of a bus.

III. IRISH ELECTRICITY SYSTEM MODEL

This section will describe the application of the method developed in Section II to the 2013 all-island Irish power system. The Irish system serves as an excellent test system for power systems studies, especially those that involve wind generation. The small size and islanded nature of the system provide heightened responses to both voltage and frequency studies that can provide valuable insight into the future behavior of larger power systems.

As wind generation increases, several issues regarding stability and reserve will come to the forefront of operating the Irish system with high penetrations of wind. Large penetrations of wind generation will displace significant portions of dynamic reactive power support and spinning inertia. This will require study of not only the voltage stability impacts, but also the need for increased reserve requirements for secure system operation [27]; changes in unit commitment schedules to handle the uncertainty of wind and manage its variability [28]; improvements in the methods of frequency control and regulation [29], [30]; and increased accuracy in capacity value calculations [31].

The model used in this analysis is the full island model, meaning that the system includes both the Northern Ireland (NI) power system along with the Republic of Ireland (ROI) power system. It is important to note that these two synchronous systems interconnect wind generation at two different voltage levels; the NI system interconnects wind generation at the 33-kV level while the ROI system interconnects at the 20-kV. In the all-island model, the transmission system is considered to be at voltages greater than and including 110-kV, while the distribution system lies at all voltages below the 110-kV level. Wind generation was added to the system based on the resource analysis compiled in the All-Island Grid Study [32]. Overall, 2188 MW of wind generation was installed across the island. Of this, 1930 MW was DFIG generation, while 258 MW were existing FSIG machines.

A. Identification of Worst-Case Scenarios

In the ROI and NI system, the two loading scenarios that are traditionally incorporated into power flow studies are the Summer Night Valley (SNV) and the Winter Peak (WP). The SNV represents the minimum loading and generation operating point. Traditionally this is where the system is most susceptible to low voltage collapse and occurs during the warm summer night generally between July and August. The WP is the maximum loading and generation operating point and is when the transmission system is most severely stressed. The WP occurs during the colder winter evenings from December to January. Studies around these two operating points were sufficient in determining the Irish system's steady-state stability. However, as wind penetration increases, the worst-case operating point shifts. Often, it will not coincide with the traditional loading scenarios and an analysis of the time-series data needs to be completed to determine the new worst-case point.

TABLE I
CRITICAL OPERATING POINTS IN THE IRISH SYSTEM

Date	Load (MW)	Wind Penetration (Instantaneous Penetration)
May 5, 2004	2564	73%
January 1, 2005	2374	79%
October 31, 2006	2491	86%
May 19, 2007	2596	67%
July 1, 2008	2417	76%
December 15, 2006 (WP)	5848	2.4%

For this study, 15-min interval wind power output and loading data were gathered for several farms across the country from 2004 until 2008. The number of farms ranged from seven in 2004, to 74 in 2008. The 15-min wind power output data were deemed sufficient in order to assess the voltage stability of the system for a time-series power flow simulation based on the definition of long-term, small-disturbance voltage stability [33]. In [33], this type of voltage stability encompasses the small-disturbances in the system, such as changes in load or generation over the slower acting equipment in the system, such as tap-changing transformers, thermostatically controlled loads, and generator current limiters.

It should be noted that the time-series data used in these simulations are based on the wind power output of the farms rather than wind power output data for particular regions. The use of wind power output from actual farms accounts for several characteristics that may be lost if only wind speed data were used. These include the topology of the farm and the aggregation of wind turbines and allows for the linear scaling procedure used to grow the system's wind generation levels in these simulations. In a dynamic simulation, the need for an appropriate aggregation technique would be necessary [34].

For each year, the loading data were scaled to meet loading levels in 2013 using a 2.6% growth factor [31]. For each data point, the instantaneous wind penetration, i.e., the amount of load served by wind generation, was calculated and can be seen along with the corresponding system load in Table I.

As seen in Table I, the worst-case points vary from year to year and are not contained to the SNV or WP of the respective years. Table I demonstrates the need to analyze a power system over multiple years in order to determine when to run the studies. The worst-case point in each year moves from season to season between the years and has little correlation with traditional loading patterns. This study will focus on the October 31, 2006 point, as this is the worst-case operating point in the years between 2004 to 2008. Also included in Table I is the WP loading and penetration from 2006. As seen in the table, the wind penetration seen on October 31 is dramatically higher than the 2.4% instantaneous penetration for the WP of the same year.

