DEMONSTRATING ENHANCED AUTOMATIC VOLTAGE CONTROL FOR TODAY'S LOW CARBON NETWORK

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ABSTRACT

Increased amounts of distributed generation and disruptive loads such as electric vehicle charging and heat pumps will increase the importance of Distribution Network Operators (DNOs) actively managing voltage on their network. Dynamic voltage control is commonplace at higher voltages; however, tighter control of voltages further into the distribution network is likely to be necessary.

This paper provides an overview of the Customer Led Network Revolution (CLNR) project and the trials involving Enhanced Automatic Voltage Control (EAVC). The proposed control methodology is discussed with a description of the Grand Unified Scheme (GUS) control system.

INTRODUCTION

The UK Government's plans to meet targets for legally binding carbon emission reductions (34% on 1990 levels by 2020) involve the proliferation of distributed generation and electrification of heating and transport [1]. The Renewable Energy Strategy suggests that 30% of electricity could come from renewable sources by 2020 [2]. These will involve significant numbers of Low Carbon Technology (LCT) installations, such as electric vehicles, heat pumps and embedded generation.

The addition of the significant loads presented by these technologies onto the network, mostly at low voltage, gives rise to challenges in voltage management and thermal stress. As LV networks are typically operated with little control or monitoring equipment, the potential for the distribution level of the grid to become a barrier to the wide scale adoption of new LCTs is significant.

As LCT penetration increases, conflicts arise using fixed parameters for network design. An example is where the network is designed with voltage at the upper permitted limit to allow maximum volt drop along feeders. This leaves little headroom for voltage rise due to embedded generation. Furthermore, network operators may have little control over the connection of additional loads or generation onto existing connections, placing more emphasis on the requirement to monitor and control voltage. Active networks, flexible customers or a combination of both are attractive prospects to extract the full capability of the network infrastructure.

CUSTOMER LED NETWORK REVOLUTION (CLNR) OVERVIEW

The Customer Led Network Revolution (CLNR) project is being run by UK DNO Northern Powergrid along with project partners British Gas, EA Technology Ltd and Durham University. The project is funded under Tier 2 of Ofgem's Low Carbon Network Fund. The project aims to trial customer propositions and network equipment with the underlying premise that additional capacity in the network can be released with additional monitoring, control and/or customer interventions.

The project is split into five core themes, termed Learning Outcomes [3]. Voltage control is part of Learning Outcome 3, which focuses on network technology, and will evaluate the extent to which the distribution network can be more flexible and the associated cost of releasing the flexibility.

A series of test cells have been developed to group either network areas, customer types (in terms of installed technology) or customer propositions. The sites are chosen to capture a range of network areas such that the trials produce results that are applicable to many network areas across the UK.

A series of novel network technologies, called Enhanced Network Devices (ENDs) will be installed across the test cells, including:

- Enhanced Automatic Voltage Control, applied between 66kV and LV;
- Electrical Energy Storage (EES), installed at 6.6kV (5MWh) and LV (between 100 and 200kWh);
- Real Time Thermal Ratings (RTTR), installed on Overhead Lines, Underground Cables, Primary Transformers and Secondary Transformers;
- Remote Monitoring Units, installed between 66kV and LV.

Operation of the technologies within each test cell will be integrated into a single control area solution, called the Grand Unified Scheme (GUS).

The test cells where EAVC will be used to demonstrate network flexibility are:

Rural Low Density: Denwick, Northumberland, UK. A

primary group with long (approx 60km) MV (20kV) overhead line with significant load and associated voltage drop.
Urban High Density: Rise Carr, Darlington, UK. A primary group with dense population and short feeders. Thermal limits are the main issue.
PV Cluster: Maltby, Rotherham, UK. An LV group with a maximum concentration of approx 30% of properties with PV installations on an LV feeder.
Heat Pump Cluster: Hexham, Northumberland, UK. An LV group with up to 90% of properties with connected domestic heat pumps.

