LONG-TERM FORECASTING OF REACTIVE POWER DEMAND IN DISTRIBUTION NETWORKS

Christos KALOUDAS
Electricity North West Ltd – UK
christos.kaloudas@enwl.co.uk

Rita SHAW
Electricity North West Ltd - UK
rita.shaw@enwl.co.uk

ABSTRACT

The declining reactive power demand seen at transmission-distribution interfaces in the UK and other European countries during periods of minimum load is considered as one of the factors posing new challenges mainly to transmission to maintain statutory voltage levels. This paper proposes a scenario methodology that uses distribution-based monitoring and network data to assess future trends in reactive power demand from the interface with transmission down to primary substations. Following the proposed approach, the significant effects of the interactions between the demand at primary substations and the upstream networks on the overall reactive power demand of distribution networks can be quantified. The implementation of the methodology is demonstrated using simple trends in underlying demand in time-series modelling of all 132 to 33kV networks in the North West of England operated by a UK distribution network operator. This methodology can be used by network planners to use potential future views of reactive power demand in impact analyses and take cost-efficient measures to tackle any issues deriving from these trends.

INTRODUCTION

An acute decline in reactive power (Q) demand during periods of minimum load has been identified within the last decade across Great Britain [1] and other European countries [2]. The declining Q demand is leading to challenges in containing statutory voltage limits on transmission and distribution networks, raising the prospect of new technical and regulatory requirements triggered by transmission-distribution (T-D) interactions [3]. Distribution-based factors, such as changes in demand at primary substations (primaries – typically 33/11 or 6.6kV in UK) and changes in distributed generation, are the critical parameters that determine Q demand trends at Grid Supply Points (GSPs – the UK T-D interfaces) and the associated T-D interactions. Therefore, it should be highlighted that Distribution System Operators (DSOs) can potentially be in a better position than transmission operators to further analyse and more accurately assess future Q demand at T-D interfaces.

Despite the fact that there are many works in the literature on the long-term forecasting of active power (P) demand in electricity grids [4]-[5], there has been limited research in Q demand. Some recent studies in other European countries have highlighted the forthcoming challenges from Q exchanges at T-D interfaces during periods of minimum load. Nonetheless, these works have mostly focused on solutions rather than long-term forecasting [2], [6].

Between 2013 and 2015 the REACT project [1], a collaboration between the University of Manchester and all British transmission and distribution network operators (DNOs), is possibly the only major recent research work that focused on a) the understanding of factors influencing Q demand in distribution networks; and, b) the assessment of future trends of Q demand at T-D interfaces. Analyses carried out in REACT across all British Distribution Network Operators (DNOs) using time-series network modelling from selected Grid Supply Points (GSPs – the T-D interface in UK) down to primary substations revealed the importance of network assets in the assessment of future Q demand. Indeed, the interactions of the declining measured active power (P) and Q demand (i.e., mix of underlying demand and generation) during periods of minimum load with network elements was found to be leading to significant reductions in the overall Q demand of distribution networks.

This paper presents a scenario-based methodology for the long-term forecasting of Q demand at T-D interfaces and at substations down to primaries. This work is part of the Architecture of Tools for Load Scenarios (ATLAS) project at Electricity North West Ltd [7]. The proposed methodology extends the approach of the REACT project by including:

- scenario assumptions for P and Q which reflect the scale and power factor of demand from Low Carbon Technologies (LCTs) and efficiency measures within domestic and non-domestic underlying demand;
- the effects of Distributed Generation (DG) units considering power factor assumptions, as well as the effects from cable circuits connecting DG units downstream primary substations; and,
- the use of historical Q/P ratio trends in the underlying true demand (i.e., loads), instead of Q/P trends in measured demand.

The implementation of this methodology is also demonstrated in this work using simple future trends of the primary demand in time-series network modelling to take into account the effects of distribution networks on Q demand at T-D interfaces. More specifically, the time-series analyses consider operational aspects (e.g., substation voltage targets) using a planning model of all 132 to 33kV networks in the North West of England operated by Electricity North West Ltd.

