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Evaluation of Advanced Operation and Control of Distributed Wind Farms to Support Efficiency and Reliability

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***Abstract*--The integration of increasing penetrations of renewable energy sources is one of the key drivers for the increased deployment of control and optimization on power systems. Much of this wind generation is connected to the distribution system, which presents a range of challenges to the operation of these networks, traditionally utilized solely for power delivery. This paper describes a demonstration programme in Ireland which addresses two of the key challenges in delivering high penetrations of wind energy in a cost effective and efficient manner. Firstly, the paper addresses a trial of the advanced reactive power control capabilities of modern wind turbines, investigating how this resource can be better utilized from a distribution and transmission perspective. The second aspect is measures to improve the efficiency of the distribution system in light of these increasing penetrations of wind energy**

***Index Terms*-- Voltage control, power distribution planning, reactive power, wind power generation, distributed generation**

I. INTRODUCTION

Electricity networks of the future will need to be smarter, more accessible and more efficient. In Europe the SmartGrids technology platform has set out deployment priorities for smart networks [1]. European Union policies mandate ambitious targets for renewable generation [2]. These targets stipulate renewable energy penetration for the year 2020: Ireland is to derive 16% of its total energy use from renewable sources by that year. To that end, the target for renewables penetration in electricity generation has been set at 40%; the vast majority of this will be met with wind generation. About 3,900 MW of additional wind capacity must be connected to deliver this, which will bring the total connected capacity to 6,400 MW, on a system with a peak demand of approximately 5,500 MW. This rapid growth of renewable energy resources, in particular wind energy has led to numerous well established challenges to power system planning and operation. Consequently, ESB Networks (ESBN), the Irish distribution system operator, and the Electric Power Research Institute, working with University College Dublin, have initiated a Smart Grid Demonstration project which aims to address key questions on the integration of distributed wind energy.

Improved utilization of the reactive power capabilities of modern wind turbines has been the focus or a range of research and demonstration in recent years. Wind farms, within which active and reactive power are completely decoupled, are now available [3]. Coupled with such technological developments have been investigations into various methods of deploying this reactive power resource [4, 5]. The potential for reactive resources associated with wind farms has also been assessed from a steady state support perspective [6] along with transient stability support through the dynamic response capabilities of such turbines [7]. Other work has focused on developing detailed controller models of doubly fed induction generators and examining controller performance and reactive power in various modes of operation [8, 9]. It has also been shown that the power electronic converters that are utilized in such wind turbines, potentially have the capability to provide significantly more reactive power than grid codes currently specify [10]. Related work has approached the issue from the perspective of optimal utilization of these reactive power resources from a system perspective, demonstrating a range of possible objectives and benefits [11-13]. The question of placement of sectionalizing switches has also gathered attention recently, with network operators considering how new switching technologies can be deployed to improve network reliability and decrease the scale and duration of outages [14]. The economics of such investments is also highly relevant [15], as is the required communications infrastructure to enable their effective utilisation. [16]**.**

The demonstration programme has two main objectives: integration of wind energy and improvement in the efficiency and reliability of the distribution network. The first aspect addressed is how the decoupled reactive power capability of modern wind turbines can be used to actively control terminal voltages at the point of common coupling. A section of distribution network which connects two wind farms and which is free of load customers is being used to demonstrate this technology. Beyond the implementation of voltage control at wind farms, a scheme for their coordinated operation will be devised to enable effective distribution operation and potentially contribute reactive power to support the wider system.

These efficiency trials are being carried out on three separate rural medium voltage (MV) distribution circuits, one of which has a wind farm connected. The investigations and trials fall into two main categories: reduction of distribution system losses and technology/controls for interoperability. Measures for reducing losses that are

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investigated include optimal and dynamic network sectionalizing to best absorb wind generation, usage of battery storage, reactive power control, conductor uprating, reducing unbalance and reducing transformer losses. Where the trials and investigations in question are carried out on networks with wind generation, the contribution this can have on primary loss reduction is a key issue. Additionally, the integration of other trial technologies with wind power offers the opportunity to discover and address any interoperability, monitoring or control issues arising.

Section II outlines the reactive power management field trial and Section III describes the efficiency measure field trial. A summary of and conclusions from the demonstration programme is given in Section IV.

II. WIND FARM REACTIVE POWER MANAGEMENT

A. Demonstration Network

The network selected for this trial is a section dedicated to wind energy, without any demand customers. It is a section of 38 kV network which connects two wind farms to a 110 kV transmission node as shown in Fig. 1. These wind farms are located in the rural South West of Ireland, in a sparsely populated region with only a modest level of distribution system development.

