VOLTAGE REGULATING DISTRIBUTION TRANSFORMERS IN COMBINATION WITH STATE ESTIMATION ENABLING CONSERVATION VOLTAGE REDUCTION AND INTEGRATION OF LOW CARBON TECHNOLOGY IN LOW VOLTAGE NETWORKS

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Abstract

Voltage regulating distribution transformers (VRDTs) leverage on a new generation of OLTC, specifically designed these transformers and constitute a new and powerful tool in grid modernization strategies. VRDTs provide voltage regulation at LV level and increase the hosting capacity of distributed generation, mainly rooftop solar, and other low carbon technologies, such as heat pumps and electric vehicles in existing low voltage networks without the need of network reinforcement. This paper introduces the principle of VRDTs and sheds light on their application to substantially increase network hosting capacity in distribution networks. The main focus lies on the application of conservation voltage reduction (CVR) in low voltage networks, where state estimation based on distributed sensors in combination with VRDT taps a substantial potential for the reduction of energy consumption, leading to reduced end customer energy bills and reduced carbon dioxide emissions. These effects have been validated in Electricity North West's (ENW) 24 month trial project "Smart Street". The paper describes the "Smart Street" project with its methodology and results, focusing on the role of VRDT as well as the resulting roll-out on a larger scale.

1 Introduction

On-load tap-changers (OLTC) have been applied for decades for voltage regulation in power transformers for transmission and distribution networks. Distribution transformers traditionally have not been equipped with these devices.

In countries where smaller generation units have been incentivised, PV and wind turbines are massively deployed MV and LV networks, posing a challenge to these networks [1]. Having been designed for load connection and the corresponding voltage drop only, these networks quickly reach their limits in hosting distributed generation units, due to the voltage rise the generation causes [2]. The main measures taken to answer the resulting voltage problem were reinforcement of the network, i.e. underground cable or overhead lines with a higher cross section or installation of additional secondary substations, in order to shorten the feeder length. Both measures are cost intensive and require a long planning lead time. This can be heavily reduced by applying voltage control in these networks [3].

1.1. Principle of state of the art VRDT

Similar to power transformers equipped with on-load tap-changers, voltage regulating distribution transformers (VRDT) enable voltage regulation through the variation of the transformer ratio. State of the art electronics and drive concepts allow a very compact OLTC design that results in a very compact VRDT design. Vacuum switching technology – meanwhile a standard for OLTCs – enable OLTCs that are factually maintenance free over the lifetime of a typical distribution transformer. With a regulating range of +/-4 steps, each 2,5% of the nominal voltage, VRDT are capable to compensate for the maximum expectable voltage variation within EN50160 [4].

1.2. Boosting hosting capacity in LV networks through VRDT

Without the use of VRDT, the last voltage controlling unit is within the primary distribution substation or a medium voltage regulator. When planning such networks, the usable voltage bandwidth must be divided between the MV line and the underlaying LV networks. Fig. 1 shows an example for typical planning parameters of a distribution network.

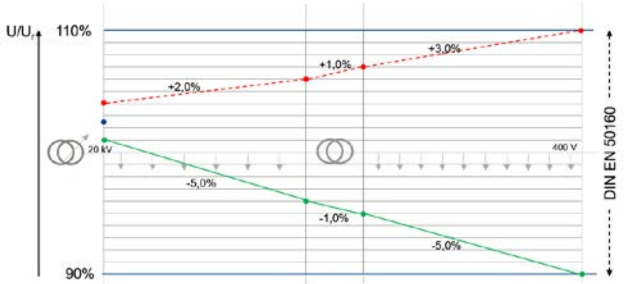

Figure 1 Example planning parameters for rural distribution network without VRDT. Red (dashed) graph: generation case. Green (solid) graph: load case

In this example the maximum admissible voltage rise for generation within the LV is 3% and the maximum admissible voltage drop at maximum load in the LV is 5% [5].

Based on the electrical data of a cable (e.g. 3x150Alrm/95 GKN underground cable) the connectable load / generation power can be shown as a function of the cable length (blue solid lines in Fig.2 and Fig. 3).

