Real-time, Centralised Voltage Control in 33kV and 11kV Electricity Distribution Networks

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ABSTRACT

This paper describes a real-time, centralised voltage control system for 33kV and 11kV electricity distribution networks, aiming to optimise the network voltages and release network capacity by dynamically adjusting the previously static target voltage settings of substations' voltage control relays. This paper is based on learning to date from Western Power Distribution's (WPD) Tier-2 Low Carbon Networks (LCN) Fund [1] project, Network Equilibrium.

INTRODUCTION

As part of the continuous transformation of the UK's electricity distribution network to a smarter, low carbon grid, the amount of low carbon technologies connected to the network is rapidly increasing. These include among others, electric vehicles, heat pumps and Distributed Generation (DG). All of these technologies contribute to the reduction of carbon emissions in electricity networks and have a significant role to play in meeting one of the main targets set to face climate change, the global carbon reduction targets.

Ensuring that the electricity distribution network can continue to facilitate the connection of low carbon technologies is therefore very important to network operators. These technologies, however, usually cause an increase in the voltage at the point of connection, meaning that the amount of connections that can be supported by the existing network depends on the headroom available before the upper statutory voltage limit [2] is reached. This headroom is further limited by the traditional voltage control methodology which, historically, has kept the voltage statically high.

This paper describes a real-time, centralised voltage control system for 11kV and 33kV electricity distribution networks, which aims to release network capacity and overcome the constraints imposed by traditional voltage control systems. The design, planning and implementation strategy of the System Voltage Optimisation (SVO) technology is presented. The centralised approach chosen is explained and the system architecture is demonstrated in detail. The methodology developed for the substation selection and the power system studies performed in the process are also discussed.

BACKGROUND

Currently, Automatic Voltage Control (AVC) relays instruct On Load Tap Changers (OLTCs) to maintain the voltage at the substation close to a fixed, pre-determined value. This static target voltage value has been historically set as high as possible, ensuring that remote parts of the network remain within statutory limits under the worst case condition of maximum demand. Although this traditional voltage control philosophy is suitable for demand dominated networks, it can be restrictive in modern electricity distribution networks with a high penetration of embedded generation. The amount of generation that can be connected to the network, for example, is often limited by the voltage rise at the point of connection and the headroom available before the upper statutory voltage limit is reached. Therefore, the existing voltage control philosophy of statically maintaining the network voltage as high as possible imposes constraints on the generation capacity of the network. This is shown in Figure 1, where the connection of the new generator is not possible as it would cause the network voltage to exceed the statutory limit of 1.06 per unit.

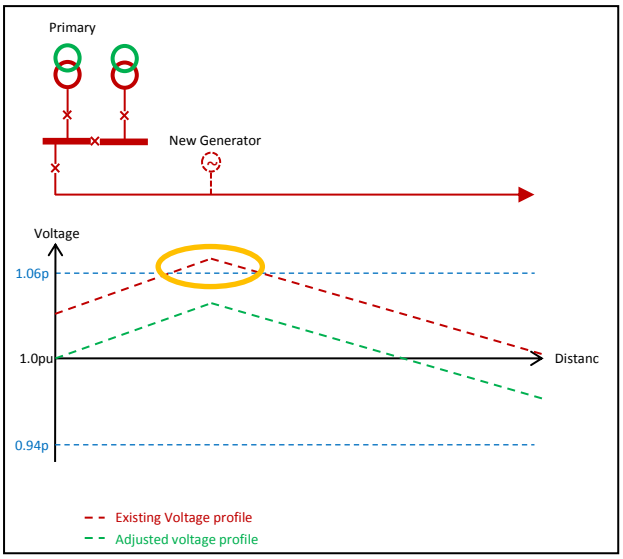

Figure 1 – Impact of new generator on network voltage

From Figure 1, it is also clear that lowering the static target voltage at the substation during times of high generation can increase the capacity of the network and allow more generation to connect. Therefore, a voltage control system that adjusts the target voltage at the substations based on the real-time network operating

conditions could overcome the restrictions imposed by traditional voltage control systems and enable better usage of the network capacity.

