Voltage Control
DS3 Advisory Council Discussion Paper

15th May 2012

1 Purpose

The purpose of this document is to stimulate discussion on voltage control issues on the Ireland and Northern Ireland power system, particularly as the generation portfolio changes. In it, the particular challenges around voltage control are outlined, and a strategy for discussion is proposed on the best way to proceed as part of the DS3 programme.

2 Background

The management of system frequency and voltage are the two main planks of power system operation and control. Frequency is a universal parameter governed by the energy balance in the system as a whole, and is managed by bringing on or off generation (or demand) as required. Conversely, voltage is a local variable: every node in the system has its own local voltage, and this voltage changes as demand for electricity varies and as network flows change across the day. This makes the control of voltage across the transmission and distribution systems different to the control of frequency, and brings its own set of unique challenges.

Reactive power is used to control voltage in a similar way as real power is used to control frequency. There is a key difference though – reactive power cannot be transmitted over long distances, whereas real or active power can be supplied at any appropriate point in the system and will affect frequency in the same way. Reactive power (Mvars) therefore must be supplied locally as much as possible. An alternative way to look at this is to think of generators as voltage supports or pillars, and loads as being like weights that pull the voltage down. In an ideal situation, the voltage profile would be flat across the transmission system. However, reactive power tends to flow from a high voltage (generators) to a lower voltage (loads), and so in order for it to flow around the system, the voltages would need to be very uneven – a highly undesirable situation if voltages need to be kept within tight limits. If loads consume reactive power (inductive loads), then it is best to supply that reactive power nearby from a conventional generator, windfarm, statcom, SVC, or capacitor bank.

The 'quality' of the reactive power depends on the source. It is also necessary to distinguish between steady-state and dynamic reactive power: steady-state refers to the reactive capability under normal operating conditions; dynamic reactive power refers to the capability to provide reactive power under abnormal or fault conditions. A conventional synchronous generator is the best source of reactive power for both as its reactive power is solid in steady state and it can provide dynamic reactive support over a wide range of operating conditions and disturbances. In technical terms, a synchronous generator acts as a constant current source in steady state, and provides significant fault current to support the system during disturbances. Other forms of technology do not perform as well in these cases. In particular, capacitors provide reactive power which varies with voltage and provides no fault current during a disturbance. Thus if the voltage falls at some point in the network (perhaps due to increasing load), the reactive support available from the capacitor bank falls away even faster.

One role of the TSOs is to maintain transmission system voltages within normal operating limits for the loss of any single item of plant. The TSOs also strive to keep the voltage relatively constant across the transmission system. In order to reduce resistive I^2R losses on the system, the TSOs operate the voltage towards the upper operating limits during the day, and reduce the voltage at night towards the lower operating limit. The DSOs use transformer tap-changers and voltage boosters to keep the distribution system voltages within very tight tolerances.

The relationship between transmission and distribution voltage control is changing as the portfolio changes. Traditionally, distribution networks were passive and each radial distribution network viewed the transmission node as being able to provide a sufficiently high sending distribution voltage through tap changer control. However, there has been a substantial shift of reactive sources onto the distribution system itself due to windfarm connections. The displacement of conventional plant can lead to lower short-circuit levels on the transmission system – in effect, the transmission system voltages may not be as 'rigid' as previously experienced. Therefore, the management of reactive sources on the distribution system, including the flows of reactive power across the bulk supply points and the provision of dynamic reactive response, is becoming increasingly important. The control of distribution voltages will have an impact on the penetration of wind and overall system stability.

2.1 Current Reactive Power Requirements

The reactive requirements for windfarms and conventional generators in the Irish Grid Code are summarised in Figure 1. The requirements for conventional generators in Northern Ireland are similar. Figure 2 shows the reactive requirements for a combined-cycle gas turbine (CCGT), taken from the Northern Ireland CCGT Minimum Functional Specification document. A comparison of the Grid Code and Distribution Code requirements for windfarms in both Ireland and Northern Ireland is given in Figure 3. Note that the Northern Ireland requirements on windfarm reactive requirements are specified differently to the Ireland requirements, with a requirement to use the full reactive capability of the windfarm over a voltage range. They are not given in the form of a P-Q chart, as is done in the Irish Grid Code. Note also that there are different connection types for windfarms in the Ireland Distribution Code, designated Type A – E. Connection types A and B have the same reactive requirement as the Ireland Grid Code for windfarms larger than 5 MW. Connection types C, D, E refer to windfarms embedded deeply in the distribution system, where there may be load connected to the same bus as the windfarm, or where the windfarm is teed into an existing feeder. The reactive requirements on these windfarms are limited to absorbing reactive power to help manage voltage on the distribution system.

