Title: **Deliverable 5. Second Year Final Report Stage 2 - REACT Project**

Synopsis: This document is the final report on the REACT project. A framework is proposed to assess future reactive demand at any GSP and future trends in reactive demand are presented for GSPs across all DNOs. An initial techno-economical assessment using shunt reactors is also presented and the considerations for future studies are discussed.

Document ID: UoM-REACT_Project_Deliverable5_v04

Date: 11th August 2015

Prepared For: REACT Project Members
National Grid, ENWL, NP, UKPN, WPD, SSE, and SPEN

Prepared By: Dr Christos Kaloudas
The University of Manchester
Sackville Street, Manchester M13 9PL, UK

Revised By: Dr Luis (Nando) Ochoa, The University of Manchester

Shanti Majithia, Energy and Climate Advisory Services

Benjamin Marshall, National Grid

Contacts: Dr Luis(Nando) Ochoa
+44 (0)161 306 4819
luis.ochoa@manchester.ac.uk

Dr Christos Kaloudas
+44 (0)161 306 4767
christos.kaloudas@manchester.ac.uk

Executive Summary

This report corresponds to Deliverable 5 "Second Year Final Report Stage 2" part of the "Reactive Power Exchange Assessment and Characterisation (REACT)" Project funded by National Grid and the six Distribution Network Operators (DNOs) in Great Britain: Electricity North West Limited (ENWL), Northern Powergrid (NP), Scottish Power Energy Networks (SPEN), Scottish and Southern Energy (SSE), UK Power Networks (UKPN) and Western Power Distribution (WPD). This project is financially managed by Energy Networks Association (ENA).

The REACT Project has been established to understand the reasons behind the decline in reactive power demand as seen by National Grid during minimum load. This will allow DNOs and National Grid establishing future trends in the reactive power exchanges at Grid Supply Points (GSPs) and adopt the most cost-effective actions as well as responsibilities for ongoing data provision, planning, design, and operational management in this area.

In particular, this report presents:

- the proposed framework and the corresponding methodology that can be used by any DNO to assess future Q demand at any of their GSPs;
- the results of the scenario-based assessment of future Q demand at GSPs across all DNOs for previously examined (ENWL, NP, SPEN, WPD) and new (SSE and UKPN) cases;
- an initial techno-economical assessment using the installation of shunt reactors at GSPs and primary substations; and,
- considerations for future studies aimed at enhancing the trends in Q demand as well as investigating distribution-based solutions.

In this final report of the REACT project a framework that consists of 4 stages is proposed to DNOs to allow a scenario-based assessment of future Q demand at any of their GSPs. The proposed approach and the corresponding methodologies are described in this report and can be followed by any DNO using their available network and monitoring data, from the GSP to primary substations.

The assessment of future Q demand for the different scenarios of the proposed framework is presented for GSPs across all DNOs. More specifically, results are presented for previously examined cases (GSPs of ENWL, NP, SPEN, WPD) and new cases (GSPs of SSE and UKPN) covering all DNOs. Results, although limited to seven GSPs, show that the declining demand trends at primary substations is the major contributor to the overall decline of Q demand during minimum load. The nationwide trends in reactive demand (analysis on 5 GSPs with available 2013 data) show that in a 5 years horizon the Q exports to transmission are expected to increase, depending on the scenario, by 55 to 120% with respect to their 2013 level.

An initial techno-economical assessment using shunt reactors is also presented. The investigation considers aspects regarding the sizing of shunt reactors at primary substations and the corresponding effects on energy losses. It also focuses on the amount and total cost of shunt reactors needed to be installed at GSPs to meet the requirements of the European Demand Connection Code (EDCC). Results using the improved network models (2 GSPs with Q exports in 2013) show that if shunt reactors are installed at primary substations instead of GSPs, slightly less VArs would be required (up to 3%). This, however, would also result in a small increase in daily energy losses: up to 4% with constant use of reactors and up to 0.9% if operated only during the critical hours. In terms of cost, an initial estimation (assuming £45k/MVAr) to tackle the VAr exports of each of the top 60 critical GSPs in Great Britain in a 5 year horizon suggests £213 to £295 millions, depending on the nationwide trend.

Finally, considerations for future work are presented. These include the enhancement of the assessment of trends in Q demand by analysing more networks and extending the analyses downstream primary substations. It is also highlighted that future work should focus on distribution-based solutions if DNOs are to meet the requirements of the EDCC (or agreed specifications with National Grid) to limit VAr exports to transmission.

Table of Contents

1 Introduction

This report corresponds to Deliverable 5 “Second Year Final Report Stage 2” part of the “Reactive Power Exchange Assessment and Characterisation (REACT)” Project funded by National Grid and the six Distribution Network Operators (DNOs) in Great Britain: Electricity North West Limited (ENWL), Northern Powergrid (NP), Scottish Power Energy Networks (SPEN), Scottish and Southern Energy (SSE), UK Power Networks (UKPN) and Western Power Distribution (WPD). This project is financially managed by Energy Networks Association (ENA).

The REACT Project has been established to understand the reasons behind the decline in reactive power demand as seen by National Grid during minimum load. This will allow DNOs and National Grid establishing future trends in the reactive power exchanges at Grid Supply Points (GSPs) and adopt the most cost-effective actions as well as responsibilities for ongoing data provision, planning, design, and operational management in this area.

The understanding of these trends is also of importance to Distribution Network Operators (DNOs) as they also are seeing real voltage containment challenges within their networks with the additional technical challenges of complying with the forthcoming European Demand Connection Code [1] which limits the exchanges of reactive power between transmission and distribution operationally and requires new distribution networks to be designed to not export reactive power at the transmission/distribution interface for loadings up to the 25% of the peak MW load at that interface.

1.1 Deliverable 5 “Second Year Final Report Stage 2”

Deliverable 5 “Second Year Six Final Report Stage 2” presents:

- A literature update regarding recent research work in European countries that focus on transmission-distribution interactions deriving from Q demand during periods of minimum load;
- the proposed framework and the corresponding methodology that can be used by any DNO to assess future Q demand at any of their GSPs;
- the results of the scenario-based assessment of future Q demand at GSPs across all DNOs for previously examined (ENWL, NP, SPEN, WPD) and new (SSE and UKPN) cases;
- an initial techno-economical assessment using the installation of shunt reactors at GSPs and primary substations; and,
- considerations for future studies aimed at enhancing the trends in Q demand as well as investigating distribution-based solutions.

In this final report of the REACT project, an update on the literature review from the first report of Deliverable 1 (March 2014) [2] is presented in subsection 1.2. Although most of the work still focuses on the operational and market perspectives, there are some initial studies within 2015 in other European countries regarding transmission-distribution Q exchanges during periods of minimum load.

Section 2 proposes a framework that can be used by DNOs to assess future Q demand at any of their GSPs during periods of minimum load. The described approach consists of 4 stages and can be carried out using original DNO network and monitoring data (from GSPs to primary substations) together with information related to future demand/generation scenarios and network changes from National Grid and DNO network planners.

In Section 3 all results of the scenario-based assessment of future Q demand are presented for the seven GSPs analysed. Apart from the previously examined cases (GSPs of ENWL, NP, SPEN, WPD [3]), future Q demand during periods of minimum load has been also assessed for new cases (GSPs of SSE and UKPN). The new cases include the improved model (validated for multiple days) of City Road (UKPN) and the semi-improved (mimicking GSP behaviour for a single day) network model of Lovedean (SSE). Using the results of the scenario-based assessment of future Q demand on 5 GSPs with available 2013 data (GSPs of ENWL, NP, SSE, WPD, UKPN) the nationwide trends are assessed. The corresponding limitations are also discussed.

In Section 4 an initial investigation on technical and economic aspects using the installation of shunt reactors is carried out to limit Q exports to transmission during periods of minimum load. First, the analysis on 2 critical GSPs (Norton-NP and Kearsley-ENWL) focuses on the sizing of shunt reactors at primary substations and the corresponding effects on energy losses so as to compare the benefits from GSP installations. Next, using the derived nationwide trends in Q demand (Section 3), an initial cost estimation of the required volume of shunt reactors to tackle the VAr exports of each of the 336 GSPs in Great Britain in a 5 year horizon is carried out.

In Section 5 considerations for future work are presented. The suggested studies include the enhancement of the assessment of trends in Q demand by analysing more networks but also extending analysis downstream primary substations, i.e., modelling –to some extent– HV and LV networks. Additionally, it is suggested that future work should focus on distribution-based solution (e.g., investigating alternatives that do not require the installation of new assets) if DNOs are to meet the requirements of the EDCC (or agreed specifications with National Grid) to limit VAr exports to transmission.

Finally, conclusions are drawn in Section 6.

1.2 Literature Review Update: Recent Studies in Europe

The literature review in the first report of REACT project (Deliverable 1 - March 2014) [2] revealed that most of the studies until 2014 had focused on the operational and market perspectives (e.g., control of distribution voltages [4]-[6], provision of services from distribution to transmission [7]), rather than on transmission-distribution interactions during periods of minimum load. There was very limited documentation investigating the decline in reactive power demand of distribution networks, i.e., at the transmission-distribution interfaces.

More recently, mainly in 2015, initial studies have emerged in other European countries regarding transmission-distribution interactions during periods of minimum load. A research work carried out for ERDF in France [8] highlights that reactive power demand in French primary substations has been declining during periods of minimum load. However, there are no historic trends presented in this work. Other works from Germany [9]-[10] focus on distribution-based solutions to absorb VArs during periods of minimum load. It is noteworthy that the German Transmission System Operator aims at limiting reactive power imports and exports at the interfaces with distribution during minimum demand. A work from Italy [11] also highlights forthcoming limitations to DNOs regarding VAr exports to transmission and the need to consider this objective in operational planning of distribution networks.

It should be also noted that in major conferences in the USA, such as the IEEE Power & Energy Society General Meeting 2015 (where [12] was presented to disseminate the studies of the REACT project), most studies from outside Europe do not investigate the transmission-distribution reactive exchanges during periods of minimum load.

2 Framework for the Assessment of Future Trends

National Grid (and TSOs in general) traditionally consider the historic and future trends of P and Q demand at GSPs without modelling the actual distribution networks. Although declining trends in Q demand have been identified in different GSPs of all DNOs, the extraction of empirical rules that could allow DNOs and National Grid to assess future Q demand at GSPs without modelling the actual networks could lead to results that do not take into account the effects from:

- the differences in topologies (e.g., SPEN networks are meshed);
- the differences from the total line lengths per voltage level from 132 to 33kV;
- the different loadings per line that determine the corresponding Q gains;
- the differences in the types of lines (e.g., City Road - UKPN is 100% cables whereas other networks have 50+% of overhead lines); and,
- the interactions of demand characteristics with the networks (e.g., from North to South, urban and rural networks).

