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Investigating the Declining Reactive Power Demand of UK Distribution Networks

Christos G. Kaloudas

Luis F. Ochoa

The University of Manchester,
Manchester UK

christos.kaloudas@manchester.ac.uk

luis_ochoa@ieee.org

Ian Fletcher

Northern Powergrid,
Newcastle, UK

Ben Marshall

National Grid,
Warwick, UK

Shanti Majithia

Energy & Climate
Adv. Services
Berkshire, UK

Abstract— The significant decline of reactive power (Q) demand in the UK is considered one of the factors that led in 2011 to over-voltages in the 400kV network. To examine this, a distribution network known to have this decline is modelled in detail (from the transmission interface, 132kV, to 33kV) and validated using monitoring data. In particular, the effects from replacing overhead lines with cables as well as P and Q demand trends (at primary substations) on Q exchanges at the GSP are investigated. Results for this particular distribution network show that high cable penetrations in 132kV circuits lead, during minimum demand, to Q gains many times larger than its 2013 level. In addition, the identified P and Q demand trends at primary substations highlight the future larger Q injections through the transmission interface. These findings can be used to coordinate operational and planning actions between networks operators.

Index Terms—cable penetration, demand trends, distribution networks, reactive power.

I. INTRODUCTION

National Grid, the Transmission System Operator (TSO) in the UK, has reported over 160 voltage excursions in the 400kV transmission grid across Great Britain from 2011 to 2012 [1]. This is a significant number compared to only one reported from 2007 to 2010. Typically, factors that lead to higher voltage levels are related to transmission asset design, the variable loading of the network, and the exchanges of reactive power between transmission and distribution.

An initial investigation on the total active (P) and reactive power (Q) demand of UK distribution networks has revealed a significant decline in Q/P ratios at their interface with the transmission system during periods of minimum load and indeed across other time periods. Specifically, from 2005 to 2013 the decline of P during minimum load decreased nationwide from 22 to 18GW, whereas the corresponding decline in Q was more significant, from 7.5 to 2.1GVAR [2].

In the UK, Grid Supply Points (GSPs) are the interface between transmission and distribution networks (typically 400/132kV and 275/132kV). Since 2010, many GSPs have

shown a capacitive behavior (i.e., injecting Q) during minimum load whilst in previous years they were clearly inductive [3]. The identification of the most critical GSPs in terms of Q/P decline was carried out in [3] considering all the 336 GSPs across Great Britain.

Understanding the decline trends in Q demand is critical for the UK TSO to schedule cost-effective measures and tasks for network planning and voltage control. This is also important for Distribution Network Operators (DNOs) given that they could also face voltage containment challenges. In addition, DNOs in Europe would further be required to comply with the forthcoming European Demand Connection Code (EDCC) [4], which, recognizing this is an international trend in demand, has been proposed to address this issue. According to the EDCC, MVar exchanges from distribution to transmission will not be allowed when demand is lower than the 25% of the maximum capacity of the interface. Additionally, the implementation guide of the EDCC allows TSOs, in certain circumstances, to specify MVar exchanges across existing interface sites.

In this work, the distribution network corresponding to one critical GSP located in the North of England is analyzed in detail. In particular, the effects from replacing overhead lines with cables as well as P and Q demand trends (at primary substations) on Q exchanges at the GSP are investigated.

This paper is structured as follows: Section II presents the process by which the network model is validated using half-hourly P and Q monitoring data for years 2012 and 2013. In section III, the effects of cable penetrations in 132 to 33kV circuits are investigated by carrying out a sensitivity analysis per voltage level, as well as considering possible mixes across voltages. The effects of demand trends at primary substations (typically 33/11kV) are quantified in section IV considering a seasonal linear regression analysis of the monitoring data from 2012 to 2013. Conclusions are drawn in section V.

II. NETWORK MODELLING

This section presents the network modeling process for the examined GSP using monitoring data. The proposed approach

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improves network model currently used by DNOs in order to mimic the actual network behavior, particularly at times during minimum demand.

A. GSP Under Study

The system under study is a large distribution network in the North of England that extends from the low voltage side of the GSP transformers (132kV) to the low voltage side of primary substations (typically 33/11kV). The network analyzed in this work is shown in Figure 1.

