COORDINATED OPERATION OF ENERGY STORAGE AND ON-LOAD TAP CHANGER ON A UK 11KV DISTRIBUTION NETWORK

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ABSTRACT

The move towards a Smart Grid electricity system is a target of the UK government over the next 20 to 40 years. The use of energy storage as part of the smart grid has been identified as the UK's electricity system continues to evolve due to proliferation of low carbon technologies, increasing electricity demand, and ageing assets. This paper looks at using Energy Storage Systems (ESS) as an investment alternative for DNOs to meet future challenges caused by growing demand, integration of renewables, in this case PV, and ageing infrastructure (cables, and transformer).

This paper evaluates the impact that a projected demand increase would have on an 11kV distribution network in the UK with an examination of overpower, voltage excursion, tap change operations and power losses. The paper then discusses the impact of reinforcing a network with ESS and coordinating its operation with On-Load Tap Changers (OLTC) to fix or mitigate ascertained issues with the aim of deferring costly network upgrades and thereby provide benefit to the DNO and customers.

INTRODUCTION

The power system in Great Britain is expected to evolve over the next 40 years to cope with the anticipated future challenges which include an increase in electricity demand and prices, decarbonisation, and a reduction in security of supply caused by ageing assets. The UK government, working towards decarbonisation, has set targets to electrify heating and transportation by 2030[1]. This is in addition to the normal increase in demand which from 1970 to 2000 was over 59% for residential customers and 140% for commercial and public service customers [2]. A depiction of the expected increase from 2010 in demand over a week is shown in Figures1 and 2.

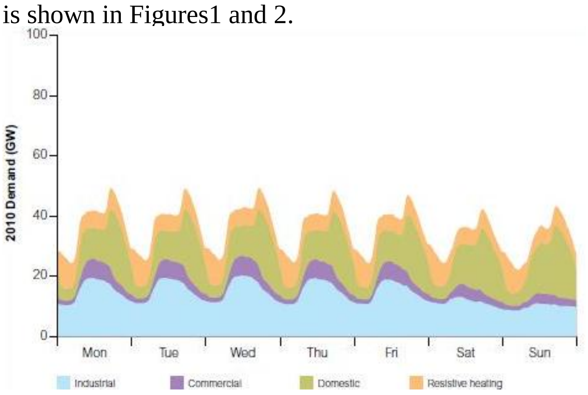

Figure 1 – One week demand profile in 2010[1]

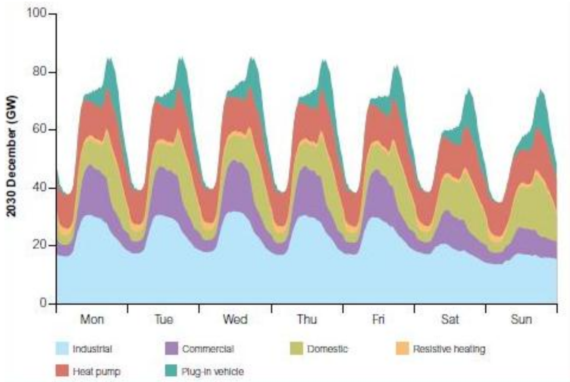

Figure 2 – One week demand profile in 2030[1]

The 2030 demand profile shows an increase in peak electricity demand by more than 70% and a larger variation in demand. Distribution network assets currently have a 40 to 60 year average life and the rate of UK installations reached their peak in the 1960's [3]. Therefore, a large amount of assets in the distribution network are soon due for replacement as they are over 50 years old.

BACKGROUND OF STUDY

Distribution cost contributes to approximately 20% of electricity bills. Under the new RIIO-ED1 electricity price control review commencing in 2015, DNOs will be rewarded for investing in cost effective innovative methods and systems to manage the impact of the changes that are expected in the distribution network. Energy Storage Systems (ESS) can be used as an innovative and alternative investment to mitigate the projected issues that may arise on the distribution network as discussed in [4].

This paper will evaluate the ability of ESS installation in the 11kV distribution network to resolve or mitigate voltage excursions that would occur as a result of increasing and varying demand; reduce power losses and overpower on the network which may lead to operation of network components over their thermal limits. The follow-on effect of this would be an improvement in the operating costs and condition of the network and delaying network upgrades by prolonging the life of the OLTC, transformer, and network cables. The result is aimed at improving network availability and reliability which is one of six outputs in the in the new RIIO-ED1 regulation.