This section first proposes a framework that consists of 4 stages and can be used by any DNO to assess the future Q demand at any of their GSPs during periods of minimum load. Next, the methodology for each of these 4 stages is described. Processes presented in the previous reports of Deliverables 1 to 4 have been embedded in the proposed approach, allowing DNOs to use their original historic monitoring and network data (from GSP to primary substations) together with TSO/DNO network planning information to assess future Q demand at GSPs.

2.1 Proposed Framework

The proposed 4-stage framework is shown in Fig. 1. Monitoring data (e.g., half-hourly) for the aggregated P and Q demand of primary substations are seasonally analysed in Stage 1 to assess daily minimum P and corresponding Q/P ratios during minimum load and extract the corresponding trends.

In Stage 2, network and monitoring data are used to improve the original DNO network models. As mentioned in the report of Deliverable 3 [13], original DNO models traditionally focus on periods of peak demand, and hence do not cater for the Q gains from cables and overhead lines. Thus, improved network models are needed to mimic the actual behaviour of transmission-distribution interfaces in time-series simulations during periods of minimum load.

In Stage 3, information from TSO and DNO network planners regarding scheduled/future network, distributed generation (DG) and demand changes are gathered and considered to cater for their effects on the overall Q demand of the examined distribution networks.

The assessment of future Q demand during minimum load at the examined GSPs is carried out in Stage 4 using multiple scenarios. These scenarios are defined taking into account future uncertainties regarding financial affordability and policies supporting sustainability.

The following subsection describes the methodology for each of the 4 stages of the proposed framework to assess future Q demand at GSPs during periods of minimum load.

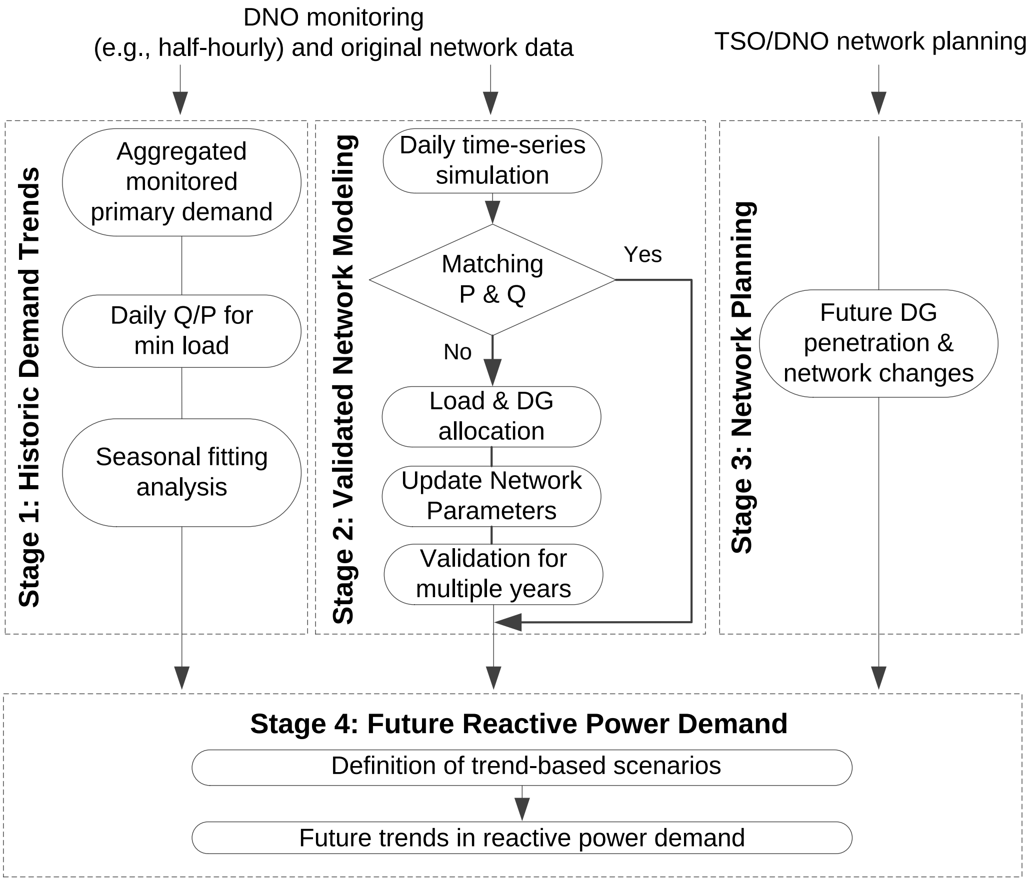

Fig. 1. The proposed framework to assess future Q demand at GSPs during periods of minimum load.

2.2 Methodology

The methodology that needs to be followed for each of the 4 stages of the proposed framework of Fig. 1 is presented in this subsection. It should be noted that the proposed approach is flexible and can be adapted to cater for the analysis of other factors that have not been considered in the REACT project (e.g., significant penetrations of wind generation or CHPs).

2.2.1 Stage 1: Historic Demand Trends

Primary substations are typically the last points of real-time monitoring of demand in distribution networks, and hence of time-series historic data (although stored with longer sampling intervals). This data is crucial in the proposed framework as it allows validating upstream network models and capturing the aggregated demand behaviour downstream primary substations, i.e., residential, commercial and industrial loads, DG, and network changes.

To extract the historic demand trend for a given GSP, the daily minimum aggregated P demand, as well as the corresponding Q demand and Q/P ratios of the primary substations are calculated per season. Once these trends are identified using an adequate fitting approximation (e.g., linear, exponential – see Deliverables 3 [13] and 4 [3]), they can be applied to impact analyses of the different scenarios (Stage 4).

In cases where time-series monitoring data (e.g., half-hourly P and Q) are available, downstream primary substations, the corresponding models can be extended to lower voltage levels. However, it should be highlighted that the successful use of the proposed approach depends on the identification of representative historic demand trends during long time intervals.

2.2.2 Stage 2: Improved/Validated Network Modelling

In order to carry out a thorough analysis of the main factors affecting Q demand, the corresponding distribution network models have to be produced. For this purpose, the available DNO network and monitoring data is used to create improved or semi-improved models (see Deliverable 3 [13]) that mimic the behaviour of the corresponding transmission-distribution interfaces.

Network data, such as line susceptances, that are crucial for the assessment of Q demand during periods of minimum load (due to the Q gains) might not be considered adequately by DNOs, which traditionally focus on periods of peak demand.

In terms of monitoring data, in practice, not all BSPs and/or primary substations have available P and Q monitoring data. More specifically, there have been cases where only apparent power (MVA) data are available, no monitoring devices are available, erroneous data have been recorded, or confidentiality issues exist (e.g., generation profiles).

Based on the above, Stage 2 proposes the production of improved network models (presented in detail in Deliverable 3 [13] for Norton GSP –NP). This process can be summarized with the following four steps:

Step 1: Perform daily simulations using the available DNO network and monitoring data (e.g., half-hourly) to identify the mismatch in P profiles ($P_{mismatch}$) between simulations and monitoring data at the GSP and intermediate substations (BSPs and primary substations).

Step 2: Minimize the $P_{mismatch}$ by allocating P and Q profiles for loads and DG. This is done by adopting an approach that allocates load and generation profiles proportionally to the size of the corresponding BSPs and/or primary substations (see Appendix C of Deliverable 3 [13]).

Step 3: Match Q profiles at the GSP by updating line susceptances across all voltage levels. In the case that the type of lines is not available, this can be achieved iteratively starting from the assumption that all lines are overhead and then different cable penetrations are adopted progressively (see Deliverable 3 [13] for details).

Step 4: To confirm the adequacy of the updated line susceptances repeat steps 1 and 2 for different days.

2.2.3 Stage 3: Network Planning

Scheduled network and demand changes, as well as DG penetrations can affect the future Q demand of the examined GSPs and therefore should be considered in the scenario-based assessment of future Q demand during minimum load.

In the report of Deliverable 4 [3] the scenario-based assessment of future Q demand at the examined GSPs (seven in total) takes into account future PV penetrations according to the Future Energy Scenarios (FES) of National Grid [14]. Apart from the FES, any available information from National Grid or DNO network planners regarding scheduled/future network, generation and demand changes need to be considered in the assessment of future reactive demand.

More specifically, the following information from National Grid and DNO network planners should be taken into account:

- installation of new power cables (particularly upstream 33kV);
- replacements of overhead lines with power cables;
- network reconfigurations that affect the loadings of circuits (particularly upstream 33kV);
- installation of capacitor banks;

- penetration of small and medium-size renewables (e.g., PV and wind generation); and,
- connection of other DG plants (e.g. CHP units).

2.2.4 Stage 4: Future Reactive Power Demand

Having accomplished the processes of Stages 1 to 3, the scenario-based assessment of the future Q demand at GSPs during minimum load can be carried out in Stage 4. First, the different scenarios need to be defined, as described in the report of Deliverable 4 [3]. In a similar approach with that of the European Network of Transmission System Operators for Electricity (ENTSO-E) [15] and the National Grid's FES [14], the uncertainties regarding economic growth conditions and support on policies and regulations towards more sustainable energy systems are considered.

Both ENTSO-E and National Grid carry out impact analyses using four future scenarios. Three of these scenarios that consider slow progression, fast progression and significant DG penetration are also included in the proposed methodology. Two extra scenarios are defined in order to have a final set of scenarios that also incorporate current trends and practices ("Existing Trends" scenario) and the effects from loads becoming even less inductive (or even capacitive) downstream primary substations due to energy efficiency measures ("Effective Loads" scenario).

In the REACT project the five trend-based scenarios have been defined in the report of Deliverable 4 [3]. The scenarios that have been used to assess future Q demand at GSPs across all DNOs during minimum load are:

1. "Existing Trends": This is what can be considered as the *business as usual* scenario taking into account the continuation of the identified historic trends (Stage 1) in the P and Q demands of primary substations. The future trend in PV penetrations is considered to be in the middle of the expected range according to National Grid FES [14]. No future network changes are considered from GSPs (132kV) downstream to primary substations.

2. "Go Green Scenario": Policies and regulations towards more sustainable energy systems are taken into account in this scenario. This scenario is different from the "Existing Trends" scenario in the sense of considering higher future PV penetrations (maximum PV penetration trend according to FES).

3. "Effective Loads": High future economic growth trends are taken into account in this scenario. This scenario is different from the "Existing Trends" scenario in the sense of considering less inductive or even capacitive future loadings of primary substations due to energy efficiency measures. Therefore, a more acute future Q/P ratio decline in primary demand during minimum load is considered.

4. "Slow Progression": Slow future economic growth trends together with weak policies towards more sustainable energy systems are taken into account in this scenario. Therefore, less declining Q/P ratios in future P and Q demand of primary substations during minimum load and slower PV penetration trends (minimum future PV penetration trend according to FES) from the "Existing Trends" scenario are considered.

5. "Fast Progression": High future economic growth trends together with strong policies and regulations towards more sustainable energy systems are considered in this scenario. The significant PV penetration trends of "Go Green" scenario and the Q/P ratio declining trends of primary demand in "Effective Loads" are considered. Since this corresponds to the worst case scenario, it is the only scenario considering replacements of 33kV overhead lines with cables.