It is clear from Figure 1 and Figure 2 that the reactive capabilities and requirements of conventional machines are significantly greater than windfarms. In particular, the reactive capability of a conventional plant is very significant as long as the machine is synchronised, whereas the reactive capabilities of induction-based windfarms taper inwards towards zero at low active power outputs. Full-converter based windfarms can supply reactive power at low or zero active power output, though this feature is generally not installed in Ireland because of cost.

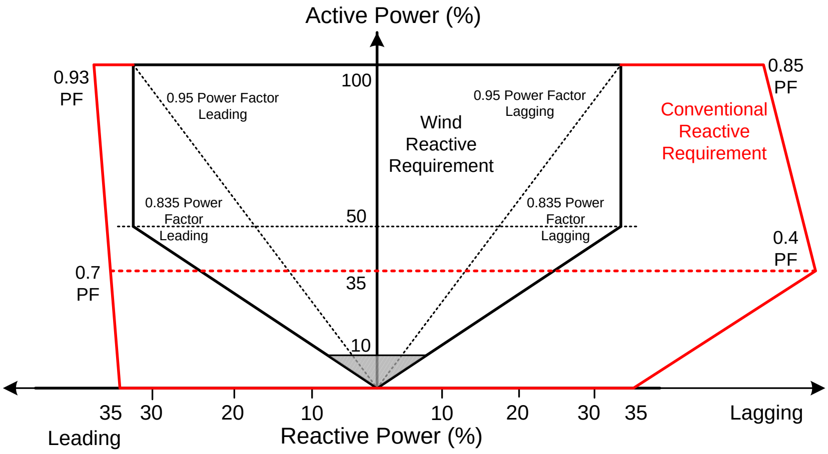

Figure 1 Reactive Requirements for Conventional Generators and Windfarms in the Irish Grid Code