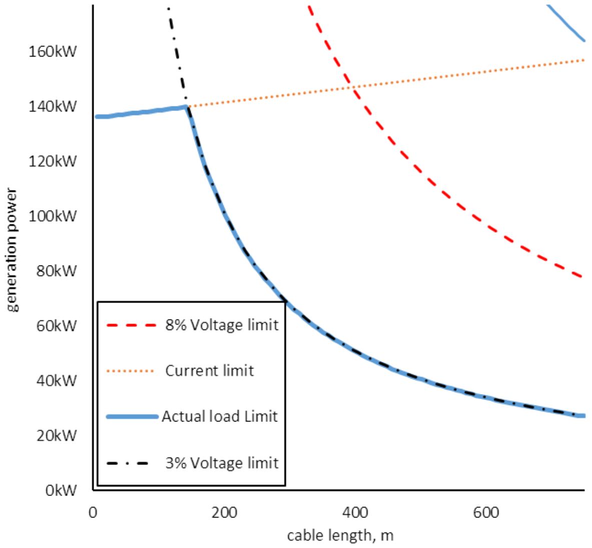

Figure 2 Maximum connectable generation power for a 3x150Alrm/95 GKN underground cable based on cable length. Limit with conventional network planning (blue - solid). 3% voltage limit (black - dash-dotted), current limit (orange - dotted). 8% voltage limit with VRDT (red – dashed)

Fig. 2 shows the generation case. The orange (dotted) graph is the connectable generation power at the end of the feeder as a function of the feeder length. The determining factor here is the current carrying capacity of the cable. The black (dash-dotted) graph is the connectable generation power at the end of the feeder as a function of the feeder length, based on the maximum admissible voltage rise (here 3%) defined by network planning rules for conventional network planning with non regulated distribution transformers. The blue (solid) graph shows the maximum connectable generation power as a result of both graphs black (dash-dotted) and orange (dotted). The red (dashed) graph shows the maximum connectable generation power based on a voltage rise limit of 8%, that results from a set-voltage at nominal voltage and a regulation bandwidth of +/-2% (within statutory limits of +/-10%). Fig. 2 shows that to a cable length of 145 metres, the maximum generation power that can be connected, is limited by the current carrying capacity of the cable to 140,5 kW. For cable lengths above 145 metres the limit factor is the planned maximum voltage rise of 3%, reducing the power value with increasing length. By applying 8% planned maximum voltage rise – enabled by a VRDT with above described regulating parameters – voltage is no longer a limiting factor up to a cable length of 395 metres, allowing a connected generation power of 146,7 kW. Compared to 51,4 kW with conventional network planning, VRDT increase the hosting capacity by 185%. For cable lengths above 395 metres the maximum generation power is limited by the maximum voltage rise of 8%.

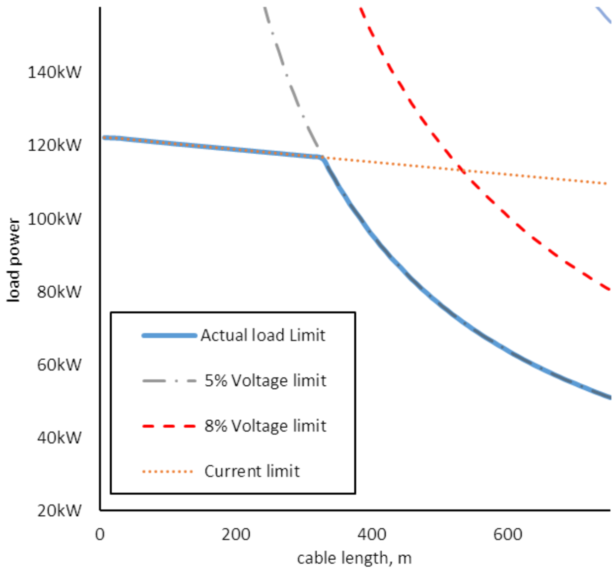

Figure 3 Maximum connectable load power for a 3x150Alrm/95 GKN underground cable based on cable length. Limit with conventional network planning (blue - solid). 5% voltage limit (grey - dash-dotted), current limit (orange - dotted). 8% voltage limit with VRDT (red – dashed)

The considerations for the load case (Fig. 3) are analogue regarding connectable load. By applying a dynamic, load depending set-point, instead of a static, maximum admissible voltage drop and rise to be considered, can be even increased above the mentioned 8%, leading to a higher capacity boost for both generation and loads with the existing feeder that can reach a factor of 2 to 4 [6].