Having defined the scenarios, the improved or semi-improved network models (Stage 2) can be used in daily time-series simulations to assess future Q demand at GSPs.

2.3 Summary

In summary, the proposed framework to assess future reactive power demand at GSPs during periods of minimum load has the following characteristics:

- unlike traditional approaches followed by National Grid and, in general, transmission operators around the world, the proposed framework uses distribution network models (from GSPs to primary substations) and takes into account the effects of the actual networks, such as the type and length of circuits as well as the interactions of demand and generation;
- the proposed framework can be directly used by DNOs for any of their GSPs using their network and monitoring data;
- DNOs can use the framework to investigate and plan distribution-based solutions if they are to meet the EDDC requirement (or any agreed specifications with National Grid) to limit VArs to transmission during periods of minimum load;
- the framework consists of 4 stages that include the identification of historic demand trends, the production of improved/validated network models, the incorporation of network planning information and the scenario-based assessment of future reactive demand; and,
- the proposed framework is flexible and can be adapted to cater for the analysis of other factors that have not been considered in the REACT project (e.g., significant penetrations of wind generation or CHPs).

3 Future Reactive Power Demand

The future Q demand at GSPs during periods of minimum load can be assessed for different scenarios following the proposed framework of the previous section (Section 2) of this report. The future trends in Q demand have been assessed following this framework for ENWL, NP, SPEN and WPD GSPs (5 GSPs) in the report of Deliverable 4 [3]. In the present final report the future trends in Q demand for the same scenarios are presented in detail for new cases of UKPN and SSE GSPs.

In the following subsections the final results for future trends in Q demand are first presented for the previously examined cases (ENWL, NP, SPEN and WPD). Next, the corresponding results are presented for the new cases (SSE and UKPN).

3.1 Summary of Previously Presented Cases

In the report of Deliverable 4 [3] the future trends in Q demand at Kearsley (critical-ENWL), Norton (critical-NP), Chesterfield (critical-WPD) and the interconnected Fiddler's Ferry (critical-SPEN) and Carrington (control-SPEN) GSPs were assessed for the different scenarios (see Table 2 of Deliverable 4 [3]). The network models corresponding to 18th June 2013 (year 0) were used in time-series simulations for ENWL, NP and WPD GSPs. Due to the availability of monitoring data, the network model corresponding to 18th June 2010 was considered for the interconnected SPEN GSPs.

The results of the 5 scenarios using the improved networks of Norton (NP) and Kearsley (ENWL) GSPs in Fig. 2 and Fig. 3 indicate that the continuation of the declining trends in the demand of primary substations is the main factor that can lead to significant VAr exports towards transmission in the mid-term. The increased VAr exports in a 2 to 5 year horizon at both GSPs highlight the fact that, if a similar behaviour is to be found in other GSPs in the North of England, this could deteriorate National Grid's ability to maintain statutory voltage levels in the region but also the challenge to be faced by DNOs to comply with the EDCC requirements.

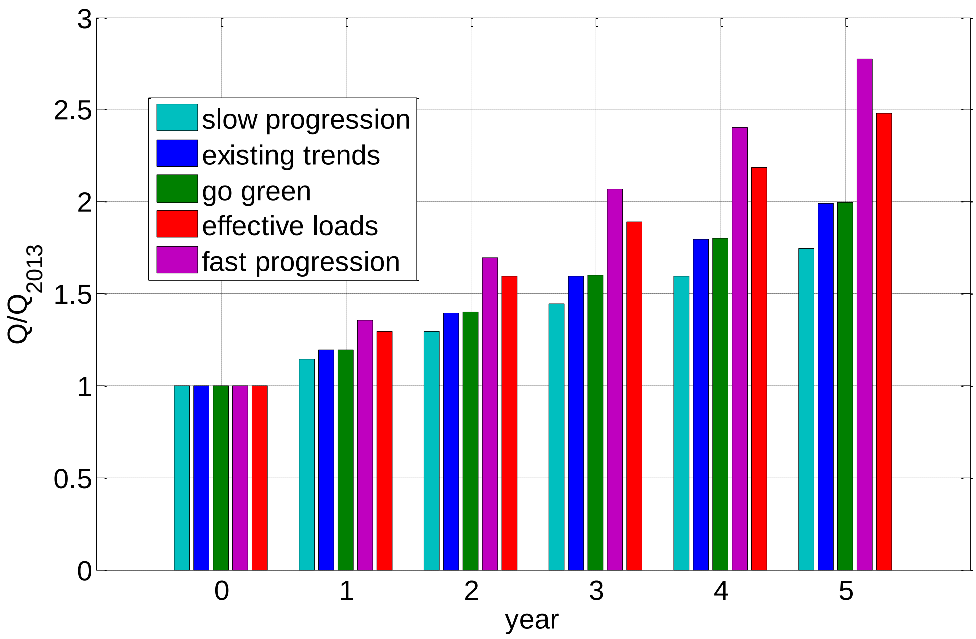

Fig. 2. Future Q demand at Norton (NP) GSP for different scenarios.

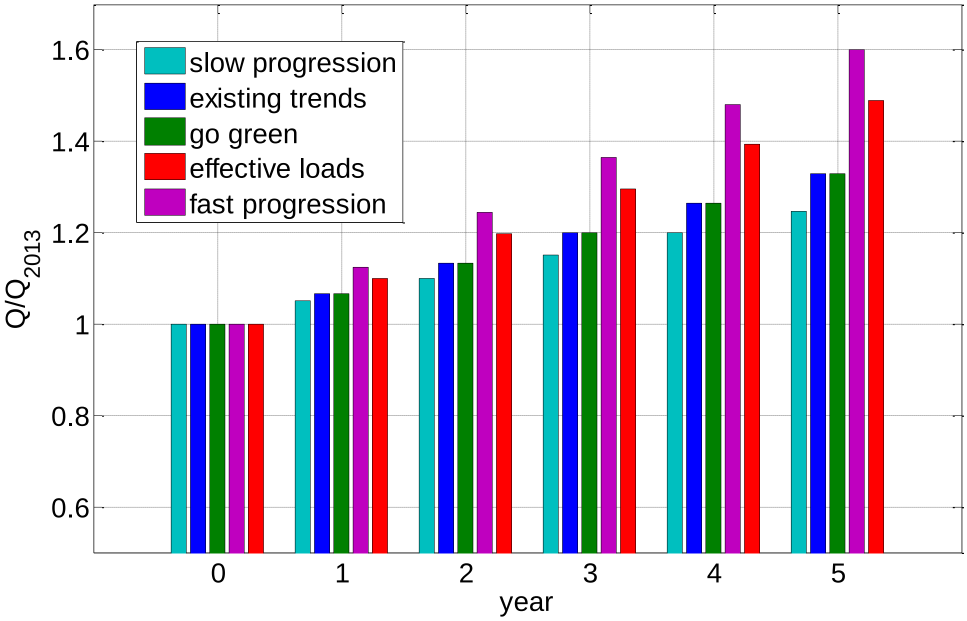

Fig. 3. **Future Q demand at Kearsley (ENWL) GSP for different scenarios.**

Unlike the analysis for ENWL and NP GSPs, the implementation of the scenario-based assessment of future Q demand at the WPD and SPEN GSPs in Fig. 4 and Fig. 5, respectively, exhibited significant drawbacks. Although the semi-improved network models for the examined WPD and SPEN GSP groups matched in daily time-series simulations the P and Q demand at GSPs, there are two major issues deriving from practical modelling challenges:

- the historic trends in P and Q demand at primary substations could not be identified; and,
- the cable penetration has not been estimated.

Consequently, the original DNO data for line parameters was not updated in the examined WPD and SPEN networks and the primary demand trends in the corresponding scenarios were considered as equal to the 2009-2013 historic Q/P ratio trends at these GSPs using National Grid half-hourly data.

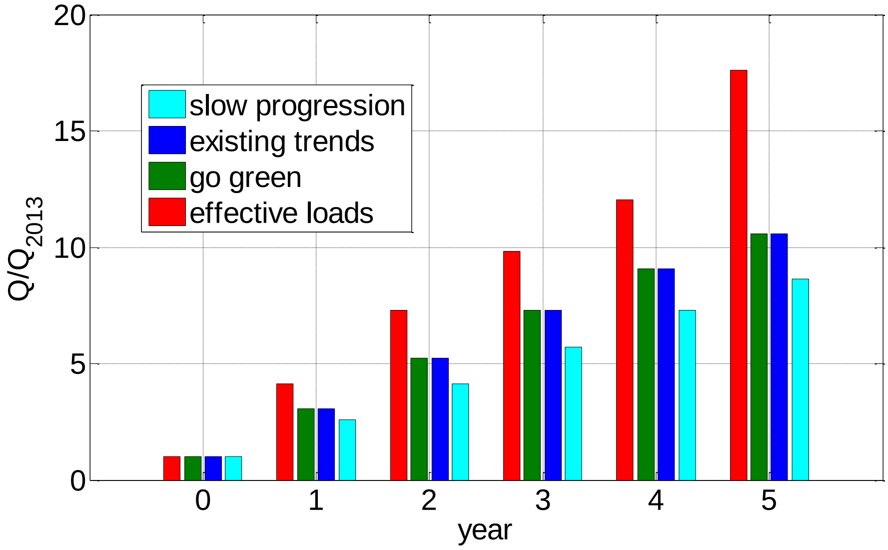

Fig. 4. **Future Q demand at Chesterfield (WPD) GSP for different scenarios.**

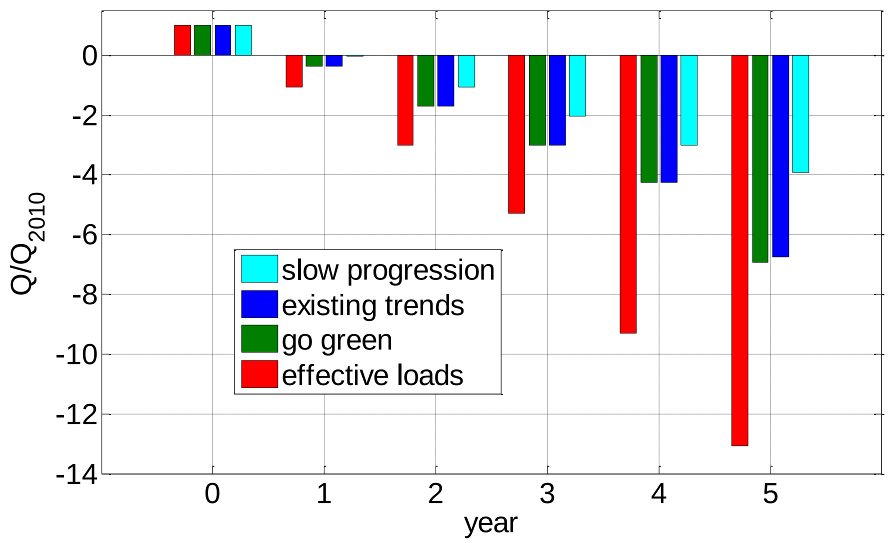

Fig. 5. Future aggregated Q demand of Fiddler's Ferry and Carrington (SPEN) GSPs for different scenarios.