The total line lengths of 132, 66 and 33 kV circuits in this network are 180, 78 and 325 km, respectively. The network is modeled in OpenDSS [5] using technical data, operational aspects (e.g., OLTC voltage targets), and half-hourly P and Q monitoring data, all provided by the UK DNO Northern Powergrid. As shown in Figure 1, the monitoring points are at the low voltage side of transformers in the GSP, the Bulk Supply Points (BSPs – typically 132/33kV) and primary substations. Table I presents the voltages and ratings of the transformers installed in all BSPs of the examined network. The available monitoring data are for 2012 and 2013 and correspond to 7 of the 9 BSPs and 31 of the 39 primary substations of this GSP group. Consequently, load and generation profiles have to be created for those locations without monitoring data.

B. Matching Network Models and Measurements

Studies performed by DNOs traditionally focus on peak loading conditions. Consequently, the use of line susceptance values or the need to accurately calculate Q flows at the GSPs during minimum load might not be of importance to them. However, in this work it is crucial to produce network models that can adequately mimic the network behavior, particularly at the interface with transmission. The network models for the examined GSP are produced using monitoring data to improve the models in critical days (within critical weeks when low Q/P ratios are identified at GSPs across Great Britain [3]).

First, time-series simulations with the original network model are carried out using the available half-hourly monitoring data for one critical day. The mismatch of daily P profiles between monitoring data and simulation results ($P_{mismatch}$) are then calculated at the GSP and all BSPs. The unknown k -th load and m -th DG profiles are allocated taking into account the $P_{mismatch}$ at the GSP and all BSPs using the following equations:

$$P_{DG,m} = \frac{-S_{DG,m}}{\sum_{i=1}^n S_{load,i}} \cdot P_{mismatch} \quad (1)$$

$$P_{load,k} = \frac{S_{load,k} \left(1 + \frac{\sum_{i=1}^n S_{DG,m}}{\sum_{i=1}^n S_{load,i}} \right)}{\sum_{i=1}^n S_{load,i}} \cdot P_{mismatch} \quad (2)$$

where S_{load} , S_{DG} are the nominal capacities in MVA for load dominated substations and DG units with unknown profiles, respectively.

Figure 1. GSP under study.

Figure 2. Allocated load and DG profiles for BSP #1

TABLE I. SUBSTATIONS FED BY 132 kV

Substation	$V_{transformer}$ (kV)	$S_{transformer}$ (MVA)
BSP #1	2x(132/66)	2x150
BSP #2	2x(132/33)	2x90
BSP #3	2x(132/33)	2x90
BSP #4	2x(132/33)	2x90
BSP #5	2x(132/33)	2x60
BSP #6	1x(132/33)	1x90
BSP #7	2x(132/25)	2x18
BSP #8	2x(132/11)	2x30
BSP #9	2x(132/6.6)	2x30

The load allocation process is demonstrated in Figure 2. for the 28th May 2012 (1st day of critical week 22 [3]). The average power losses in this day are 0.67% of the monitored daily P profile at GSP (taken into account by the $P_{mismatch}$). The allocated load of 2 relatively large primary substations of the same size and the generation of one DG unit are shown in this diagram for BSP #1 (with most unknown profiles). The final mismatches from this allocation process are shown in Figure 3. for 3 BSPs and the GSP (average errors from 0.1 to 1.2%).

Next, using the network model from the previous step, is to examine the mismatch of simulated Q exchanges ($Q_{mismatch}$) at the GSP with the corresponding monitoring data for the same day. Figure 4. shows the significant $Q_{mismatch}$. It is noteworthy that the calculated Q profile does not exhibit

Figure 3. Final P profiles at the GSP and 3 BSPs (28th May 2012).

negative values (injection of Q upstream), whereas they do exist in the monitoring data during periods of minimum load (0 am to 8 am and 11 pm to 12 pm).

To identify the reasons for the $Q_{mismatch}$, first the Q demand of the primary substations without monitoring data is estimated. Two DG units (>10 MW each) are connected to these primary substations and their combined operation can inject up to 0.5 MVar (close to unity power factor operation, common in the UK). The other substations are small with no significant DG. Therefore, they are expected to have inductive behaviors similar to that of their corresponding BSPs. Consequently, the behavior of the primary substations with unknown load and DG data is likely to have limited or no effect on the Q exchanges at the GSP.

Based on the above and the fact that UK DNOs do not typically use reactive power compensation downstream GSPs, attention should be paid on the line susceptances of the original network model as they could play a significant role due to Q gains during minimum load. Indeed, line susceptance values were not available in the original model for 33kV and 66kV circuits neither the proportion of overhead lines and cables. Therefore, it is important to analyze different cable penetrations across voltages to minimize the $Q_{mismatch}$.