METHODOLOGY

This section describes the proposed methodology developed in the ATLAS project for the long-term forecasting of reactive power demand at the T-D interfaces and substations down to primaries (i.e., normally the last point of available monitoring data to the DSO/DNOs). The typical configuration of UK distribution networks down to primary substations is shown in Fig. 1.

It should be noted that the proposed approach:

- uses scenarios and considers long-term horizons, thus aiming to present potential views of the future rather than a single accurate estimation of reactive demand;
- considers the assessment of future measured Q demand of GSPs, Bulk Supply Point (BSP – typically 133/32kV) and primary substations as shown in Fig. 1;
- focuses on both periods of peak and minimum demand;
- takes into account the periodic variations and trends of demand (e.g., seasonal, monthly, daily); and,
- uses half-hourly averaged resolution in demand data and associated analyses.

The overview of the proposed Q forecasting methodology is shown in Fig. 2. It is evident in this figure that the assessment at GSP and BSP substations can be done only after obtaining the corresponding scenario results of the associated primary substations. Thus, scenario results from a P forecasting tool need to be used as inputs for the Q forecasting, showing the strong dependence of future Q demand on future P.

Inputs

The inputs to the Q demand forecasting methodology are:

- the historical 'processed' time-series (e.g., half-hourly) true (i.e., underlying) P and Q demand data of primary substations;
- scenario results for future true P demand and latent P demand (generation) at primary substations;
- assumptions for the Q effect of changes in the constituent types of true and latent P demand, and,
- network data from T-D interfaces to primary substations.

'Processed' time-series data correspond to monitoring data that has been properly adjusted for being erroneous, missing or not representative of system normal demand.

In ATLAS a methodology and prototype tool have been developed to achieve this [8]. Scenario results for true and latent P demand also need to be fed as inputs for the Q demand forecasting. In the ATLAS project this is done using a combination of internal and external consultancy resources. A prototype tool has been already produced for scenario results for true demand. This true demand model

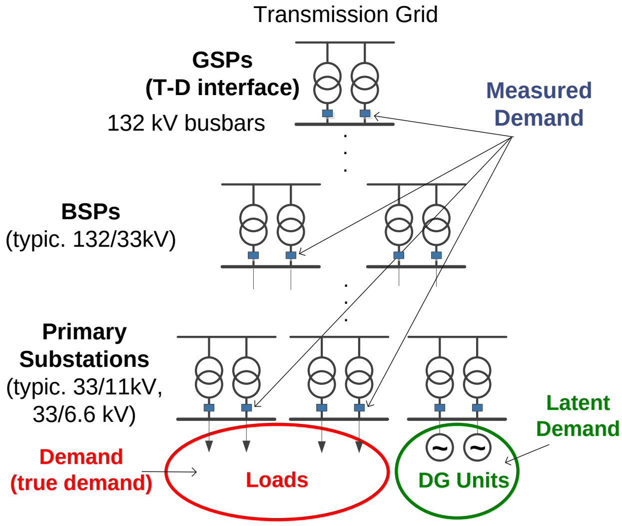

Fig. 1. Typical configuration of UK distribution networks.

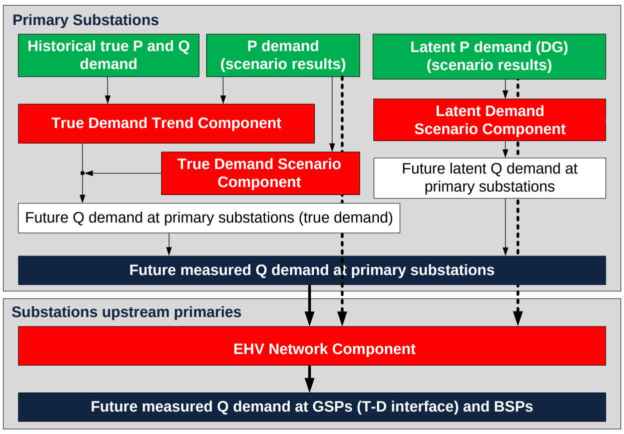

Fig. 2. The proposed methodology for the long-term forecasting of reactive power demand.

includes:

- the effects of Low Carbon Technologies (LCTs – i.e., heat pumps and e-vehicles) and new demand from air conditioning using appropriate half-hourly profile data and maintaining half-hourly resolution in scenario results as well;
- the use of data indicating domestic and non-domestic customers down to post code sectors; and,
- projections of econometric and demographic data tailored to different local authorities within the North West of England.