The probability density functions for instantaneous wind penetration were calculated for each year, and can be seen in Fig. 2. Fig. 2 demonstrates that the five years of data have similar distributions and the point observed in this study, October 31, 2006, is the worst-case operating point in terms of maximum wind penetration during that five-year period. Rather than combining
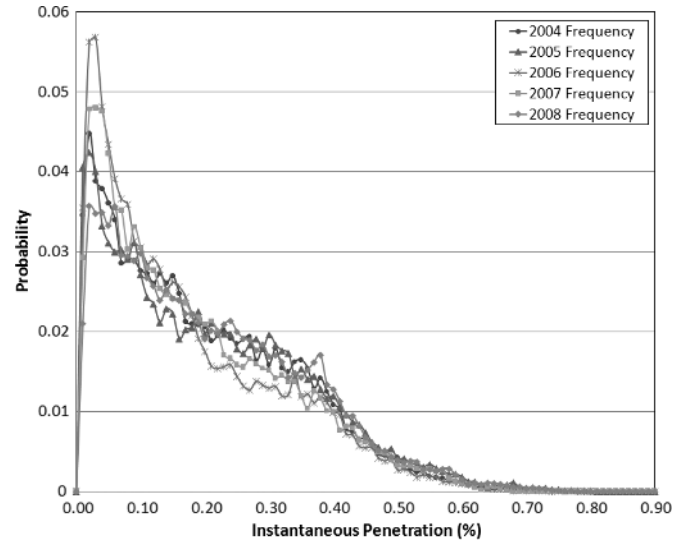

Fig. 2. Probability density function for instantaneous wind penetration for 2004–2008.

TABLE II
2013 IRISH POWER SYSTEM WIND CHARACTERISTICS

Case	Loading Scenario	Max. Wind (MW)	Mean Wind (MW)	Min. Wind (MW)
A & B	Oct. 31, 2006	2051	649.2	13.14
C & D	WP	1998	770.1	10.39

the multiple years of data, into a single probabilistic time-series, the methodology used in this paper deterministically simulates around a single point.

There are many more high wind days included in the two-week simulation period in October, and as such, the simulations contain many other extreme operating points of the system above the 79% level seen on January 1, 2005. The loading scenario around October 31, 2006 was compared to the traditional worst-case study for a given year, the WP. This allowed for a proper comparison of traditional steady-state techniques and the methodology presented in this paper.

B. Implementation of Voltage Control on the Irish Power System

DFIGs have two main control schemes: terminal voltage control and fixed PF control. In this paper, four TSPF cases were simulated: cases A, B, C, and D, two for each of the two selected loading scenarios; October 31, 2006 and the WP from 2006 were all scaled and applied to the 2013 Irish power system. The wind penetration levels and the loadings scenarios associated with each of the cases A, B, C, and D can be seen in Table II. In Table II, although the WP has a higher average level of wind generation, the load demand in the system at this time is much greater. As a result, the wind serves a smaller proportion of the demand in the WP scenario. This demonstrates the need to identify the appropriate loading scenario for study when examining systems with high penetrations of wind.

In all four cases, transmission level voltage control was implemented by DFIG farms larger than 35 MW. Based on recommendations and practice of the Irish transmission system oper-
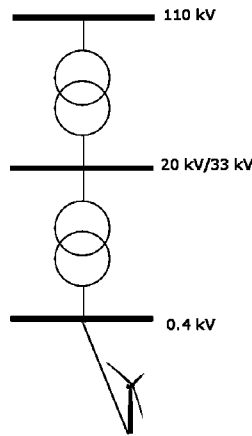
Fig. 3.   One-line diagram of the transformer connections for wind farms in the all-island Irish power system.

ator [35], 35 MW was deemed to be a large enough wind farm to cope with the MVA losses across the two levels of transformers through which wind farms were connected to the transmission system. These farms were operated from 0.95 PF for Q_{max} and 0.9 PF for Q_{min}, providing a range of reactive power from 11.50 MVAr to -16.95 MVAr for 35 MW farms. These values were scaled based on the size of the farm. Farms below 35 MW did not have the required reactive power capabilities to provide sufficient control at the 110-kV level. In the test system, there were 973.90 MW of DFIG generation capable of providing transmission level control.