Fig. 1 shows a diagram of the Rural Low Density Test Cell as an example of the scale of the test cells and the technology to be installed.

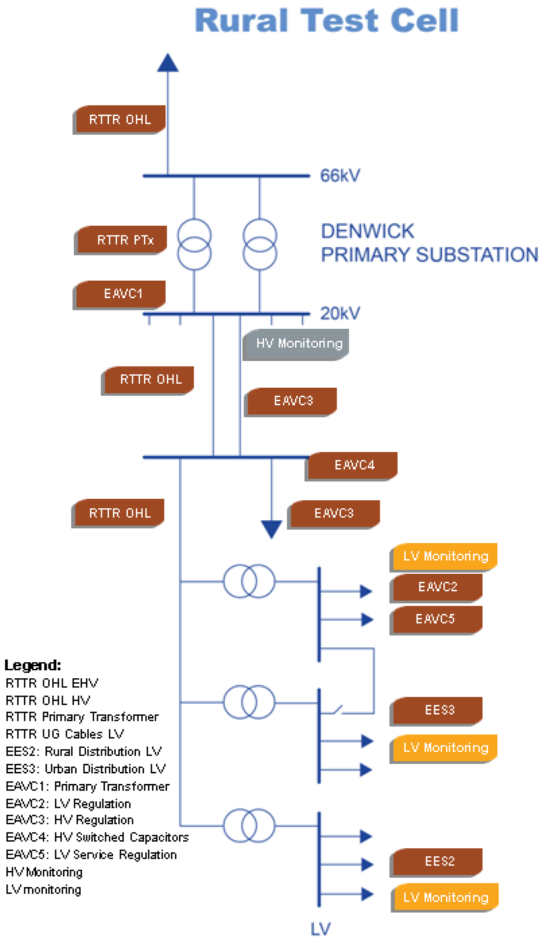

Figure 1 – **Rural Test Cell diagram**

EXISTING VOLTAGE CONTROL

Conventional voltage control in the distribution network makes use of On-load Tap Changers (OLTC) attached to the power transformers and controlled by Automatic Voltage Control (AVC) relays. In the UK penetration of voltage control is typically down to primary transformer level (e.g. 11kV output). A voltage control relay controls the tap changers based on a fixed setpoint with biases to ensure any circulating current is kept under control.

Line Drop Compensation (LDC) may also be used to offset voltage drops by estimating the effect of load on the output feeders. Measurements of current and voltage are taken at the transformer and used to calculate the expected volt drop on the end of the feeder most likely to witness the lowest voltage level. LDC uses total transformer current as the basis for correcting voltage and becomes inaccurate where loads on the output feeders are uneven, either due to distributed generation, a general occurrence of load unbalance or due to reconfiguration of the network during an outage.

Voltage control is currently setup for homogenous networks where all areas of a network act similarly. Advanced devices are available, such as GenAVC^{TM}, which have the ability to use remote references such as the voltage at a generation site to manage voltage [4]. However, predictions for the increase in LCTs, particularly distributed generation, at both the MV (e.g. 11kV) level and significantly at LV suggest a fixed setpoint and penetration of voltage control only as far as the primary level is unlikely to be sufficient.

ENHANCED AVC (EAVC)

The need for voltage control intervention is likely to only arise under demanding conditions such as circuit outages and peak load or generation periods. The project will trial the concept that voltage controllers do not require direct access to remote voltage references in order to adequately control voltage. EAVC devices will operate autonomously most of the time with a given setpoint as a target output voltage.

Enhanced AVC, as opposed to AVC, simply has the additional ability to accept a voltage setpoint from a remote system.

A key benefit of setpoint control is that existing functionality of the AVC are not interfered with. For instance, functions designed to reduce circulating currents in paralleled transformers will operate normally as the central system is advising a target output voltage as opposed to directly controlling tap positions (although setpoints given to parallel AVCs should be equal). Also, many of the existing modern voltage relays in operation would require minimal modification to enable setpoint control.

