

# All-scale Modelling of Wind Generation and Responsive Demand in Power System Studies

Barry P. Hayes, Adam J. Collin, Ignacio Hernando-Gil, Jorge L. Acosta, *Student Members, IEEE*, Sam Hawkins, Gareth P. Harrison, *Member IEEE*, and Sasa Z. Djokic, *Senior Member, IEEE*

**Abstract**--This paper presents a general methodology for a more accurate assessment of performance of networks with a high penetration of wind-based energy generation and fully enabled responsive demand capabilities. The presented methodology allows to include in the analysis wind-based generation at all scales of implementation, starting from highly dispersed micro and small-scale units connected at LV, to medium-size wind parks connected at MV, to large-scale wind farms connected at HV. An advanced model of wind energy resources is applied to generate realistic input wind data at all scales of implementation, while newly developed and improved aggregate models are used for the correct representation of micro/small wind generation connected in parallel with demand-responsive system loads. The proposed methodology is specifically intended for the analysis of planning and operation of transmission systems. The approach is illustrated using a case study of an actual section of transmission network, where available measurements at wind parks and other sites are used for the validation of obtained results.

**Index Terms**--Demand side management, distributed generation, power system simulation, responsive demand, steady state power system analysis and load modelling, wind-based energy generation, wind energy resources, wind farms/parks.

## I. INTRODUCTION

Wind-based generation is now present at all scales and levels of implementation, ranging from multi-megawatt units installed in large numbers in wind parks (WPs) and wind farms (WFs), to sub-kilowatt units operating in even larger numbers of individual installations. Regardless of their size, however, the performance of wind-based generation systems is strongly affected by the variability of input wind energy resources, ultimately resulting in inability to both accurately predict and fully control their power outputs.

Operation and control of networks with high penetration levels of distributed generation (DG) impose additional requirements for flexibility, particularly regarding the efficient demand-supply balancing, assessment of generation and system capacity margins and maintenance of required reliability and power quality performance levels. Practically all relevant studies have identified more advanced and coordinated control of DG resources and implementation of

responsive demand capabilities as the two important functionalities for providing this flexibility, (e.g. [1]-[2]). The accurate assessment of the influence of variable wind-based generation and responsive demand technologies on the overall network performance, however, requires their realistic representations at all scales of implementation and all levels of aggregation. Such an "all-scale" approach is still missing in the existing literature on modelling wind generation (an overview is given in [3]), and on equivalent/agggregating networks with demand-responsive loads and variable wind generation at different voltage levels (e.g. [4]-[5]).

This paper presents a general methodology for the accurate representation of all-scale wind generation and demand-responsive loads in realistic networks, specifically intended for steady state analysis of transmission systems. Presented models of wind generation include highly dispersed micro and small-scale wind units, as well as medium/large-scale WPs and WFs, while system load models of equipment and devices found in main load sectors (e.g. residential or commercial) include correct representation of demand-responsive loads and demand side management (DSM) functionalities. Two important parts of the presented analysis are: a) the application of a new approach for the assessment of availability of wind energy resources at all scales of interest, allowing for a more accurate correlation of the outputs of wind generation with the system loads, and b) the implementation of a new methodology for the aggregation of system loads at all voltage levels, allowing to incorporate supplying networks and connected wind generation in the aggregated models.

The paper is structured as follows: Section II discusses the modelling of wind generation at all scales of implementation, including embedded wind generation connected to the MV and LV networks. These models are validated in Section III using available measurements from existing WPs. Section IV discusses how improved aggregate load models can be incorporated in the analysis, including correct representation of demand-manageable portion of loads in the total demand. Section V presents results of the network analysis. Section VI discusses main conclusions and suggestions for further work.

## II. ALL-SCALE MODELLING OF WIND ENERGY GENERATION

Modelling and representation of large-scale wind generation systems, e.g., WF directly connected to HV transmission and sub-transmission networks, is extensively analysed in available literature (e.g. [3], [6]-[7]), including assessment of their influence on overall system performance.

---

This work was partially supported by two UK EPSRC Projects (grant numbers EP/E04011X/1 and EP/G052530/1).

B.P. Hayes, A. J. Collin, I. H.-Gil, J. L. Acosta, G.P. Harrison and S. Z. Djokic are with the Institute for Energy Systems, University of Edinburgh, Edinburgh, UK (Corresponding Author E-mail: b.hayes@ed.ac.uk). S. Hawkins is with Vattenfall Wind Power, Holyrood Road, Edinburgh, UK.

Network operators typically monitor operation of large WFs in real-time, recording parameters such as total real and reactive power outputs at the HV point of connection, which allows them to directly estimate their impact. In the case of MV-connected WPs, however, network operators often have only limited visibility, and generally have no information on outputs of wind-based generation connected at LV, [8].

In this paper, the term “embedded wind generation” (EWG) denotes MV and LV-connected wind-based generation systems which are not metered. For example, EWG in the UK are WPs and other wind generation systems which are not required to provide metering data, or take part in the grid balancing mechanism (generators classed as “small” in [8]). This classification is typically based on the EWG’s installed capacity, and the corresponding limits vary according to the network operator and country/region. As EWG is not monitored, its impact on the transmission network can be observed only indirectly, e.g. through a reduced demand at HV substations, or changes in system fault levels. Generally, EWG can contribute to a number of network operating issues, including: mismatches between forecasted and actual system demands (which can result in an increase of the number of required balancing/corrective actions), errors in the expected/estimated fault levels (which can result in the incorrect operation of protection systems), and inaccuracies in the calculated transmission system operating constraints and limits (which can increase risks to system security).