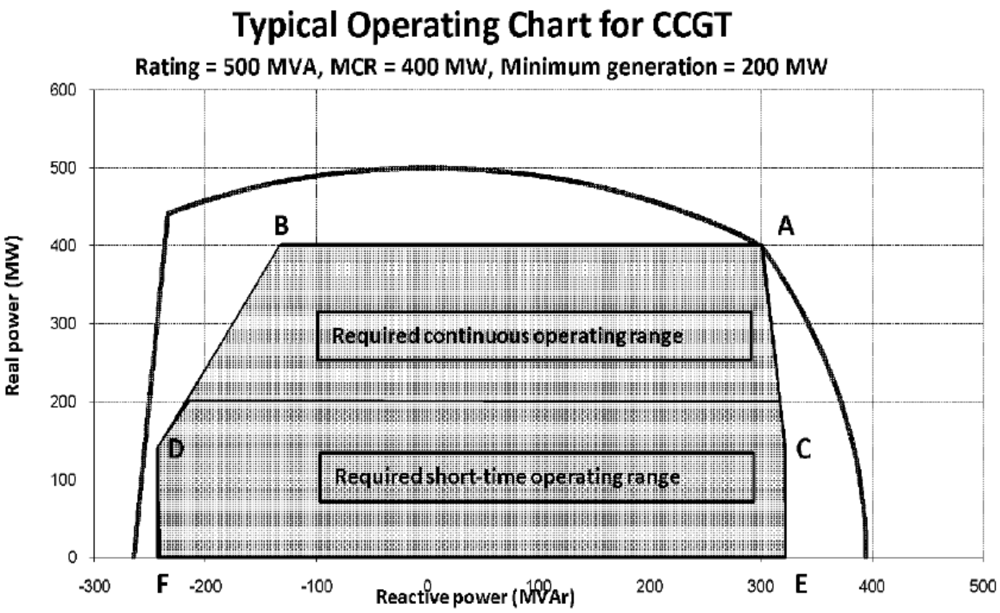

Figure 2 Minimum Functional Specification for a CCGT in Northern Ireland

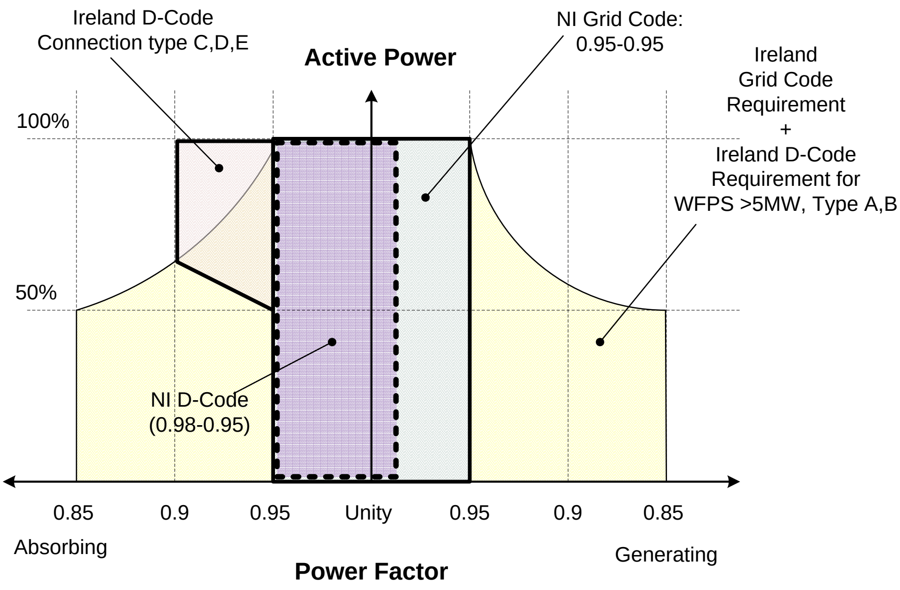

Figure 3 Comparison of Grid Code and Distribution Code requirements for Windfarms in Ireland and Northern Ireland

In Ireland and in Northern Ireland, there are Operational Security Standards that are adhered to when controlling the transmission system voltages. These standards set out the normal voltage operating ranges and the voltage ranges allowed following a contingency, and are typically in the range of 0.95-1.1 per unit(pu) for base case and 0.9-1.11 pu following a contingency. The power system control engineers dispatch reactive power from conventional plant and switch in or out reactive devices as required to maintain the transmission system voltages within these specified limits. It is also possible to use transmission-connected windfarms to control voltage, although this depends on the windfarms' availability.

2.2 Projected Reactive Power Requirements

By 2020, there is expected to be over 4000MW of wind generation installed on the Ireland and Northern Ireland power system. The amount of synchronous reactive power is forecast to drop by up to 25% as windfarms displace conventional units (see Figure 4 and Figure 5). The leading reactive capability of the generation portfolio will be severely affected (leading reactive capability means the ability of the plant to absorb reactive power). Leading reactive capability is particularly important for managing high voltages that can occur at low loads, or as a result of cable networks, such as are found in cities like Dublin. Under normal operating conditions, cables produce reactive power (they are electrically capacitive), and this can make it more difficult to control voltage in some parts of the network.

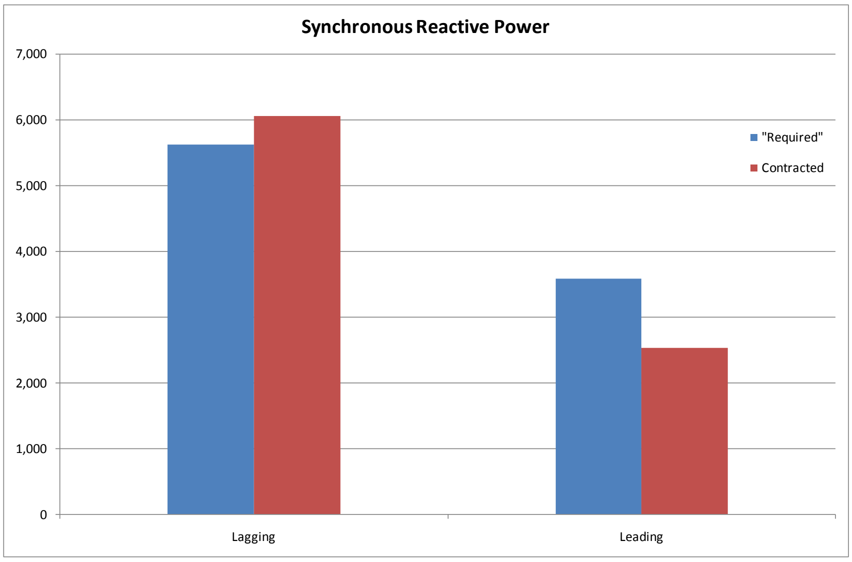

Figure 4: Projected Synchronous Reactive Power Capability versus Reactive Power Requirements in 2020