This P forecasting tool is currently being updated to produce scenario results for latent P demand, i.e. the amount of demand suppressed by DG. This is particularly important for Q forecasting, given that increased DG penetrations can lead to lightly loaded 132 to 33kV lines and thus increased Q gains from these circuits.

Components

The proposed methodology for Q demand forecasting has a modular structure that consists of four components, which are:

1. the True Demand Trend Q component;
2. the True Demand Scenario Q component;
3. the Latent Demand Scenario Q component; and,
4. the Extra High Voltage (EHV) Network component.

The first three of the above mentioned components are used for the assessment of future Q demand at primary substations for the different scenarios. These scenario results are then used together with the associated future true and latent P demand at primary substations as inputs to the fourth component, for the forecasting of Q demand at substations at higher voltage levels.

True Demand Trend Q Component

This component uses as inputs the scenario results of future true P demand at primary substations, combined with trends derived from the historical true P and Q demand data (i.e., in Electricity North West for the last five years). The identification of historical half-hourly true demand data can be a challenging task for distribution operators. In ATLAS all available monitoring data for DG units have been used together with estimates of the non-monitored generation per half-hour to identify the true demand per primary substation [8]. The monitored demand data are used to identify the historical Q/P ratio trends of true demand. This process requires:

- investigations for different fitting approximations (e.g., linear, exponential);
- individual analyses for periods of peak and minimum P demand;
- investigations for different periodicities (e.g., seasonally, per month etc); and,
- justification of identified historical trends based on error analyses and visual sense checks for the different fitting approximations and periodicities.

The historical Q/P ratio trends (i.e., seasonally and for periods of peak and minimum load) can then be considered for the different scenarios to continue with the same/ faster/ slower pace into the future. These trends are combined with the scenario results of true P demand to derive the associated scenario results of the future background Q demand. The obtained true Q demand trend per scenario is one of the two variables needed to assess the future true Q demand at primary substations. The other one is the output of the Reactive Power (Q) True Demand Scenario component, which is described in the following subsection.

True Demand Scenario Q Component

Efficiency measures taken by domestic and non-domestic customers are expected to affect the Q demand levels. Some practical examples of this trend are:

- the replacement of old lighting devices with inductive power factor (PF) with new ones with unity or even capacitive PF;
- the extensive use of inverter driven motors with closer to unity PF values (e.g., inverter driven air conditioners, as well as industrial or e-vehicle motors); and,
- the use of eco friendly appliances by domestic customers.

The future effects of the above mentioned factors on true Q demand at primary substations, above the historic trend already captured in the True Demand Trend component, are modelled in the Q Demand Scenario component. Given the uncertainties around future trends in factors downstream of primary substations affecting true Q demand, scenario assumptions around the PF of LCTs, new technologies and efficiency measures should be used to capture the associated effects. The scenario-based PF assumptions can then be combined with the P scenario results to estimate the associated effects on future Q demand at primary substations. The outputs of the True Demand Scenario and the True Demand Trend components are next combined to obtain the future true Q demand of the examined primary substation.

Latent Demand Scenario Q Component

The effects of DG units connected downstream of primary substations on the Q demand are quantified in the Latent Demand Scenario component. The Latent Demand Scenario component uses the latent P demand scenario results to:

- estimate the future Q demand of DG units taking into account scenario-based a) future penetrations of different types of DG (i.e., scenario results for latent P demand); and, b) potential requirements for PF settings (e.g., set by DSOs) for existing and/or new DG; and,
- estimate the Q gains from long HV cables connecting PV and wind farms (e.g., lightly loaded cables during early morning hours connecting PV).

The output of the Latent Demand Scenario component can then be added to the existing latent demand (i.e., monitored and estimated non-monitored) to assess for every scenario the future latent Q demand of primary substations. The measured Q demand of primary substations can then be forecasted as the combination of the scenario results of true and latent Q demand, together with any potential scenario assumptions for the penetration of shunt-reactors and/or capacitors in HV and LV networks, as shown in Fig. 2.

