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Enhanced Voltage Control

Distributed Generation Controllers and Voltage Managed Connections

Fundamentals Reference F9183

19/11/2018

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Enhanced Voltage Control
ENWL

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About this report

Version Information

Rev	Date	Purpose of Issue / Changes	Authored	Checked	Approved
1.0	19/11/2018	First Issue	H. Shishtawi	H. Shishtawi	H. Shishtawi

Table of Contents

Abbreviations

DG	Distributed Generation
EAVC	Enhanced Voltage Control
PCC	Point of Common Coupling
RPF	Reverse Power Flow
HV	High Voltage
ANM	Active Network Management
DNO	Distribution Network Operator
DSO	Distribution System Operator
CLASS	Customer Load Active System Services
LV	Low Voltage
AVC	Automatic Voltage Control
SCADA	Supervisory Control And Data Acquisition
MW	Mega Watt
MVAr	Mega Volt Ampere reactive
CBM	Conditional Based Maintenance
CB	Circuit Breaker
kV	Kilo Volt
LDC	Load/Line Drop Compensation

1 Introduction

The 'Enhanced Voltage Control' project aims for studying the effects of Distributed Generation (DG) on the voltage of the grid and how can these effects be mitigated with an Enhanced Voltage Control (EAVC) technology. The EAVC technology considered in previous part of this project focused on the classic voltage control at local (primary) substations and grid substations utilising On-Load Tapchangers (OLTC) to adjust the network voltage level dynamically in relation with the DG plant export/import status.

This part of the project explores other voltage control options that:

- Can support integration of additional DG capacity into the existing network.
- Can support maintaining a healthy system voltage profile.

Some of the main challenges introduced by DG sources are:

- Voltage rise at the Point of Common Coupling (PCC).
- Reverse Power Flow (RPF).
- Load masking.

Additionally, as these energy plants exist naturally in a scattered way within the distribution network, coordinating these plants to a achieve a common objective can be challenging. Moreover, some of these DG plants depend on energy sources affected by weather conditions and other variables; such as wind farms and solar farms. This introduces another layer of complexity to the system as it makes forecasting and planning even a harder job to do.

OLTC based voltage control systems can be enhanced to cope with these negative effects. However, OLTC voltage control is a centralised type of voltage control with a wide effect on a significant portion of the network. This centralised effect makes it hard to optimise the voltage level at or around PCC points without affecting the whole system served by the same HV substation.

This report considers a decentralised voltage control approach where DG plants can provide the voltage control needed for the system. This makes the voltage level optimisation easier and more efficient.

1.1 Generator Controller Specification

Although Enhanced Voltage Control project studies the interaction between DG plant operation and their effects on the system voltage level and how to enhance the voltage control operation to optimise this interaction; however this opportunity has been taken further to include a proposal on what can a DG controller offer not only from a voltage control point view but also from other aspects as discussed in the subsequent sections of this report.

2 Focus Areas

Before proposing a new decentralised voltage control approach some aspects should be considered. These are referred to as 'focus areas' in this document. The focus areas are:

- Active Network Management (ANM) and system operation.
- Fault conditions, network losses and voltage levels.
- Flexible connection offerings and RPF.
- Transforming DNOs to DSOs.
- Generation types.
- CLASS.

2.1 Active Network Management

ANM systems can play an essential role in the system voltage optimisation. If:

- ANM systems have visibility over a sufficient number of network nodes,
- Can observe the network conditions at PCC points,
- And can also interact with DG plants,

Then a system optimisation strategy can be set up and DG plants can contribute towards achieving the desired results.

Hence, any decentralised voltage control system should be capable of interfacing and interacting to ANM systems.

2.2 Flexible Connection Offerings and RPF

The term 'Flexible Connection' refers, in this context, to the collection of offerings and approaches used in the United Kingdom to encourage connection of new DG plants into the distribution network despite the existing challenges.