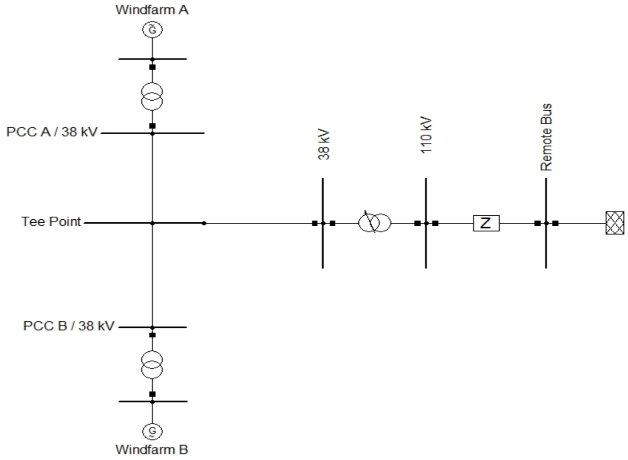

Fig. 1 Single line diagram of test wind farm network

Wind farm A has a maximum export capacity of 22.5 MW. This is realized with nine 2.5 MW turbines. Wind farm B comprises thirteen 1.5 MW turbines, with a total maximum export capacity of 17.2 MW (installed capacity is 19.5 MW). The interface point between the distribution network section and the transmission system is a 110/38 kV transformer rated at 63 MVA. These transformers have historically been the principal means of distribution system voltage control, with their on load tap changers maintaining sending voltages on the 38 kV side within a tight band in the face of varying voltage at the transmission level. PQ meters were installed at each wind farm and at the Bulk Supply Point (BSP) recording data at a 30 second resolution. The absence of load on the network identifies it as a sensible test platform for demonstrating a new voltage control regime.

B. Reactive Power Capability

Each of the wind farms comprise modern wind turbine generator technology that offers reactive power that is largely decoupled from active power output. The objective of utilising the voltage control capability of the network is to investigate if a coordinated policy can be developed for the operation of these farms. The question being addressed is firstly to assess voltage control operation on a live network and beyond that to determine the optimum setpoints and overall strategy for managing voltage and reactive power on distribution networks with wind energy. Of particular interest is the potential for voltage control at distribution level and to investigate the potential for export of reactive power from the wind farms, determining if there is potential for distributed wind to be part of the solution of the power system's reactive power needs.

As shown in Fig. 2 modern wind turbines such as those employed in this trial have a significant reactive power capability, which is decoupled from active power over a wide range of operating points. The dashed line indicates the extra capability of wind farm B over wind farm A at active power outputs below 0.2 pu. For wind farm A, the reactive power capability is not fully decoupled from active power. As has been demonstrated in [14] this capability is network and turbine dependent.

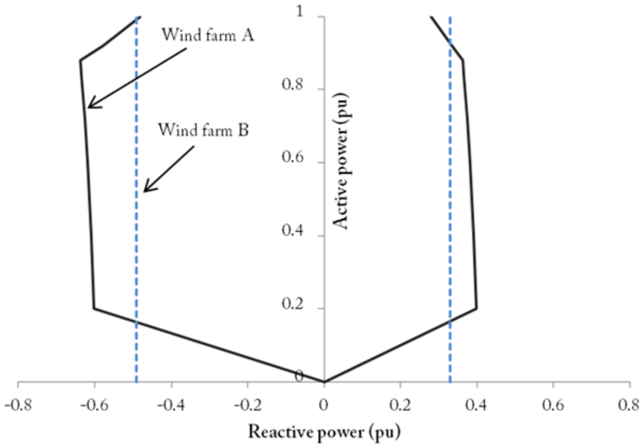

Fig. 2 P-Q Capability chart for the two wind farms

C. Time Series Power Flow Simulations

The first stage of this demonstration was to determine the existing state of the network and the wind farms by collecting data under the initial operating points. Fig. 3 shows the active power output of the two wind farms over a sample period with a data resolution of 30 seconds. It illustrates what is evident from all the time periods of investigation, which is a closely related active power output for both wind farms, as expected given their locations 9 km apart.

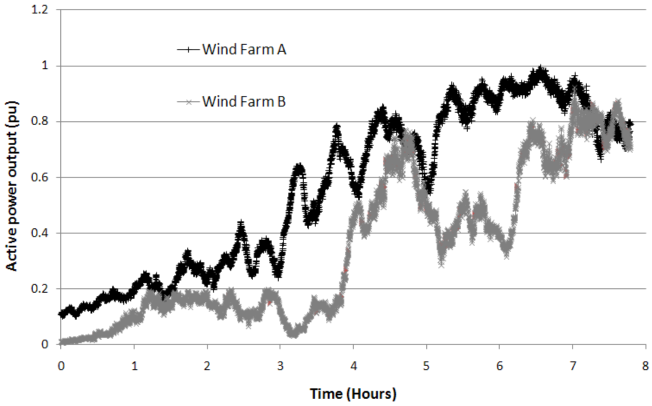

Fig. 3 Active power output of the two wind farms for a sample period

The tap changer at the BSP is an important variable in the control of local voltages and consequently in determining the reactive power output of the wind turbines. Time series power flow simulations at a resolution of 30 seconds were carried out under varying scenarios to determine what voltage set points, droop and tap changer configuration would provide the maximum insight into the controller performance and network operation for the duration of the trial. Two scenarios are described here in detail as means of illustration.