This is exactly what Western Power Distribution's (WPD) SVO technology aims to achieve. SVO is a real time, centralised voltage control system for 33kV and 11kV electricity distribution networks. As part of the UK's Low Carbon Networks Fund, WPD is delivering a Tier 2 project, Network Equilibrium [1], which involves the development and trial of SVO.

The SVO system will be implemented using Siemens' Spectrum Power 5 technology [3] and control the target voltage settings of the AVC relays at eight 132/33kV and eight 33/11kV substations in South West England.

THE SYSTEM ARCHITECTURE

SVO will receive network monitoring information from WPD's Network Management System (NMS), to assess the state of the network. Following the state estimation, optimised target voltage settings will be calculated and sent to WPD's NMS, to be forwarded to the substations' AVC relays through the existing communications infrastructure. The system architecture is demonstrated in Figure 2.

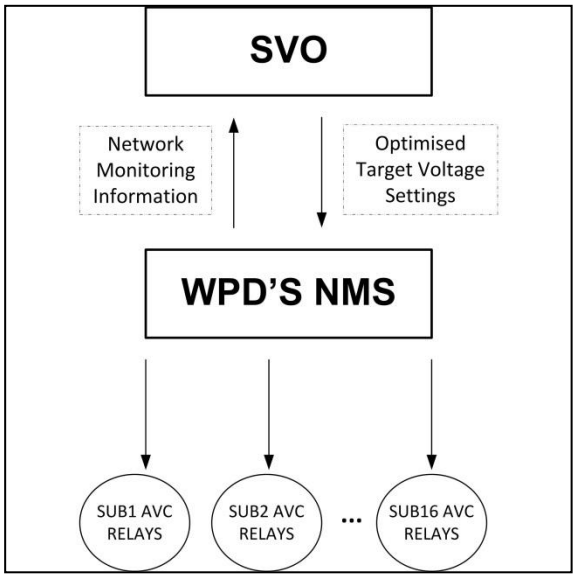

Figure 2 - SVO System Architecture

DESIGN STRATEGY

The centralised architecture formed the core of the design of this dynamic voltage control system. A number of factors were taken into account when deciding between a distributed system structure and the chosen centralised system.

The increased penetration of generation in the distribution network is causing complex, bi-directional power flows. These power flows are often unpredictable due to the intermittent nature of most DG connected to the network. To be able to calculate the optimised target voltage settings in real-time, it is necessary to know exactly how the network is operating in that moment in time. To enable this dynamic network state estimation, the system needs to have overall visibility of every node in the network. The easiest way to achieve this is by interfacing SVO with the existing NMS which already receives all the real-time network information, thus implementing a centralised approach.

From an operational point of view, having a centralised voltage control system that interfaces with the NMS is favourable for the Control engineers who operate the network through the Distribution Network Operator's (DNO) existing NMS. This is because a centralised approach provides more information on its operation, allows easier access and greater control over the system.

The interface between the WPD's NMS and the dynamic voltage control system is implemented using the Inter-Control Centre Communications Protocol (ICCP).

To be able to estimate the power flows and voltages in the network, SVO uses the real-time network information it receives from the NMS over ICCP. This information includes analogue measurements at key network points of current, voltage, power, status of circuit breakers and transformer tap position indicators. It then imports all this information to the electrical model of the network and performs power flow calculations to estimate all remaining power flows and voltages.

A key part of the design process was mapping all the existing monitoring information to the SVO network model to enable the successful import of the real-time information to the system. This mapping then formed the ICCP Bilateral Table and is demonstrated in Figure 3, where a specific monitoring point has the unique identifier "X" within the NMS and is mapped to ICCP ID 1 which corresponds to component "Y" within the SVO model.