Voltage excursions occur in a distribution network as a result of a change in the demand downstream, change in the supply voltage upstream at the Grid Supply Point (GSP), and varying output from Distributed Generation (DG). This study only covers change in the downstream load. The software package used for analysis assumes a steady state voltage from the GSP hence upstream supply voltage change is not considered.

Under the DNOs Licence Obligation, voltages in the MV network must be kept within 6% above or below the nominal voltage[5]. OLTCs with Automatic Voltage Control (AVC) relays are widely used in distribution networks to maintain the voltage across the network within statutory limits [6]. Voltage regulation is achieved by the OLTC altering the transformer turns ratio on the windings of the transformer. In distribution networks, the OLTC is operated based on set points determined by DNOs from network analysis and planning. Substations are usually set with a narrow bandwidth of +/- 1.75% of the target voltage [7]. This is a conservative way to account for the voltage variation along the feeder that would ensue as a result of changing demand during the day and in different seasons. Repeatedly altering these settings is impractical and may prove expensive and disruptive to customers. Also frequent operation of the tap changer can lead to wear and reduced service life. The OLTC is critical in the reliability of the transformer and is responsible for about 41% of transformer failures[8]. Most OLTCs can operate up to 100000 switches before needing replacement. This study aims to reduce the tap change operations by using ESS to manage voltage on a distribution network. The goal of this tap change reduction is to improve the asset management of the OLTC and transformer for DNOs.

NETWORK

The network under study is located in North Wales. The topology is a variant of a radial network configuration and is split into two parts comprising three and five feeders. The two parts are connected to the GSP via two feeder substations with 7.5 MVA, 33/11kV OLTC transformers. A simplified single line diagram of the network under study is shown in Figure 3. The network has 256 busbars with a total load peak load on the network of approximately 10.7 MW/3.5 MVAr. The share of load between substation A is 59% and substation B is 41%. For this study, the transformer operates based on a target voltage with a fixed bandwidth of +/- 2%. The OLTC has a tap range of 20% in 16 steps of 1.25%.

METHODOLOGY

The method considered in this paper is used to assess the improvements that can be realised by using ESS with or without OLTC operation to mitigate or resolve voltage excursion primarily and then peak shave. Steady state analysis was carried out on the network using IPSA+. IPSA+ uses the fast-decoupled load flow method to compute the voltage drop at each feeder, power flow in all branches and feeders, and the voltage at each bus.

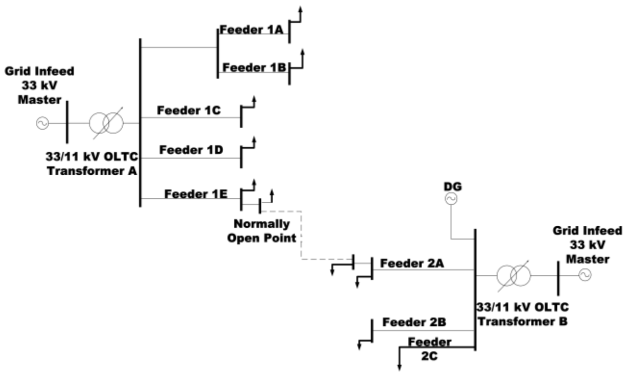

Figure 3 – Assessed UK MV distribution network

One minute load flow simulations were carried out over a week period (10,080 loadflows) for four different seasons. The present demand on the network was assessed along with a 30% and 60% increase in demand, which is the projected demand increase by 2050 [9]. Python scripts were used to automate the load flow and ESS control on the MV network model.

Assessment was made of the impact present and future demand has on the network based on conventional operation of OLTC using automatic voltage regulation (AVR); using an ESS (case 1); and using an ESS coordinated with the OLTC (case 2). The method employed for ESS and OLTC coordination limits the number of tap changing operations by employing ESS to resolve voltage issues. The following steps were carried out:

- Assess the impact of demand increase on the network by considering the number of tap changes, thermal constraints, and voltage excursions.
- Locate the ESS at worse affected busbars and use a control algorithm for the ESS operation to rectify identified problems on the network while limiting tap changing operations.

The ESS in case 2 was used to perform voltage regulation by providing reactive power compensation as shown in Table 1. During peak periods, the ESS is also used to provide real power to reduce peak power flows at the transformer and feeder. The ESS was used to provide voltage regulation by sourcing and sinking reactive power. Although the *X/R* ratio of distribution networks is low, Real Power (*P*) was not used to improve the voltage as it led to thermal excursions on the heavily loaded network. It was found that Reactive Power (*Q*) compensation was more effective in improving the voltage conditions. An overloading limit of 99% for the cables and transformers was evaluated during simulations. Increase in demand by 30% and 60% was considered as an N-1 contingency operation. However, during normal operating conditions, the cables and transformers can have up 25 to 50% of their available capacity in order to be able to provide support during system reconfiguration in the event of an outage on the network.