An example of the impact of EWG is illustrated in Fig. 1, which shows demand data at 04:00 hours on summer nights over the course of 3 years (2009-2011) for a group of MV nodes in North-East region of England where significant EWG is connected. The reduction in demand on windy summer nights due to EWG can be clearly seen (before carrying out the analysis, the raw demand data were “normalized” using linear regression to remove all other variables which affect demand, such as day of week, seasonality, temperature, etc.). With increasing penetrations of EWG, it becomes more difficult for network operators to accurately predict system demands and power flows [9]. Even with improved metering capabilities, provided by, e.g. “smart” metering technologies, future networks will require significantly more advanced modelling tools and techniques than those currently in use for system planning and operation, as supply-demand patterns will become significantly more variable. Accordingly, a method for modelling and aggregation of wind generation at all scales, from large-scale HV-connected WFs, to EWG connected at MV and LV, is presented in this section of the paper.

#### A. Modelling of wind energy resources

One of the largest sources of error during the estimation of the power outputs of wind-based generation systems in network studies is related to the uncertainties in the assessed input wind energy resources. The accuracy and resolution (both spatial and temporal) of the wind energy data are, therefore, crucial for the analysis.

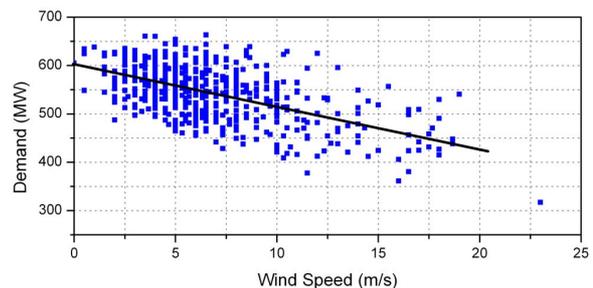


Fig. 1. Measured reduction in demand due to EWG at 04:00 hours on summer nights at selected nodes/buses in North East England [9].

Wind speed measurements from weather stations can be used for the analysis, but their locations are often far away from the EWG, and even if they are relatively close, local terrain features (such as hills and forestation, or buildings in urban areas) may have significant impact on actual wind profiles. Alternatively, wind resources can be modelled for a particular site using computational fluid dynamics software (e.g. [11]). However, this method is computationally intensive and requires detailed topology information, making it generally unfeasible for modelling wind energy resources over a large area.

One promising approach for assessing wind energy resources is to use the available weather station data and some information on the larger terrain features in the region of interest to build so called “mesoscale” wind model (e.g. the Weather Resource and Forecast (WRF) model described in [12]). Accordingly, this paper uses a wind data set in which the WRF model has been applied to UK wind profiles over the period 2001-2010 [13]. This data set provides hourly wind speeds over a 10-year period for the entire UK region, at a spatial resolution of 3 km x 3 km. The wind speeds obtained as the output of the model can be adjusted to the required height above the ground or sea level (e.g. for the actual hub heights at the locations of modelled EWG systems). The “mesoscale” modelling approach and WRF model can also be applied to short-term forecasting (i.e. prediction of wind profiles for day-ahead planning [12]).

The wind data set used in this paper is obtained after the re-analysis of the long-term UK wind resource from the WRF model, in order to provide a high-resolution data required for accurate modelling of wind resources at all scales of implementation. However, the presented methodology for all-scale modelling and aggregation of wind generation described below can be applied using any other high-quality wind data set, e.g. from commercial weather forecast sources. Furthermore, the presented methodology can be easily integrated into network analysis tools for days-ahead to several hours-ahead planning, using the forecasted wind speed data in place of the historical data used here.

In the following analysis, the wind resources for a selected network region, corresponding to Southern Scotland, UK, are assessed. The output from the “mesoscale” wind resource model described above is compared to recorded data from met office stations in the region. The wind resource model is then

validated (and adjusted, or fine-tuned if necessary) using the available measurement data from within the region. Fig. 2 shows the location of the ten met stations (M1-M10) used to provide the recorded data [10].

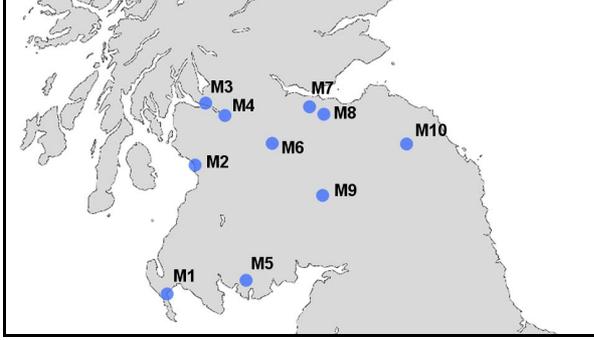


Fig. 2. Met station wind measurement locations in the selected region.

Fig. 3 shows a comparison of time series for the recorded wind speeds (averaged across all sites, M1-M10, for the period from 2007 to 2009) and results from the wind resource model. Annual mean modelling error for aggregate wind speed across the entire Southern Scotland region using the WRF model re-analysis data was 3.9%.

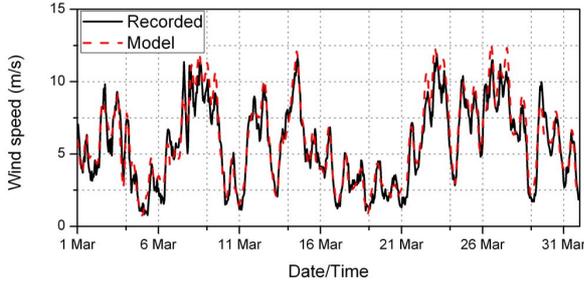


Fig. 3. Comparison of time series for model outputs and recorded data, aggregated for Southern Scotland region (one month only shown).