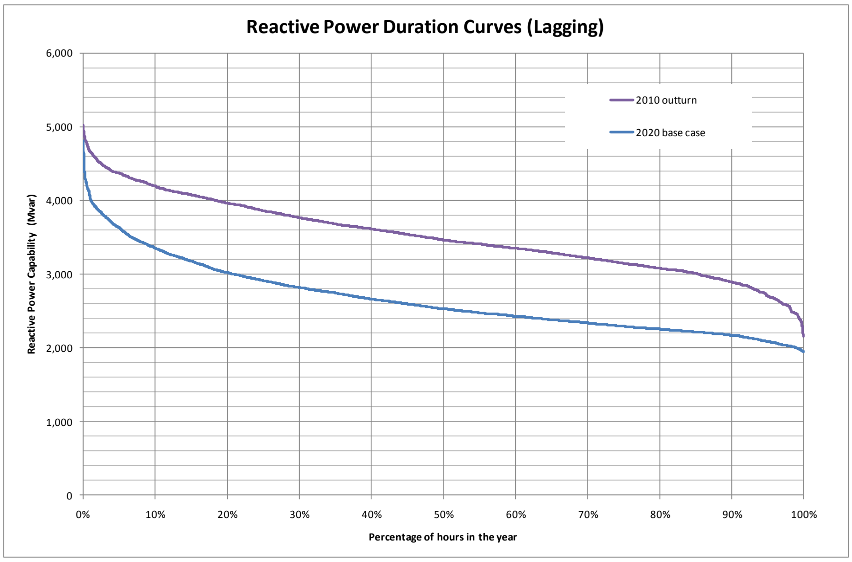

Figure 5: Reactive Power Capability in 2010 and Projected Capability in 2020

The Facilitation of Renewables study from 2010 [**1**] showed that one of the impacts of less synchronous generation would be a loss of transient stability at high wind penetrations (see Figure 6). Transient stability refers to the ability of the machines on the power system to stay synchronised to each other during and following a fault. Loss of stability would entail the power system breaking up into smaller electrical islands, and ultimately blacking out. One possibility for mitigating this issue is to increase the dynamic reactive capability of windfarms.

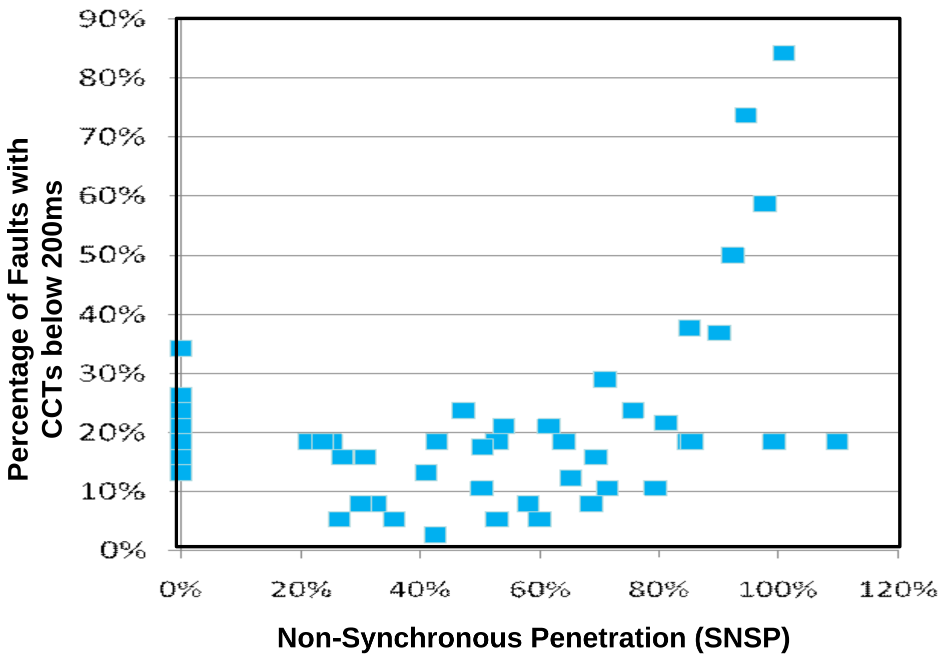

Figure 6 Transient Stability at various System Non-Synchronous Penetration Levels

3 The Challenges

3.1 Changing Nature of the Reactive Sources

A recent study [**2**] by EirGrid and SONI has shown that by 2020, there will a 25% reduction in the amount of online synchronous reactive sources in aggregate. An increase in the number of transmission- and distribution-connected windfarms could assist in balancing out this reduction in reactive power sources. However, this is not a like-for-like replacement. Windfarms are normally located remote from load centres, and are connected at 110 kV/132 kV and lower. The short-circuit strength of the transmission system nodes will be affected by this shift. It is important that the wind industry, the DSOs and the TSOs work closely together to ensure ongoing voltage stability.

A key issue that has recently surfaced is the effect of variable wind farm output on the available reactive power. There was an incident in Donegal in December 2010 where system voltages decreased precipitously as load increased and reactive support fell away due to decreasing wind. This could have led to a voltage collapse had the situation evolved unchecked.