	Voltage Deviation	Thermal Excursion (Transformer and cables)
Limits	+/- 5.99 %	99%
Control Scheme	*Q* sink, *Q* source, Tap coordination	*P* Source

Table 1 – Assessment limits and ESS control scheme

RESULTS

Overpower was found to be the major problem as the network equipped with OLTCs was robust enough to handle voltage excursions. All busbars close to badly affected branches were tested as possible locations to install the ESS. The ESS was most effective when placed at the substation A busbar and this was the final location used for analysing the ESS effectiveness. From the results obtained, issues with overpower affected transformer A shown in Figure 3.

The base case results were used as the foundation to specify the ESS device. Peak power flows were examined to determine the power and energy requirement for the ESS. ESS with *P* and *Q* ratings of 1, 3 and 5 MW/ MVAr were used for present demand, 30% and 60% demand increase respectively with a 5 MWh energy capacity. The power rating was carefully chosen because a non-optimal rating will lead to thermal excursion during an ESS charge operation. The control would not charge the ESS if this happens and this would lead to a low State of Charge (SoC). This was a main feature in the control algorithm and restricted the amount of peak shaving in both cases utilising ESS. Figure 4 shows the results of using ESS in case 1, and case 2 where tap movement is restricted and the resulting voltage excursions that may occur.

While providing real power for peak shaving, the ESS used in case 1 causes a high amount of switching operations due to the counterproductive effect of the OLTC operation and ESS operation in resolving any voltage events. The OLTC sees a drop or rise in the normal voltage levels caused by the ESS operation as a decrease or increase in demand and taps up or down to resolve the issue. The ESS in case 2 reduces tap changing operations with no voltage excursions as seen in Figure 4 until the 60% demand increase scenario where there is overvoltage. This is especially true in the winter due to the high amount of power supplied by the ESS for peak shaving where approximately 30% reduction of peak power through the transformer was achieved as shown in Figure 5.

At 60% demand increase, the power rating of the ESS needs to be increased to enable adequate reactive power compensation; and the control scheme needs to be optimised to ensure that both peak shaving and reactive power compensation work effectively in unison to prevent voltage excursions.

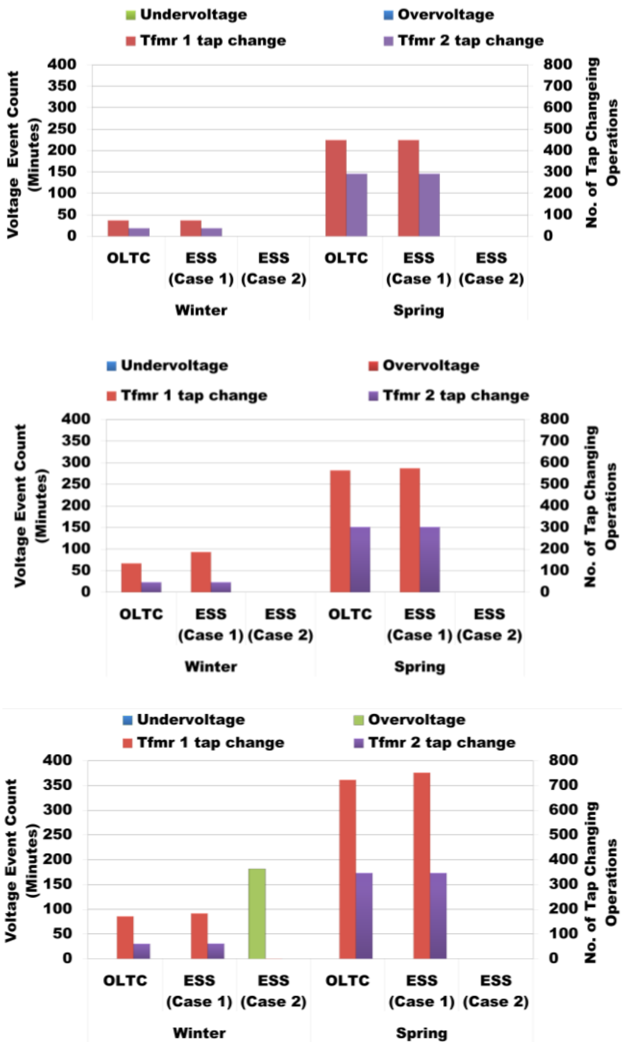

Figure 4 – Voltage events and tap changing operations: present demand (top), 30% increased demand (middle), 60% increased demand (bottom)