The probability distribution functions (PDFs) for the recorded data and results from wind resource model across the region in 2007-2009 are shown in Fig. 4. A standard assumption, often used in the assessment of wind resources, is that wind speed variations follow a Weibull distribution (1):

$$W(v; \lambda, k) = \frac{k}{\lambda} \left( \frac{v}{\lambda} \right)^{k-1} e^{-(v/\lambda)^k} \quad (1)$$

where:  $v$ -wind speed;  $k$ -shape factor;  $\lambda$ -scaling factor. For the recorded data, the "best fit" Weibull distribution (obtained using maximum likelihood estimation) has scaling factor  $\lambda=5.253$  and shape factor  $k=1.925$ . The same calculation for the model data gives scaling factor  $\lambda=5.513$  and shape factor  $k=1.985$  (Fig. 4). Mean recorded and modelled wind speeds by season are compared in Table I. These results show a generally good performance of the wind resource model in the region selected for the analysis.

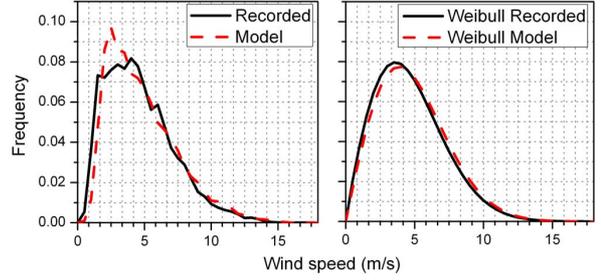


Fig. 4. Comparison of recorded and modelled wind speeds showing PDFs of data averaged across the region, and corresponding Weibull "best fits".

TABLE I  
COMPARISON OF SEASONAL AVERAGE WIND SPEEDS (2007-2009)

	Mean wind speed (m/s)			
	Spring	Summer	Autumn	Winter
<b>Recorded</b>	5.0	4.2	4.4	5.0
<b>Model</b>	5.2	4.3	4.5	5.5

In the following sections, it is shown how this wind resource model can be used to estimate the steady state power outputs of all EWG installed in the region of interest. Aggregation of power outputs at all scales of implementation is performed separately for HV, MV, and LV-connected EWG systems.

#### B. Modelling of HV-connected wind generation

As previously mentioned, WFs connected directly to HV transmission and sub-transmission networks are typically continuously metered by the system operators (both input wind speeds and output powers). When metered data are available, the standard "measured power curve" approach, recommended in [14] for modelling an individual wind turbine (WT), can be extended to accurately model actual performance of a whole WF using a methodology presented in [15]. This is briefly discussed in the further text.

The standard [14] specifies a general procedure for measuring performance (i.e. output power) of a WT connected to the electrical network. The standard acknowledges the fact that the actual performance of a WT, represented as a "measured power curve", may be different from the one specified by the manufacturer ("manufacturer's power curve"). These differences may be due to a number of site or application-specific factors, including wake and "wind shadowing", terrain characteristics and effects of turbulence. The measured power curve of an individual WT is determined by collecting simultaneous measurements of input wind speeds and output powers for a long enough period of time, and can be used to estimate the WT energy production. As the measured power curve outlined in [14] applies only to a single WT, this approach is generalised in [15] to represent the whole WF using the "aggregate WF measured power curve". For this purpose, "method of bins" is used to obtain the aggregate measured power curve from the simultaneous wind speed and power output measurements at individual WTs within a WF, where each "bin" represents one specific wind speed from the selected range of measured values:

$$V_i = \left( \sum_{j=1}^{N_i} V_{i,j} \right) / N_i, P_i = \left( \sum_{j=1}^{N_i} P_{i,j} \right) / N_i, \text{ for } i=1, \dots, n \quad (2)$$

where:  $V_i, P_i$  - average values of all measured wind speeds and power outputs allocated to bin  $i$ ;  $V_{i,j}, P_{i,j}$  - measured  $j$ -th values of wind speed and power output in bin  $i$ ;  $N_i$  - total number of measured values in bin  $i$ ;  $n$  - total number of bins. The bin size used was 0.5 m/s. Fig. 5 illustrates the procedure for creating an aggregate measured power curve for an actual UK WF, where Fig. 5a shows measured data after filtering (it is important to filter recorded data to remove measurement errors and outliers), while Fig. 5b compares manufacturer's and measured power curves. This approach is in accordance with common practice to build an aggregate WF model by using one equivalent machine for each radial line or group of WTs at the end of a major feeder, and also to create separate equivalents for each turbine type in cases where different WTs are installed at the same site [3]. The calculation of the aggregate measured WF power curve model is successfully validated in [15].

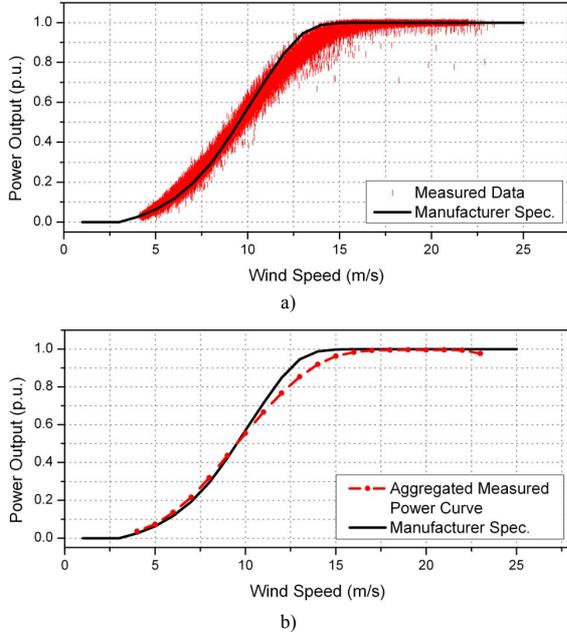


Fig. 5. Measured aggregate WF power curve model for an actual UK WF: a) normalised scatter plot; b) aggregate power curve for the whole wind farm.

