APPLICATION OF DISTRIBUTED GENERATION REACTIVE POWER CONTROL MODES TO INCREASE SYSTEM STABILITY

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ABSTRACT

With 940MW of Distributed Generation (DG) currently connected to the NIE Networks' distribution system and a summer valley demand of c505MW it is essential that generation is operated in a manner that ensures system stability is not jeopardised. This paper presents the application of various Distributed Generation (DG) reactive power control modes, with specific focus on the innovative variants of voltage control employed within NIE Networks', in order to improve local and global system stability.

1. INTRODUCTION

The Department of Enterprise, Trade and Industry (DETI) in its Strategic Energy Framework document [1] issued an ambitious target that Northern Ireland will seek to achieve 40% of its electricity consumption from renewable resources by 2020. Consequently the volume of DG connected to the NIE Networks' distribution system has dramatically increased over the last 5 years. This has resulted in the evolution from a passive distribution system to an active one, with bidirectional power flows at many substations; this poses many challenges to a network operator, which includes but is not limited to: maintaining feeder voltages within statutory limits and ensuring that sufficient reactive power resources are available on the system.

Traditionally voltages on the NIE Networks' distribution system were managed through the operation of On Load Tap Changers (OLTCs) on substation power transformers. However, as the number of DG connections have increased it has become increasingly difficult to manage voltage levels. Furthermore, the displacement of conventional generation with intermittent DG has increased the difficulty in managing the reactive power on the system. The aforementioned concerns have caused NIE Networks' to consider the most prudent use of DG reactive power control modes on the system.

To ensure that distribution voltage, reactive power flows and losses are managed appropriately, NIE Networks' have mandated, through their network codes, that generators greater than 5MW must be able to deliver three reactive power control modes: power factor; reactive power dispatch and voltage control. The application of these control modes and selection of set points is essential to ensure that the distribution system operates effectively.

2. ISSUES ASSOCIATED WITH DG

In this section, some of the issues associated with operating a distribution system heavily connected with DG are highlighted.

2.1. Voltage Management

2.1.1. Feeder Voltage Regulation

Whenever DG is connected to a feeder the voltage at the connection point will rise in accordance with Equation 1 [2]. To manage this NIE Networks currently use Voltage Control Relays (VCR's) in conjunction with Load Drop Compensation (LDC) to control the On Load Tap Changer (OLTC) on substation power transformers and therefore manage the feeder voltages.

$$\Delta V = V_r - V_s = R.P - X.Q \quad (1)$$

Where: Vs = Sending end voltage; Vr = Receiving end voltage; R = Resistance of feeder; X = Reactance of feeder; P= Active Power flow; Q = Reactive Power flow

The operation of the VCR and LDC functions are well understood and offer significant benefits to the distribution system; however, the benefits of such voltage control schemes dwindle as penetration levels of DG increase. The following is a non-exhaustive list describing voltage management issues associated with a substation heavily connected with DG:

1) As DG outputs increase the current measured at the substation decreases resulting in reduced LDC boost and therefore insufficient voltage levels at the receiving end of circuits [3].
2) As DG outputs exceed feeder demand, the voltage at the DG connection point will rise beyond the substation busbar voltage. In an attempt to counteract this voltage rise a reverse LDC setting may be applied to ensure that substation voltage is decreased in proportion to reverse power flow. This will alleviate voltage rise problems on feeders which contain high generator outputs but may serve to exacerbate low voltage problems on feeders with low DG outputs.
3) Latency exists between the voltage at the substation power transformers exceeding limits and the OLTC initiating an operation. This delay is present to avoid unnecessary OLTC operations and is configurable up to 120s. Consequently, during the time between voltage exceedance and OLTC operation the voltage at the DG connection point may exceed statutory limits.

2.1.2. Excessive OLTC Operation

As the levels of DG connecting to the NIE Networks' distribution system have increased it has been witnessed that the number of power transformer OLTC operations have also increased: illustrated in Figure 1. This is due to the volatile nature of intermittent DG which causes the voltage at the upstream substation to fluctuate and initiate OLTC operations. Excessive OLTC operations are undesirable and can result in increased maintenance and reduced OLTC lifespan.