Unlike firm connections, flexible connections:

- Can be contracted to operate on reduced capacity,
- Can be curtailed by a network operator when needed,
- And can be tripped by a network operator if their output exceeds the agreed capacity.

DG utilisation, on the other hand, can also cause the excess of generated power to flow in reverse from the LV network to the HV network. Some existing assets and network operational equipment suffer from RPF limitations as bidirectional power flows where not considered during design and type test stages. Examples of these are Asymmetrical Pennant Cycle OLTCs and some Automatic Voltage Control (AVC) systems.

2.3 Transforming DNOs to DSOs

DNOs in the UK currently look after their networks by virtue of maintaining them and making sure they are healthy, operable and fit for their purpose. On the other hand, the system operator looks after the global system vitals; such as balancing the supply with the demand and maintaining the system frequency within limits.

With the increasing DG penetration at the distribution network side of the network, a significant portion of the supply is located closer to the load.

DG plants have a lot of disadvantage; such as they are environmentally friendly. However, and stated in section 1, coordinating the output of these plants is difficult especially for supply-demand balancing reasons.

If DNOs become DSOs then they may be responsible, or at least partially responsible, for balancing the supply and the demand to their system. In a simplistic way, this means that DSOs will need to be able to control the output of the DG plants that exists at their network or system. A system that allows this control should then exist to empower DSOs to do so.

3 DG Plant Control and Operation

The DG plant control, for the purpose of this report, refers to how the objective the DG plant aims for is achieved by adjusting its output.

On the other hand, this report uses the term operation mode to refer to the control source of the DG plant controller; i.e. controlled with SCADA interaction or independent control.

3.1 Existing Control Modes

Currently, DG plant controllers can operate in two different modes:

- Power factor control mode,
- And voltage control mode.

These two modes are explained in section 3.1.1 and section 3.1.2.

3.1.1 Power Factor Control Mode

This mode dictates the power factor the DG plant should operate at; hence the reactive power export (or import) is dependent upon:

- The power factor set point,
- The current real power output,
- And the maximum DG plant capacity.

For instance, if the power factor set point is 0.95 lag (a DG plant exporting reactive power) and the current MW output of the DG plant is 1 MW, then the DG plant should produce 0.329 MVAr.

This control mode is suitable for DG plant connections electrically close to the nearest local (primary, grid, etc) substation. Otherwise the DG plant will operate in voltage control mode and conflict will exist between the substation voltage control system and the DG plant voltage control system.

From a network planning point of view, this control mode is considered easier than the voltage control mode; because there is only one unknow, the Watts output, as the other unknown, the VArs output, can be implicitly expressed as a function of the Watts variable.

Connection of this type can be modelled as PQ buses for load flow analysis considerations.

3.1.2 Voltage Control Mode

DG plants operating in this mode do not only adjust their real power outputs, but also aim to control the voltage at the coupling point by virtue of changing their reactive power outputs. Since the real and reactive power outputs are constrained by the capacity of the DG plant, the reactive power output is dependant upon the existing coupling point voltage and the voltage target of the DG plant, therefore, the real power output is constrained by:

- The nearest electrical substation busbar voltage level,

- The feeder impedance,
- And the power flowing through the feeder.

The busbar voltage of the nearest substation will continuously change based on the power flowing through the transformers supplying the substation. The supplied power is also a function of the output of all DG plants connected to this substation. If the DG plant, for instance, is a solar farm or a wind far, then another layer of complexity will be added as these plants rely on weather conditions to output real power.

This type of connections can be modelled as a PV bus for load flow analysis purposes.

DG plants operating in voltage control mode are more adequate for connections electrically far away from for the nearest local substation. They are also suitable for operating networks in islanding mode.

3.2 New Proposed Control Modes

The following two sections discuss newly proposed control modes. These control modes do not currently exist as a DG plant control mode and address several issues observed throughout the first part of the 'Enhanced Voltage Control' project.