### C. Modelling of MV-connected wind generation

Generally, MV-connected WPs are embedded in the distribution network, and system operators often do not meter or monitor their power outputs. As mentioned, the legislative requirements for WP capacity at which metering data should be provided vary depending on the country/region and network operator (e.g. [8]). Typically, MV EWG is concentrated in certain local areas (parts of the network), rather than uniformly distributed throughout the system, [16]. The methodology applied here aggregates all EWG in a particular region, based on publicly available information on the WP capacity and type of installed WTs. This approach has two main advantages: a) grouping of many highly dispersed

EWG reduces the model complexity and computational burden, and b) wind modelling and forecasting errors for a network region are significantly smaller than the errors for an individual site, due to averaging and cancellation effects [17]. The selected EWG regions should correspond to a group of bulk supply point nodes with a high local EWG penetration, based on a prior knowledge of installed EWG capacity. The aggregation methodology is illustrated for the selected region of Southern Scotland.

In the absence of metering data, it is difficult to accurately estimate the performance (i.e. power outputs) of WPs. Typically, the selected EWG regions will have a mixture of wind turbine (WT) technologies and sizes. A survey of all EWG currently installed in the Southern Scotland region, based on public statistical data in [16] and [18] was carried out. The performance characteristics (i.e. power curves) of each WT type installed in this region were per-unitized, and the proportion of each WT type in the total EWG was calculated. This allows the performance of all WTs in the EWG region to be summarized by a single generic WT.

The approach is illustrated in Fig. 6, where "Generic WT" represents the performance characteristics of all WT in the Southern Scotland EWG region. The EWG units are generally required to operate within a specified range of leading or lagging power factors. In this paper, it is assumed that all EWG meets the requirements outlined in [19], and controls the voltage at the point of connection within the power factor range of 0.95 lagging, to 0.95 leading.

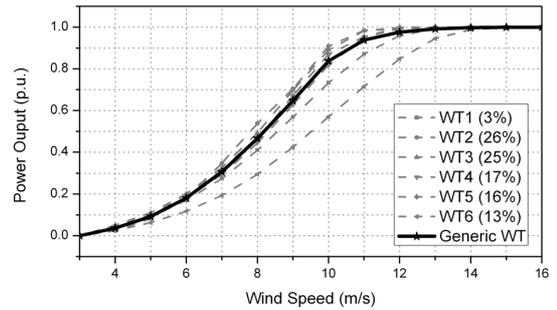


Fig. 6. WT power curves and generic WT model for Southern Scotland region (only the non-linear part of the power curves are shown).

### D. Modelling of LV-connected wind generation

Although highly dispersed and small in size, the total number of micro/small EWG units in a large urban area can be high, when their aggregate effects are essentially similar to those of medium to large-scale WT technologies. In [20], micro-wind is identified as one of the main technologies in the future microgeneration mix, while [21] indicates that up to 1.3 GW of micro-wind could be installed in the UK by 2020. It is generally assumed that the main effect of micro-wind is a reduction of the overall demands at certain supply points. However, there is virtually no work in the existing literature on modelling and aggregation of LV-connected EWG, which will be required for evaluating impact of higher penetration levels of micro-EWG on overall network performance.

This paper uses aggregate models of micro/small WTs connected at LV described in [22], which are based on generic models of permanent magnet synchronous generator WTs. These generic models are identified from a survey of all currently available micro/small WTs on the UK market. Full details on the model development and conversion efficiencies of the generic WT models are provided in [22]. The aggregate power output for the generic LV-connected EWG can be expressed as a function of input wind speed:

$$P_{WT_{Aggregate}} = (e^{-0.75v} - 1)(7.9v - 2.9v^2 + 0.084v^3) \quad (3)$$

where:  $v$  - input wind speed in m/s, and  $P_{WT_{Aggregate}}$  - power output of aggregate wind-based microgeneration model at a given wind speed, in  $W/m^2$  of the WT swept area. One of the main difficulties associated with modelling of LV-connected EWG is that most micro- and small-scale WTs are typically installed in urban areas, where the effect on wind profiles due to surrounding buildings and other obstructions is likely to be far more significant than in the case of large-scale commercial WPs [23], [24]. A survey of 5 sites in a typical UK urban area (Edinburgh city) was carried out, where recorded wind speeds were compared with the corresponding outputs from the wind model described in Section II (Fig. 7).

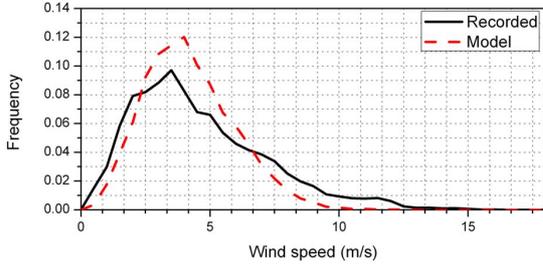


Fig. 7. Comparison of PDFs for recorded urban site wind speeds and wind resource model data for the year 2007.

Comparison of the wind model outputs with the recorded data at the selected urban sites allows to estimate the scaling factor for LV-connected EWG, (4), which provides a measure of how much the wind model overestimates the wind speeds in a given urban area (a conservative estimate of the available wind resources). According to the calculated scaling factor (0.73, in example in Fig. 7), the wind resource model can then be adjusted, or fine-tuned. This figure is in a similar range to the results obtained from the trial measurements of micro-wind installations in urban locations described in [23]-[24].

$$S_{\mu EWG} = 1 - \sum_{n=1}^{N_{sites}} \left( \frac{v_i - w_i}{w_i} \right), \quad \text{for } i=1, \dots, N_i \quad (4)$$

where:  $S_{\mu EWG}$  - scaling factor for micro/small EWG;  $v_i$  -  $i$ -th value of wind speed output from mesoscale model;  $w_i$  -  $i$ -th value of recorded wind speed;  $n$  - measurement site number;  $N_i$  - total number of data points;  $N_{sites}$  - total number of sites in EWG region. The described small/micro EWG model is connected at LV and aggregated together with the detailed models of the system loads and distribution networks (the results of the analysis are shown in Section IV).