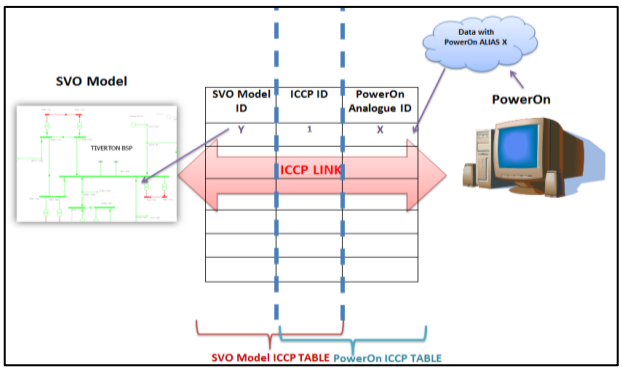

Figure 3 - Mapping of monitoring information to SVO model

PLANNING AND IMPLEMENTATION STRATEGY

Site Selection

Selection Methodology Overview

In the trial area of Network Equilibrium there are 28 Bulk Supply Points (BSP) and around 200 Primary substations, out of which only eight of each were to be selected for the trials of SVO.The criteria used when selecting the sites were:

1. Amount of embedded generation connected to each substation's network;
2. Window of available target voltage amendment;
3. Existing AVC capability;
4. Site Condition;
5. Connected customer impact; and
6. Customer connection activity.

Initially, 12 BSPs and 10 Primaries were selected out of the 228 sites. This involved performing power system analysis to identify the BSPs that have the highest number of voltage constraints and would therefore benefit the most from SVO. The Primary substations supplied by those 12 BSPs were then investigated to shortlist those with the largest amount of embedded generation connected to their networks; these would be most likely to have the least headroom for generation and greatest need for optimisation.

The next stage of the site selection involved splitting the 12 BSPs and 10 Primaries into four categories based on the window of available target voltage amendment and then scoring based on Criteria 1-5.

Substation Categorisation

In the selection of the final eight BSPs and eight Primaries, the main aim was to ensure a diverse representation of the entire network to enable robust conclusions be made on the implementation of SVO as Business As Usual (BAU). To achieve this, a combination of substations with different characteristics was required.

For this reason, four categories of BSP substations and two categories of Primary substations to be included in the trials were identified each offering a different type of learning.

The BSP substation categories were determined based on the window available for target voltage adjustment and are demonstrated in Table 1.

In order to understand in which category each of the 12 BSPs belonged, the networks were analysed using Siemens Power System Simulator for Engineering (PSS/E).

Table 1 - BSP Categories

Category Name	Description	Static Vs Dynamic Voltage control settings
Category A	Substations with significant target voltage modification capability. Changing the voltage control settings at these sites is expected to be easily achievable, ensuring the full testing of the SVO solution.	With existing planning tools, static changes to AVC settings are possible.
Category B	Substations with good target voltage modification capability. Changing the voltage control settings at these sites is expected to be achievable for the majority of time.	With existing planning tools, small static changes to AVC settings are possible.
Category C	Substations with limited target voltage modification capability. Changing the voltage control settings at these sites is expected to be achievable but challenging at certain times.	With existing planning tools, static AVC setting changes of very small magnitude are theoretically possible but practically unrealistic.
Category D	Substations with very limited target voltage modification capability. Changing the voltage control settings at these sites is expected to be challenging for the majority of time.	With existing planning tools, static AVC setting changes are not possible making dynamic voltage control through SVO the only solution to release network capacity.

This analysis quantified the worst case target voltage reduction that could be applied at each BSP without violating the statutory voltage limits of ±6% and ensuring that no restrictions were imposed on the traditional voltage control of the surrounding transformers.

It involved simulating the network in the most restrictive operational conditions (minimum generation and maximum demand) and calculating the worst case target voltage reduction (*VTreduction*) using:

$$VTreduction = Vmin - 0.94 \quad (1)$$

where *Vmin* is the minimum voltage on the BSP network and 0.94 is the lower statutory voltage limit expressed in the per unit system.