1. Voltage control is enabled at both wind farms, regulating voltage to 41.6 kV and the sending voltage at the BSP set to 41.6 kV
2. The tap changer is locked to a low tap setting, resulting in a no load voltage of 39.36 kV and again control is enabled at both wind farms[1].

From Fig. 4 the reactive power exchange at the bulk supply point over the period of simulation can be examined. In scenario 1 it is evident that the network is demanding reactive power from the transmission system, even with both voltage controllers enabled and regulating to a high local voltage set point. This is due to the active power output of the wind farms and the tap changer set point. Over the eight hour period the influence of the active power output is particularly evident. The increasing active power output causes local voltage rise, which is counteracted by the voltage controllers resulting in an increased reactive power requirement at the local wind farms and thus the 110 kV BSP. The degree of voltage rise and the relative effect of active and reactive power on the voltages is a function of the network impedance and in particular the X/R ratio.

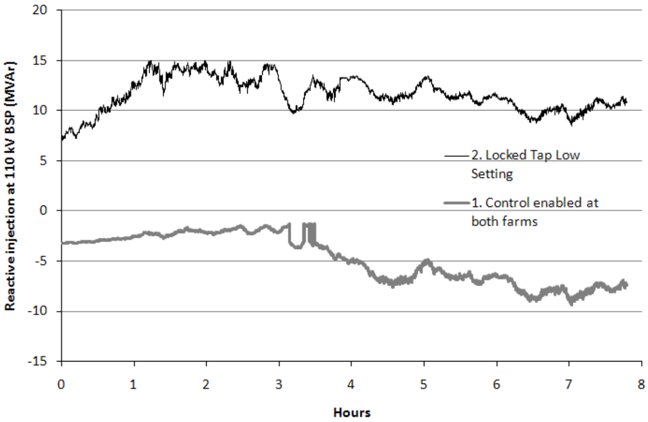

Fig. 4 Reactive power at BSP under scenario 1 and 2

In scenario 2 the low sending voltage depresses the voltage out along the feeders to the wind farms. This lower voltage results in the voltage controllers specifying capacitive operation with the resulting supply of reactive power from the wind farms at the BSP evident in Fig. 4.

Fig. 5 shows the resulting voltage at the BSP. It can be observed that devolving control to the wind farms in scenario 2 results in a more variable voltage at the BSP, whereby the voltage at the BSP is now driven largely by the active and reactive power flows from the wind farms, assuming a nominal voltage on the transmission system.

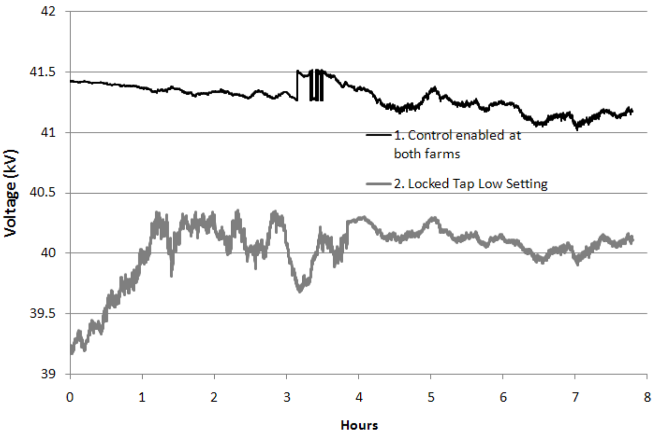

Fig. 5 Voltage at the BSP under scenario 1 and 2

D. *Trial Results*

The next stage of the trial was to enable voltage control at each wind farm individually, with the other wind farm operating at the business as usual fixed power factor of 0.95 inductive. The network was operated under each configuration for a period of approximately three weeks each starting in May 2011 and running until August 2011. Initially, wind farm A was specified to operate with a 1% droop (regulation slope) and a voltage set point of 41.6 kV. Fig. 6 shows a sample of the measured data from wind farm A. The operation along the droop characteristic is evident, with reactive power operation in both inductive and capacitive halves of characteristics as was desired for the purposes of the technology trial.