It is important to highlight that the identification of cable penetration from 33 to 132kV circuits cannot be carried out per BSP because 132kV circuits are likely to have a significant effect on Q exchanges at GSP. Consequently, a uniform cable penetration across all voltage levels is considered. Typical per unit length susceptance values for overhead lines and cables (different per voltage level) are used in a parametric analysis that aims to estimate the cable penetration.

Figure 4. shows daily Q profiles at the GSP corresponding to monitoring data and simulation results (for different levels of cable penetration). For example, a 20% cable penetration means that every line is assumed to have cable susceptances for 20% of its length. The other 80% corresponds to an overhead line. Assuming three different cases of 20, 30 and 40% cable penetration, the best mismatch between monitoring data and simulation results is achieved with the 30% case.

The same process is carried out to other critical days (that

Figure 4. Q profiles at the GSP (28th May 2012).

Figure 5. Q profiles at the GSP: a) 28th May; and, b) 18th June 2013.

can be in different years). Figure 5 shows the simulation results for the 28th May and 18th June 2013 (1st day of critical week 25) [3]. A 30% cable penetration leads, again, to a more satisfactory mismatch (average errors from 25 to 32%). This is in agreement with the fact that not significant network changes were carried out in this period.

The improved network model, including allocated load and generation profiles, can at this stage be considered as a validated model, i.e., mimicking real-life behavior. Now, it is possible to carry out different studies to further understand the effects of future changes in this network on Q exchanges.

III. EFFECTS OF CABLE PENETRATION

The effect that the future replacement of overhead lines with power cables has on Q exchanges at the GSP is investigated in this section. Different cable penetrations per voltage level are considered using the improved network model on 18th June 2013.

First, the cable penetration is increased towards 100% independently for 33, 66 and 132kV circuits. For example, a 100% cable penetration in 33kV circuits means that all 66 and 132kV lines still remain with the cable penetration found for the improved model (30%).

Figure 6. shows the maximum daily Q exchanges at the GSP (Q injections upstream) for different cable penetrations per voltage level (occurring at 6:00am, Figure 5b). The

Figure 6. Q exchanges at the GSP for different cable penetration levels.

Figure 7. Q exchanges at the GSP for different cable penetrations: a) 40% in 132kV, b) 60% in 132kV, c) 80% in 132kV and d) 100% in 132kV.

exchanges due to cable penetrations in 132kV circuits can be many times higher than the original 2013 level (20 MVar capacitive). On the other hand, the increase in the exchanges at the GSP from 30 to 100% cable penetration in 33 and 66kV circuits is much lower, specifically around 16 and 9 MVar, respectively. Consequently, for the studied GSP, the voltage level with the largest overall effect on the Q exchanges is 132kV. It is important to highlight that the noticeable linear behavior of the increase in the Q exchanges at the GSP with cable penetration is due to the fact that voltage profiles remain practically the same in all cases due to the specified voltage targets at GSP, BSP and primary substations and available tap headroom.

Given that overhead lines can in practice be replaced by cables across voltages, different mixes should also be investigated. Specifically, starting from 40 to 100% cable penetrations, all possible mixes of overhead lines and power cables are taken into account using 20% steps. Figure 7. shows the corresponding results for the daily maximum Q exchanges at the GSP. It is noteworthy that any combination of cable penetrations for 33 and 66kV circuits result, at most, in an extra Q injection of 23 MVar at the GSP, i.e., doubling the original value. Additionally, for any of these combinations, a further 20% cable penetration in 132kV (i.e., 50% cables, 50% overhead lines) could lead to extra 30 MVar of Q injection. This analysis suggests that, similarly to the previous one, the

effects of high cable penetrations in 33 and 66kV are relatively small when compared to the 132kV circuits.

IV. EFFECTS OF DEMAND TRENDS AT PRIMARY SUBSTATIONS

In this section the effects of demand trends at primary substations on Q exchanges at the GSP are investigated. Network changes, more efficient loads or DG penetration downstream primary substations are among the factors that can affect their aggregated P and Q demand. Here, monitoring data at primary substations are used to identify the aggregated P and Q demand trends during minimum load from 2012 to 2013. The identified trend is considered together with other scenarios to assess future Q exchanges at the GSP.

