COORDINATED VOLTAGE AND POWER FLOW CONTROL IN DISTRIBUTION NETWORK

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ABSTRACT

The UK government is pushing for continuous increases in Low Carbon Technologies (LCTs) which consists of electrical loads and microgeneration in the UK low voltage (LV) distribution networks. This is likely to pose significant changes on the voltage and power flow in the LV networks and consequent challenges to network devices and infrastructure. To solve the voltage and power flow problem without upgrading entire distribution networks, a coordinated voltage and power flow control method is proposed in the paper. This proposed method is evaluated by simulation and Network-in-Loop (NIL) emulation in the Smart Grid Laboratory at Durham University and shows benefits over conventional methods.

INTRODUCTION

The UK's policy is expected to lead to continuous increases in LCT penetrations, including loads such as heat pumps (HP) and electric vehicles (EV) and microgeneration such as solar photovoltaic (PV) and combined heat and power (CHP). This is likely to pose significant changes on the voltage and power flow in the LV networks and consequent challenges for network devices, infrastructure, and Distribution Networks Operators (DNOs). With these issues in mind, the GB's Office of Gas & Electricity Markets (Ofgem) has instigated the Low Carbon Network Fund (LCNF) to facilitate investigation into the impact of LCTs on the GB electricity system. The largest project funded by the LCNF, is the Customer Led Network Revolution (CLNR) which is currently the UK's largest Smart Grid pilot project. Four typical networks have been chosen for trials of different combinations of smart grid network interventions and supervisory systems. The results from trials are analyzed in Durham University to investigate the value of the network interventions and supervisory control with particular reference to their capability to accommodate high penetrations of LCTs.

Previous research has found that voltage problems are the main constraints encountered by LV networks with high penetrations of LCT loads and generation [1, 2]. A large and unregulated usage of LCT loads such as HPs and EVs will cause significant voltage drop along the LV feeders, while a large number of rooftop PV will cause voltage rise on sunny days. However this will not be the only problem encountered by LV networks in the future. While the penetration of LCT loads and generations keep rising, the devices on the networks such as MV/LV transformers will soon be overloaded by either LCT loads or reverse power from micro generations unless they are to be upgraded with a considerable amount of money.

Due to the likely co-occurrence of power overloading and voltage problems, the effect of individual voltage control or power flow control are limited and may conflict with each other in the worst case. In this paper a coordinated voltage and power flow control method is proposed. The control method makes use of electrical energy storage (EES) coordinately with other network devices such as on-load tap changer (OLTC) to solve the voltage and power flow problem in LV distribution networks. It is evaluated through simulations in Real Time Digital Simulator (RTDS) and NIL emulation in the Smart Grid Laboratory of Durham University. A part of an LV network in one of the four trial networks of the CLNR project is chosen for the case study presented while real domestic and LCT loads and generation profiles are being used.

PROPOSED CONTROL METHOD

Previous research has demonstrated the benefits of the application of EES system in a power system, such as supporting a heavily loaded feeder and minimizing OLTC operations [1]. It was proposed in [2] that EES can improve the solar PV generation system by solving those issues such as high ramp rate and unstable frequency and voltage. In [3] it was proposed to use EES to regulate the reverse power flow caused by large quantities of solar PV. All of the aforementioned methods use EESs individually to tackle either voltage problems or power flow problems.

It is proposed in this paper to control the voltage and power flow in the LV distribution network co-ordinately rather than individually. The proposed control method is explained in Figure 1. At the beginning of each cycle, once the controller receives the required measurements it checks if there is violation of voltage or power flow. For voltage violation if there is an OLTC equipped at the LV transformer it will be considered first. However, since the tap changing at the transformer will affect the voltage of other downstream loads, forecasting will be performed before the implementation to ensure the tap operation will not cause violation at other places. If OLTC is not available or a violation would occur, the controller will turn to other solutions such as EESs, checking the effectiveness (voltage sensitivity factor, *VSF*) of each

EES in solving the voltage violation. *VSF* is given by:

$$VSF_{i,j} = \left\| \frac{dV_j}{dP_i} \right\|, \quad (1)$$

where VSF_{ij} denotes how effective a power change at location i changes the voltage at location j. The EES with highest *VSF* value will be chosen.