EAVC allows a systems approach to voltage control allowing voltage levels of network areas to be centrally co-ordinated whilst allowing local devices to operate without regular feedback. By importing data into a central system, a wide range of possibilities exist to solve non-homogenous network voltage issues [5].

In the CLNR project the remote alteration of target voltage will be applied to a variety of voltage control technologies:

Primary Substation
On-load Tap Changers on parallel Primary Transformers
MV (6.6kV) connected EES

MV (20kV) Feeders
In-line three phase regulators (star connected auto-transformers)
Shunt mechanically switch capacitor bank

Secondary Substation
On-load Tap Changer on Secondary Transformers
In-line three phase LV Regulators
LV connected EES

Passive Co-ordination

Initially, EAVC devices within the test cells will operate without direct co-ordination between the devices, instead using a default setpoint. Some co-ordination is required to avoid hunting and control methodologies have been proposed such as the use of time delays and dead time to co-ordinate series device operation. This is a common method of co-ordinating grid and primary substations – the grid AVC is set to operate with minimal delay, whilst the primary has an in-built delay. Should system loading change (and hence voltage), an opportunity is given to the grid transformer to correct first. This is achieved without communication between the control devices and is an example of co-ordinated yet independent operation. This rationale can also be extended to lower voltage EAVC devices.

Active Control

As a second stage to the project the GUS control system will assess the network area through a combination of monitoring and modelling to identify constraints. The system will then passively co-ordinate devices by issuing revised setpoints if required. The devices will continue to regulate output voltage to the given setpoint until advised of a new value, reducing the reliance on communication links. This approach will allow the voltage in non-homogenous network areas (e.g. high load in one area and high generation in another) to be better controlled. Where setpoints are changed, consideration must be given to downstream EAVC devices to avoid hunting.

Additional functionality of the voltage controller will be implemented to mitigate against lost communications or failure of the central system. A process of graceful degradation is proposed whereby EAVC devices gradually revert back to a default setpoint during unavailability of the central system.

GRAND UNIFIED SCHEME CONTROL SYSTEM

GUS is the name commonly used within the project to describe the overarching control system of the CLNR. The GUS will provide a supervisory control function to effectively manage the ENDs. The main requirement of the GUS control system is to close the feedback loop between ENDs, such as EAVCs and network monitoring ENDs, including RTTR systems and conventional network monitoring. Establishing this feedback loop will allow the distribution network to be controlled using real-time information, rather than specific scenarios or simple approximation methods. The target network sampling rate is 1 sample/minute, which is expected to be faster than required for business as usual (BAU) but will inform the decision of BAU configuration.

The benefit in creating a real-time control strategy is to maximise network utilisation. This is achieved by allowing the configuration of ENDs to be flexible enough to adapt to real-time changes in the behaviour of the distribution network and availability of control resources (e.g. EES).

GUS sits outside the existing Network Information Systems, including the Network Management System (ENMAC^{TM}). GUS does not attempt to duplicate existing functionality such as automatic switching and fault restoration. The purpose of de-coupling the two control systems is to simplify and de-risk the implementation of the CLNR control system and safeguard the integrity of safety-critical processes.

A hierarchical control architecture has been developed for the project. This is due to the expected benefits associated with scalability, supplier independence and reduced dependence on communication links. However, for the purposes of the trial only two levels of the hierarchy (see Fig 2) have been implemented making the trial system akin to a centralised architecture.