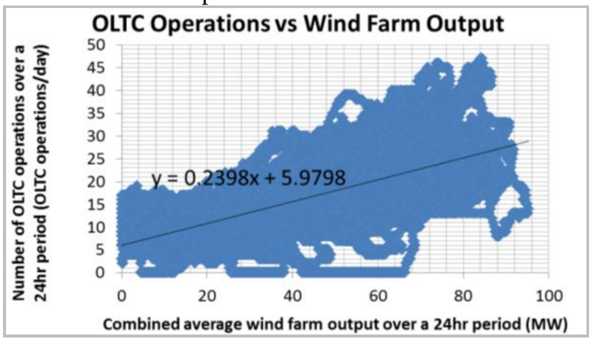

Figure 1

2.2. Reactive Power Burden

Traditionally generators connecting to the NIE Networks' distribution network have been induction machines operating on a leading power factor. Combined with the intrinsically inductive nature of the electricity network and connected demands some substations have very low and variable power factors, demonstrated in Figure 2.

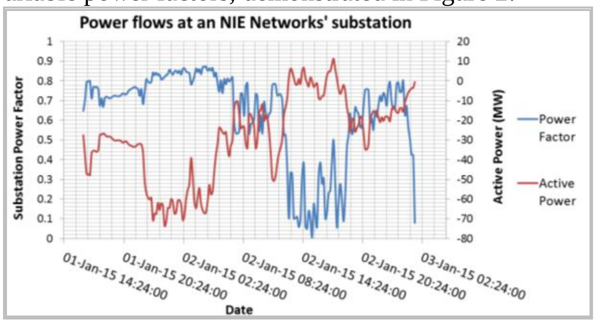

Figure 2

The distribution system therefore acts as a large reactive power sink which, as well as increasing losses, may cause voltage stability issues in the absence of network reinforcement. The impacts of reactive power shortfalls on electricity networks have been well documented and the North American Electric Reliability Council attributed a large proportion of the blame for the 2003 North American blackout, which affected 50million people, to a shortage of reactive power resources [4]. To prevent reactive power shortfalls, both in steady state and in transient conditions, it is anticipated that reactive compensation devices will be required at strategic positions on the NIE Networks' electricity system.

3. APPLICATION OF DG REACTIVE POWER CONTROL MODES

This section describes in detail the operation of NIE Networks' mandated DG reactive power control modes and how they are employed to mitigate the issues outlined in section 2.

3.1. Voltage Control

As described in section 2.1managing distribution system voltage levels, if heavily connected with DG is complex. One method is to operate the connected DG in voltage control mode. NIE Networks currently employ several variants of DG voltage control: voltage control on slope; direct voltage control and direct voltage control with slope.

3.1.1. Voltage Control on Slope

Figure 3 demonstrates the operating principals of voltage control on slope. The system slope is determined by the $\Delta V/\Delta Q$ relationship of the system at the connection point. The DG will operate on the DG control slope which determines the magnitude of reactive power response to voltage perturbations and is configurable from 2% - 7%: if system voltage reduces the DG will move towards +Qmax and if the system voltage increases the DG will move towards –Qmax. In this fashion the DG attempts to control system voltage.

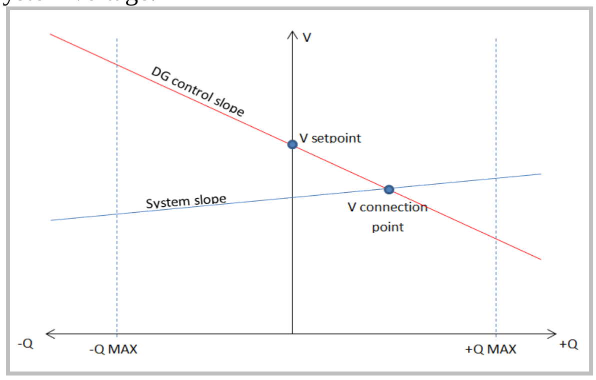

Figure 3

Voltage control on slope is used sporadically across Europe; however, it is a relatively rudimentary form of voltage control and has several limitations:

1) Whenever the network operator's control engineer is amending the DG voltage control set point they will be unaware of what the actual voltage will be at the connection point. The actual voltage will be subject to the intersection between the system slope and control slope. If the system slope has a high gradient (weak system) then DG voltage control set point changes will result in a large change in voltage at the connection point, potentially pushing voltages outside of statutory limits and causing the DG to disconnect on under/over voltage protection.

2) If the system slope and control slope do not have the same gradient then the DG will either overcompensate or undercompensate for system voltage perturbations. This

issue was witnessed during wind farm compliance testing as the OLTCs at the upstream substation operated: shown in Figure 4. Since the DG control slope gradient did not match the system slope gradient, the reactive power response of the DG was unable to keep the voltage constant. This can be mitigated to some degree by determining the system slope through power flow studies and/or examining historic data, after which the DG control slope can be set to match.