If there is power flow violation, the controller will have a pre-determined priority of EES or demand side response (if available) to mitigate over power flow. Similarly, the controller will forecast and make sure the voltage over the network is not to be violated by power flow regulation using EES, following:

$$dV_j = VSF_{i,j} \times dP_i, \quad (2)$$

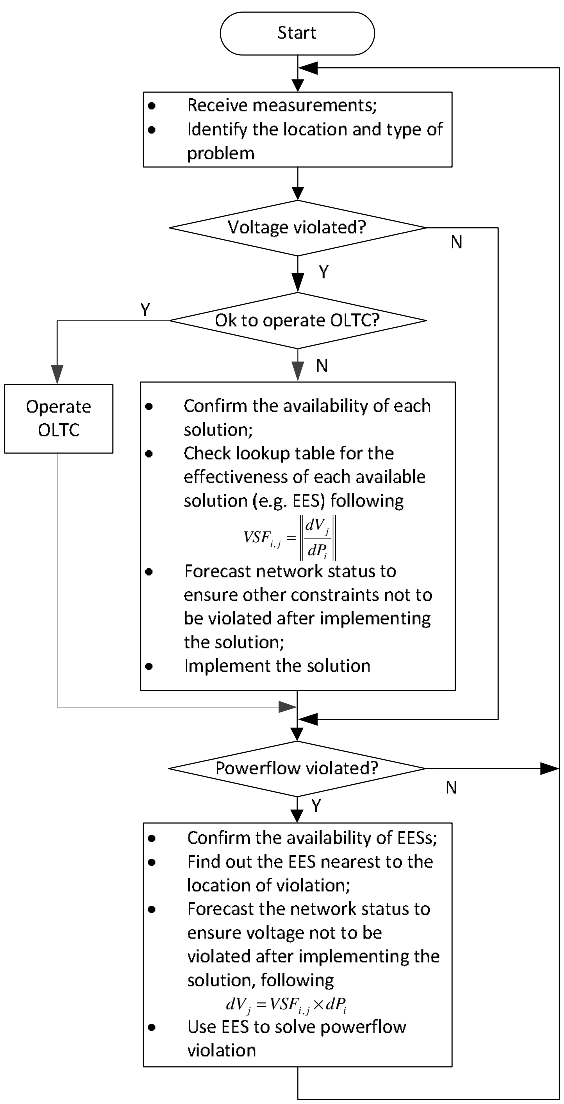

Figure 1. Coordinated control of voltage and power flow

CASE STUDY

A part of the LV network in one of the four trial networks of CLNR project is chosen for a case study in this paper, as shown in Figure 2, to evaluate the proposed coordinated control method. The network starts with a MV/LV 0.315 MVA OLTC transformer and supplies power to 196 domestic houses. The penetrations of LCT loads and generation among these houses are: 60% with EV, 60% with HP and 90% with solar PV. A 100kVA EES is located at the substation. The OLTC and EES are used for voltage and power flow control. The case study network runs in RTDS.

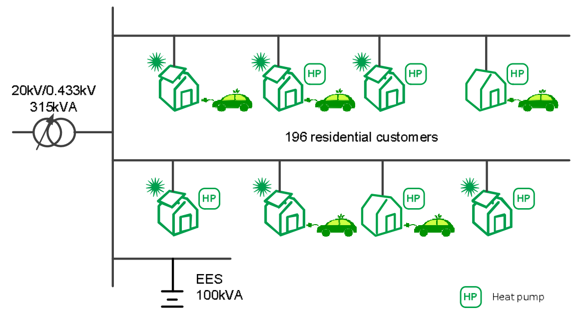

Figure 2. Case study network with high penetration of HP, EV and solar PV.

An average domestic house load profile from CLNR smart meter data of 5000+ customers in the period of May 2011 to May 2012 is used in this case study, together with typical consumption profiles of EV and HP cited from the Smart Grid Forum report [4]. They are shown in Figure 3. An average solar PV generation profile of winter time from 20+ British Gas customers in North East England, as shown in Figure 4, is used for the PV model in RTDS which consists of a solar panel model, a DC/AC inverter and simple P/Q controller.

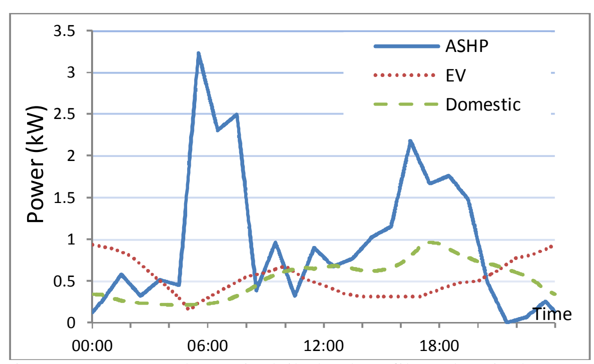

Figure 3. Average domestic daily load profile and typical consumption profile of HP and EV

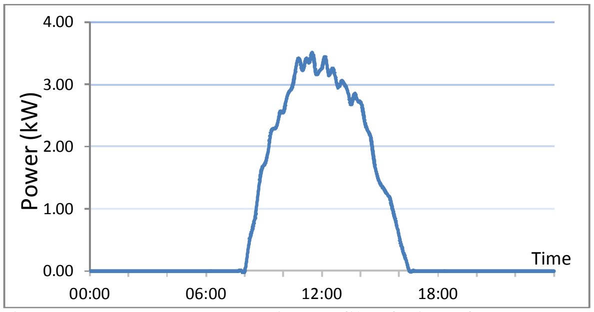

Figure 4. Average PV generation profile of winter from 20+ British Gas domestic customers in 2011