The findings regarding the previously examined cases of ENWL, NP, SPEN and WPD networks can be summarized as follows:

- Future Q demand at GSPs are mainly affected by the future trends in P and Q demand at primary substations and any possible cable penetration, even in 33kV circuits;
- the expected future trends in PV penetrations do not significantly affect Q demand at GSPs;
- using improved network models the VAr exports to transmission for the ENWL and NP networks are expected to be increased by 30 to 175% until 2018;
- using semi-improved network models the VAr exports to transmission for the WPD and SPEN networks are expected to be many times higher than the corresponding for ENWL and NP networks; and,
- results using semi-improved network models for the WPD and SPEN networks might not be representative because of the use of original DNO (not updated and validated) line parameters for 132 to 33kV circuits and Q/P ratio trends at primary substations using GSP monitoring data.

3.2 New Cases

Two new cases have been examined in this final report of the REACT project considering the proposed framework of Fig. 1: City Road GSP (critical-UKPN) and Lovedean GSP (critical-SSE). Unlike the previously presented cases, the new cases are in the South of Great Britain.

3.2.1 City Road GSP (UKPN)

The future Q demand during minimum load is assessed in this subsection for the City Road GSP (critical-UKPN) using different scenarios according to the proposed framework of Fig. 1. City Road is a large distribution network with 812MW peak load in 2013. The minimum Q demand at this GSP in 2013 was inductive at 7MVAr (336MW minimum load in 2013). In fact, this is the only GSP out of the top 2 critical and top 2 control GSPs per DNO (28 GSPs in total) that exhibited inductive minimum annual Q demand during 2013 (see Deliverable 3 [13]).

To assess the future Q demand at City Road GSP, the improved network model of 18th June 2013 (year 0) is considered in time-series simulations (see Appendix 8.1.1). The minimum daily Q demand at the GSP (maximum VAr exports to transmission) is assessed for every scenario (see Stage 4 in Section 2 of this report) in year 0. Fig. 6 shows the normalized Q demand (Q/Q_{2013}) at City Road GSP in a 5-year horizon. The Q demand at the GSP is the same for all scenarios in year 0 (Q/Q_{2013}=1). Specifically, the Q demand in year 0 (18th June 2013) is 40MVAr (inductive).

It is noteworthy that City Road is a large urban network with 100% cable penetration in 132 to 33kV circuits. Nonetheless, the total length of 132kV circuits is considerably lower (circa 45km) compared to other networks (e.g., Lovedean GSP of SSE with approximately 50km total length of cables and 300km of overhead lines in 132kV – next subsection).

Since there is 100% cable penetration in 33kV circuits, the “Fast Progression” and “Effective Loads” scenarios do not exhibit any difference. Results show that future Q demand at GSP is reduced for all scenarios, but demand remains inductive for all scenarios until year 4. It is noteworthy that a 80% decrease in Q demand at City Road GSP is expected according to the “Existing Trends” scenario in a 5 years horizon. Only in year 5 there are Q exports during minimum load according to the “Fast Progression/Effective Loads” scenario (Q=-8.7MVAr).

Emphasis should be given to the fact that City Road is the network that exhibits the most acute decline in P demand at primary substations during periods of minimum load (-2.6% per year – see seasonal analysis in Deliverable 4 [3]) among all analysed GSPs with available P and Q monitoring data at primary substations. The corresponding decline in Q demand at primary substations (-8.7% per year) is very similar to other GSPs (e.g., Norton-NP, Kearsley and South Manchester-ENWL).

It should be noted that although City Road was inductive in 2013, the other critical and control GSPs were capacitive. Taking this into account, if similar acute declining trends in the P demand of primary substations is identified in future studies in other UKPN networks that are currently capacitive, they will lead to lower loadings of 132 to 33kV lines and therefore significant Q gains.

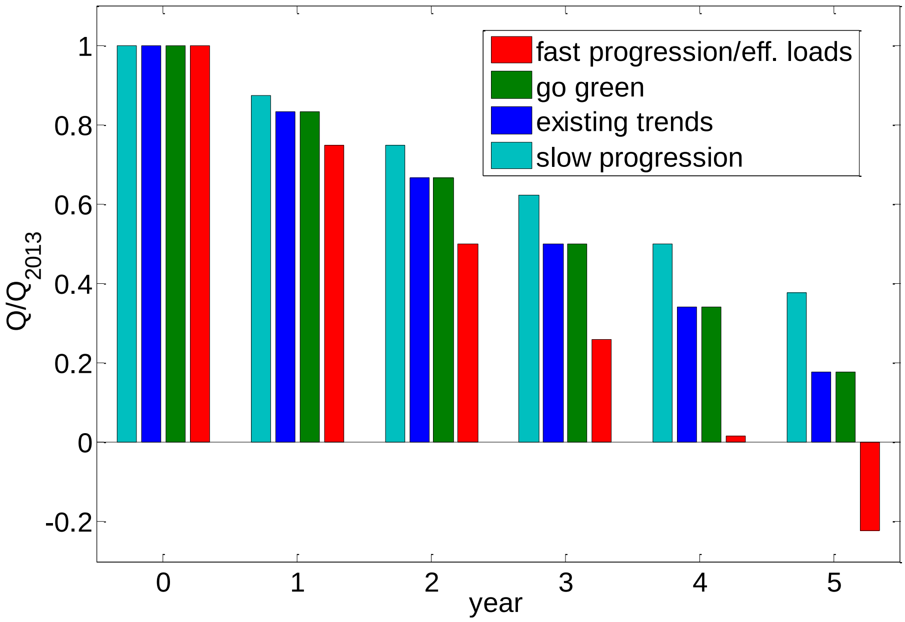

Fig. 6. Future Q demand at City Road (UKPN) GSP for different scenarios.

3.2.2 Lovedean GSP (SSE)

The future Q demand during minimum load is assessed in this subsection for the Lovedean GSP (critical-SSE) using the different scenarios (see Deliverable 4 [3]). Lovedean GSP group is a large distribution network with 592MW peak load in 2013. The minimum Q demand at this GSP in 2013 was -186MVAr (161MW minimum load in 2013).

It is noteworthy that Lovedean, together with Fleet (SSE) GSP, are the 2 GSPs that exhibited the lowest Q demand in 2013 during minimum load across all critical and control GSPs (28 GSPs) selected across all DNOs. It is also noteworthy that both networks are in the same license area of SSE in the South of Great Britain.

To assess the future Q demand at Lovedean GSP, the semi-improved network model of 18th June 2013 (year 0) is considered using time-series simulations (see Appendix 8.1.2). Since the cable penetration could not be estimated in 33kV circuits, the "Fast Progression" and "Effective Loads" scenarios are the same for this GSP. The minimum daily Q demand at GSP (maximum VAr exports to transmission) is assessed for every scenario from year 0 (2013) to year 5 (2018). Fig. 7 shows the normalized Q demand (Q/Q_{2013}) at Lovedean GSP in a 5-year horizon. The Q demand at the GSP is the same and equal to -174MVAr for all scenarios in year 0 (Q/Q_{2013}=1).

Results show that at least 15% increase in VAr exports to transmission is expected at Lovedean GSP after 5 years according to the "Slow Progression" scenario. The corresponding increase in VAr exports is 30% according to "Fast Progression"/"Effective Load" scenarios. Results for the "Existing Trends" and "Go Green" scenarios show that the higher PV penetrations of the "Go Green" scenario are not expected to affect Q demand at the examined GSP.

The significant increase of Q exports found in Lovedean (15 to 30% in a 5 year horizon) combined with the significant decrease of Q imports found in City Road (62 to 121%) highlight that the South of Great Britain might pose challenges to National Grid. In fact, if similar behaviours are to be found in other GSPs in the South of England, this could deteriorate National Grid's ability to maintain statutory voltage levels in the region. In addition, tackling the effects of these trends will also be challenging to DNOs if they are to comply with the EDCC requirements (particularly for SSE).

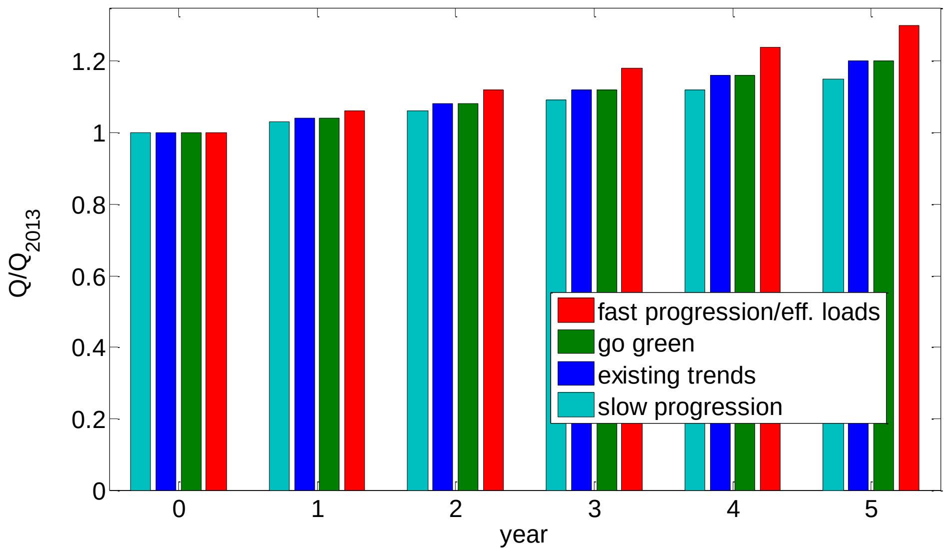

Fig. 7. Future Q demand at Lovedean (SSE) GSP for different scenarios.

3.3 Nationwide Trends in Q Demand

Using the proposed framework of Fig. 1, the future Q demand during minimum load has been assessed at 7 GSPs (5 GSPs in Deliverable 4 [3] and 2 GSPs in subsection 3.2 of this report) out of the 336 GSPs across Great Britain. Although the examined GSPs had an aggregated peak demand of approximately 6% of the 2013 peak demand across Great Britain, the corresponding trends can be used to understand the potential behaviour of all GSPs nationwide.

For consistency, the GSPs from which the nationwide trends will be extract should consider the same day of analysis. This applies to 5 GSPs out of 7: Kearsley - ENWL, Norton - NP, Lovedean - SSE, City Road - UKPN and Chesterfield - WPD (18th June 2013)

The aggregated Q demand of the 5 GSPs in year 0 (18/6/2013) for all scenarios is the same and equal to -193MVAr. The nationwide trends are derived taking into account the aggregated future Q demand for these GSPs (see subsection 3.2) in its normalised form (Q/Q_{2013}), as shown in Fig. 8. The aggregated future Q demand in actual MVAr values are presented in Table 1. Results are not presented for the “Fast Progression” scenario, since cable estimation in 33kV circuits was not possible in semi-improved network models.