Therefore, *VTreduction* shows by how much the voltage in the 33kV network could be reduced before the voltage at any network node reaches the minimum statutory limit. The network voltages are reduced by amending the target voltage at the BSP, hence *VTreduction* indicates the reduction in target voltage that can be applied at the BSP while maintaining all network voltages within statutory limits.

To ensure that no restrictions were imposed on the traditional voltage control of the surrounding transformers when the calculated target voltage reduction was applied, the tap positions of all transformers were calculated. A check was then made to ensure that the current tap position was at least three steps away from the top/bottom tap. This confirmed that there was enough room available for the traditional voltage control to be able to regulate the voltage to the target value.

In the selection of the final eight Primaries, the substations were separated into categories following a similar procedure as for the BSPs. However, due to the lack of load monitoring data available for the 11kV networks fed by the Primary substations, certain inaccuracies were introduced to the modelling. For this reason, the Primary substations have been split to only two categories as shown in Table 2.

Table 2 - Primary substation categories

Category Name	Description	Static Vs Dynamic Voltage control settings
Category 1	Substations with good target voltage modification capability. Changing the voltage control settings at these sites is expected to be achievable, ensuring the full testing of the SVO solution.	With existing planning tools some static changes to AVC settings are possible.
Category 2	Substations with challenging target voltage modification.	With existing planning tools, static changes to AVC settings are not possible.

Substation Scoring

With the BSPs and Primaries categorised into groups dependent on the voltage reduction that could be achieved, a method was developed to score each substation to determine which should be selected for the SVO implementation. Table 3 below shows the four areas that each substation was scored against along with the weighting of each area.

Table 3 – Selection Criteria and Weightings

Area	Weighting
Existing AVC capability	50%
Site Condition	30%
Connected customer impact	10%
Customer connection activity	10%

The existing AVC capability corresponds to the capability of the existing AVC equipment at each substation. Substations that have already been equipped with modern AVC relays that can be easily adapted for SVO will be more cost effective and involve less risk compared to sites that require AVC relays to be replaced.

The site condition represents the condition of the substation where SVO is to be implemented as it can have a major impact on the success of the trial. Where a substation has equipment that is in poor condition it may generally require more regular maintenance intervals and experience more frequent electrical and mechanical problems.

Implementing SVO is likely to result in voltage profiles varying more than compared with the current static AVC set points. Customers that could, potentially, be sensitive to voltage variation were considered when deciding which sites to select for SVO, corresponding to the connected customer impact criterion.

Finally, the customer connection activity was considered since by implementing SVO in areas that have high levels of customer connection activity, the benefits are more likely to be realised during the project lifetime.

After the scoring was complete, the two best performing BSPs were chosen from each BSP Category leaving one BSP as a backup option in each Category. The four best performing Primaries were also chosen from the two Primary Categories, leaving one Primary in each Category as a backup option.

Network model creation

The SVO network model was created by extracting the required area from an existing power system model which was generated using information from WPD's Geographical Information System (GIS). To ensure that the performance of the system would not be compromised, the aim was to keep the network model as small as possible.

The challenging task was defining the areas that would need to be extracted from the full model. In order for SVO to do all the appropriate calculations to find the optimal voltage set point for the substation it is controlling, the entire feeders fed by the substation need to be represented as a minimum and the model end points need to be defined.

Figure 4 shows the 33kV feeder fed by the BSP that will be controlled by SVO with a Normal Open Point (NOP) in the middle, separating the SVO BSP feeder from the feeder that is normally fed by BSP 2. Case b in Figure 4 also demonstrates that if the network is modelled only up to the NOP of the SVO BSP feeder, then in the case of network re-configuration where the NOP moves to a different location, SVO will not be able to assess the state of the network accurately as it will not have the full network now fed by the SVO BSP in its model.