### III. MODEL VALIDATION

In order to validate the EWG wind resource and power conversion models, measurements at six WPs/WFs in the selected region were used (W1-W6 in Fig. 8). Recordings of output powers at the points of connection to the network were available for one full year (2009), and these measurements are used for the validation of the wind resource and aggregated MV EWG models described in Section II. Before carrying out the analysis, all recorded power output data were filtered, in order to remove bad data points due to missing entries, fault recordings, measurement errors, or EWG unit unavailability.

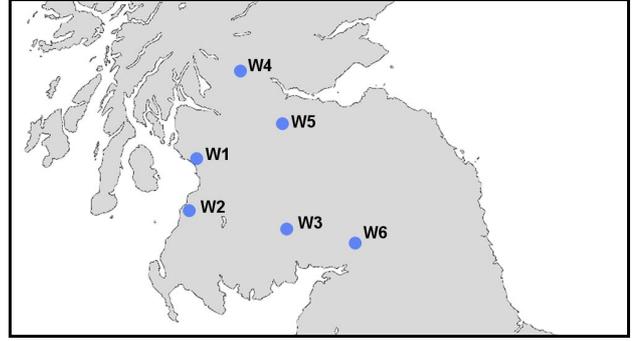


Fig. 8. Wind farm locations used for the validation of the EWG models (W1=18MW, W2=13MW, W3=30MW, W4=37.5MW, W5=27.6MW, W6=36.8MW, total EWG=162.9MW).

Fig. 9 shows a comparison of time series for the recorded normalized power output from W1-W6 EWG units and from the combined wind resource model and EWG generic model. Mean annual modelling error was calculated to be 8.9%.

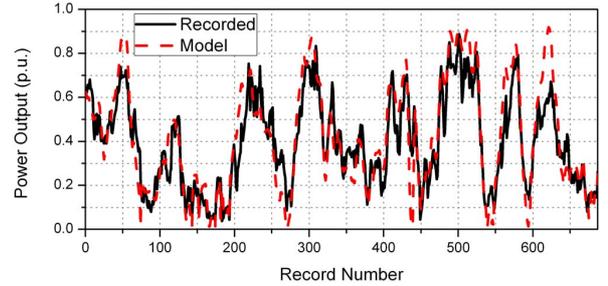


Fig. 9. Time series comparison of model output with recorded data aggregated for specified EWG region (one month of data).

These results demonstrate that the methodology discussed in Section II can be used for the accurate modelling of EWG (i.e. wind-based generation systems which are not directly monitored by the system operator). Although only statistical data on the installed EWG type and capacity are used, a good matching between the model and recorded data is obtained.

The presented approach was applied to estimate the impact of EWG on total demands in the region, and to compare the results obtained using the proposed models for MV- and LV-connected EWG. The reduction in demand at 04:00 hours on summer nights is calculated for two scenarios in which EWG penetration was equal to 10% of the peak demand: (i) all EWG is represented as MV-connected WPs, and (ii) all EWG is modelled as LV-connected micro-wind.

For the MV-connected EWG case, demand is reduced by 30MW per 1 m/s increase in wind speed (Case (i) in Fig. 10). The corresponding reduction in demand for the LV-connected EWG case (Case (ii) in Fig. 10) is far less significant (6.5MW per 1 m/s increase of wind speed). This is due to the much lower conversion efficiencies of micro/small EWG and the reduced wind resources in locations where these devices are typically installed. In both cases, however, the impact of EWG in a given region can be significant, particularly for low demand/high wind scenarios (see also Fig. 1, Section I).

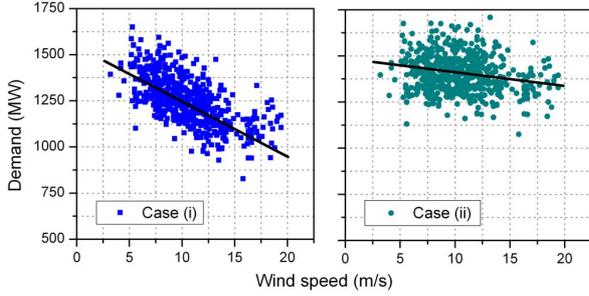


Fig. 10. Estimated reduction in demand in region at 04:00 hours on summer nights with EWG penetration equal to 10% of the peak demand, where EWG is represented as: (i) MV-connected EWG, and (ii) LV-connected EWG.

#### IV. LOAD AGGREGATION AND DEMAND SIDE MANAGEMENT

Future electricity networks (“smart grids”) will introduce significant changes on the “demand side”, including changes in the composition of system load, improved energy efficiency, and increased levels of flexibility and control. Accordingly, this paper implements a new methodology for the aggregation of system loads at all voltages, allowing for the ongoing and anticipated changes in the load structure and the supplying networks to be directly incorporated in the network analysis. This section of the paper builds on previous work in [25] and [26], where component-based LV load models are built using the measurements, statistical information, and other available data on the active/reactive power demands. Fig. 11 gives an example of the decomposition of a residential load curve into the various load component types. Fig. 12 shows a “flow chart”, illustrating the used aggregate load modelling approach, [25]. Essentially, these load models can be modified to examine the impact of any changes in the load mix, e.g. due to the implementation of specific DSM schemes, [26].