Results show that at least 55% increased VAr exports to transmission are expected for the aggregated demand of these 5 GSPs after 5 years according to the “Slow Progression” scenario (Q=-307MVAr). The corresponding increase in VAr exports is approximately 75 and 120% according to the “Existing Trends” and “Effective Loads” scenarios. Results for the “Existing Trends” and “Go Green” scenarios show that the higher PV penetrations of the “Go Green” scenario are not expected to affect Q demand at the examined GSPs.

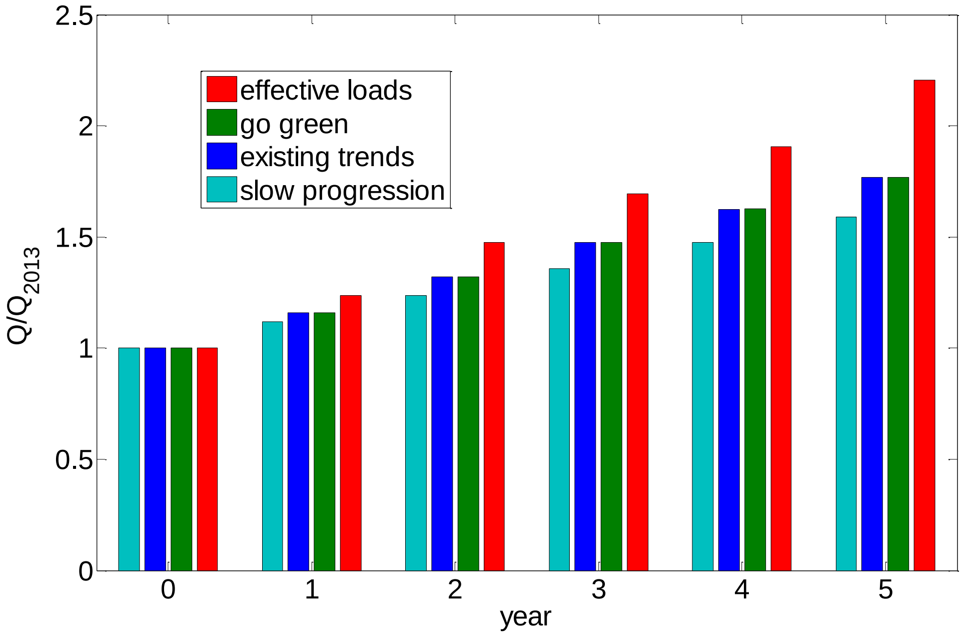

Fig. 8. Nationwide trends in reactive demand during periods of minimum load. Results for the aggregated Q demand of 5 GSPs corresponding to circa 5.5% of GB peak MW in 2013.

Table 1. Future aggregated Q demand at 5 examined GSPs

Scenario	Year 1	Year 2	Year 3	Year 4	Year 5
Existing Trends	-223.647	-254.609	-285.003	-313.598	-341.086
Go Green	-223.675	-254.663	-285.083	-313.702	-341.214
Effective Loads	-238.915	-284.95	-327.278	-367.61	-425.587
Slow Progression	-216.166	-238.943	-262.206	-285.003	-306.683

Although the studied GSPs cover all DNOs, it is important to highlight that the adequacy of the derived nationwide trends has the following limitations:

- The studied GSPs correspond to an aggregated peak demand of only circa 6% (3.4GW) of the nationwide peak demand in 2013;
- 4 GSPs have been modelled with semi-improved network models that match P and Q profiles in time-series simulations for a specific day and are not validated in multiple days;
- the historic primary demand trends are an important component in the proposed framework to assess future Q demand (see section 3) and available P and Q monitoring data for over 5 years have been made available and used in analyses only for 2 of these GSPs; and,
- future Q demand has not been assessed for any network in Scotland.

Emphasis should be given in future studies not only to the enhancement of analyses (e.g., with modelling networks downstream primary substations), but also to expand the analyses to more GSPs that will update and/or improve the derived nationwide trends.

3.4 Summary

The future trends in reactive Q demand during periods of minimum load can be summarized as follows:

- In all examined cases (7 GSPs – previously presented and new cases) across all DNOs the continuation of identified historic trends in the demand of primary substations can result in significant decline of Q demand during periods of minimum load;
- to analyse the future trends in UKPN and SSE GSPs, the improved network model of City Road (UKPN) and the semi-improved model of Lovedean (SSE) have been used in analyses;
- 62 to 121% reduction in Q demand during minimum load (still inductive with 61% decrease, but getting capacitive at 121%) is expected in a 5 years horizon at the UKPN GSP;
- extra 15 to 30% Q exports are expected in a 5 year horizon at the SSE GSP; and,
- nationwide trends in reactive demand (analysis on 5 GSPs with available 2013 data) show that in a 5 years horizon the Q exports to transmission are expected to increase, depending on the scenario, by 55 to 120% with respect to their 2013 level.

4 Techno-Economical Assessment Using Shunt Reactors

The adoption of shunt reactors in distribution networks could be a potential solution that will help National Grid maintain statutory transmission voltage levels. It will also allow the DNOs to limit their Q exports to transmission, particularly if they are to meet the EDCC [1] requirements (i.e., no VAr exports to transmission for loadings below the 25% of the transmission-distribution interface capacity [1]).

In the following subsection the potential advantages and disadvantages from the installation of shunt reactors at primary substations instead of GSPs are first investigated. The analysis is carried out using the available 2013 improved network models. It is noted that improved network models have been produced for Kearsley (ENWL), Norton (NP) and City Road (UKPN) GSPs. Unlike Kearsley (ENWL) and Norton (NP) GSPs that exhibited Q exports to transmission within 2013, City Road (UKPN) was inductive in 2013 and therefore is not considered in the investigations. The analysis focuses on:

- the potential ability to size shunt reactors with less aggregated VArs when installed at primary substations instead of at the corresponding GSP; and,
- the effects on energy losses resulting from installing shunt reactors at primary substations with and without time control strategies.

Next, the identified nationwide trends (see Fig. 8 in Section 3) in Q demand are considered in a 5 years horizon to produce an initial cost estimation of shunt reactors required to tackle the VAr exports of each of the top 60 critical GSPs in Great Britain (top 10 per DNO).

4.1 Installation of Shunt Reactors at Primary Substations

Shunt reactors can be installed by DNOs at the GSPs or any other network point downstream (e.g., BSPs or primary substations). A potential benefit from using shunt reactors at primary substations could be the sizing of shunt reactors with less aggregated VArs at primary substations compared to the corresponding amount of VArs needed to be installed at the GSPs.

In the following subsections the sizing of shunt reactors is first investigated using the improved network models of Kearsley (ENWL) and Norton (NP). Next, the corresponding effects on energy losses from the installation of shunt reactors at primary substations are presented for these two networks. The analysis also focuses on the reduction of energy losses that can be achieved when time control strategies are adopted.

4.1.1 Relationship of VArs at the GSP and Primary Substations

Focusing on potential solutions that could tackle the effects from the declining Q demand at GSPs, it was highlighted in the report of Deliverable 4 [3] that any solution at primary substations (e.g., installation of shunt reactors) could potentially have a larger positive effect at GSPs. This point for further investigation derived from the observation of future trends in 2 different GSPS (Kearsley - ENWL and Norton - NP (Norton), where 1MVAr less in the minimum daily aggregated Q demand at primary substations corresponded in simulation results by ~1.5MVAr decline in the minimum daily Q demand at GSPs. This relationship, however, is not appropriate as it considered different (uncorrelated) time instants throughout the day.

Here, the relationship of Q demand at the GSP (Q_{GSP}) and that of primary substations ($Q_{primaries}$) is investigated again considering the same (correlated) time instant in the studied day. Fig. 9a and Fig. 9b show the $Q_{GSP}/Q_{primaries}$ ratios for the daily time window that Q exports to transmission (i.e., 0 am to 7 am) during 18th June 2013 take place in Norton and Kearsley GSPs, respectively. The mean value of the $Q_{GSP}/Q_{pimaries}$ ratio is –0.44 and -0.8029 for Norton and Kearsley GSPs, respectively.

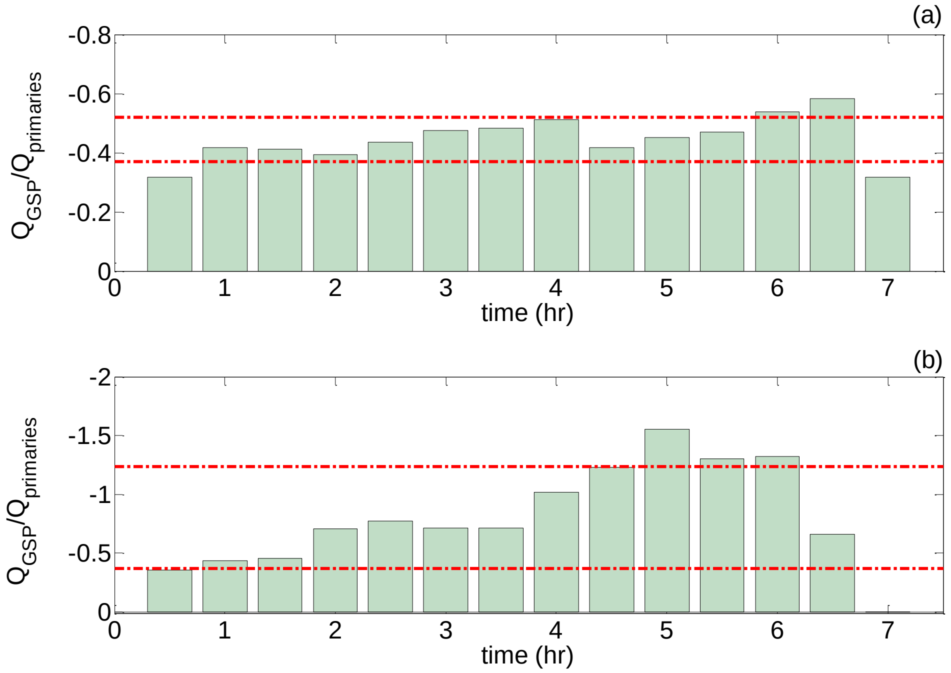

Fig. 9. Standard deviations (red lines) of the ratios of Q at GSP to the aggregated Q demand of primaries for a) Norton (NP); and, b) Kearsley (ENWL) GSPs.

The standard deviation in Fig. 9 (red lines showing the variation from the mean value) is 0.075 and 0.434 for Norton and Kearsley GSPs, respectively. The calculated standard deviations, particularly for Kearsley GSP, give a first indication that the relationship between Q_{GSP} and $Q_{pimaries}$ is highly dependent on the time of the day, and therefore a single value would not be realistic.