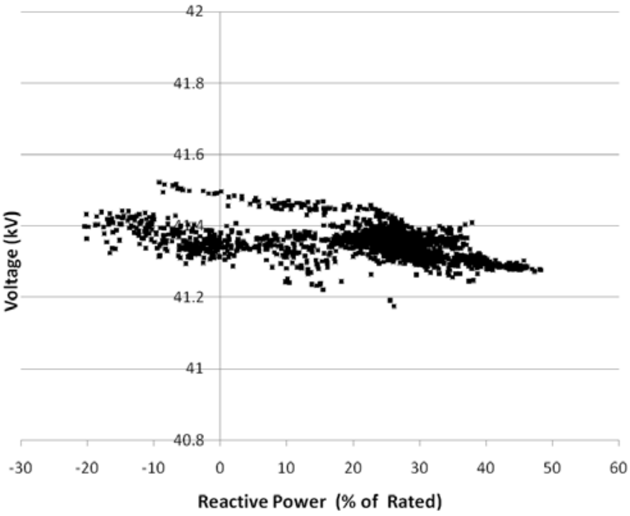

Fig. 6 Q-V measurements from wind farm A with voltage control enabled

The same procedure is followed with wind farm B, in this case operating with a voltage set point of 42 kV and with a droop of 4%. The 4% droop as compared to 1% introduces a wider variation in the achieved voltage. Fig. 7 demonstrates the successful operation of the wind farm in constant voltage mode. The turbines can be seen to be operating successfully along the defined droop. One feature to note in comparing Fig. 6 and 7 is the different width of the cluster of points. It is evident that wind farm B controls the voltage with a greater degree of adherence to the droop setting. Relevant factors at play here may be the time constant of the controllers, along with other controller gain inputs, which are tuned by the manufacturers on a wind farm by wind farm basis.

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[1] 39.36 kV is outside planning standards and normal busbar operation standards

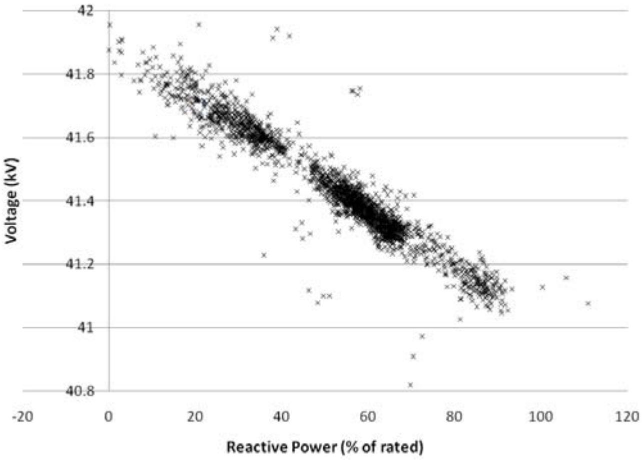

Fig. 7 Q-V measurements from wind farm B wind voltage control enabled

The final stage of the trial was to enable voltage control at each wind farm simultaneously. In this case both wind farms were regulating to 41.8 kV with a droop of 2%. Fig. 8 shows a 3 dimensional plot of the voltage controller operating at wind farm A.

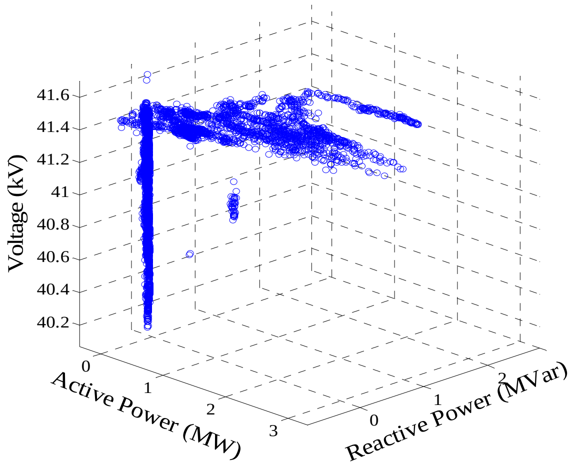

Fig. 8 3-D plot of voltage, active and reactive power measurements at wind farm B from dual voltage control trial period

The droop is evident when the reactive power and voltage axes are compared. When the reactive power and active power are compared it can be seen that they are largely decoupled as per the capability chart shown earlier in Fig. 2. This represents a marked difference from the fixed power factor regime that represents the business as usual case for many distribution connected wind farms. Also of note are the operating points with 0 MVAr corresponding to times of low active power output. As seen earlier in Fig. 2, when the active power of wind farm A is below 0.2 pu on any turbine the reactive power capability at that turbine gradually reverts to 0 MVAr.

Fig. 9 shows the relationship between the reactive power operating points of both wind farms over the dual voltage control period. A surprising feature is the absence of points in the bottom left quadrant. This shows that there are no times when both wind farms absorb reactive power. While the majority of recorded operating points are in the top right quadrant, when both farms export reactive power, outside of this quadrant many instances occur, where one wind farm supplies reactive power to the other.