Wind farms were modeled as follows: The turbines were first aggregated at a low voltage, 0.4 kV, collector bus. This bus was then connected through a transformer to a distribution voltage level bus, generally 20 kV in the ROI and 33 kV in NI. It was then connected to the transmission system through another transformer, going from the distribution level to the transmission level of 110 kV. A diagram representing the general method of connection of the wind farms can be seen in Fig. 3. Farms larger than 35 MW controlled the terminal bus voltage of the 110-kV bus in all the cases. However, in the cases where distribution level control was implemented, the 20-kV bus became the terminally controlled bus. Along with the operation of the transmission connected wind farms, fixed speed turbines were operated at a fixed 0.95 inductive PF in all four cases. As such, there is 258.44 MW of wind generation that is never controlled.

The control varied between the rest of the DFIG wind farms smaller than 35 MW. In cases A and C, no voltage control was implemented and the DFIG wind farms operated using a fixed 0.95 inductive PF. In cases B and D, DFIGs utilized the voltage control feature and applied terminal voltage control at the distribution level bus of 20 kV or 33 kV. The distribution of voltage control strategies in DFIG wind turbines for the four study cases can be seen in Table III.

C. Unit Commitment and Economic Dispatch

In order to achieve a load/generation balance between each time-step of the TSPF, a unit commitment and economic dispatch was necessary. Using the WILMAR planning tool [28],

TABLE III
WIND TURBINE CONTROL DISTRIBUTION

Case	Terminal Voltage Control (MW)	0.95 PF Inductive (MW)
DFIGs at fixed PF (A & C)	973.90	1214.55
DFIGs controlled (B & D)	1930.01	258.44

[36], along with the corresponding time-series data for load and wind, a unit commitment schedule was developed. The unit commitment schedule determined the units that would be available during a particular day.

The generation load balance between the 15-min time-steps required an economic dispatch. This was accomplished using the automated economic dispatch application built into PSS/E by Siemens PTI [37]. Heat rate curves for each of the conventional units in the system were written into the economic dispatch application and based on the unit commitment schedule provided the load/generation balance between each time-step [36].

D. Data Recording and Analysis

Four two-week periods were simulated for a total of 5376 individual power flow analyses. The voltage at all of the 110-kV, 33-kV, and 20-kV buses at which wind generation was interconnected at was recorded along with the power from each wind farm for every power flow. As such, for each two-week period, 1344 data points were recorded for the bus voltage and wind power output. From these data records, PV curves were constructed at the varying bus voltages that allowed for the determination of the system's steady-state voltage stability.

IV. RESULTS AND DISCUSSION

The main application of this methodology is to obtain PV curves that provide insight into the voltage stability margin of the Irish system.

For large farms that were connected directly to the transmission system, the goal was to control the terminal voltage of the 110-kV bus at a specific target voltage. Whereas wind farms that connected in the distribution system (below the 110-kV level) controlled at either the 33-kV or the 20-kV level, the goal was to improve the stability margin at the 110-kV level. The reasoning behind this was that higher and more predictable voltages in the distribution system would provide greater benefit for the transmission system.

In the current operation of wind turbines in the Irish system, large levels of reactive power are consumed by the distribution system in order to operate the wind farms at 0.95 inductive PF. This draws large levels of reactive power resources away from the transmission system, thus negatively impacting the transmission level voltages. To illustrate this result, the bus observed in this section has three DFIG wind farms connected totalling 95 MW. As such, control at each farm is applied at the 20-kV distribution bus.