The voltage collapse phenomenon can be studied using Power-Voltage curves (PV curves). These curves show how voltage changes at the far end of a line as more power is sent down it can have an upper (stable) part, and a lower (unstable) part. Only a finite amount of power can be sent down a particular line, and is dependent on the voltage level and the electrical characteristics of the line itself. Generally speaking, as more power is sent down a line, the voltage at the receiving end decreases. The right extremity of the PV curve is called the 'nose', and once this point is reached, voltage collapse ensues. At this point, the voltage and power being sent down the line fall away towards zero. Referring to the PV curves in Figure 7, the use of capacitor banks can help to boost the voltage and keep it within normal range, but that could lead to a voltage collapse occurring while voltages are within their normal ranges.

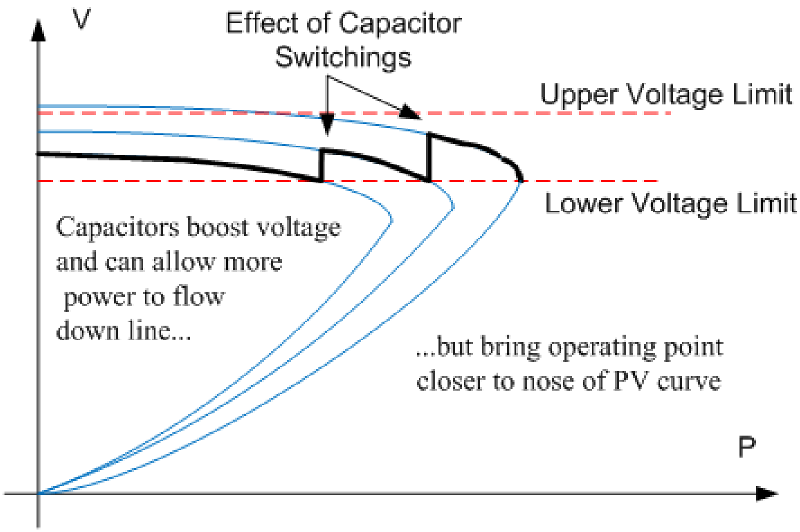

Figure 7 Effect of capacitor banks on PV curves: The curves change shape allowing more power to be transmitted, but shift nose of the PV curve upwards so that it can occur within normal operational voltage limits.

The curves in Figure 8 show the voltages in Donegal falling away rapidly, heading towards the nose of the PV curve. Action by control engineers enabled the voltages to recover by increasing the reactive power output of the hydro units at Cathaleen's Fall. Note that under-voltage load-shedding relays are the final line of defence to prevent voltage collapse occurring. These relays can disconnect customers on the distribution system if the voltages go outside normal operational limits.

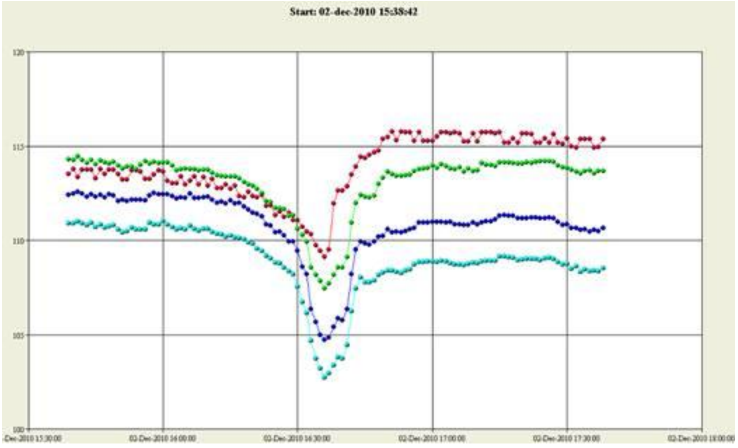

Figure 8 Voltages at Sorne Hill (light blue), Letterkenny (blue), Cathaleen's Fall (green) and Moy (red).

The key challenge is to ensure that reactive capability does not fall away as wind power output decreases, or as voltage decreases. It is the combination of decreasing wind, increasing load, and decreasing voltages that can lead to less reactive power from windfarms and capacitor banks at the very same time as the demand for reactive power is increasing on the distribution system.

3.2 Changing location of the Reactive Sources

Conventional generation in Ireland and Northern Ireland has always tended to be located near the main load centres, e.g. Dublin, Belfast, Cork, Limerick, Derry. From a reactive power control viewpoint, this makes sense, as high loads will act to pull the voltage down during the day, requiring nearby reactive supports. During the night, cable networks in cities can cause voltages to rise very high, and so reactive power absorption capability is required, which has also been traditionally been provided by conventional machines. If conventional machines near the main load centres are displaced by windfarms in rural locations, the dynamic reactive power will need to be found elsewhere. There are a number of possibilities, including installation of network devices such as statcoms or synchronous condensers, or converting existing synchronous conventional machines into synchronous condensing plants.