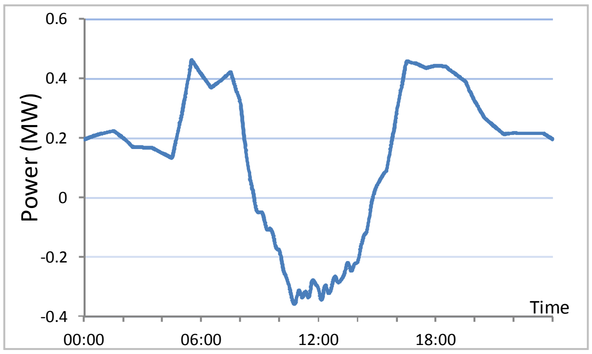

Figure 5. Projected daily power flow profile of LV distribution transformer

Based on the above loads and generation profiles and their penetration levels, the power flow of the transformer can be calculated as:

$$P_{TX} = (P_{dom} + P_{EV} \times 60\% + P_{HP} \times 60\% - P_{PV} \times 90\%) \times 196,$$

where P_{TX} denotes the transformer power, and P_{dom} , P_{EV} , P_{HP} and P_{PV} denote domestic load, EV consumption, HP consumption and PV generation respectively. Figure 5 shows the 24h power flow of the transformer calculated with this formula. The positive power peaks in early morning and late afternoon and the massive reverse power at mid-day have potentials to overload the transformer in both directions.

The proposed method is evaluated with RTDS simulation and NIL emulation with real EES in the laboratory, as shown in Figure 6. The network model running in RTDS connects to the laboratory LV network through a 6kW 4-quadrant power amplifier. The 5kW EES in the laboratory is used to emulate a part of EES in the case study network.

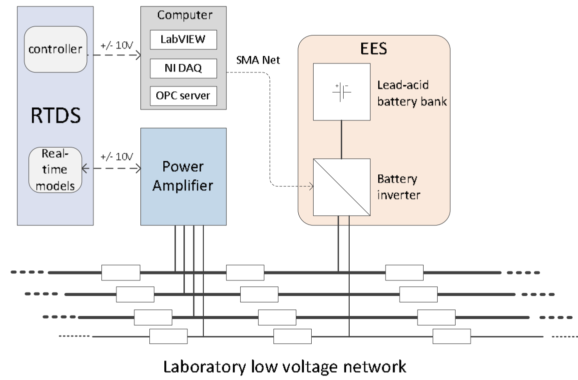

Figure 6. NIL emulation setup in Smart Grid Laboratory of Durham University

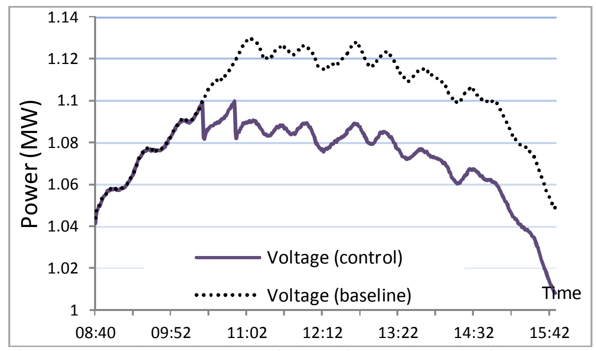

Figure 7. Feeder end voltage in baseline study and with coordinated control

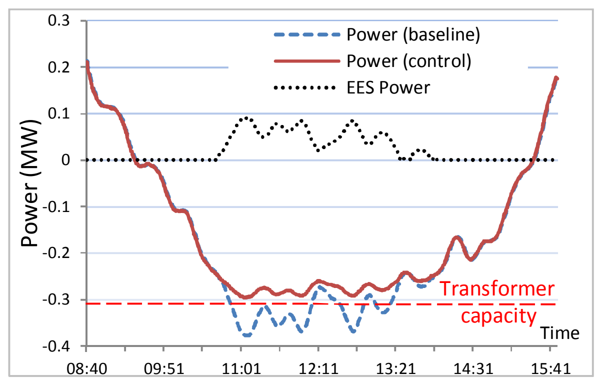

Figure 8. Transformer reverse power flow absorbed by EES

Figure 7 and 8 shows the voltage at the end of the feeder and the power flow of the transformer respectively in the baseline study (without OLTC or EES) and with coordinated control of OLTC and EES at day time. It shows that when the PV generation rose the transformer power flow reversed around 9 o'clock and the reverse power caused a voltage rise at the feeder end and overloading of the transformer at mid-day during the baseline study. As shown in Figure 7, when the voltage reached an upper limit (1.1p.u in UK), the controller called the OLTC to reduce the voltage. When the transformer was overloaded the controller commanded the EES to absorb the excess power and mitigated transformer overloading as shown in Figure 8.