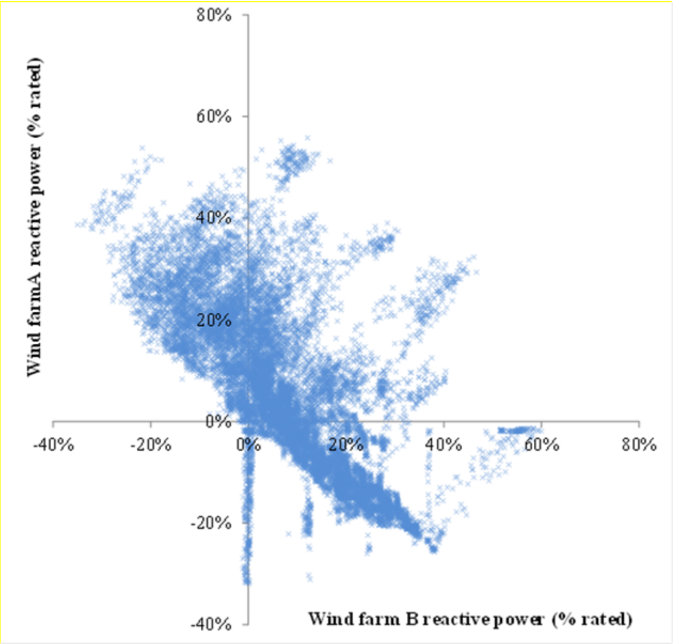

Fig. 9 Relationship between concurrent reactive power operating points at each wind farm

The data in Fig. 9 can be expanded by a time-domain analysis. In Fig. 10 a twenty four hour period is shown, giving reactive power flows at each wind farm. It is evident that for the first twelve hours, both wind farms operate in harmony. Just after 09:00 a shift is seen, with wind farm B moving to a reactive power absorption regime, while wind farm A retains an export regime. Examination of the Q-V curves for this time period reveals that wind farm A deviates from it defined droop. This deviation is due to the open loop control in operation at this wind farm, whereby the farm level control will calculate the required reactive power set-point and issue a reactive power dispatch to each turbine. In some cases the required reactive power may not be available from every turbine or between issuing the instruction and achieving the reactive dispatch the active power of the wind turbines may have altered, thus shifting the operating point from the droop characteristic at the time of measurement.

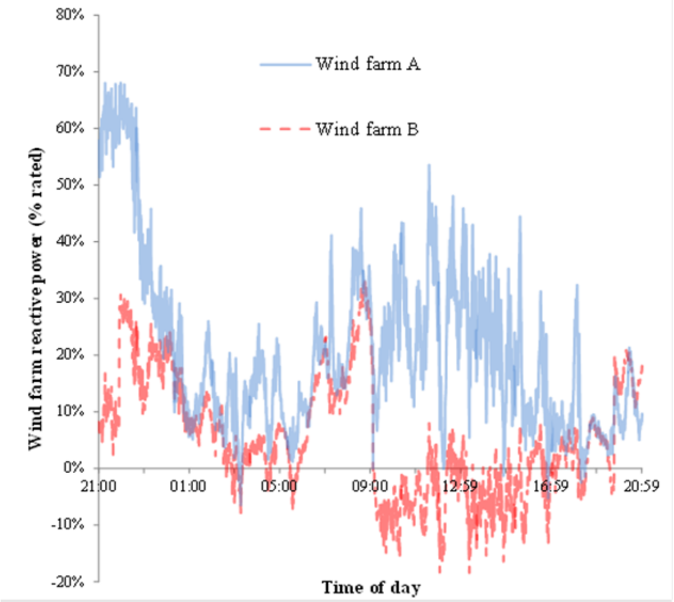

Fig. 10 24 hour period showing variation in reactive power at each wind farm

E. Potential System Benefits

There are a number of benefits which greater reactive power control may deliver. As expanded upon in Section III any reduction in losses is always welcome. From the measured data an estimate of the relative losses may be made by comparing the measured reactive power flows against the business as usual case (0.95 wind power factor) for the same period. From the measured data the average of absolute reactive power output from each wind farm was calculated. Then for the same active power time series a power factor of 0.95 inductive for each was assumed. The resulting values are shown in Table I. It is evident that with control enabled the reactive power flow on the network will be much reduced (36%).

TABLE I
AVERAGE REACTIVE POWER UNDER DIFFERENT CONTROL REGIMES (MVAR)

	Dual Voltage Control	0.95 Inductive Power Factor
Wind Farm A	0.987	1.451
Wind Farm B	0.574	0.971
Total	1.561	2.422

Table II shows the related statistics for apparent power. It can be seen that while a 0.95 power factor results in more reactive power than the voltage control case, this does not translate into increased current flow and thus losses. In fact the 0.95 power factor has slightly reduced apparent power than the voltage control case, which assuming a relatively constant voltage corresponds to reduced current and thus losses.

TABLE II
AVERAGE APPARENT POWER UNDER DIFFERENT CONTROL REGIMES (MVA)

	Dual Voltage Control	0.95 Inductive Power Factor
Wind Farm A	4.79	4.73
Wind Farm B	3.50	3.16
Total	8.29	7.89

The maximum generation capacity that can be connected to a given network is another important consideration for network operators. From load flow simulations, the enabling of voltage control and the tap changer at appropriate set points allows the voltage constraint at all local buses to be overcome and the thermal line rating becomes the binding constraints. In the case of this network there is an extra 6 MW of generation capacity permitted. This increase in capacity also indicates that the use of voltage control may be a useful consideration at the planning stage of wind connections. It should be noted that any extra capacity is enabled through inductive reactive power operation to overcome the voltage rise constraint, which will be at the expense of the potential for reactive power export.