A. Cases A and B: October 31, 2006

The plots in Figs. 4 and 5 show the same 20-kV bus under the two different voltage control scenarios for the two week period
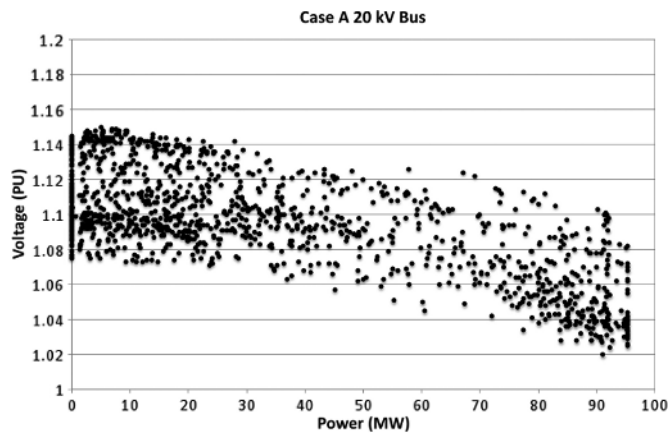
Fig. 4. The 20-kV bus PV curve for Case A, October 31, 2006. Since the DFIGs are operated at a 0.95 inductive PF, as the power output from the wind turbine increases, the bus voltage begins to drop.
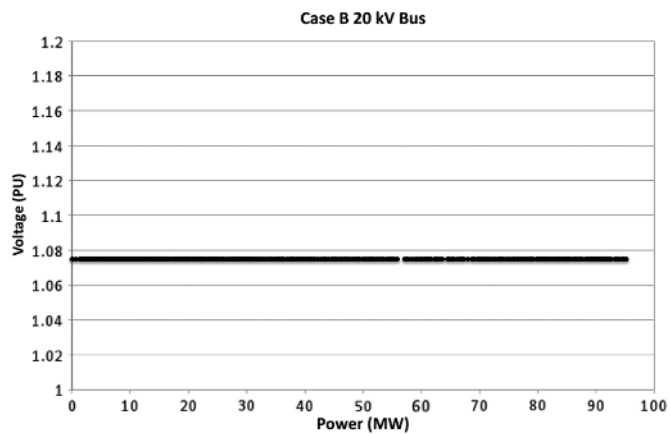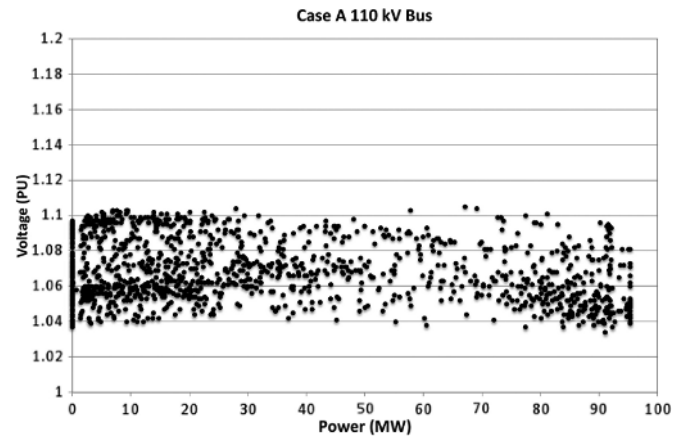

Fig. 6. PV curve for the 110-kV bus connected to the 20-kV bus for Case A, October 31, 2006. Here the voltage begins to decrease as power output of the wind farm increases.

Fig. 5. The 20-kV bus PV curve for Case B, October 31, 2006. Now the PV curve is drastically different. Terminal voltage control is enabled in all DFIGs; the bus voltage is controlled to 1.075 PU.
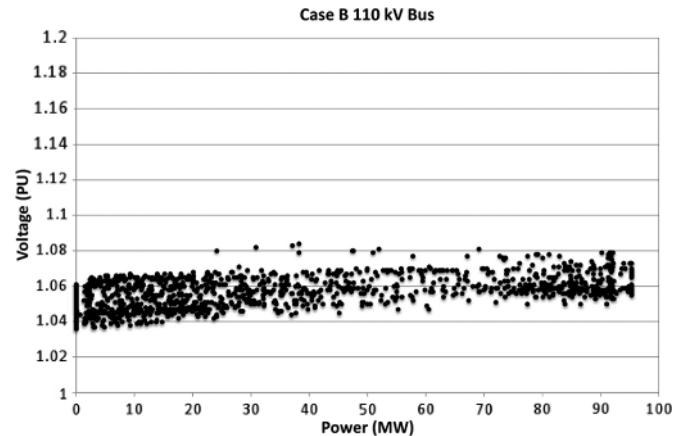

Fig. 7. PV curve for the 110-kV bus, but for Case B, October 31 2006. The increased control allows for improved voltages at higher power output levels, implying an increased voltage stability margin.

around October 31, 2006. The curve in Fig. 4 represents when a majority of the DFIG turbines are operated at the 0.95 inductive PF, Case A. As seen in the curve, the voltages are approaching significantly lower levels as the wind farms reach their maximum combined power output of 95 MW. In comparison, the curve in Fig. 5 is dramatically different. Here, every one of the 1344 power flows has achieved the target voltage of the 20-kV bus, Case B, and as such, the low voltages seen in Fig. 4 are eliminated.