4.1.2 Sizing of Shunt Reactors

To investigate if shunt reactors with less aggregated VArs can be sized at primary substations instead of GSPs, the following cases are presented for Norton (NP) and Kearsley (ENWL) GSPs:

- Case #1: no shunt reactors are installed;
- Case #2: installation of 1MVAr shunt reactors at primary substations for every 1MVAr exports at the GSP, i.e., direct sizing of VArs as seen at the GSP; and,
- Case #3: installation of minimum amount of VArs of shunt reactors at primary substations that can lead to zero MVAr exports to transmission, i.e., fine-tuned sizing of VArs as actually required by the GSP.

The analysis for both GSPs is carried out using the corresponding improved network models of the 18th June 2013. During this day the maximum Q exports at Norton and Kearsley GSPs are 20 and 32.4MVAr, respectively. Norton and Kearsley GSP groups have 39 and 37 primary substations, respectively. It is important to highlight that, for simplicity, in both networks the size of shunt reactors in each of the primary substations is the same, i.e., VArs are evenly distributed. In addition, shunt reactors are continuously switched on (no time control).

The simulated Q profiles at Norton and Kearsley GSP for Cases #1 to #3 are shown in Fig. 10a and Fig. 10b, respectively. For Case #2 the size of shunt reactors per primary substation are 513 (20MVar / 39) and 876kVAr (32.4MVar / 37) for Norton and Kearsley GSPs, respectively. The resulting reactive power seen at the GSPs are 0.58 and 0.39MVar, respectively. This highlights that the siting of shunt reactors at primary substations have a slightly extra benefit when the effect is seen at the GSP.

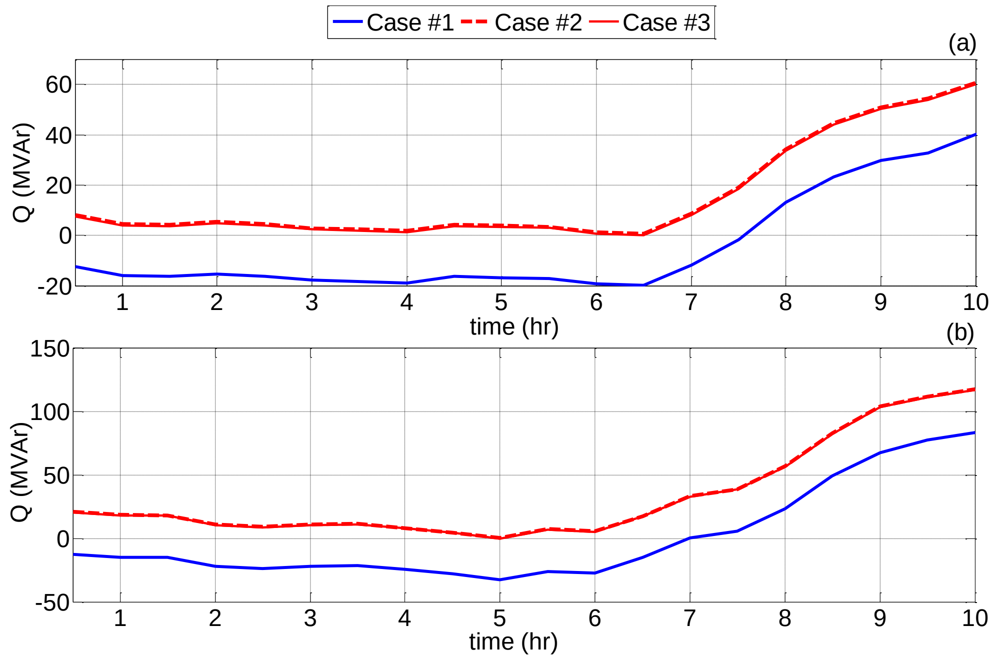

Fig. 10. Daily Q profiles at a) Norton (NP) and b) Kearsley ENWL GSP. Results from 0 am to 10 am using the improved network models of 18th June 2013.

Case #3 is used to determine the right amount of VArs needed by each GSP by iteratively fine tuning the sizes of shunt reactors at the primary substations and quantifying the effect at the GSP. It was found that to achieve zero reactive power exchanges at the GSPs during the critical instant, shunt reactors at primary substations should only not exceed 499 and 867kVAr in Norton and Kearsley GSPs, respectively.

Based on the above results, it can be concluded that 1MVAr from shunt reactors installed at primary substations can reduce the Q exports to transmission by 1.03 and 1.01MVAr in Norton and Kearsley GSPs, respectively, which in turn can lower the corresponding capital cost.

The cases presented in this analysis do not investigate the optimal siting, sizing and control of shunt reactors and therefore this should be addressed in future work to understand the cost-effectiveness of different approaches.

4.1.3 Effects on Energy Losses

The adoption of shunt reactors at primary substations can increase the complex power flows through lines and transformers and therefore result in higher losses. The effects on energy losses are investigated in this subsection with and without time control strategies.

The analysis is carried out using the improved network models (18th June 2013) of Kearsley (ENWL) and Norton (NP) GSPs. The shunt reactors identified in Case #3 (subsection 4.1.1) are considered in the quantification.

The cases examined to investigate the corresponding effects on energy losses are:

- Case A: no shunt reactors are installed;
- Case B: shunt reactors absorb VArs constantly (no time control); and,
- Case C: shunt reactors absorb VArs from 0 am to 7.30 am (time controlled).

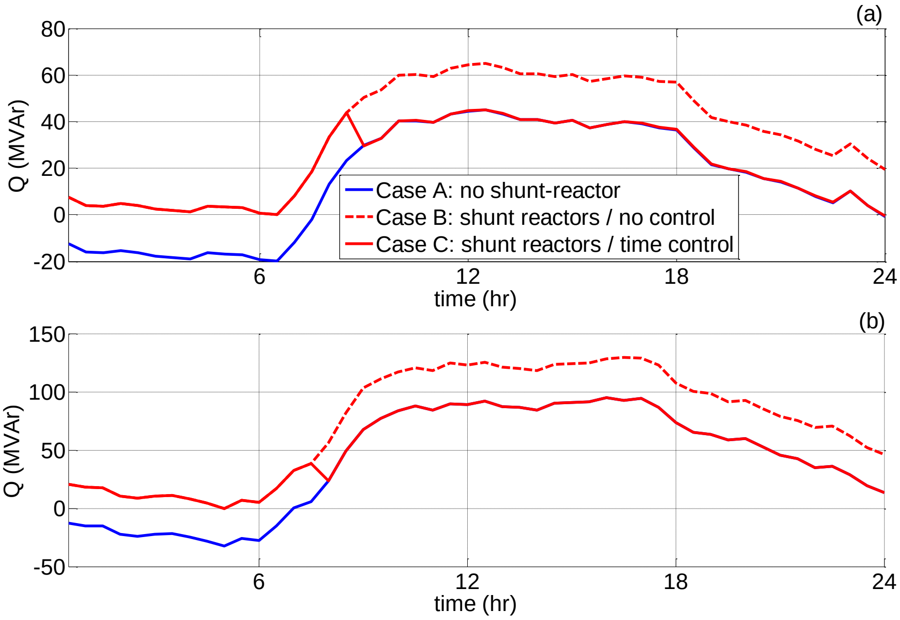

Fig. 11. Daily Q profiles at a) Norton (NP) and b) Kearsley (ENWL) GSP using the improved network models of 18th June 2013.

Fig. 11a and Fig. 11b show the daily Q profiles for all three cases for Norton and Kearsley GSPs, respectively. Although with and without any time control strategy there are no Q exports to transmission, the corresponding energy losses for Cases B and C are different. The latter is shown in Tables 2 and 3 for Cases A, B and C considering the whole 24-hour daily time window for Norton and Kearsley GSP groups, respectively.

Table 2. Energy Losses at Norton GSP Group Using Shunt Reactors at Primaries

Case	Energy Losses		
	MWh	%	Increase (%)
A: no shunt reactors	64.1	1.036	--
B: shunt reactors without time control	65.6	1.062	2.5
C: shunt reactors with time control	64.6	1.046	0.9

Table 3. Energy Losses at Kearsley GSP Group Using Shunt Reactors at Primaries

Case	Energy Losses		
	MWh	%	Increase (%)
A: no shunt reactors	88.8	1.253	--
B: shunt reactors without time control	92.4	1.304	4.1
C: shunt reactors with time control	89.5	1.262	0.7

The installation and operation of shunt reactors without any time control (Case B) increases the energy losses by 2.5 and 4.1% with respect to the original case (Case A) for Norton and Kearsley GSPs, respectively. The corresponding increase using the time control operation (Case C) is much lower, i.e., 0.9 and 0.7% of the original level (Case) for Norton and Kearsley GSPs, respectively.

It can be concluded that the time window that the shunt reactors will absorb VArs has a significant effect on the corresponding increase in energy losses and, therefore, the adoption of time-based control strategies can bring significant benefits. Nonetheless, it is important to highlight that ultimately the impacts on energy losses should be assessed considering a yearly analysis. Depending on the reactive power exchange behavior of a GSP, the use of shunt reactors can be necessary only on a few days or weeks in a year and, consequently, the impact on energy losses could be considered negligible.

4.2 Cost Estimation for the Top 60 Critical GSPs in Great Britain

This subsection presents an initial estimation of the total cost of adopting shunt reactors for the top 10 critical GSPs per DNO, i.e., a total of 60 critical GSPs in Great Britain [2]. For simplicity, the shunt reactors are sized equally to the VAr exports of each GSP. The analysis considers the nationwide trends (see Fig. 8) in a 5 year horizon and assumes a total cost of £45k per MVAr of shunt reactors (capital and installation cost).

This process allows DNOs and National Grid to have a first insight into the total cost of a solution based on shunt reactors; traditionally used in transmission networks to absorb VArs. Table 4 shows the amount of VArs and the corresponding total cost of shunt reactors per DNO for the different scenarios that define the derived nationwide trend. It is important to highlight that for each of the studied GSPs the Q demand considered for year 0 corresponds to the minimum found in 2013.

Table 4. Economic Assessment Using Shunt Reactors at top 10 critical GSPs per DNO

DNO (2013 aggregated peak demand)	Shunt Reactors	Existing Trends	Go Green	Effective Loads	Slow Progression
ENWL (2.87 GW)	*Rating (MVAr)*	650	651	811	585
	Cost (million £)	29.27	29.28	36.52	26.31
NP (2.40 GW)	*Rating (MVAr)*	491	491	613	442
	Cost (million £)	22.11	22.12	27.59	19.88
SPEN (1.61 GW)	*Rating (MVAr)*	382	382	476	343
	Cost (million £)	17.18	17.18	21.43	15.45
SSE (2.87 GW)	*Rating (MVAr)*	1211	1211	1511	1088
	Cost (million £)	54.48	54.50	67.97	48.98
UKPN (5.81 GW)	*Rating (MVAr)*	1324	1324	1652	1190
	Cost (million £)	59.57	59.59	74.32	53.56
WPD (4.85 GW)	*Rating (MVAr)*	1196	1197	1493	1076
	Cost (million £)	53.84	53.86	67.18	48.41

The range of investment for the top 60 critical GSPs is from £213 million for the most optimistic scenario (“Slow Progression”) to £295 million for the worst case (“Effective Loads”). The amount of investment, however, is not evenly distributed across DNOs. This is due to both the size of each GSP (e.g., in terms of peak P demand) and the corresponding reactive power exchange behaviour.