The potential for distributed wind to provide ancillary services is an increasingly relevant topic. At times of high wind power output, distributed wind can represent a significant penetration of overall system generation. For example, in Ireland this instantaneous penetration has reached ~25% [15]. As a result the reactive power of DG is an important consideration for voltage security and stability. In Fig. 11, the reactive power exchange is shown at the 110 kV bulk supply point. It can be seen that in this trial stage with both wind farms operating with voltage control enabled supply of reactive power from the wind farms is achievable. It is evident that at times of high active wind power output, in order to satisfy local voltage constraints, the wind farms reduce their reactive power and even switch to inductive operation at times. This illustrates a key trade-off between accommodation of active power and provision of reactive power support. This trade off of the objectives of the various stakeholders involved highlights the potential for future work in this area to assess the priority of such services and the requirements of each party.

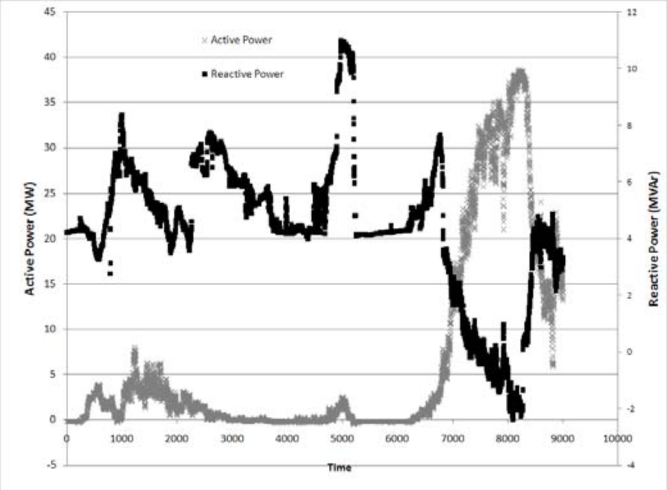

Fig. 11 Active and reactive power flow exchange at BSP

In summary the voltage controller trials have shown that satisfactory voltage controller operation is possible, with a large degree of influence from the parameters chosen and turbine technology. This will result in a flatter voltage profile on the distribution network with no effect on the ability of the wind farms to export power. Although, it has been shown that inductive operation may be required to satisfy local voltage constraints. In terms of voltage support to the transmission system, it has been demonstrated that the supply of bulk reactive power to the system is possible at times, but also that it is dependent on the network parameters, wind power output and wind turbine type. From the simulated and measured results to date there is a valuable reactive power resource which can potentially be employed for a range of objectives of benefit to different stakeholders.

It is important that the relative merit of different outcomes of this kind of control (local voltage management increasing the hosting capacity of the network, provision of reactive support for the transmission system) be assessed from the perspective of both system operators and all network users including generators. With high distributed wind generation, customer power quality must be maintained to a high level at all times, without any degradation or additional cost to mitigate this being incurred by society. If an ancillary service provided by a generator is for the sole purpose of mitigating local voltage variation due to the active power export of this generation itself, then it should be considered technology necessary for connection. Any integration of such voltage control into network operational and connection policy, network standards and any contractual arrangements in future should reflect this while realising the benefits such voltage control can offer. Future work will focus upon strategies to balance the priorities of the different stakeholders ranging from system operators, generators and demand customers.

III. EFFICIENCY AND OPERATIONAL SOLUTIONS WITH DISTRIBUTED WIND

A related set of field trials to the reactive power control trial described above were run to determine the effectiveness of a range of technologies in conjunction with wind generation in reducing losses and improving general network efficiency.

A. Demonstration Networks

Three MV rural demonstration networks on or near the west coast of Ireland were selected for these trials. This is a region with very high levels of wind connections but sparse load with low industrial development and very low population densities. Two of the networks, at Dungloe and Kilcolgan, are currently feeding at 10 kV while the third, in Kerry is feeding at 20 kV.

The Dungloe network, with distributed wind generation, comprises two 10 kV outlets, Rosses and Dungloe. These are fed in parallel from Dungloe 38 kV/MV station, with two normally open interconnection points enabling the two outlets to provide backfeed for each other in case of line faults. The Rosses outlet feeds rural loads in the vicinity of Dungloe and the island of Aran Mor via a submarine cable. The location of Dungloe and the wind farm on the distribution circuit is shown in Fig. 12. The peak load on this outlet over the baseline period during Winter 2009/2010 was 2,463 kW. The Dungloe outlet and the wind farm which is located at the rural extremity of the circuit feed the town load. The peak loading on this outlet in 2009/2010 was 2,132 kW. The wind farm comprises a single 660 kW turbine and peak export over the baseline period was 651 kW. The peak load on the combined outlets over this period was 4,543 kW.