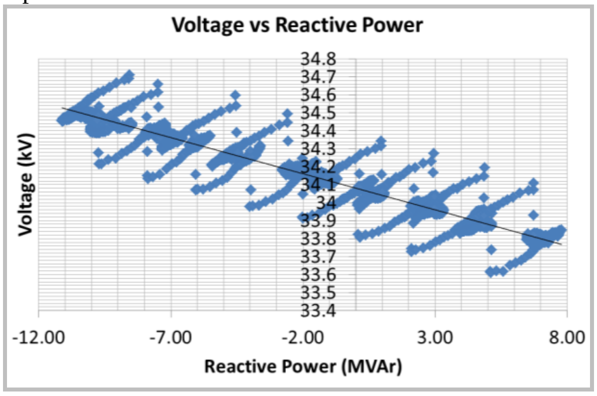

Figure 4

3.1.2. Direct voltage control with feedback

NIE Networks require DG with an MEC greater than 5MW to be able to operate in direct voltage control with feedback. The operation of this variant of voltage control is illustrated in Figure 5. The DG will operate on a closed loop control system to ensure that the voltage at the connection point equates to the DG voltage set point, if it has the reactive power capability to do so. In response to system voltage perturbations, the DG will deliver the correct magnitude of reactive power to ensure that the voltage at the connection point remains constant.

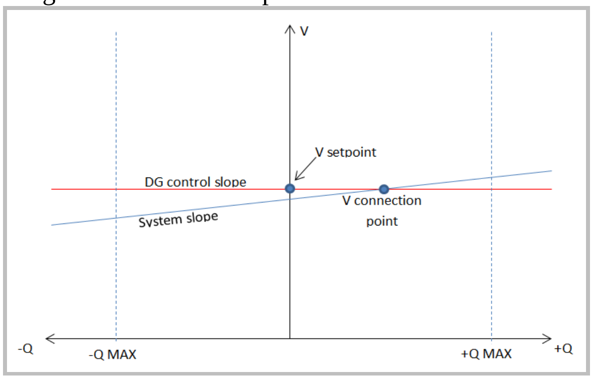

Figure 5

It is important to ensure that the correct voltage set point is chosen; otherwise unwanted interaction may occur between the DG and other voltage control devices in close electrical proximity. Moreover, if this control mode is employed by several generators in close electrical proximity then the possibility exists for large reactive power overshoots, hence voltage overshoots, to be experienced in response to system voltage perturbations.

3.1.3. Direct voltage control with slope

This voltage control variant is a hybrid of direct voltage control with feedback and voltage control on slope and is considered, by NIE Networks, to be the most prudent form of voltage control. It ensures, on receipt of a new voltage set point, that the voltage at the connection point equals the voltage set point whilst mitigating the potential unwanted interference and excessive overshoots.

Figure 6 illustrates the operation of this voltage control variant. Upon receipt of a new voltage set point the DG engages direct voltage control with feedback. Whenever the voltage at the connection point equals the voltage set point the DG reverts to voltage control on slope; however, to ensure that the switch between direct voltage control and voltage control on slope is bumpless and does not cause the voltage at the connection point to change, the DG controller must calculate a new voltage set point and apply that whenever voltage control on slope is engaged.

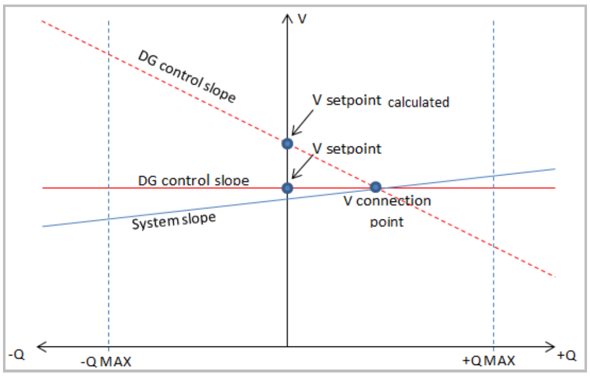

Figure 6

3.2. Case Study

In order to quantify the benefits of operating generators in voltage control mode, voltage stability and OLTC operations at an upstream substation were monitored over a period of time as a downstream 15MW wind farm was first operated in power factor control mode and then in direct voltage control with slope.