3.2.1 Local VARs Compensation Mode

The load power factor in the United Kingdom is usually in the range of 0.97 lagging; this means that most of the domestic load is thermal (resistive) with a very small portion of rotating masses loads (such as fridges, washing machine, etc.). However, nowadays a lot of 'switch-mode power supplies' use domestically can have a leading power factor; examples of these are battery chargers and laptop power supplies. But generally, the domestic load remains lagging.

The existing business model for supply of energy in the United Kingdom pays the energy supplier for the Watts output they provide and do not award anything for any reactive power contribution. This encourages energy suppliers to generate at, or around, unity power factor.

With DG plants providing real power downstream, the reactive power needs of domestic loads must be supplied through the nearest electrical substation. Transformer impedance are mostly reactive by nature, hence most of the voltage drop across transformers is caused by the reactive power flowing throw them:

Equation 1 Voltage drop across transformers

$$V_{drop} = I_{Tx} \times (R_{Tx} + j\, X_{Tx})$$

Assuming that the resistance of transformers is negligible:

Equation 2 Approximated voltage drop across transformers with negligible resistance

$$V_{drop} = jX_{Tx} \times (I\, Tx_{Real} + j\, I\, Tx_{Reactive})$$

The real current flowing through transformers causes a voltage drop vectorially perpendicular to the source voltage (90° leading the voltage reference vector) while the reactive current flowing through transformers causes a voltage drop vectorially negates the reference voltage (180° out of phase to the reference vector). Therefore, reactive current flowing through transformers causes a voltage drop that directly subtracts from the reference voltage.

Transformers equipped with OLTCs can compensate for the voltage drop across their impedances by virtue of changing their operational tap positions. Therefore, the higher the rate of change of reactive current flowing through transformers the more OLTC operations will be performed.

It is proposed that, through the local VARs compensation mode, the reactive power requirements of loads are supplied through DG plants connected to the same circuit rather than importing the needed amount of reactive power from the grid.

Using this DG plant control mode can result in:

- Reduced transformer losses.
- Higher capacity availability for transformers and circuit cables of the HV network.
- An optimised operation of OLTC that should result in less maintenance requirements; provided that OLTCs are maintained based on their conditions; i.e. Conditional Based Maintenance (CBM).

For this mode to operate, the reactive power needs of the local circuits should be known to the DG plant controller.

3.2.2 Ancillary Services Control Mode

The main ancillary services provided to the support the power system operation are:

- Frequency response.
- Voltage/reactive power support.

DG plants operating in this mode can support system operators to maintain the system healthy and operable.

3.2.2.1 Frequency Response

It is assumed throughout this report that the DG controller is capable of monitoring the voltage of the coupling point, the current from/to the plant and hence measure and monitor the frequency of the system. Based on the measured frequency level the DG controller can change the set points of the DG plant and change the real power output accordingly to support the system operator maintain the frequency of the system within limits.

Alternatively, an approach similar to programming a droop characteristic curve can be programmed into the DG controller to support the system frequency as well. The controller can also have a frequency dead band setting programmed into it where it adjusts the output of the DG if the measured frequency is above or beyond the defined dead band.

3.2.2.2 Reactive Power Compensation

DG plants can also support the system voltage by virtue of adjusting their reactive power output. For instance, and using a solar farm with a four-quadrant inverter as an example, DG plants can substitute for using capacitor banks and can also substitute for using shunt reactors.

If the transmission system is suffering from high voltages at night due to high amounts of reactive power circulating through the network, then these capable DG plants can start acting as reactors and hence absorb the excess of reactive power existing in the system. In the same manner, and for low voltage situations, DG plants can export more reactive power to support the system voltage.

3.2.2.3 Operational Interaction

One of the problems introduced by connecting additional DG plants is their contribution to a higher fault current level and hence to stability of the system. With this proposed DG controller this can be mitigated by allowing a control engineer to interact with the controller:

- By inhibiting, limiting or boosting the DG output as needed.

- By operating the DG plant connection CB when needed.