The existing demand trends at primary substations can be identified using the available monitoring data for the examined network. Figure 8. shows the linear fitting (red line) of the daily minimum P, Q for minimum P and Q/P ratios for minimum P (blue dots) that correspond to all May to July days in 2012 and 2013. The P, Q and Q/P ratio values are calculated using the aggregated half-hourly P and Q monitoring data of 30 primary substations in the examined network. Linear fitting results show yearly declines of 2, 9.1 and 7.3% for the minimum P and Q during minimum demand, as well as the corresponding Q/P ratio, respectively.

The identified linear decline trend (business as usual) and two other trends ($\pm 50\%$ of the identified trend) for P and Q demand during minimum demand are presented in Figure 9. for a horizon of 10 years. In year 0 (corresponding to 18th June 2013) the aggregated Q demand of the primary substations is 30.7 MVar and decreases yearly by 2.8 MVar considering the identified trend. The yearly changes for the -50 and +50% trends are 1.4 and 4.2 MVar, respectively. Even for a mid-term horizon of 5 years it is noteworthy that the business as usual trend leads to an aggregated Q demand at primary substations of nearly a half (54%) of that at year 0. It is also evident from Figure 9 that only the worst case scenario (+50% trend) leads to an aggregated capacitive Q demand at primary substations but this could happen at year 8.

To quantify the Q exchanges at the GSP within the same horizon of 10 years, the three trends considered above are used in simulations with the improved network model (18th June 2013). Figure 10. shows the Q demand at the GSP for a horizon of 10 years. The Q demand at the GSP exhibits a yearly decrease of 4.2 MVar (21% of the 2013 level) for the business as usual trend. The yearly decreases for the -50 and +50% trends are 2.1 MVar and 6.3 MVar, respectively. A comparison between Figure 9 and Figure 10 shows that in all three trends a 1 MVar decrease in the aggregated Q demand at primary substations results in 1.5 MVar decrease in the Q demand at the GSP. This highlights that any potential solution that can be found to tackle the Q demand trends at primary substations can have a larger positive effect at the GSP.

The results of Figure 10. suggest that the continuation of 2012-2013 demand trends at primary substations can lead in a mid-term horizon of 5 years to double Q exchanges at the GSP from the original 2013 level. Even with a slower pace towards less inductive loadings at primary substations (-50% trend),

the Q demand at the GSP could be reduced within the same 5 years interval by 50% of that of year 0.

Figure 8. Linear trends of aggregated demand at primary substations for May to July in 2012 and 2013 for: a) minimum daily P b) Q for minimum daily P; and, c) Q/P ratios for minimum daily P.

Figure 9. Decline trends for the aggregated Q primary demand.

Figure 10. Q exchanges at GSP for different primary demand decline trends.

The above analyses demonstrate the importance of quantifying Q trends as this can help understanding the extent of voltage containment challenges within both transmission and distribution networks.

V. CONCLUSIONS

In this work the declining nature of reactive power (Q) demand in UK distribution networks was investigated given

that it is considered one of the factors that led in 2011 to over-voltages in the 400kV network. For this purpose, a large distribution network in the North of England that is known to exhibit capacitive Q exchanges at the Grid Supply Point (GSP, interface between transmission and distribution) was modeled considering 2012-2013 monitoring data from the GSP (132kV) to primary substations (typically 33/11kV). The effects from the replacements of overhead lines with cables and from the demand trends at primary substations on the Q exchanges at the GSP were examined.

Results for the studied distribution network show that cable penetration in 132kV circuits can lead to multiple times higher Q exchanges at the GSP than the original 2013 level, whereas the effects of cable penetration in 33 and 66kV are relatively smaller. This highlights that, if possible, planned replacements of overhead lines by cable should also consider solutions to tackle the corresponding reactive power gains.

Results based on the identified declining trends for the aggregated P and Q demand at primary substations of the studied network, show that the continuation of the identified demand trends at the primary substations can lead in a mid-term horizon of 5 years to double the capacitive Q exchanges at the GSP from the original 2013 level. Results also show that a 1 MVar decrease in the aggregated Q demand of primary substations leads to a 1.5 MVar decrease seen by the GSP. This highlights that any potential solution that can be found to tackle the Q demand trends at primary substations can have a larger positive effect at the GSP.

The findings of this work can be used by transmission and distribution network operators to coordinate their planning and operational actions and have a better understanding of the corresponding interactions. From a European perspective, this work also allows a better insight into the future challenges to comply with the forthcoming European Demand Connection Code that requires limited Q exchanges at the GSP.

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