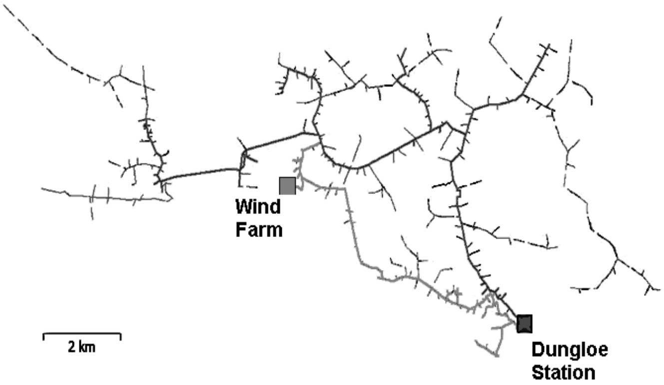

Fig.12 Dungloe trial circuit, with distribution connected wind farm.

B. Dynamic sectionalization with distribution connected wind

Dynamic, or otherwise, sectionalization of networks offers the potential to reduce distribution losses and reduce the loading on the supplying 38/10 kV station transformer. The potential for practical implementation of dynamic sectionalization on the test networks is limited by the number of remotely controllable network switches. For two back-to-back radial feeders typically two switches per feeder and an additional switch at the normally open (NO) tie point are required.

In developing the case for dynamic sectionalization it is vital to find the optimal sectionalization for loss reduction and a frequency of sectionalization where the operational burden does not outweigh the efficiency benefits [14, 15]. Time series power flow simulations of the Kerry network revealed that even with hourly switching, only a 0.7% reduction in annual distribution energy losses is achievable, while less dynamic regimes, e.g. simply choosing an alternative static sectionalization point, offered reductions of just over 0.06%.

Far greater potential for loss reduction was evident on the Dungloe network, where wind generation is present. Load flow calculations indicate that the presence of the wind farm on the Dungloe network leads to reductions of 23%. Time series power flow simulation of the 10 kV feeder and downstream (neglecting 38 kV station transformer) indicated that this may be an over estimate. This is supported by the fact that the majority of the load on this outlet is located remotely from the wind farm. In addition, the higher network voltages due to the wind generation lead to higher distribution transformer iron losses and similar increases in power drawn by constant impedance loads.

Time series power flow simulations with the circuits reconfigured such that the wind generation feeds onto the Rosses outlet, which has a greater proportion of its load nearer the wind farm, give annual primary line loss reductions of 8%, with the NO point moved to point A and by 20% with the NO point moved to point B as shown in Fig. 13. Operating the circuit in closed loop configuration, i.e. non-radially, with the wind farm present gave a reduction of 34-54%, dependent on the wind power output. Closed loop operation requires that the network protection offers bi-directional capabilities, to date not required due to the strictly radial operation of the network. Based on the experience of a communications independent self healing loop, the existing non-directional overcurrent reclosers were maintained, with the addition of a null point recloser set to operate more quickly than the other reclosers. This enables them to subsequently isolate the fault on the reconstituted radial networks.

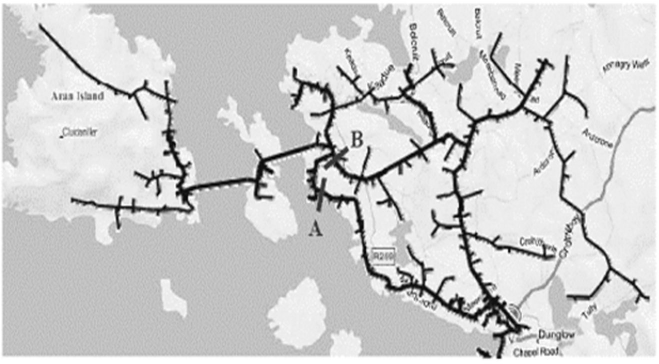

Fig. 13 Alternative sectionalization points (A and B)

C. Voltage control and optimization

Wind generation on distribution networks leads to elevated and variable network voltages. In specific cases this can be advantageous. In Section II-E, it was seen that the implementation of voltage control did not result in a significant change in losses. Here, load flow modeling reveals that the sectionalization proposed in Section III-C could offer voltage support to more extreme points on the Rosses network which otherwise could suffer low voltage conditions. Although, due to the variability of wind generation, this voltage support could not be relied upon.

The current approach to ensure that voltages do not rise outside standard for supply customers is the reinforcement of the network to cater for the worst case scenario of high wind and low load conditions. The novel use of an autotransformer was trialed on a network with two wind farms to buck rather than boost the voltage at the point on the network from which customers are fed. Fig. 14 shows the tap changer position of the autotransformer and the voltage on either side of the transformer. From 2pm the wind power output increases and load reduces causing an increase in the line voltage, as shown in Fig. 14. However, the regulator tapping ensures that during this period the voltage at the demand busbar is kept below the line voltage and within strict limits. This method of regulation moves the overvoltage to beyond the demand busbar to the far side of the regulator. This sterilizes a portion of network, which is not currently serving any demand customers and is at the start of a long line back to a 38 kV station. This has no effect on the current load serving capability of the network while enabling the accommodation of the two wind farms without the need for network reinforcements.