3.3 Operation Modes

As mentioned earlier, this section described the different control hierarchies the DG plant can be controlled by.

3.3.1 Autonomous Operation Mode

In the autonomous mode, the DG plant is fully operated by the DG controller with minimum human interaction:

- For this to work, a comprehensive set of preconfigured settings and set points should be adjusted into DG controller.
- Using these settings, the DG controller can then operate the DG plant in voltage control mode, power factor control mode or ancillary services mode.
- The local VARs compensation mode can be used if the local VAR requirements are known via a preconfigured trend, or any other means, into the DG controller.

3.3.2 Hierarchical Operation Mode

The DG controller operated as part of an ANM system in this mode. All the required set points, and hence the DG plant objectives, are conveyed to the DG controller via a SCADA links in the form of set points, commands or similar.

4 Voltage Managed Connections

In section 1 of this report the voltage rise at the PCC is mentioned as one of the down sides of DG plants. The voltage rise issue is caused because of the RPF also mentioned in this report.

4.1 The Voltage Rise Caused By RPF

As the network where the DG plant is connected is usually stronger than the DG plant itself, the DG plant cannot influence the voltage of the network but the network can influence the voltage at the DG plant busbar or connection point. Figure 1 shows an example of a typical power system with a wind turbine connected at the load end; voltage levels, voltage drop across feeders and the voltage rise at the DG point are all also shown. The voltage at the DG coupling point can be calculated using Equation 3.

Equation 3 Coupling point voltage equation

$$V_{Coupling} = V_{11kV\ bus} - (I_{feeder} \times Z_{feeder})$$

If the net power[1] flowing through the feeder is from the 11kV busbar towards the load, then the voltage drop, which is the second term of Equation 3, will be positive and hence the resultant coupling point voltage will be less than the 11kV busbar voltage.

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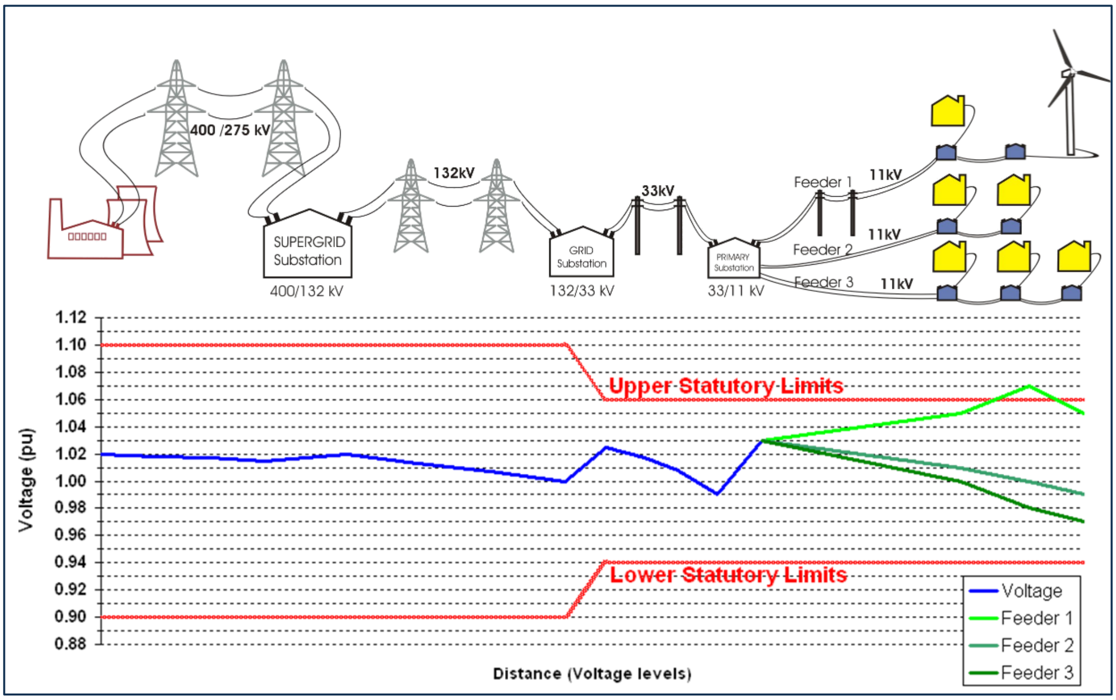
[1] The term 'net power' is not entirely accurate here as the voltage drop is a function of the real and reactive power flowing through the real and reactive parts of the feeder impedance.