3.3 Enhancing transient stability during high wind scenarios

Transient stability refers to the ability of the power system as a whole to withstand major shocks to the system, such as arise from electrical faults and generator trippings. When a fault occurs on the transmission system, it has the effect of pulling voltages down towards zero. This causes machines to accelerate as they can't export as much electrical power due to the depressed voltages. Conventional machine excitation systems respond to this by increasing the field strength within the machine. This increased field strength tends to keep all of the conventional machines synchronised together and helps the voltage recover quickly once the fault is cleared.

The ability of the system to remain transiently stable is affected in high wind scenarios. If there are less conventional machines online, and they are electrically further apart, they will find it harder to stay synchronised following a severe fault. The Facilitation of Renewables study showed that a key mitigation strategy was fast dynamic reactive support from windfarms, or installation of network devices to provide dynamic reactive support.

3.4 Integrated Voltage Control Strategies

In future high wind scenarios, the transmission system may not be able to supply reactive power on demand to the distribution system. The reason for this is much of the generation will reside within the distribution system itself. There will be a need for much closer co-ordination of voltage control between the TSOs and DSOs. The Donegal voltage incident is an example of what could go wrong if voltage controls are uncoordinated. Figure 9 shows the 110kV and 38kV voltages in Letterkenny during the 2010 incident. It shows that on-load tap changer (OLTC) actions on the distribution transformers have the effect of reducing the 110kV voltage, while trying to maintain the 38kV voltages within their normal limits. When the transmission system voltages are low, or the transmission system is in a weakened condition, this has the effect of demanding additional reactive power from the transmission system. If the transmission system has insufficient reactive support in the area, then it will be unable to supply those Mvars, and voltage collapse can ensue. Indeed this mechanism has been responsible for many different blackouts and brownouts across the world. Figure 10 and Figure 11 illustrate the mechanism more clearly. It shows a simulation of voltage drop due to a line tripping (Kilkenny-Kellis), followed by OLTC action. The OLTC action eventually pulls the transmission voltage down so far that under-voltage load-shedding is required to save the system from collapse.

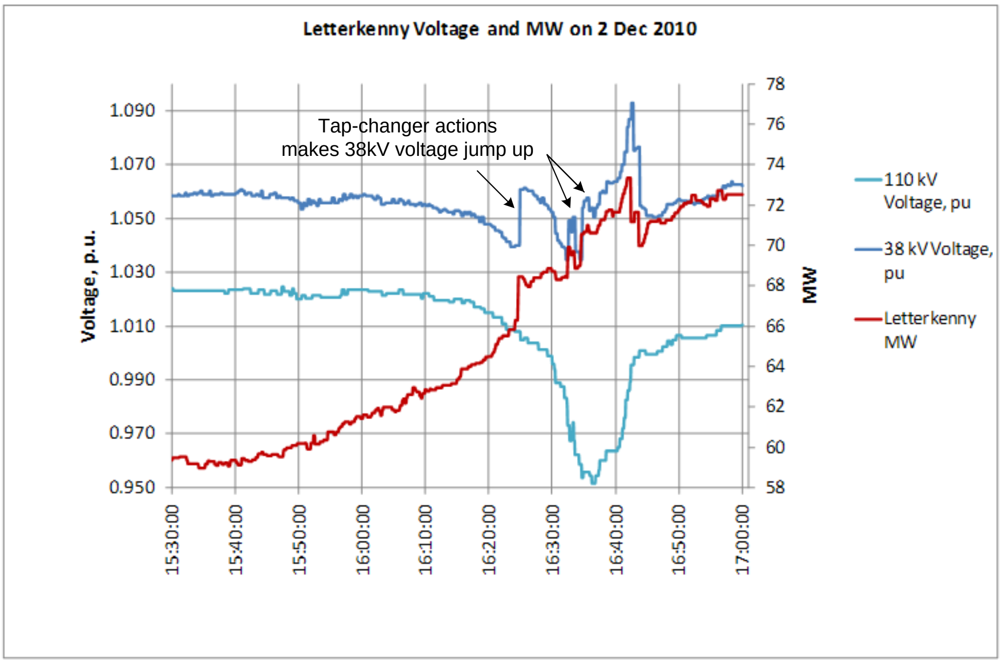

Figure 9 Donegal 110kV and 38kV voltages during the 2010 incident, and the load in Letterkenny