DNOs that operate in the South of Great Britain (i.e., SSE and UKPN) would require the highest investments according to the results of Table 4, a combined total of £103 to £142 million depending on the scenario. The aggregated peak demand for the 20 GSPs of these two DNOs account for 8.68 GW (43% of the top 60 critical GSPs in 2013). In particular, the highest investment appears for UKPN (from £54 to £74 million). On the other hand, the top 10 critical SPEN GSPs would require the lowest investment (from £15.45 to £21.43 million depending on the scenario). A significant component in this large difference between UKPN and SPEN is due to the relative sizes of the GSPs. Indeed, the aggregated peak demand of the top 10 critical SPEN GSPs account only for 8% (of the 60 GSPs analysed) whereas for UKPN this figure is 28%.

Although Q/P ratio trends are very similar across Great Britain, there are also other aspects that should be taken into account to explain the different levels of investment. In particular, the interactions between minimum P demand and network characteristics can play a significant role when comparing networks of the same size in terms of peak demand. For instance, City Road GSP (UKPN) presents a declining Q demand trend but has not exported VArs in 2013 (see subsection 3.2.1). On the other hand, Lovedean GSP (SSE), with smaller peak demand, has significant VAr exports in 2013 (see subsection 3.2.2).

4.3 Summary

The findings from the sizing of shunt reactors and the techno-economic assessment can be summarized as follows:

- based on the studies carried out on Norton and Kearsley GSPs, it was found that 1 to 3% less VArs of shunt reactors would be needed if installed at primary substations instead of at the GSP;
- the installation of shunt reactors at the primary substations do increase energy losses but this is only by 4% (Kearsley GSP). This effect can be significantly curbed by adopting time-based control strategies, i.e., switching on shunt reactors during the critical hours;
- the range of investment needed to install shunt reactors considering the top 60 critical GSPs in Great Britain and a 5 year horizon is from £213 to £295 million, depending on the nationwide trend;
- DNOs in the South of Great Britain (i.e., SSE and UKPN) would require higher investment for their top 10 critical GSPs (a combined total of £103 to £142 million depending on the scenario);
- SPEN would require the lowest investment across all DNOs (from £15.45 to £21.43 million); and,
- to explain the different levels of investment is important to consider not only the Q/P ratio trends (similar across Great Britain) but also the interactions between minimum P demand and network characteristics.

5 Considerations for Future Work

Future work should aim not only to enhance the outcomes of the current project but also to investigate potential DNO-led solutions that can tackle the effects of the decline in reactive power demand. This is needed if DNOs are to meet the requirements of the EDCC (or agreed specifications with National Grid) to limit VAr exports to transmission.

The key objectives of future work should be to:

- Produce improved network models for more critical and control GSP groups for all DNOs (note that currently original models of 19 GSPs have been produced but improved and semi-improved models for only 7 GSPs have been completed by the current REACT project). The new models will be used to enhance trend-based scenarios to assess the mid and long-term reactive power exchanges at the GSPs. Future trends in electrification of heat and transport should be also included in the enhanced scenarios. The analyses should also consider more recent monitoring and network data (after 2014).

- Use available historic statistics for network and demand changes downstream primary substations to assess corresponding trends and investigate potential correlations with the identified by the current REACT project declining Q/P ratios trends in primary demand during periods of minimum load.

- Investigate potential solutions that do not require the installation of new assets in distribution networks and the extent of their benefits. This includes, tap staggering of primary substations, the adequate settings for DG power factor (e.g., fixed, time based, scheduled), and the adoption of different voltage targets at GSPs and BSPs during minimum load so as to reduce gains on the corresponding circuits. Different deployment scenarios across GSPs could be considered so as to quantify the overall benefit to National Grid in terms of reactive power demand.

- Investigate the adoption of VAr sources, in particular shunt reactors, in distribution networks considering optimal sizing (i.e., minimum cost) and siting of the corresponding devices across voltage levels. Different deployment scenarios across GSPs could be considered so as to quantify the overall benefit to National Grid in terms of reactive power demand.

- Investigate the potential benefits to DNOs and National Grid from large-scale demand side management strategies that could in the future be made available by aggregators (e.g., smart appliance aggregators, commercial load aggregators, electric vehicle aggregators, etc.). In particular, the extra demand required to reduce GSP exports of reactive power during periods of minimum load could be quantified. This could allow understanding the availability of demand side management services needed to make this a future alternative.

6 Conclusions

The REACT project has been funded by National Grid and the six Distribution Network Operators (DNOs) in Great Britain: Electricity North West Limited (ENWL), Northern Powergrid (NP), Scottish Power Energy Networks (SPEN), Scottish and Southern Energy (SSE), UK Power Networks (UKPN) and Western Power Distribution (WPD). This project has been financially managed by Energy Networks Association (ENA).

The REACT project has been established to understand the reasons behind the decline in reactive power demand as seen by National Grid during minimum load. This will allow DNOs and National Grid establishing future trends in the reactive power exchanges at GSPs and adopt the most cost-effective actions as well as responsibilities for ongoing data provision, planning, design, and operational management in this area.

This final report of REACT project includes:

- the proposed framework and the corresponding methodology that can be used by any DNO to assess future Q demand at any of their GSPs;
- the scenario-based assessment of future trends in Q demand at GSPs across all DNOs for previously examined (ENWL, NP, SPEN, WPD) and new (SSE and UKPN) cases;
- an initial techno-economical assessment using the installation of shunt reactors at GSPs and primary substations; and,
- considerations for future studies aimed at enhancing the trends in Q demand as well as investigating distribution-based solutions.

Proposed Framework

A framework that consists of 4 stages is proposed to DNOs to assess future trends in Q demand at any of their GSPs during periods of minimum load. The proposed framework has the following characteristics:

- unlike traditional approaches followed by National Grid and, in general, transmission operators around the world, the proposed framework uses distribution network models (from GSPs to primary substations) and takes into account the effects of the actual networks, such as the type and length of circuits as well as the interactions of demand and generation;
- the proposed framework can be directly used by DNOs for any of their GSPs using their network and monitoring data;
- DNOs can use the framework to investigate and plan distribution-based solutions if they are to meet the EDDC requirement (or any agreed specifications with National Grid) to limit VArs to transmission during periods of minimum load;
- the framework consists of 4 stages that include the identification of historic demand trends, the production of improved/validated network models, the incorporation of network planning information and the scenario-based assessment of future reactive demand; and,
- the proposed framework is flexible and can be adapted to cater for the analysis of other factors that have not been considered in the REACT project (e.g., significant penetrations of wind generation or CHPs).

Future Reactive Power Demand

Following the proposed framework, the scenario-based assessment of future trends in Q demand during minimum load is presented in this final report for GSPs across all DNOs. More specifically, results are presented for previously examined cases (GSPs of ENWL, NP, SPEN, WPD) and new cases (GSPs of SSE and UKPN) covering all DNOs. Results, although limited to seven GSPs, demonstrate that:

- the declining demand trends at primary substations is the major contributor to the overall decline of Q demand during minimum load;
- future Q demand at GSPs can be significantly affected by any possible cable penetration, even in 33kV circuits;

- the expected future trends in PV penetrations do not significantly affect Q demand at GSPs;
- using improved network models the VAr exports at the ENWL and NP GSPs are expected to be increased by 30 to 175% until 2018;
- using improved network models the VAr imports for the UKPN GSP are expected to be decreased by 62 to 121% until 2018; and,
- results using semi-improved network models for the SPEN, SSE and WPD networks might not be representative because of the use of original DNO (not updated and validated) line parameters for 132 to 33kV circuits and Q/P ratio trends at primary substations using GSP monitoring data or data for short time intervals; and,
- in a 5 years horizon the Q exports to transmission are expected to increase, depending on the scenario, by 55 to 120% with respect to their 2013 level.

<u>Techno-Economic Assessment Using Shunt-Reactors</u>
An initial techno-economical assessment using shunt reactors is also presented in this final report. The investigation considers aspects regarding the sizing of shunt reactors at primary substations and the corresponding effects on energy losses. It also focuses on the amount of investment needed to be installed at GSPs to meet the requirements of the European Demand Connection Code (EDCC). The findings from the sizing of shunt reactors and the techno-economic assessment can be summarized as follows:

- based on the studies carried out on Norton and Kearsley GSPs, it was found that 1 to 3% less VArs of shunt reactors would be needed if installed at primary substations instead of at the GSP;
- the installation of shunt reactors at the primary substations do increase energy losses but this is only by 4% (Kearsley GSP). This effect can be significantly curbed by adopting time-based control strategies, i.e., switching on shunt reactors during the critical hours;
- the range of investment needed to install shunt reactors considering the top 60 critical GSPs in Great Britain and a 5 year horizon is from £213 to £295 million, depending on the nationwide trend;
- DNOs in the South of Great Britain (i.e., SSE and UKPN) would require higher investment for their top 10 critical GSPs (a combined total of £103 to £142 million depending on the scenario);
- SPEN would require the lowest investment across all DNOs (from £15.45 to £21.43 million); and,
- to explain the different levels of investment is important to consider not only the Q/P ratio trends (similar across Great Britain) but also the interactions between minimum P demand and network characteristics.

It is important to highlight that although the REACT project has been completed as scheduled, due to the delays in the collection of data and the fact that original DNO models needed to be improved, the studies have not been carried out in all the critical and control GSPs as initially expected. Therefore, the conclusions presented in this work might not be representative across Great Britain but indicative of the trends found in critical GSPs.

<u>Future Work</u>
Considerations for future work are also presented in this final report of REACT project. These include:

- the enhancement of the assessment of trends in Q demand by analysing more networks and extending the analyses downstream primary substations; and,
- the investigation of distribution-based solutions (e.g., alternatives that do not require the installation of new assets) if DNOs are to meet the requirements of the EDCC (or agreed specifications with National Grid) to limit VAr exports to transmission.