The effect of the increased control is demonstrated in the PV curves of the 110-kV bus connected to the 20-kV bus through a transformer. Fig. 6 shows the resulting PV curve for Case A, while Fig. 7 shows the same for Case B. The impact of the increased control is evident in Fig. 7; as the power generated by the wind farm increases, voltages actually increase at the 110-kV bus. The voltages in Fig. 6 are still within the range of stability, but are seen to be noticeably falling as power production increases from the wind farm, leading to a decrease in system security. System security is defined as the ability of the power system to withstand a sudden loss or unanticipated loss of system components [33]. In Fig. 7, the voltages increase as power production from the wind farm increases. This is due to

the implementation of terminal voltage control from the DFIG farm and results in a more secure system that is able to cope with an unexpected contingency.

Based on [9], this implies that the voltage stability margin for that particular bus is extended and stability across the system is improved when terminal voltage control is implemented. Not only does the implementation of terminal voltage control improve the PV curve's voltage stability margin, it also controls the range of voltage at the 110-kV bus between a smaller bandwidth and increases system security as seen in Fig. 7. This demonstrates the value of increased terminal voltage control and allows for more predictable voltages at the transmission level, leading to more robust system operation.

B. Cases C and D: The Winter Peak

Cases C and D simulated the application of fixed PF control and terminal voltage control around the WP operating point for the Irish power system. The nose of the PV curve from Case C, where the power output of the farm begins to reach a maximum, will be compared to the nose of the PV curve from Case A. Observing the nose of the PV curve focuses on the system's voltage stability at the point of maximum power transfer. In the
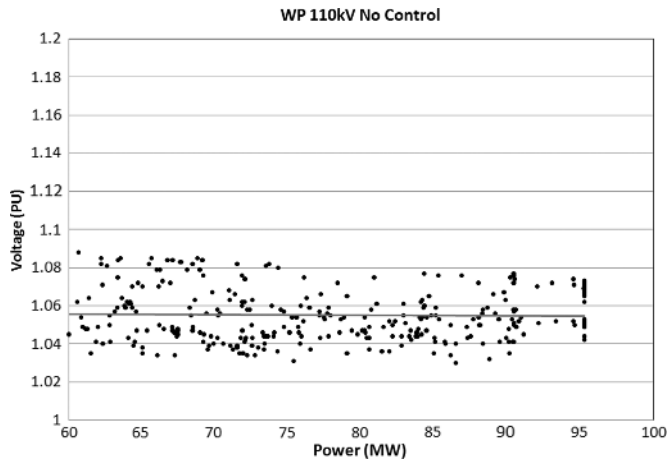
Fig. 8. Zoom of the nose of the PV curve from 110-kV bus for Case C, WP 2006. Here at the same power output levels the voltages are higher even when no control is implemented.

Fig. 10. PV curve when voltage control was implemented at the wind farm, Case D, WP 2006.
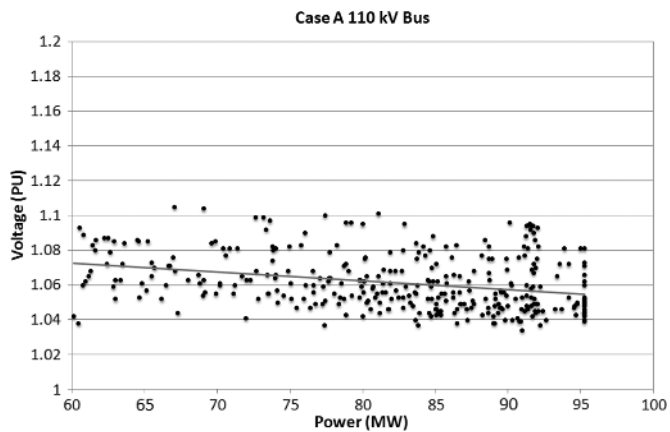

Fig. 9. Zoom of the nose of the PV curve at the 110-kV bus from Case A, October 31, 2006. As power output from the wind farm increases, the voltage falls.

Fig. 11. Here the voltage control is applied directly at the transmission level. The target voltage is set at 1.05 pu, and as a result, all voltages are controlled at or above that level, regardless of loading scenario.

case of this study, maximum power transfer is defined by the maximum size of the wind farm.

Fig. 8, in contrast to Fig. 9, demonstrates a much shallower nose, i.e., for increased levels of power output from the wind farm, the bus is able to achieve higher voltage levels. This is due to the lower relative penetration levels of wind generation in the system, seen in Table I. Since the loading is so much higher in the WP, there are more conventional generation units available to provide support to the system. As a result, the PV curve shows an increased stability margin even when no voltage control is implemented at the DFIG farm.