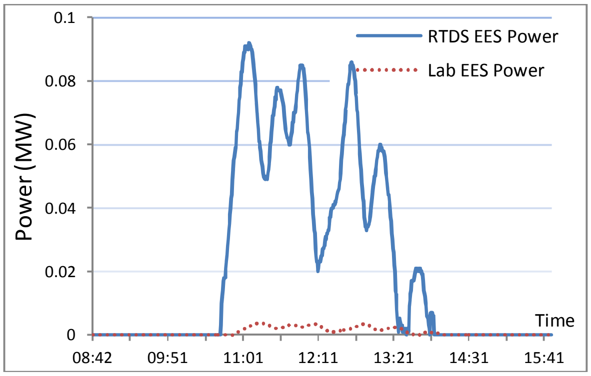

Figure 9. Charging power of EES in lab and modelled EES in RTDS

The EES power shown in Figure 8 consists of power from both the EES model in RTDS and actual EES in the laboratory, shown in Figure 9. Due to the size of inverter, the power output of the actual EES is limited compared to the power from EES model. Furthermore, although the laboratory EES power output followed the trend of RTDS EES power, there is a noticeable shift at time axis due to communication delay when the controller commands the battery inverter through an OPC link and RS485 daisy-chain network.

Figure 10 and 11 shows the voltage of the feeder end and transformer power flow respectively in the baseline study and with the proposed control in the afternoon. It was shown whilst the PV generation reduced and the domestic and LCT loads increased in the afternoon, the feeder end voltage dropped significantly while the transformer power flow changed direction again. When the voltage dropped to the lower limit (0.94p.u in UK) the controller signalled the OLTC to raise the voltage, shown in Figure 10. Figure 11 shows that when the load reached its peak and overloaded the transformer the controller commanded the EES to discharge power reducing the overloading. Similarly with Figure 9, the discharging power from modelled EES and laboratory EES are shown in Figure 12.

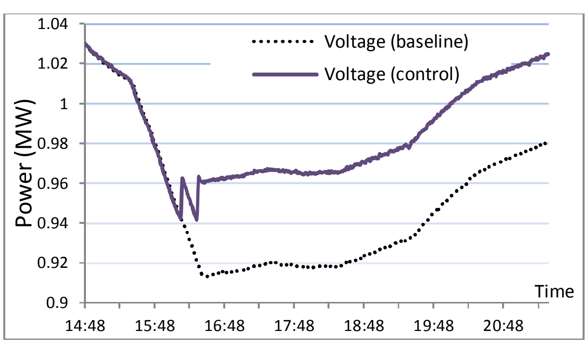

Figure 10. Feeder end voltage in baseline study and with coordinated control

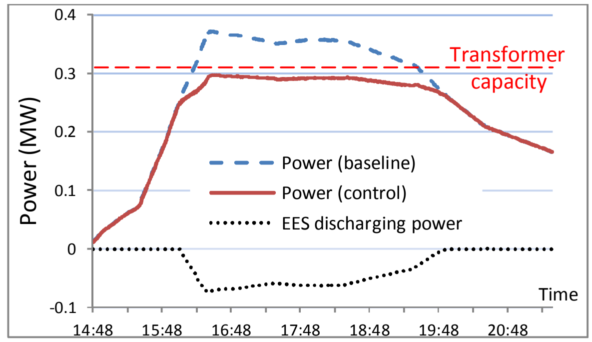

Figure 11. Transformer power flow mitigated by EES

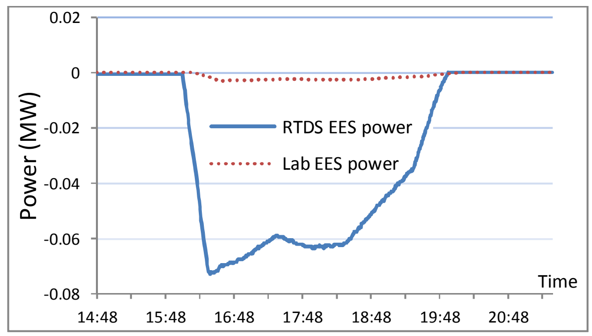

Figure 12. Discharging power of EES in lab and modelled EES in RTDS

SUMMARY

This paper proposes a coordinated voltage and power flow control method to help existing LV distribution network adapt to future scenarios with high penetrations of LCT loads and microgeneration. Evaluated by RTDS simulations and Network-in-Loop emulations, the proposed method shows benefits over conventional methods in voltage control and power flow management.

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