In regards to the load case, studies have shown that the uptake of LCT loads, such as heat-pumps and chargers for electircal vehicles, in most cases leads to voltage problems first, before current/power of cables or substations reach their limits [7], [8].

Beyond the integration of LCT loads and distributed generators in the distribution networks, VRDT can contribute to the reduction of end customer consumption by applying conservation voltage reduction.

1.3. Conservation voltage reduction (CVR)

Conservation voltage reduction has been applied for decades in North America to reduce energy consumption, related losses and reduce peak demand, by reducing the voltage in public networks. CVR utilises the voltage dependency of loads, which depends on the type of load. The power consumption of loads can have a voltage dependant, constant power and constant energy characteristic [9]. The achievable consumption reduction is heavily depending on the mix of these load types in the specific networks, the actual power flow and the network type [10]. Evaluating the benefit of CVR and network reconfiguration to reduce consumption and losses and in consequence reduce carbon dioxide emissions and cost of energy for end customers, was the goal of Smart Street Project of the UK DNO Electricity North West (ENW).

1.4. Smart Street Project

Smart Street was a four-year innovation project funded under Ofgem's Low Carbon Network (LCN) Network Innovation Competition (NIC), which sought to demonstrate the value of actively optimising the low voltage networks for a UK Distribution Network Operator (DNO). The project had a two-year trial period where a combination of VRDT, low voltage switches and capacitor banks were used to optimise the configuration of the low voltage network under the control of an autonomous centralised system. The objectives of the project were to demonstrate how this system could be used to release capacity on the network, adapt to the change in voltage profile associated with the connection of low carbon technologies (LCTs), and reduce energy consumption by consumers.

2. Methodology

During the project thirty-eight distribution substations had low voltage switchgear and capacitor banks installed. In addition, five transformers were replaced with VRDT units and six high voltage capacitor banks were installed. These sites were spread across the ENW network to cover the various network types (rural, urban, and dense urban) to determine if the system was more effective in certain areas. The devices were all linked to a centralised control system via tele-control which automatically assessed the network every thirty minutes using a volt/ Var Control (VVC) algorithm to determine the optimum running arrangement. This system was then able to send commands to the devices in order to autonomously reconfigure the network as appropriate.

A two-stage process was followed in order to determine the efficacy of the system. Initially the projects academic partners from the University of Manchester took ENW's network data for the selected sites and created a series of models using OpenDSS to represent the high voltage and low voltage networks. Under the ELEXON classification there are eight profile classes (PC) for various load types with PC1 and PC2 being domestic and PC3 to PC8 being non-domestic. For the domestic loads the CREST tool developed by Loughborough University was used to generate high granularity time varying ZIP profiles. A pool of 1,000 individual profiles was then developed for each domestic PC. For the non-domestic PCs were generated using the diversified ELEXON profiles to give a similar pool.