When control is implemented, the PV curves in the two cases are very similar, as seen in Figs. 7 and 10. This further demonstrates the significant impact that voltage control can have on bus voltages regardless of the loading scenario.

C. Transmission Level Voltage Control

As mentioned previously, the larger wind farms in the Irish system provided voltage control directly at the transmission level. Here the wind farms provide reactive power support across two transformers and control the voltage at the 110-kV bus. Fig. 11 provides an example of this control, and
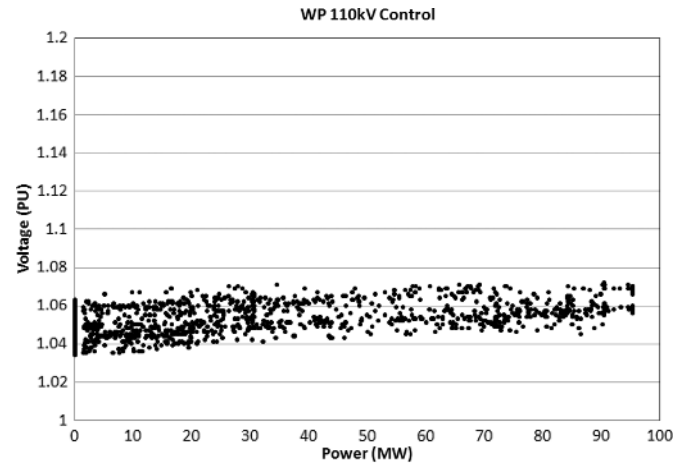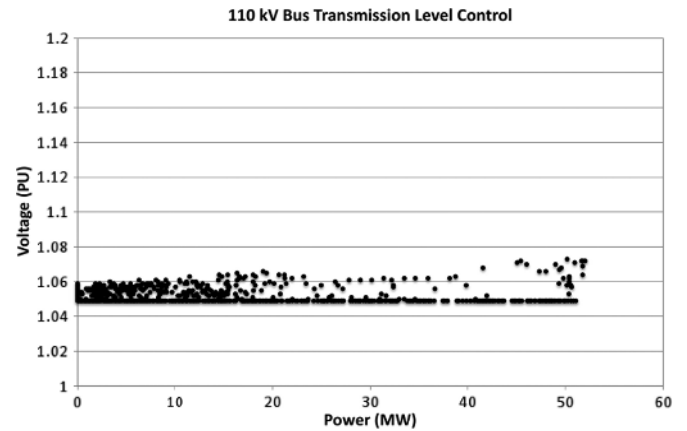
demonstrates that large farms can provide improved voltage performance and stability directly to the transmission system.

In comparison with Figs. 6, 7, and 10, the control at the farm in Fig. 11 is more direct, and as such, the voltage is more robust. This is only achieved due to the large size of the transmission connected wind farm. The size of the farm needs to be sufficient enough to provide the necessary reactive support at the transmission level.

V. CONCLUSION

As wind generation becomes a significant portion of generation portfolios, how it is modeled and studied will become increasingly important. As demonstrated by this paper, focusing studies around traditional worst-case operating points may not capture the true worst-case scenario in systems with high penetrations of wind. Along with utilizing historical time-series data, the observation variables must also be carefully selected in order to determine when the worst-case scenario would occur. In the case of this study, the point of maximum instantaneous wind penetration was the critical point for a voltage stability study. By combining power flow, economic dispatch, unit commitment and historical time-series data that capture the variability of the

wind, into a single large-scale simulation, this paper presents a methodology that is suitable for analyzing a large power system and assessing its voltage stability as well as system response to other conditions under large penetrations of wind generation.

It also shows that utilizing the control features of the DFIG wind turbine improves the voltage stability margin of both the distribution level and transmission level buses in the system. This means that based on voltage stability criteria, larger levels of wind generation could be connected without degrading the voltage stability of the system. Maintaining system stability is crucial and in particular, utilizing voltage control in DFIGs may prove beneficial in system operation. This is particularly important in a power system such as the all-island Irish system that is largely isolated and depends heavily on the import of fossil fuels.

ACKNOWLEDGMENT

REFERENCES

[1] M. Kayikci and J. V. Milanović, "Reactive power control strategies for DFIG-based plants," *IEEE Trans. Energy Convers.*, vol. 22, no. 2, pp. 389–396, Jun. 2007.