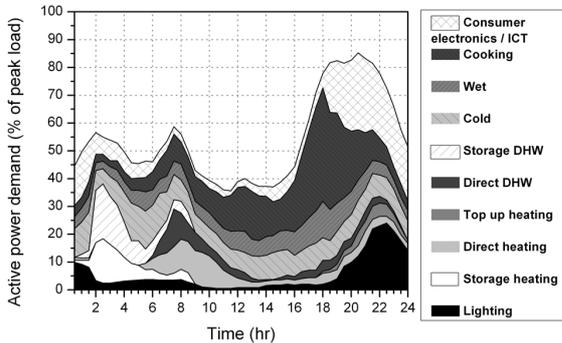


Fig. 11. An example of decomposition of load curve into load types for the UK urban residential load sector and average loading conditions, [25].

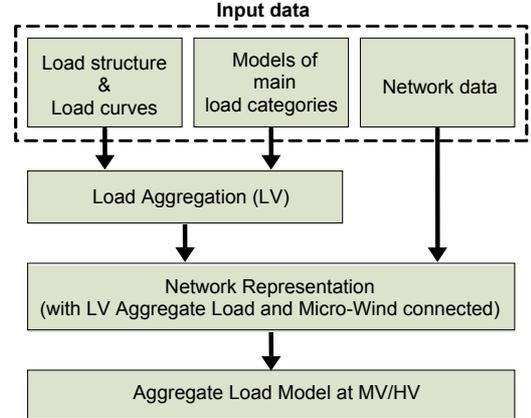


Fig. 12. The “flow chart” of load applied aggregation methodology, [25].

The aggregated load models are expressed in analytical form as polynomial/ZIP load models:

$$P = P_0 \left[ Z_P \left( \frac{V}{V_0} \right)^2 + I_P \left( \frac{V}{V_0} \right) + P_P \right] \quad (5)$$

$$Q = Q_0 \left[ Z_Q \left( \frac{V}{V_0} \right)^2 + I_Q \left( \frac{V}{V_0} \right) + P_Q \right] \quad (6)$$

where:  $P, Q, V$  - actual active and reactive powers and supply voltage;  $P_0, Q_0, V_0$  - nominal active and reactive powers and supply voltage;  $Z_P, I_P, P_P, Z_Q, I_Q, P_Q$  - ZIP model coefficients.

The network analysis presented in this paper focuses on the urban loads and network configurations presented in [25]. In a large urban area, the total number of micro/small EWG units can be high, supplying a significant percentage of local power demand. In the presented analysis, models of micro/small EWG outlined in Section II.D are connected at LV, assuming a relatively low penetration of 10% of the peak demand. Additionally, the effects of implementing a simple DSM scenario are also included in the analysis. This is based on the approach described in [26], where 40% of “wet loads” in the residential load sector are disconnected during the peak loading period (18:00-22:00) and re-connected at 22:00. The impact on operation and steady state performance of HV network (sub-transmission and transmission level) are analysed in the following section.

#### V. NETWORK ANALYSIS

The network analysis was carried out using a detailed model of the Scottish Power Transmission Ltd. (SPTL) transmission network, which supplies the Southern Scotland region in the UK. The SPTL system consists of a 400/275/132 kV transmission network, with a peak demand of 3.9 GW. The 521-bus transmission system model used in the analysis includes all network lines, transformers and voltage compensation equipment down to the level of each 33kV bulk supply point (the interface between the transmission and distribution networks). All network parameters used to build the model were provided by the system operator [27]. Bulk supply point demands were obtained from the SPTL

distribution network operator in the form of half-hourly historical measurements of MW and MVar demands at each bulk supply point in the network, recorded over a period of one year (2009). The resulting model allows for analysis of the network at any node and at any system loading level (e.g. typical or minimum summer demand, typical or maximum winter demand).

The analysis presented shows an example of the results obtained for one selected 275:33 kV grid supply point in the SPTL system, under typical spring loading levels and wind conditions. This grid supply point is the interface between the transmission and distribution networks. Statistical data in [28] indicate that the demand at this network location is composed mainly of residential load sector (i.e. domestic customers), with a relatively small contribution from commercial loads. The improved component-based LV load models are connected to a detailed model of a typical UK urban distribution network and aggregated to MV (full details on the network parameters used and the aggregation methodology are provided in [25]-[26]). The distribution network supplying the load includes tap-changing 33:11 kV transformers, which regulate voltage within the required range of 0.94 - 1.06 p.u. The aggregate MV load model is converted to polynomial/ZIP form, (5)-(6), for performing the steady state analysis at each half-hourly interval.

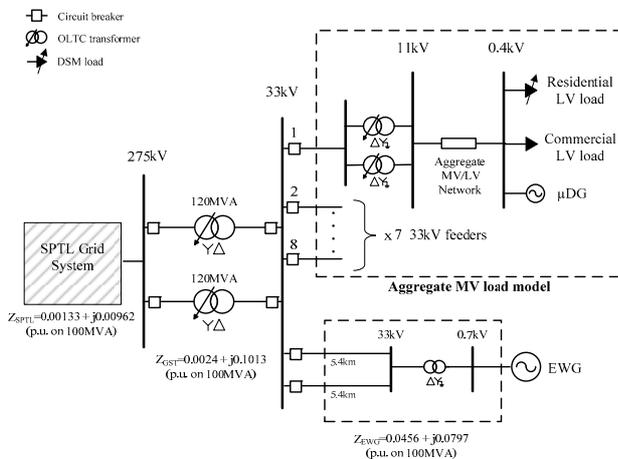


Fig. 13. Grid supply transformers and network configuration for selected network node in SPTL system.