Figure 7 shows normal distribution curves for the voltage at the upstream substation as the wind farm is operated in power factor control and direct voltage control with slope. It was identified that whilst operating in voltage control the wind farm shifted the upstream substation voltage profile and reduced the voltage variance by 14%.

Figure 8 illustrates that a considerable reduction in OLTC operations were realised when the wind farm was operated in direct voltage control with slope: 69% reduction over a 17 day period.

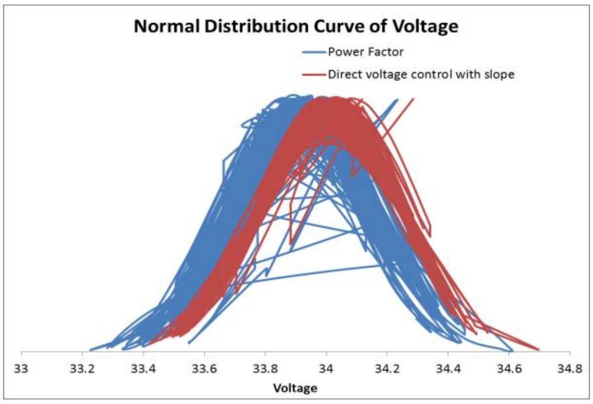

Figure 7

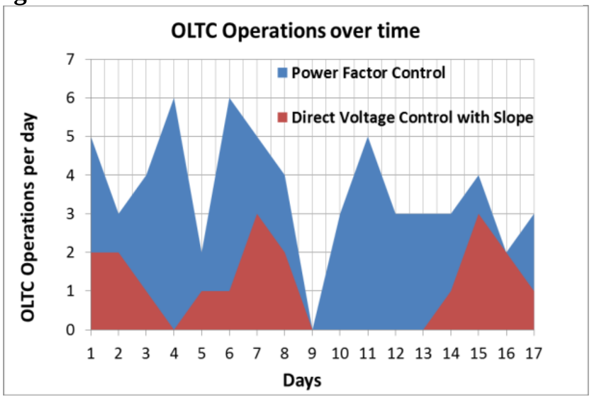

Figure 8

3.3. Power Factor Control and VAr Control

NIE Networks require DG to be able to maintain a specified power factor and reactive power (VAr) set point from full output down to the greater of the Design Minimum Operating Level (DMOL) or 15% of full output. Traditionally NIE Networks operated these generators on a leading power factor to ensure that voltage at the connection point did not exceed statutory limits. However, due to anticipated reactive power shortfalls and in an attempt to reduce losses NIE Networks have studied, from a voltage rise perspective, if each generator's power factor can be moved closer to unity or to a lagging power factor and have then implemented the change.

Since power factor control mode and VAr control mode offer no voltage regulation the potential exists for voltages at the connection point to exceed statutory limits. For this reason NIE Networks require generators to have Emergency Voltage Control (EVC).

3.3.1. Emergency voltage control

Whilst operating in power factor or VAr control mode and the voltage at the connection point exceeds 1.05pu or falls below 0.95pu then EVC will be engaged. These limits have been chosen so that DG will attempt to remedy the voltage before it goes outside of NIE Networks design limits. If triggered on high voltage the DG will target a voltage set point of 1.05pu and remain in EVC until the voltage drops below 1.04pu at which point it will revert to its previous control mode and sent set point; likewise, if triggered on low voltage the DG should target a set point of 0.95pu and remain in EVC until the voltage exceeds 0.96pu. These values have been chosen to avoid situations where the DG continually engages and disengages EVC.

4. CONCLUSION

The vast volumes of DG connected to the NIE Networks' system has caused a number of challenges, particularly around controlling distribution system voltage, limiting excessive OLTC operations and reducing the reactive power burden on the system.

NIE Networks require generators to have three main reactive power control modes: voltage control; power factor control and VAr control. The control mode is selected by NIE Networks and is specific to the needs of the local system.

Voltage control on slope is a relatively rudimentary form of control and therefore has some limitations. These limitations have caused NIE Networks to mandate alternative variants of voltage control: direct voltage control and direct voltage control with slope. Direct voltage control with slope has proven to be the most beneficial variant of voltage control on NIE Networks distribution system, limiting unwanted interaction between other voltage control devices and large overshoots, whilst ensuring that the voltage set point is achieved if the generator has the reactive capability to do so.

The performance of operating a 15MW wind farm in direct voltage control with slope was monitored for a period of time with results showing a 14% reduction in the upstream substation's voltage variance and a 69% reduction in the substation transformer's OLTC operations.

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