[2] V. Akhmatov and P. B. Eriksen, "A large wind power system in almost island operation-A Danish case study," *IEEE Trans. Power Syst.*, vol. 22, no. 3, pp. 937–943, Aug. 2007.

[3] G. Tapia, A. Tapia, and J. X. Ostolazam, "Proportional-integral regulator-based approach to wind farm reactive power management for secondary voltage control," *IEEE Trans. Energy Convers.*, vol. 22, no. 2, pp. 488–498, Jun. 2007.

[4] P. Cartwright, L. Holdsworth, J. B. Ekanayake, and N. Jenkins, "Co-ordinated voltage control strategy for a doubly-fed induction generator (DFIG)-based wind farm," *Proc. Inst. Elect. Eng., Gen., Transm., Distrib.*, vol. 151, no. 4, pp. 495–502, Jul. 2004.

[5] L. Xu and P. Cartwright, "Direct active and reactive power control of DFIG for wind energy generation," *IEEE Trans. Energy Convers.*, vol. 21, no. 3, pp. 750–758, Sep. 2006.

[6] T. Ackermann, *Wind in Power Systems*. West Sussex, U.K.: Wiley, 2005.

[7] E. Vittal, A. Keane, and M. O'Malley, "Varying penetration ratios of wind turbine technology for voltage and frequency stability," in *Proc. IEEE PES General Meeting*, Pittsburgh, PA, 2008.

[8] E. Vittal, M. O'Malley, and A. Keane, "Impact of wind turbine control strategies on voltage performance," in *Proc. IEEE PES General Meeting*, Calgary, AB, Canada, 2009.

[9] P. Kundur, *Power System Stability and Control*. London, U.K.: Mc-Graw-Hill, 1994.

[10] B. Borkowska, "Probabilistic load flow," *IEEE Trans. Power App. Syst.*, vol. PAS-93, pp. 752–759, 1974.

[11] R. N. Allan and A. M. Léite da Silva, "Probabilistic load flow using multilinearizations," *Proc. Inst. Elect. Eng. C*, vol. 128, no. 5, pp. 280–287, Sep. 1981.

[12] A. M. Léite da Silva and V. L. Arienti, "Probabilistic load flow by a multilinear simulation algorithm," *Proc. Inst. Elect. Eng. C*, vol. 137, no. 4, pp. 276–282, Jul. 1990.

[13] A. M. Léite da Silva, S. M. P. Ribeiro, V. L. Arienti, R. N. Allan, and M. B. Do Coutto Filho, "Probabilistic load flow techniques applied to power system expansion planning," *IEEE Trans. Power Syst.*, vol. 5, no. 4, pp. 1047–1053, Nov. 1990.

[14] R. Billinton and W. Wangdee, "Reliability-based transmission reinforcement planning associated with large-scale wind farms," *IEEE Trans. Power Syst.*, vol. 22, no. 1, pp. 34–41, Feb. 2007.

[15] R. Billinton, H. Chen, and R. Ghajar, "A sequential simulation technique for adequacy evaluation of generating systems including wind energy," *IEEE Trans. Power Syst.*, vol. 11, no. 4, pp. 728–734, Nov. 1996.

[16] D. J. Burke and M. J. O'Malley, "Optimal wind power location on transmission system—A probabilistic load flow approach," in *Proc. Int. Conf. Probabilistic Methods Applied to Power System*, 2008.

[17] A. G. Bakirtzis, P. S. Dokopoulos, E. S. Gavanidou, and M. A. Ketselides, "A probabilistic costing method for the evaluation of the performance of grid-connected wind arrays," *IEEE Trans. Energy Convers.*, vol. 4, no. 1, pp. 34–40, Mar. 1989.

[18] N. D. Hatziargyriou, T. S. Karakatsanis, and M. Papadopoulos, "Probabilistic load flow in distribution systems containing dispersed wind power generation," *IEEE Trans. Power Syst.*, vol. 8, no. 1, pp. 159–165, Feb. 1993.

[19] T. Boehme, A. R. Wallace, and G. P. Harrison, "Applying times series to power flow analysis in networks with high wind penetration," *IEEE Trans. Power Syst.*, vol. 22, no. 3, pp. 951–957, Aug. 2007.

[20] M. Thomson and D. G. Infield, "Network power-flow analysis for a high penetration of distributed generation," *IEEE Trans. Power Syst.*, vol. 22, no. 3, pp. 1157–1162, Aug. 2007.