Additionally, there is an 18.5 MW EWG capacity connected at the MV bulk supply point. In order to model the wind resource, a typical spring daily wind speed profile was used (hourly wind speeds averaged over the whole region, Fig. 14a). The calculated results show active and reactive power flows, and voltage at the HV side of the selected grid supply transformer. The analysis is carried out for four cases: (i) base case - no EWG and constant P/Q loads; (ii) MV-connected EWG and constant P/Q loads; (iii) MV- and LV-connected EWG, with improved aggregate MV load model, but no DSM, and (iv) MV- and LV-connected EWG, with modified load model implementing the DSM scheme described in Section IV (40% of residential “wet loads” are disconnected during peak loading hours, 18:00-22:00, and re-connected at 22:00 hours).

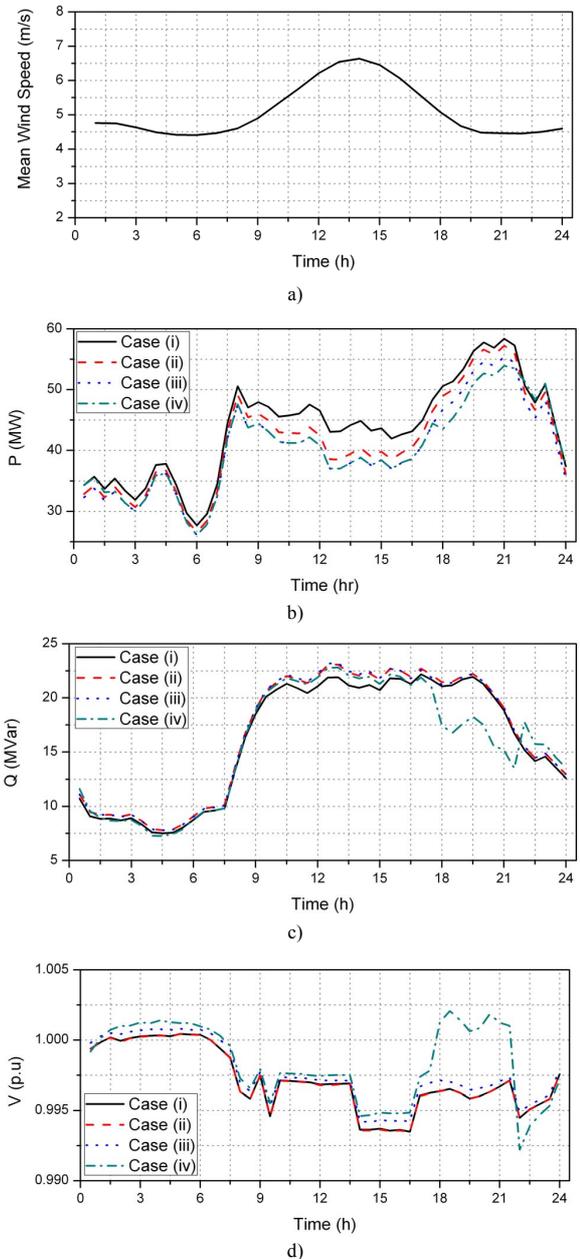


Fig. 14. Results of steady state analysis at HV side of selected 275:33 kV grid supply transformer for typical spring day: a) input wind profile; b) active power flow; c) reactive power flow; d) voltage.

The results show that MV-connected EWG may reduce active power flow by up to 10%, with a further 2% reduction when LV-connected EWG is present. As the modelled MV and LV-connected EWG operate at leading power factor, there is also a reduction in reactive power demand (5% and 1% respectively). The applied DSM scheme substantially reduces peak active power demand and has an even bigger impact on reactive power flow and voltage control. Although the analysis shows only one day, the presented approach can be applied for the analysis of various network operating scenarios.

## VI. CONCLUSIONS AND FURTHER WORK

This paper presents an “all-scale” approach to modelling wind generation and demand-responsive load, which is missing from the existing literature. The presented methodology is intended for planning and operation studies of transmission systems with high penetrations of wind at various scales of implementation. The paper demonstrates that embedded wind generation (EWG), connected to the network at MV and LV, can have a significant impact at the higher voltage levels. The methodology outlined in this paper proposes modelling of EWG on a regional basis, where each region corresponds to a group of bulk supply points with high local EWG penetration. An advanced “mesoscale” model is used to estimate wind resources in the EWG region, while previously developed aggregate and generic models of WTs and WPs are used for the power conversion at each scale of implementation. The presented methodology is validated using available recorded data from actual wind farms and met stations.

The paper also describes implementation of a new methodology for the aggregation of system loads at all voltage levels, allowing for the correct representation of DSM functionalities. The effects of implementing a simple DSM scenario (active control of “wet loads” in the residential sector) may have significant impact on the aggregate load characteristics, as well as on the key system performance parameters. The general applicability of the presented modelling approach is demonstrated using a practical case study of an actual section of the UK transmission system. It is shown that the presented all-scale modelling framework allows for a more accurate correlation of wind generation and system loads, and can be particularly useful for analysing the impact of EWG and demand-responsive loads on the improvement or deterioration of network performance.

Further work will focus on determining the optimum EWG region size for different types of network study, and will examine the range of possible interactions between EWG and other realistic DSM schemes. The presented analysis considers a part of the system supplying primarily residential load and an urban distribution network topology. Future studies will include other load sectors and corresponding distribution network topologies in the analysis.

## VII. ACKNOWLEDGMENT

The authors would like to thank M. Magill (National Grid Plc.), A. Ferguson (Scottish Power Ltd.) and A. Porpodas (Vestas Wind Systems A/S) for providing the network measurements and wind park data used in this paper.