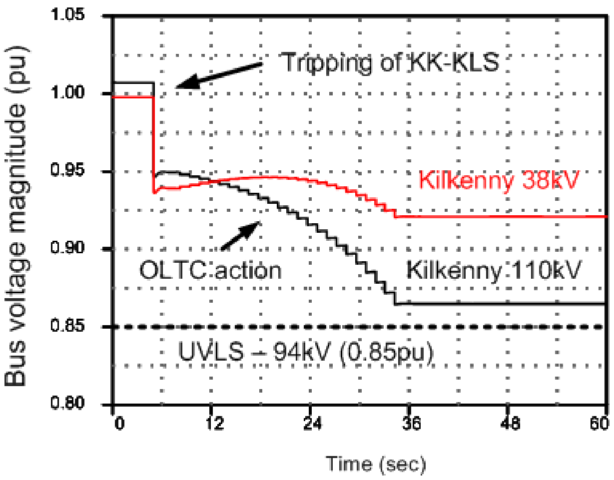

Figure 10 Simulation of OLTC action trying to restore a 38kV bus voltage to within normal range. It has the effect of further depressing the transmission system voltage

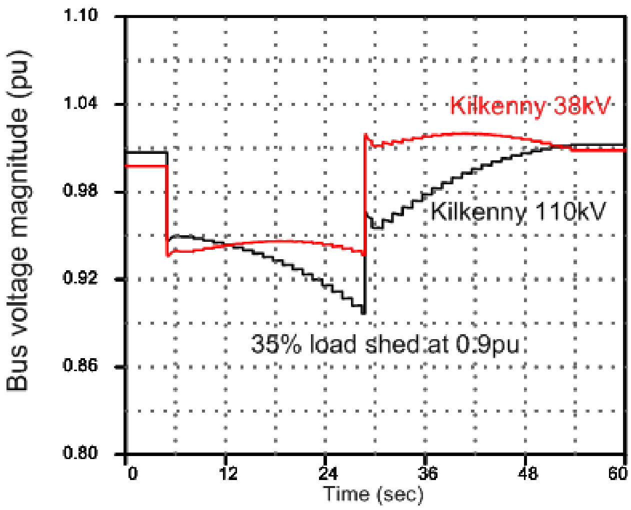

Figure 11 Simulation of how voltages recover to normal following the action of under-voltage load shedding relays

Solutions to this issue include the use of OLTC blocking when transmission system voltages are very low, and reducing the overall flow of Reactive power from the transmission system to the distribution system. Another potential solution is to use windfarms to actively control voltage on the distribution system if voltages are outside limits, rather than operating in a constant leading power factor mode. This would have to be investigated and studied on a local basis by the DSOs and TSOs – there is no 'one size fits all' solution.

4 Current Status and Next Steps

4.1 Recent Developments

There have been several key developments related to voltage control in the last few months.

- A Joint Grid Code Working Group has been set up with cross-industry participation to look at windfarm standards
- Regular meetings of the TSOs and DSOs are now occurring to progress the issues outlined in this paper
- A set of principles, known as the Universal Windfarm Standards, have been agreed among the TSOs and DSOs on the broad capabilities that windfarms should possess
- EirGrid and SONI have opened direct dialogues with several different windfarm manufacturers on windfarm capabilities
- Several Ireland Grid Code modifications have been drafted and presented to industry for discussion
- A windfarm power station settings schedule has been developed to progress the modifications to wind farm standards in Northern Ireland.

4.2 Next Steps

There are three key elements to the voltage control workstream that need to be progressed in parallel. These are standards review, control and management practices and studies.

4.2.1 Standards Review

There is a requirement to set appropriate standards for reactive power capability and control on connecting generation, both renewable and conventional plant . These standards are in the following areas:

- Steady state Reactive Capability and Voltage Control Modes for Renewable Generators and embedded conventional plant
- Dynamic Reactive Power Provision from transmission and distribution connected wind farms and transmission and distribution conventional plant
- Controllability of Wind farms

This element of work is being co-ordinated via both the Grid Code and performance monitoring workstreams as part of the DS3 programme. The revised standards are being discussed at the DS3 Joint Grid Code working group and with windfarm manufacturers. It is expected that clarified standards should be ready for GCRP approval for November 2012.

4.2.2 Control and Management Practices

There is a need to develop appropriate system operational policies to utilise the capability of transmission and distribution connected plant. This needs to be fully co-ordinated between the transmission and distribution systems of Ireland and Northern Ireland.

The TSOs and DSOs are working together to investigate how voltage control should evolve on the power system in the context of the changing portfolio of plant and its location on the power system.

4.2.3 Studies

The network has to be designed while allowing for changed capabilities of connecting generation, particularly embedded in the distribution system. The following analysis/demonstration will have to be carried out.