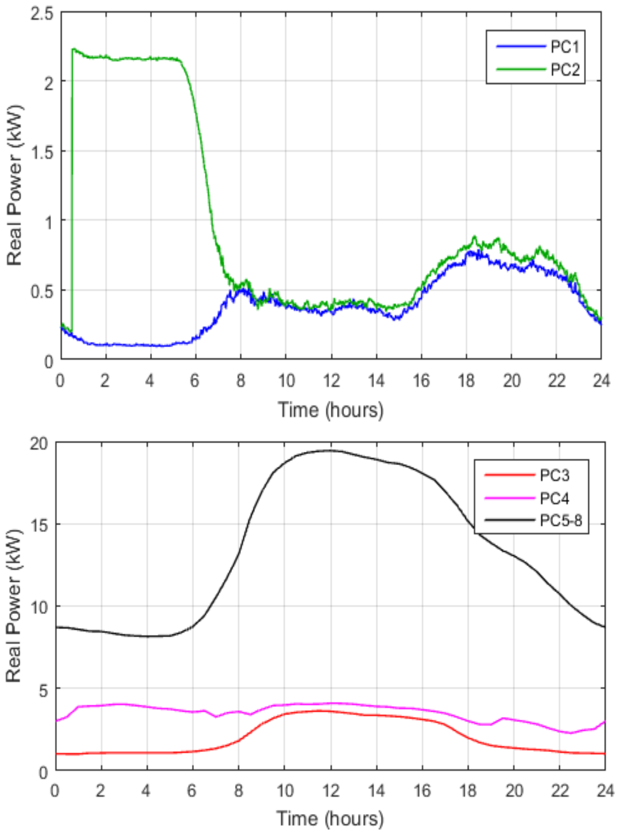

Figure 4 Applied profile classes 1 and 2 (a) and 3 - 8 (b)

For the HV models the load profiles were aggregated across the network based on the customer numbers and load composition for the sites fed from that network.

The Monte Carlo method was used to randomly assign PC profiles to the customers fed by the LV networks. A load flow calculation was then carried out on the network following which the various parameters, i.e. tap position and LV switch state, were adjusted until the optimum arrangement was identified

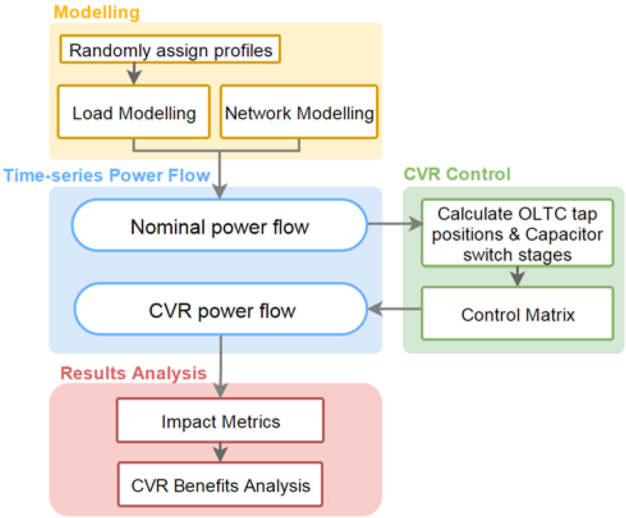

Figure 5 Flow chart for modelling process

This process was repeated 54 times across the trial networks to determine the impact of CVR. These results and the accompanying models were then passed to the second set of academic partners at Queens University Belfast. Their role was to compare the outputs of the simulations to the data collected by the live devices during the trial period. Their analysis indicated that the results of the simulations were consistent with the trial data and that a reduction in energy consumption of between 5,5% to 8,5% could be achieved through use of the Smart Street system through applying a voltage reduction of 5% – 8%. This finding was consistent with the outputs of ENWs previous NIC project – CLASS, which looked to use the primary tap changers to provide demand control services for the electricity system operator. Furthermore, use of the system demonstrated a reduction in network losses of up to 15%, although values in the range 6% - 8% were more typical. A pareto analysis of the data was made to determine how to balance the trade-off between voltage reduction with the related reduction in low-voltage energy consumption (LVE) and high voltage loss reduction (HVL), which demonstrated that the reduction in energy consumption associated with the lowered voltage delivered a reduction in losses as well so targeting the optimisation software accordingly would deliver the optimal benefits.