EHV Network Component

Scenario results of measured Q demand of primary substations produced from all three above mentioned components are then used for the forecasting of Q demand at substations operating at higher voltage levels. The EHV Network component (132 to 33kV in England) requires the use of:

a) the scenario results of both P and Q demand at primary substations;
b) data about the networks between the T-D interface and primary substations (i.e., EHV network);
c) historical data and future trends of large non-domestic customers and/or DG units connected upstream primary substations (i.e., at 33kV or above in the UK).

These data and scenario results/assumptions can be used to assess the future trends of measured Q demand at GSPs (typically 400 or 275/132kV) and BSPs (typically 132/33kV). Results are demonstrated in this paper considering a detailed time-series network modelling approach. This approach is more complex than using an empirical rule (i.e., recommendation of REACT project) - a method also investigated in ATLAS - but can provide more accurate results regarding the effects of networks on overall Q demand.

Outputs

The outputs of the proposed methodology are the measured Q demand at substations from the T-D interface down to primary substations, as shown in Fig. 2. These outputs are half-hourly scenario results of Q demand.

ASSESSMENT OF FUTURE Q DEMAND AT THE INTERFACE WITH TRANSMISSION

This section focuses on the forecasting of Q demand at T-D interfaces. As shown in Fig. 2 of the proposed methodology, the future P and Q demand at primary substations need to be fed to the EHV Network component to assess the future trends of Q demand at the interface with transmission for the different scenarios.

Fig. 3 shows the implementation of the proposed methodology in the ATLAS project to assess future trends of Q demand at T-D interfaces using time-series network modelling. The available half-hourly SCADA and metering data for P and Q demand at primary substations and DG units are first used together with estimates of non-monitored generation to obtain the processed *true* P and Q demand of primary substations [8]. This data is then used as input to the P demand forecasting tool. As described in the proposed methodology, the forecasted P at primary substations is then used to forecast the corresponding Q. Scenario results for future P and Q demand at primary substations, together with a) data for large generators and non-domestic customers; and b) modelling assumptions (e.g., allocated profiles for primaries without available data) are then fed into the IPSA-Python tool, as shown in Fig. 3. This is a prototype tool (i.e., Python scripts) that uses the half-hourly scenario data in time-series power flows using the EHV network planning models of Electricity North West. These are models in IPSA software that consider all associated operational aspects (e.g., substation voltage targets, tapping time delays of on-load tap changers). It should be noted that the total length of 132 and 33kV circuits modelled in these networks is

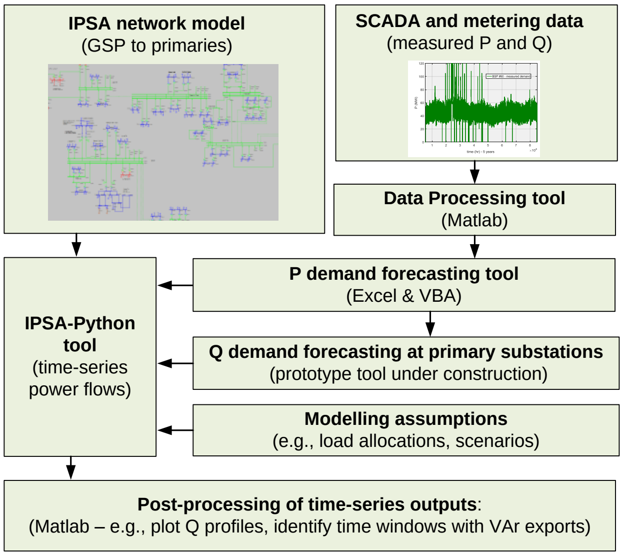

Fig. 3. The implementation of the proposed methodology to assess future Q demand at T-D interfaces.

over 5,300km; around 60% of this length corresponds to underground cables which can lead to significant Q gains during periods of minimum load. Conversely, there are in total circa 500 GSP, BSP and primary substations where VArs are absorbed at the transformers. Adequate modelling of both factors is crucial factor to assess Q demand at T-D interfaces.