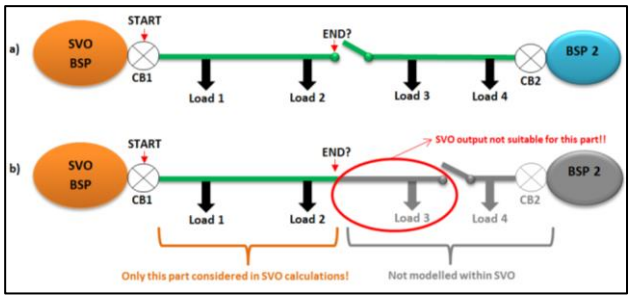

Figure 4 – Establishing the model end points for operation in both normal and abnormal conditions

Therefore, to ensure that SVO can work in both normal and abnormal conditions, in the example of Figure 4, it would be necessary to also model the feeder of the neighbouring substation, BSP 2. In general, the feeders of all neighbours of the SVO controlled substations would need to be modelled. It is important to note that in order to keep the network size as small as possible, only the first NOP was considered, therefore any feeders beyond the second NOP, shown in Figure 5, were not modelled. The SVO operation would be affected only when both NOP1 and NOP2 move, and in that case SVO would stop optimising and the voltage control settings would revert to the traditional settings. However, as that event is unlikely to take place often, its effect in the trials is expected to be negligible.

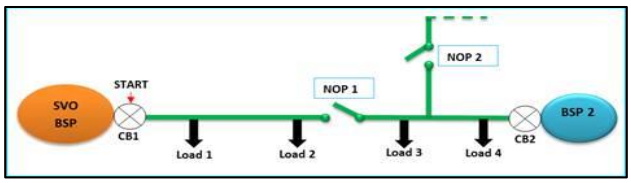

Figure 5 - Network beyond NOP2.

The next step in the creation of the SVO network model, was finding the neighbours of the SVO substations that would need to be included in the model. In the 11kV network specifically, this is incredibly challenging due to the complex interconnectivity of the network.

Therefore, to be able to establish the most appropriate model boundaries efficiently, a detailed network connectivity investigation study was undertaken. As part of this work, a spreadsheet was extracted from the NMS that listed all switches connected to the feeders of each substation up to the first NOP. A python script was then created to analyse this data. Finding which substations each SVO controlled substation has common switches with means its immediate neighbours were identified. This is demonstrated in Figure 4, where NOP1 is the common switch between the SVO substation and one of its neighbours, BSP2.

This network connectivity analysis, provided the list of substations and their feeders that had to be included in the SVO model.

CONCLUSIONS

SVO, the real-time voltage control system being developed could overcome the constraints imposed by traditional voltage control methodologies and release previously unused network capacity. This paper described the design, planning and implementation strategy of SVO. The system has been designed based on a centralised architecture to ensure it can efficiently communicate with the NMS to have full visibility of the network operation. The system will be implemented at eight BSPs and eight Primary substations in South West England. To ensure that valuable information is collected from the trials to support the possible future implementation of the technology as Business As Usual (BAU), the site selection aimed to ensure that substations of different characteristics are utilised within the trials. As part of this, a significant number of power system studies were performed to calculate the available window for target voltage amendment at each candidate site and investigations on each site's AVC capability, condition and connected customers were completed. After selecting the sites, a detailed scripted connectivity investigation was performed to specify the substations and feeders that had to be included in the SVO network model.

NEXT STEPS

The trials of SVO will provide valuable information on its true operation, enabling evaluation of the benefits of the technology and make recommendations on the voltage control system that should be implemented as BAU. Among other data, the target voltage amendments the system will perform will be captured and their effect modelled in power system analysis software to evaluate the network capacity when using SVO. Similar power system studies will be performed by setting the voltage control settings to the conventional values and evaluating the network capacity for the trial period of SVO. The two sets of results will then be compared to calculate the change in network capacity with the usage of SVO during the trial period, evaluating the benefits of the technology.

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