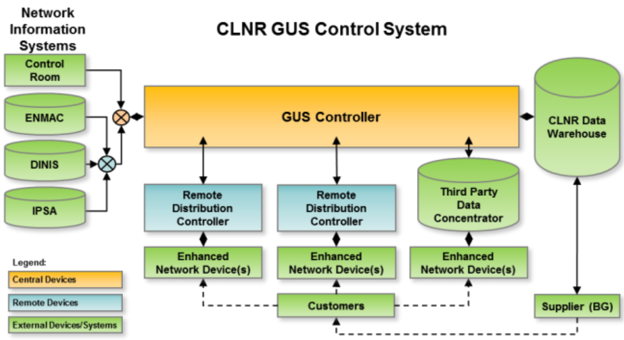

Figure 2 – **GUS Control System**

GUS THEORY OF OPERATION

The control system operates using the principle of delegated authority. A GUS Controller is provided with operational goals and a control area to manage. Primary operational goals are ensuring that the system remains within voltage and thermal operating limits, however as the system develops, advanced operational goals will be introduced to optimise utilisation of assets. Advanced goals may include: minimising losses, maximising embedded generation, minimising tap operations, etc.

The GUS Controller monitors the distribution network and provides control by issuing setpoints to ENDs. On receiving the setpoint the END accepts the authority to control the network and maintain the given setpoint; however the GUS Controller retains overall responsibility for wide area control.

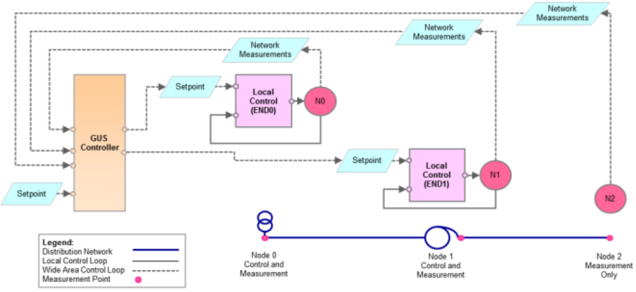

Figure 3 – GUS Theory of Operation

The END will use local network measurements to control the network in line with the setpoint. However, if the local measurement is outside the setpoint the END will act to return the local measurement within the setpoint. This principle of operation is shown in Fig. 3. This figure shows a system with three nodes representing a simple MV distribution network feeder with control nodes at the start and middle of the feeder and a dedicated monitoring node at the end of the feeder.

The GUS Controller will generate setpoints and delegate authority to control nodes 0 and 1 to END0 and END1 respectively. Each END must now monitor its local network and control it within the given setpoint. The GUS retains overall responsibility for the control area and monitors the network parameters of all connected nodes.

If the network measurements at node 2 go outside of limits the GUS Controller must act to return the node to within given limits. To do this the GUS Controller will determine new setpoints for one or more of the control nodes. The control system will ensure that all nodes gracefully transition to their new setpoint based on the passive co-ordination of ENDs discussed earlier.

Similarly if the control nodes reach limits of their operating range (e.g. maximum tap or storage depleted), the GUS Controller must act to relieve the control nodes by revising END setpoints elsewhere in the network.

CONCLUSION

This paper has given an overview of the CLNR project network flexibility test cells, specifically the EAVC schemes and the overarching control system (GUS). As discussed above and shown in Fig. 1 the CLNR project will utilise many novel technologies and customer propositions to increase network performance and flexibility. The control system will need to be able to influence a variety of ENDs connected in series and parallel.

The initial findings of the project are that a GUS control system will be able to facilitate connection of LCTs by improving voltage control on non-homogenous networks. Due to customer incentives for LCTs, voltage control mechanisms deeper into the network will be required. Voltage control will simply and effectively be managed using similar equipment to traditional methods by allowing voltage control ENDs to accept voltage setpoints. Limiting the reliance on communications will reduce the risks involved with implementation of additional network control.

FURTHER WORK

Learning Outcome 3 of the CLNR is to determine the extent and cost of network flexibility. The purpose of GUS is to enable this learning by demonstrating the level of additional benefits from combining EAVC, EES and RTTR.

A secondary outcome of LO3 will be to specify an enduring control system to best enable network flexibility at minimum cost and complexity. The future specification will consider:

- Balance between distributed intelligence, passive co-ordination and active supervisory control;
- Optimal number of ENDs per GUS Controller;
- Scalable architecture for wide-area deployment;
- Communications topology;
- How often setpoints need to change;
- Optimal network sampling rates; and
- Resilience to communications loss or cyber attack.

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