Fig. 4 and 5 overleaf show results of time-series analyses for the following future trends in the demand of primary substations, as a % of year 0:

- Case 1: per year reduction of both P and Q at primaries by 1 %;
- Case 2: per year reduction of P by 1% and Q by 2%;
- Case 3: per year reduction of only Q by 2%; and,
- Case 4: per year reduction of only P by 2%.

It should be highlighted that the trends considered for the parametric analysis of Cases 1 to 4 do not correspond to historic or forecast demand trends at primary substations. They are only used to demonstrate the effects of the networks upstream of primaries on overall Q demand at GSPs (T-D interfaces). Simulation results have been obtained using half-hourly demand data (i.e., measured P and Q at primary substations, large generators and large non-domestic customers connected at 132 and 33kV) in time-series analyses for the first week of April 2016 (7 days). This week corresponds to a traditional period of minimum demand. Nonetheless, the results presented aim to highlight the advantages of time-series modelling in the proposed methodology. Network planners should carry out similar analyses for different periods of the year to identify seasonal future Q demand trends across substations.

Fig. 4 shows for cases 1 to 4 the % increase of the maximum VAr exports to transmission for the whole Electricity North West license area (over 4 GW peak

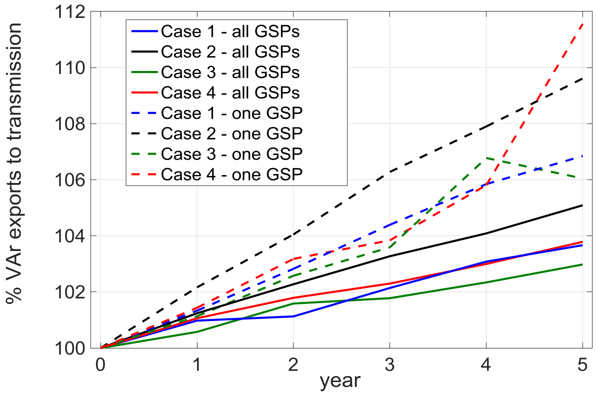

Fig. 4. Simulation results for future increase in Q exports to transmission relative to the first week of April 2016.

Fig. 5. Simulation results for the proportion of time of Q exports to transmission for all GSPs in April 2016 and after 5 years of chosen trends at primary substations.

demand in 2016) and for one large GSP in an urban area (i.e., ~500 MW peak demand in 2016), respectively. Results for the whole area (18 GSPs) in solid lines correspond to maximum VAr exports to transmission at a time that is not coincident with the time that individual GPSs exhibit their maximum VAr exports (dashed lines). Comparing case 4 (primary P decline only) with case 3 (primary Q decline only) highlights that declines in either P or Q at primary substations can lead to increased Q exports to transmission. Comparison between cases 1 and 2 shows that declining Q/P ratios (case 2) for the same reduction in P demand at primaries can lead to higher VAr exports to transmission.

Fig. 5 shows the proportion of time that GSPs belonging to Electricity North West would be expected to export VArs to the transmission network. Simulation results for year 0 correspond to the first week of April 2016, whereas cases 1 to 4 correspond to year 5. It is noteworthy that the proportion of time that GSPs are exporting VArs to transmission increase in all cases from 56% in year 0 up to over 60% for case 2 and could pose additional challenges to the transmission operator to maintain statutory voltage levels. These results highlight that the use of time-series analyses can facilitate the investigation of time-based solutions (i.e., during periods of increased Q exports) by both transmission and distribution network planners.

CONCLUSIONS

This paper proposes a methodology for the long-term forecasting of reactive power in distribution networks using scenario assumptions and distribution-based monitoring and network data. Following this approach, future Q demand at substations up to T-D interfaces is assessed taking into account trends in underlying demand and generation, as well as the corresponding interactions with network assets. To demonstrate the benefits from the use of time-series network modelling as part of the proposed methodology, future Q exports at individual and aggregated T-D interfaces and the proportion of time for these exports are quantified. This considered the whole 132 to 33kV network belonging to a UK DNO. This methodology can be used by distribution network planners to identify future trends in Q demand at the T-D interfaces and substations down to primaries. The associated scenario results should not only be used to analyse the associated impacts (e.g., effects on voltages) in distribution networks, but also to investigate potential solutions to limit Q exchanges at T-D interfaces.

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