On the other hand, and if the net power[1] flowing through the feeder is from the load, or DG plant in this case, to the 11kV busbar, then the voltage drop will be negative, as seen from the 11kV busbar, and hence the resultant coupling point voltage will be higher than the 11kV busbar voltage.

Figure 1 The voltage rise at the PCC caused by RPF



4.2 Mitigating the Voltage Rise at the PCC

Historically, voltages at the end of feeders were maintained either by using Load/Line Drop Compensation (LDC) techniques to compensate for these voltage drops by virtue of changing the transformer tap position. These techniques relied on a combination of the load flowing through the supply point transformer and either the feeder impedance characteristics or the maximum voltage drop at full load.

With the penetration of DG plants at different feeders, these techniques became less significant because:

- DG plants mask the true load.
- Some feeders will have voltage rise issues while others will suffer from voltage drops.

The OLTC compensation technique will either be able to increase the voltage profile on all of the outgoing feeders; and hence run the generation feeder on a very high voltage, or reduce the voltage profile on all of the outgoing feeders leaving some of them suffering from very low voltages. Hence, the OLTC compensation technique is not adequate to address this issue and can impose operational limitations.

Another way of looking into a solution is by observing Equation 3 and expanding it into:

Equation 4 Expanded coupling point voltage equation

$$V_{Coupling} = V_{11kV\ bus} - ((I\ feeder_{Real} + j\ I\ feeder_{Reactive}) \times (R_{Tx} + j\ X_{Tx}))$$

Assuming that the DG plant is exporting real power to the 11kV grid, one way we can offset the voltage rise at the PCC can be using the expression in Equation 5.

Equation 5 Offsetting the voltage rise at the PCC

$$I\,feeder_{Real} \times (R_{Tx} + j\,X_{Tx}) = -j\,I\,feeder_{Reactive} \times (R_{Tx} + j\,X_{Tx}))$$

Hence, by injecting the correct amount of reactive current into the feeder with the net export real power we can inject reactive power into the same feeder to create a voltage drop in the opposite polarity that can offset the voltage rise and normalise the PCC voltage to the 11kV busbar voltage.

4.3 A Voltage Managed Connection DG Control Mode

As the DG controller can measure the PCC voltage, and by rearranging the terms in Equation 3, the 11kV busbar voltage can be calculated by the DG plant. The DG plant can measure the magnitude and direction of the net real and reactive current flowing through the feeders, hence, and if the feeder impedance information from the PCC to the load is known, the DG controller can also calculate the end user voltage.

The DG controller can then aim to either:

- Maintain the customer voltage,
- Or offset the voltage rise at the PCC.

In both cases, the DG plant reactive power output must be varied in order to achieve the desired objective(s).

The constraint that should be mentioned here is the total DG capacity. Varying the reactive power net export/import from the DG plant means the output real power is also affected and can, sometimes, be dropped below desired levels to maintain the connection voltage.

4.4 Commercial Consideration

Operating a DG plant in voltage control mode can be helpful for DNOs/DSOs. However, unfortunately, DG plants are currently only paid for their real power contribution and are incentivised enough to contribute towards providing reactive power and system voltage support.

If DG plants are incentivised to support the network voltage via changing their net reactive power import/export, and if there is a mechanism to measure how efficiently DG plants can support maintaining customer voltages, then DG penetration can be increased resulting in a more dynamic and resilient grid that is capable of coping with much more operational scenarios and loading conditions.