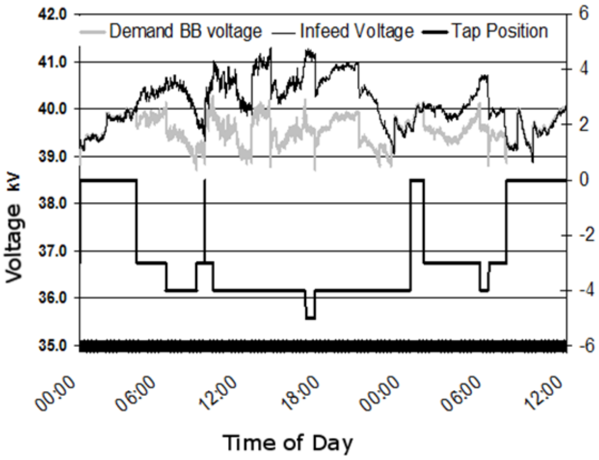

Fig. 14 Load point voltage regulation mitigating wind generation induced voltage rise

As described above, trials of conservation voltage reduction (CVR) entail reducing the supply voltage so that many consumer devices consume less energy or operate more efficiently. This has been shown to lead to significant demand reduction on networks with high levels of air conditioning and other highly inductive loads [16]. However, initial trial measurements have revealed typical power factors of 0.97 - 0.99 on rural Irish networks. This, coupled with the lack of significant air conditioning load indicates that the load mix in Ireland has less potential for demand reduction by this means. To date results for CVR have indicated its suitability to heavily loaded urban networks rather than the low load factor, rural outlets that prevail in Ireland [17].

Initial results from the proof of concept stage of the CVR trials offer insight which could be valuable in the context of distributed wind integration and the associated reactive power requirements. As illustrated in Fig. 15, the instantaneous reactive power demand of the circuit is reduced by an average of 20%. While these results are based on a single sample set, thus not claimed to be statistically valid, there appears to be a strong trend, observable in Fig. 15, with this lower reactive power demand visible over the course of the day. The reactive power demand available for this reduction is likely influenced by the proportionally high population of distribution transformers. The highest relative reduction is seen when overall loading is lowest, thus the contribution of transformer iron losses is proportionally highest.

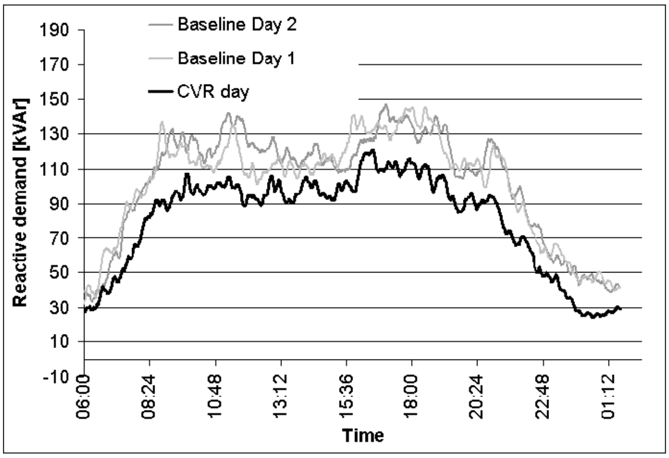

Fig. 15 Measured reactive demand with conservation voltage reduction

IV. CONCLUSIONS

This smart grid demonstration programme has tackled two broad challenges facing DSOs; the connection of high penetrations of wind generation and the on-going challenge of improving the efficiency and reliability of their networks.

The management of reactive power resources is an increasingly relevant challenge for system operators. The trial described in Section II demonstrates the technical capability of modern wind turbines and provides important insight into the variables and parameters at play in determining network generation capacity and the required control equipment to facilitate higher penetrations of distributed wind generation. The trial results indicate that the reactive power capabilities of modern wind turbines can be used for a range of objectives, such as loss reduction, local voltage control and reactive power export. It is important to note, however, these objectives may be conflicting, dependent on a range of factors such as wind power output, network impedance and the state of the transmission system.

The second suite of trials informs the integration of new systems, which facilitate highly efficient, secure network operation with high wind penetrations. They offer a unique opportunity for ESBN to optimize the amount of wind generation which can be harnessed, revealing the challenges in terms of control, communications, interoperability and integration. Earlier self healing loop experience is aiding the development of protection for closed loop operation with distributed wind. The results reveal the potential for wind export to be maximized through smart sectionalization of networks, while the employment of various voltage regulators at multiple voltage levels is showing potential to reduce energy usage and facilitate higher wind penetrations.

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