[21] A. J. Wood and B. F. Wollenberg, *Power Generation Operation and Control*. New York: Wiley, 1996.

[22] R. Baldick, "The generalized unit commitment problem," *IEEE Trans. Power Syst.*, vol. 10, no. 1, pp. 465–475, Feb. 1995.

[23] M. El Moursi, G. Joos, and C. Abbey, "A secondary voltage control strategy for transmission level interconnection of wind generation," *IEEE Trans. Power Electron.*, vol. 23, no. 3, pp. 1178–1190, May 2008.

[24] M. D. Ilić, X. Liu, G. Leung, M. Athans, C. Vialas, and P. Pruvot, "Improved secondary and new tertiary voltage control," *IEEE Trans. Power Syst.*, vol. 10, no. 4, pp. 1851–1862, Nov. 1995.

[25] A. R. Bergen and V. Vittal, *Power Systems Analysis*. Englewood Cliffs, NJ: Prentice Hall, 2000.

[26] C. Taylor, *Power System Voltage Stability*. Dallas, TX: McGraw-Hill, 1993.

[27] A. Tuohy, E. Denny, P. Meibom, R. Barth, and M. O'Malley, "Operating the Irish power system with increased levels of wind," in *Proc. IEEE PES General Meeting*, Pittsburgh, PA, 2008.

[28] A. Tuohy, P. Meibom, E. Denny, and M. O'Malley, "Unit commitment for systems with significant wind penetration," *IEEE Trans. Power Syst.*, vol. 24, no. 2, pp. 1380–1385, May 2009.

[29] G. Lalor, A. Mullane, and M. O'Malley, "Frequency control and wind turbine technologies," *IEEE Trans. Power Syst.*, vol. 20, no. 4, pp. 1905–1913, Nov. 2005.

[30] R. Doherty, G. Lalor, and M. O'Malley, "Frequency control in competitive electricity market dispatch," *IEEE Trans. Power Syst.*, vol. 20, no. 3, pp. 1588–1596, Aug. 2005.

[31] Generation Adequacy Report, EirGrid Plc., Dec. 2008.

[32] All Island Renewable Grid Study—Workstream 1A, Renewable Energy Resource Assessment. [Online]. Available: http://www.dcmnr.gov.ie.

[33] P. Kundur, J. Paserba, V. Ajjarapu, G. Andersson, A. Bose, C. Canizares, N. Hatiziargyriou, D. Hill, A. Stankovic, C. Taylor, T. Van Cutsem, and V. Vittal, "Definition and classification of power system stability," *IEEE Trans. Power Syst.*, vol. 19, no. 2, pp. 1387–1401, May 2004.

[34] M. Steurer, J. Langston, S. Suryanarayanan, P. Riberiro, R. Meeker, and P. Søensen, "Model validation and voltage deviation analysis of an existing wind farm using high fidelity real time digital simulation," in *Proc. 19th Int. Conf. Electricity Distribution*, Vienna, Austria, 2007, CIRED.

[35] EirGrid Plc. [Online]. Available: http://www.EirGrid.com.

[36] All Island Renewable Grid Study—Workstream 2B, Wind Variability Management Studies. [Online]. Available: http://www.dcmnr.gov.ie.

[37] PSS/E 30.3.2, Siemens Power Transmission & Distribution, Inc. Power Technologies International, Nov. 2005.

Eknath Vittal (S'07) received the B.E. degree from the University of Illinois Urbana-Champaign and the M.S. degree from Iowa State University, Ames, both in electrical engineering, in 2005 and 2007, respectively. He is currently pursuing the Ph.D. degree at University College Dublin, Dublin, Ireland.

His research interests are in power system operation and planning.

Mark O'Malley (S'86–M'87–SM'96–F'07) received the B.E. and Ph.D. degrees from University College Dublin, Dublin, Ireland, in 1983 and 1987, respectively.

He is currently a Professor of electrical engineering at University College Dublin and Director of the Electricity Research Centre with research interest in power systems, control theory, and biomedical engineering.

Andrew Keane (S'04–M'07) received the B.E. and Ph.D. degrees in electrical engineering from University College Dublin, Dublin, Ireland, in 2003 and 2007, respectively.

He is currently a Lecturer with the School of Electrical, Electronic, and Mechanical Engineering, University College Dublin with research interest in power systems planning and operation, distributed energy resources, and distribution networks.