## VIII. REFERENCES

- [1] J. Brearley and S. Cook, (2010, Feb.). "A smart grid roadmap". Electricity Networks Strategy Group, London, UK [Online]. Available: <http://www.ensg.gov.uk/>
- [2] M. G. Lauby, R. Villafranca, and E. Rollinson, (2010, Aug.). " Potential reliability impacts of emerging flexible resources". North American Electric Reliability Corporation, Atlanta, GA.. [Online]. Available: [http://www.nerc.com/files/IVGTF\\_Task\\_1\\_5\\_Final.pdf](http://www.nerc.com/files/IVGTF_Task_1_5_Final.pdf)
- [3] CIGRÉ Technical Brochure 328, “Modeling and dynamic behaviour of wind generation as it relates to power system control and dynamic performance,” Tech. Rep. CIGRÉ. WG C4.601 , August 2007.
- [4] X. Feng, Z. Lubosny, and J.W. Bialek, “Identification based dynamic equivalencing,” in *Proc. 2007 IEEE PES Europe Conf. PowerTech*, pp. 267-272.
- [5] J. V. Milanovic, H. Ali, M. T. Aung, “Influence of distributed wind generation and load composition on voltage sags,” *IET Gen, Trans. & Dist.*, vol. 1, no. 1, pp. 13-22, 2007.
- [6] J.G. Slootweg, S. de Haan, H. Polinder, and W.L. Kling, “General model for representing variable speed wind turbines in power system dynamics simulations”, *IEEE Trans. Power Sys.*, vol. 18, no.1, pp. 144-151, 2003.
- [7] B. C. Ummels, M. Gibescu, E. Pelgrum, W.L. Kling, and A.J. Brand, , “Impacts of wind power on thermal generation unit commitment and dispatch”, *IEEE Trans. Energy Conv.*, vol. 22, no.1. pp. 44-51, 2007.
- [8] National Grid, The Grid Code Issue 4 Rev.6 (2011, July). [Online]. Available: <http://www.nationalgrid.com/uk/Electricity/Codes/gridcode/>
- [9] National Grid, Embedded wind and transmission constraints, Internal Report, Aug. 2011.
- [10] UK Meteorological Office. MIDAS Land Surface Stations data (1853-current), British Atmospheric Data Centre, 2011, [Online] Available: <http://badc.nerc.ac.uk/data/ukmo-midas/>
- [11] RISO National Laboratory for Sustainable Energy. Wind Atlas Analysis and Application Program (WAsP) [Online]. Available: <http://risoe.dtu.dk/WAsP.aspx>
- [12] W.C. Skamarock, J.B. Klemp, J. Dudhia, D.O. Gill, D.M. Barker, X.-Y. Huang, W. Wang, and J.G. Powers, “A description of the advanced research WRF version 3,” National Center for Atmospheric Research, Boulder, CO, USA, Tech. Rep. NCAR/TN-475+STR, June 2008.
- [13] S. Hawkins and G.P. Harrison, “A re-analysis of UK wind speeds using the WRF mesoscale model,” presented at *EWEA European Wind Energy Conf.*, Warsaw, Poland, 2010.
- [14] *Power Performance Measurements of Electricity Producing Wind Turbines*. IEC European Standard EN 61400-12-1, Jun. 2006.
- [15] B.P. Hayes, I.-S. Ilie, A. Porpodas, S.Z. Djokic, and G. Chicco, “Equivalent power curve model of a wind farm based on field measurement data,” *Proc. IEEE PES Europe Conf. (PowerTech)*, Trondheim, Norway, 2011.
- [16] BWEA, British Wind Energy Association, [Online]. Available: <http://www.bwea.com/ukwed/operational.asp/>
- [17] H. Holttinen, “Hourly wind power variations in the Nordic countries,” *Wind Energy*, vol. 8, pp. 173–195, 2005.
- [18] J.R. McLean, “Equivalent wind power curves”, Garrad Hassan and Partners Ltd., European Wind Energy Association TradeWind Tech. Rep. WP2.6, Oct. 2008.
- [19] Scottish Power, The Distribution Code, Issue 4 (Aug. 2004). [Online]. Available: <http://www.scottishpower.com/>
- [20] UK Department for Business, Enterprise and Regulatory Reform, *Our Energy Challenge: Power from the People*, Microgeneration Strategy and Microgeneration Strategy Progress Report, 2008.
- [21] BWEA, Small Wind Systems, British Wind Energy Association, Market Report, 2009.
- [22] J. L. Acosta, K. Combe, S. Z. Djokic, and I. H.-Gil, “Performance Assessment of Micro and Small-Scale Wind Turbines in Urban Areas”, *IEEE Systems Journal, Special Issue on Integration of Intermittent Renewable Energy Resources into Power Grid*, 2011. (in press)
- [23] Encraft, *Warwick Wind Trial*, Final Report, Encraft 2009.
- [24] Energy Saving Trust, *Location, Location, Location: Domestic Small-scale Wind Field Trial Report*, DTI, July 2009.
- [25] A. J. Collin, J. L. Acosta, I. H.-Gil and S. Z. Djokic, “An 11kV Steady-State Residential Aggregate Load Model (Parts 1&2)”, in *Proc. 2011 IEEE PES Europe Conf. PowerTech*, Trondheim, Norway, 2011. (two papers).
- [26] A. J. Collin, J. L. Acosta, I. H.-Gil and S. Z. Djokic, “Realising the potential of smart grids in LV networks (Parts 1&2)”, in *Proc. 2011 ISGT Europe Conf. PowerTech*, Manchester, UK, 2011. (two papers).
- [27] National Grid (2011, May). GB seven year statement. [Online]. Available: <http://www.nationalgrid.com/uk/Electricity/SYS/current/>
- [28] Department of Energy and Climate Change (DECC). Sub-national electricity consumption data 2005-2009.