- Planning Studies (TSOs & DSOs)
- Network Solutions (TSOs & DSOs)
- Demonstration Projects

Together these elements of work encompass the different time frames illustrated in Figure 12, going from millisecond timescales of excitation system responses following system disturbances up to minutes and hours which relate to the overall ability of the generation portfolio to control the system voltages as demand varies throughout the day.

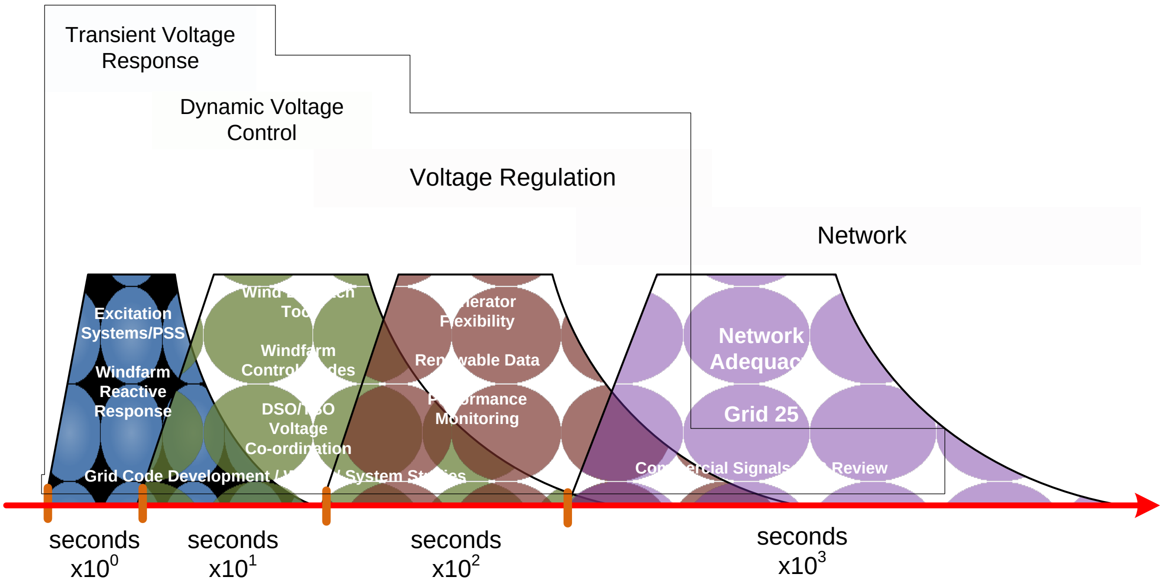

Figure 12 Voltage Control strategies over various timescales

4.3 Milestones

The milestones outlined below are per the published DS3 programme plan.

Decision/Deliverable	Responsible	Due by
Decision: Steady state Reactive Power Control from Wind farms	**TSOs, DSOs**	**Q3 2012**
Engagement between TSOs and DSOs on agreed standards universal Windfarm standard and appropriate controls for embedded conventional plant	TSOs , DSOs	Q1 2012
Grid Code and Distribution code changes brought to industry for discussion	TSO, DSO, All	Q2 2012
Decision: Steady state Reactive Power Control for embedded conventional plant	TSOs, DSOs	Q2 2012
Decision: Dynamic Reactive Power Provision from transmission and distribution connected wind farms	TSOs, DSOs	Q4 2012
Engagement between TSOs and DSOs on agreed standards universal Windfarm standard including dynamic reactive power provision	TSOs , DSOs	Q1 2012
Grid Code and Distribution code changes brought to industry for discussion	TSO, DSO, All	Q2 2012
Decision: Dynamic Reactive Power Provision for transmission and distribution conventional plant	TSOs, DSOs	Q3 2012
Grid Code changes brought to industry for discussion	TSOs	Q2 2012
Controllability of Wind farms	TSOs, DSOs	On-going
Implementation of new standards and a consideration of retrospection Steady State voltage control	TSOs	Q1 2014
Implementation of new standards and a consideration of retrospection on dynamic voltage control	TSOs	Q1 2014
Pilot Projects	TSOs, DSOs	Q1 2013
Planning Studies (TSO & DSO)	TSOs, DSOs	Q2 2013
Develop TSO Reactive Power Management Policy	TSOs	Q1 2014
Develop TSO/DSO Voltage Control Policy	TSOs, DSOs	Q1 2014

5 References

[1] EirGrid, "Facilitation of Renewables Report," 2010.

[2] EirGrid, "Ensuring a Secure Reliable and Efficient Power System in a Changing Environment," 2011.

[3] Z. Wenjuan, L. Fangxing, and M.L. Tolbert, "Review of Reactive Power Planning: Objectives, Constraints, and Algorithms," *IEEE Transactions on Power Systems*, vol. 22, pp. 2177-2186, 2007.