The ESS in case 2 is not more effective than ESS in case 1 for peak shaving; this is because the OLTC resolves overvoltage caused by peak shaving in case 1 before the ESS has to act. As the ESS in case 2 has restricted tap movement and Q capacity, overvoltage events occur when recharging or peak shaving. This restricts the amount of time the ESS in case 2 can peak shave. The reactive power loss increases when using the ESS in case 2 by an average of 5.7% and reduces by 2.6% when the ESS in case 1 is used as shown in Figure 6. As the tap movement is restricted, voltage excursions occur when the ESS reaches its limits. This means in resolving overvoltage, the ESS sinks high amounts of reactive power which results in higher reactive power losses. Loss reduction is vital to

DNOs but the two control schemes evaluated were not optimised to reduce real and reactive power losses.

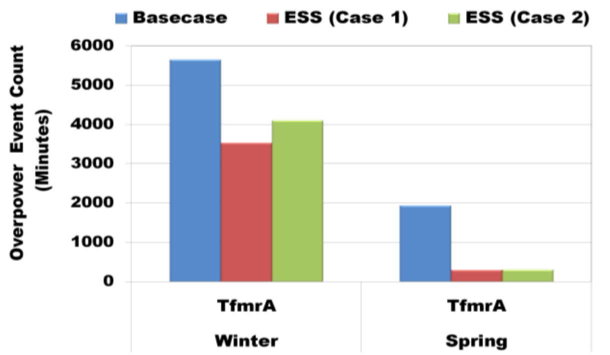

Figure 5 – Transformer peak shaving under 60% increase in demand

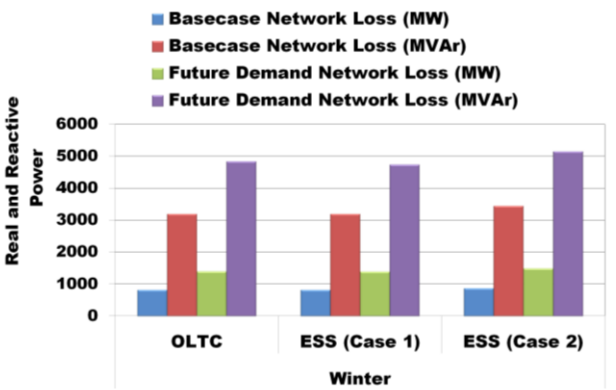

Figure 6 – Real and reactive power loss under present demand and 30% increase in demand

ANALYSIS AND CONCLUSIONS

Increasing demand over the next four decades is a major concern to DNOs. For the Welsh network analysed, under both increasing and more variable demand, voltage excursions were not an issue. However, tap change operation reduction and peak shaving to defer OLTC and transformer upgrade were the main concern. This paper shows the 11kV network can be reinforced with ESS in future to prolong OLTC life and mitigate or resolve thermal excursions. By using the amount of reactive power as the real power used for peak shaving, the ESS with restricted OLTC movement was effective in reducing the tap changing in all scenarios while maintaining the network voltage and peak shaving. The reduction in the frequency of tap changes leads to improved network reliability as increased number of tap changes increases the chances of transformer outages. However, voltage control, by the use of reactive power, is limited by increasing losses and thermal capacity limits. This was a significant issue encountered during this study.

To surmise, a trade-off has to be made on the amount of tap operation reduction required as this would limit the amount of peak shaving the ESS can provide due to overvoltage occurrences. Utilising ESS on a distribution network with high consumer demand can enable upgrade deferral of the tap changer and transformer whilst maintaining voltage levels on the network. However, the power rating and capacity of the ESS is limited by the conductor thermal limits as well as the type of transformer, and the cost of ESS. This was the case in the assessment for the 30% and 60% increase in demand where the ESS reached its limit and was also unable to fully charge due to charging causing further thermal excursions. These factors would need to be considered in future network analysis.

RECOMMENDATIONS FOR FUTURE WORK

This investigation shows that ESS can be used to reduce tap changing operations and resolve voltage and thermal excursions. Further work would be carried out on optimising the control scheme for optimal tap operation and peak shaving, and converting the technical benefits provided into financial benefits for DNOs in the UK. As discussed in [3], it is paramount that the need for investing in ESS along with an efficient design, lifecycle cost, and installation at the appropriate time needs to be established before moving forward with ESS investment.

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