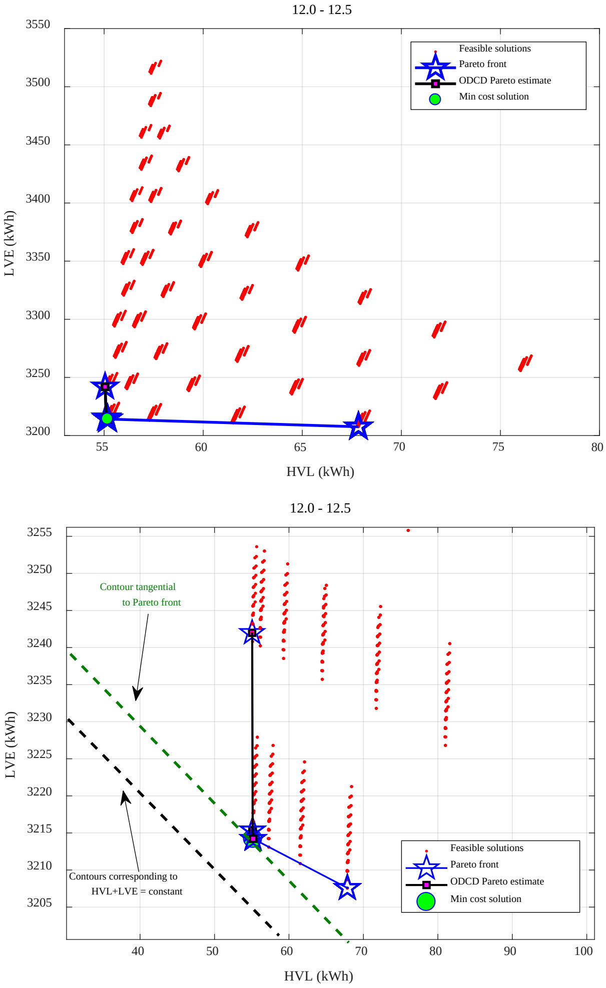

Figure 6 Trade-off between LVE and HVL midday on a weekend winter (a) and zoomed in (b)

Finally, the third set of academic partners from the Tyndell Centre carried out a carbon impact assessment of the deployment of Smart Street compared to traditional methods of responding to load increases and voltage issues on the LV network. This demonstrated a significant reduction in CO2e emissions from the installation of the Smart Street technology. Extrapolating the results of the project out to a ENW wide deployment.

Table 1 Summary of greenhouse gas emissions savings (MtCO2e) potential with full Smart Street rollout across Electricity North West area, 2016-2060, based on differend scenarios

	Scenario	HV	LV Low	LV High
Two degrees	OLTC	5.13	7.24	10.84
	OLTC + Cap	5.11	7.07	10.81
	OLTC + Cap + Mesh	5.11	7.13	10.78
Slow progress	OLTC	6.3	8.91	13.33
	OLTC + Cap	6.28	8.74	13.26
	OLTC + Cap + Mesh	6.28	8.79	13.26
Steady state	OLTC	15.14	21.45	32.06
	OLTC + Cap	15.11	21.28	31.99
	OLTC + Cap + Mesh	15.11	21.3	31.93
Consumer power	OLTC	8.09	11.43	17.12
	OLTC + Cap	8.08	11.28	17.05
	OLTC + Cap + Mesh	8.08	11.31	17.05

3 Results

Applying the Smart Street system has shown a consumption reduction between 5,5% and 8,5%, with a near 1:1 relationship to the voltage reduction achieved. The roll-out of the system within the ENW network would achieve a carbon dioxide emissions reduction of between 5,11 and 15,14 MtC02e on the HV network driven by reduced consumption for the period 2016-2060. The main contribution is achieved by applying voltage regulation with OLTC. Application in the low-voltage networks (mainly VRDT) will significantly increase these values.

4 Conclusion

Following the success of the original Smart Street project ENW applied for an adjustment to the RIIO-ED1 price control under the innovation roll-out mechanism (IRM) to deploy Smart Street in a business as usual manner. This bid was successful and ENW were awarded funding to install the controlling software, along with VRDT and LV switchgear at 180 sited across their network. Furthermore ENW have made a proposal to include VRDT as an option in the national standard documentation. Electricity North West are looking to further roll the Smart Street System out during the RIIO-ED2 price control and will be setting this out in the upcoming submission to Ofgem.

5 References

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