7 References

[1] ENTSO-E., "Draft Demand Connection Code", 2012. [Online]. Available: https://www.entsoe.eu/resources/network-codes/demand-connection/
[2] REACT project, “Deliverable 1. Fourth Month Report - REACT project”, Mar. 2014.
[3] REACT project, “Deliverable 4. Second Year Six Month Report - REACT project”, Apr. 2015.
[4] P. M. S. Carvalho, F. Correia Pedro, L. F. Ferreira, “Distributed Reactive Power Generation Control for Voltage Rise Mitigation in Distribution Networks” IEEE Trans. on Power Systems, vol. 23, no. 2, pp. 766-772, May 2008.
[5] P. N. Vovos, A. E. Kiprakis, A. R. Wallace, G. P. Harrison, “Centralized and Distributed Voltage Control: Impact on Distributed Generation Penetration”, IEEE Trans. on Power Systems, vol. 22, no. 1, pp. 476-483, Feb. 2007.
[6] L. F. Ochoa, A. Keane, G. P. Harrison, “Minimizing the Reactive Support for Distributed Generation: Enhanced Passive Operation and Smart Distribution Networks”, IEEE Trans. on Power Systems, vol. 26, no. 4, pp. 2134-2142, Nov. 2011.
[7] K. L. Lo, Y. A. Alturki, "Towards reactive power markets. Part 1: reactive power allocation," IEE Proc. - Generation, Transmission and Distribution, vol.153, no.1, pp.59,70, 12 Jan. 2006.
[8] J. Morin, F. Colas, X. Guillaud, S. Grenard, "Determination and Origins of Reactive Power Flows in HV/MV Substations", Proc. CIRED 2015, paper 0414, Lyon, 15-18 Jun., 2015.
[9] P. Schafer, H. Vennegeerts, S. Krahl, A. Moser, "Derivation of Recommendations for the Future Reactive Power Exchange at the Interface between Distribution and Transmission Grid", Proc. CIRED 2015, paper 0760, Lyon, 15-18 Jun., 2015.
[10] I. Talavera, P. Franz, S. Weck, J. Hanson, S. Stepanescu, R. Huber, H. Abele, "Flexible Reactive Power Exchange Between Medium and High Voltage Networks: case Study", Proc. CIRED 2015, paper 0964, Lyon, 15-18 Jun., 2015.
[11] L. Cocchi, A. Cerretti, E. Deberardinis, F. Bignucolo, A. Savio, R. Sgarbossa, "Influence of Average Power Factor Management on Active Distribution Networks", Proc. CIRED 2015, paper 0634, Lyon, 15-18 Jun., 2015.
[12] C. G. Kaloudas, L. F. Ochoa, I. Fletcher, B. Marshall, S. Majithia, "Investigating the Declining Reactive Power Demand of UK Distribution Networks", Proc. IEEE PES General Meeting 2015, Denver, Jul. 2015.
[13] REACT project, “Deliverable 3. First Year Report Stage 1 - REACT project”, Nov. 2014.
[14] National Grid, "UK Future Energy Scenarios", 2014. [Online]. Available: http://www2.nationalgrid.com/uk/industry-information/future-of-energy/future-energy-scenarios/
[15] ENTSO-E (2012 Dec.). ENTSO-E Network Code on Demand Connection. [Online]. Available: https://www.entsoe.eu/major-projects/network-code-development/demand-connection/Pages/default.aspx
[16] REACT project, “Deliverable 2. Eighth Month Report REACT project”, Jun. 2014.

8 Appendices

8.1 Appendix A – Production of improved and semi-improved network models

8.1.1 City Road GSP (UKPN)

Fig. 12 shows the single line diagrams from the original UKPN digital file (DIgSILENT file) for the 132 and 33kV circuits. It is noteworthy that there is a significant interconnection in City Road network with an adjacent GSP at 132kV (Bankside F – 132kV).

City Road GSP group has been modelled from the low voltage side of the GSP transformers (132kV) downstream to primary substations. The proposed methodology to produce improved network models in Deliverable 3 (Section 2) does not need to be followed for City Road group. More specifically, since half-hourly P and Q monitoring data have been provided by UKPN for years 2009 to 2014, only the load profiles of Paternoster-11kV primary substation has been allocated.

Additionally, since the type of lines (e.g., XLPE insulated cables, oil insulated cables etc) have been provided for all 132 to 33kV circuits, there is no need to estimate the corresponding cable penetrations. For limited number of power cables (oil insulated) there has been an update in their line susceptances using typical values.

Fig. 13 and Fig. 14 show the daily simulation results and monitoring data for P and Q demand at City Road GSP during 18th June 2013 (1st day of critical week 25 [16]) and 28th May 2013 (1st day of critical week 22 [16]).

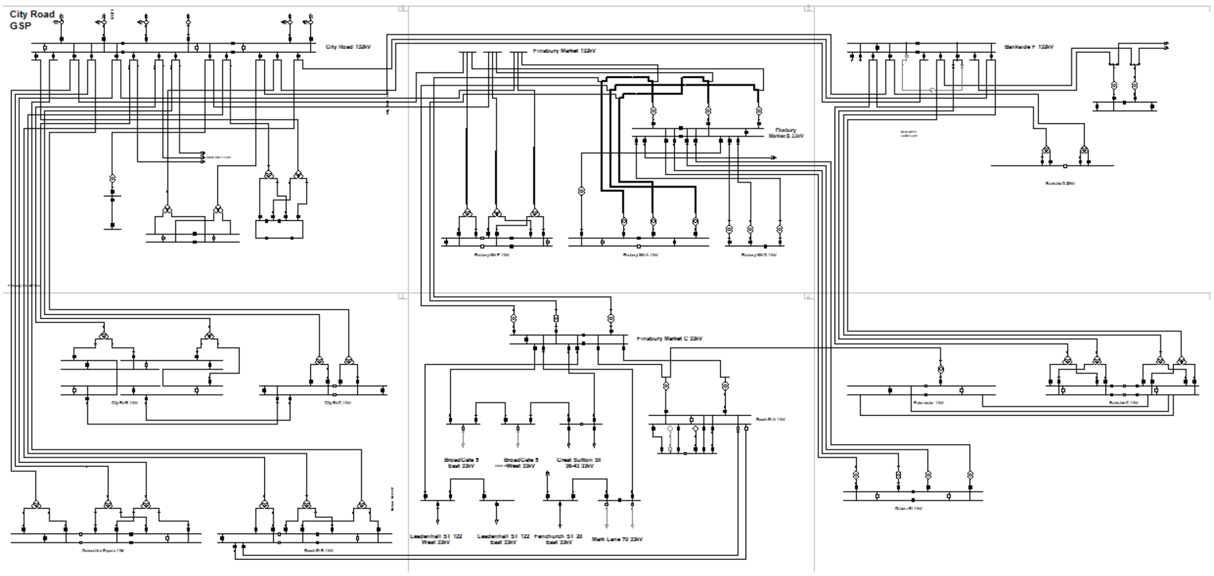

Fig. 12. Single line diagram of City Road GSP group.

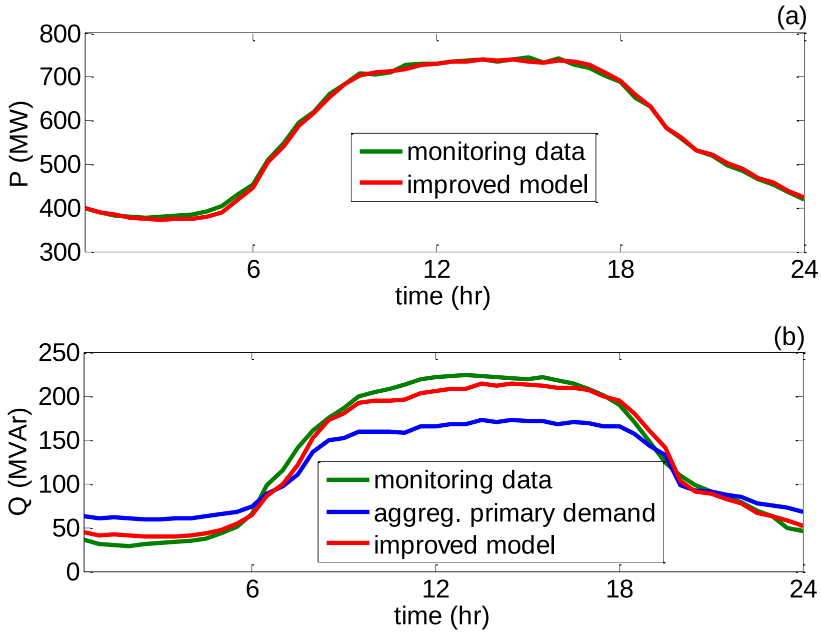

Fig. 13. Simulation results and monitoring data for City Road GSP for a) P profile and b) Q profile. Analysis for 18th June 2013.

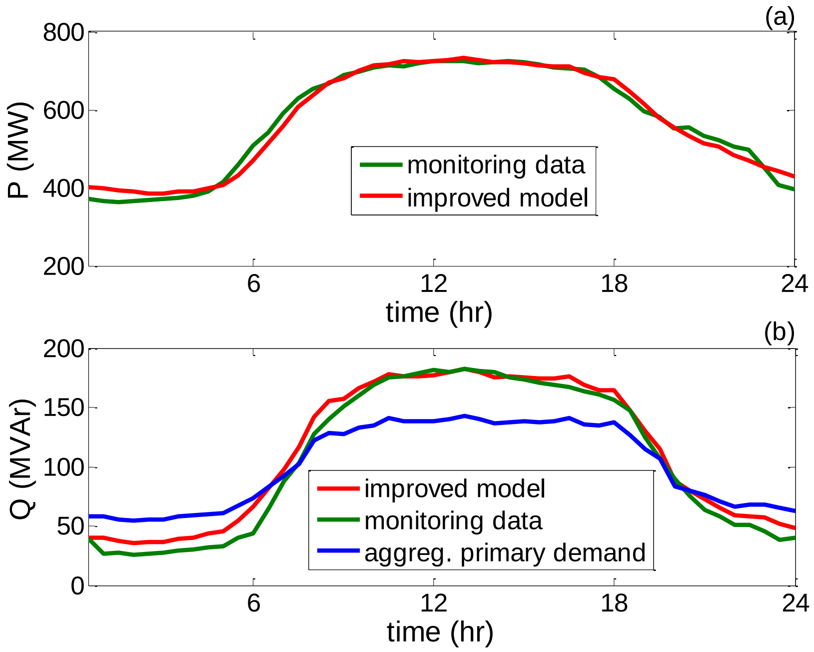

Fig. 14. Simulation results and monitoring data for City Road GSP for a) P profile and b) Q profile. Analysis for 28th May 2013.

8.1.2 Lovedean GSP (SSE)

Fig. 15 shows the single line diagrams from the original SSE digital file (PSS/E file) for the Lovedean GSP group. Although only MVA data have been provided for this network, the types of lines (e.g., cable or overhead line) have been provided by SSE for the 132kV circuits of this network. More specifically, circa 50km of the aggregated 350km of 132kV circuits correspond to cables (circa 15% of 132kV circuits are cables).

The most challenging task in the modelling of Lovedean GSP group has been the availability of only half-hourly apparent power (MVA) data for the vast majority of BSPs and primary substations. Since P and Q monitoring data are not available for most primary substations, an improved network model with realistic Q demand at primary substations cannot be produced for Lovedean GSP. Nonetheless, the produced semi-improved network model of Lovedean network can match in daily simulation the P and Q monitoring data at GSP.

Fig. 16 shows the simulation results and monitoring data for P and Q demand at Lovedean GSP during the 18th June 2013. After the load and DG allocation (see Section 2 / Deliverable 3 [13]), a uniform power factor across all primary substations without available Q data was considered and Q was allocated accordingly so as to approximate the Q demand at GSP.

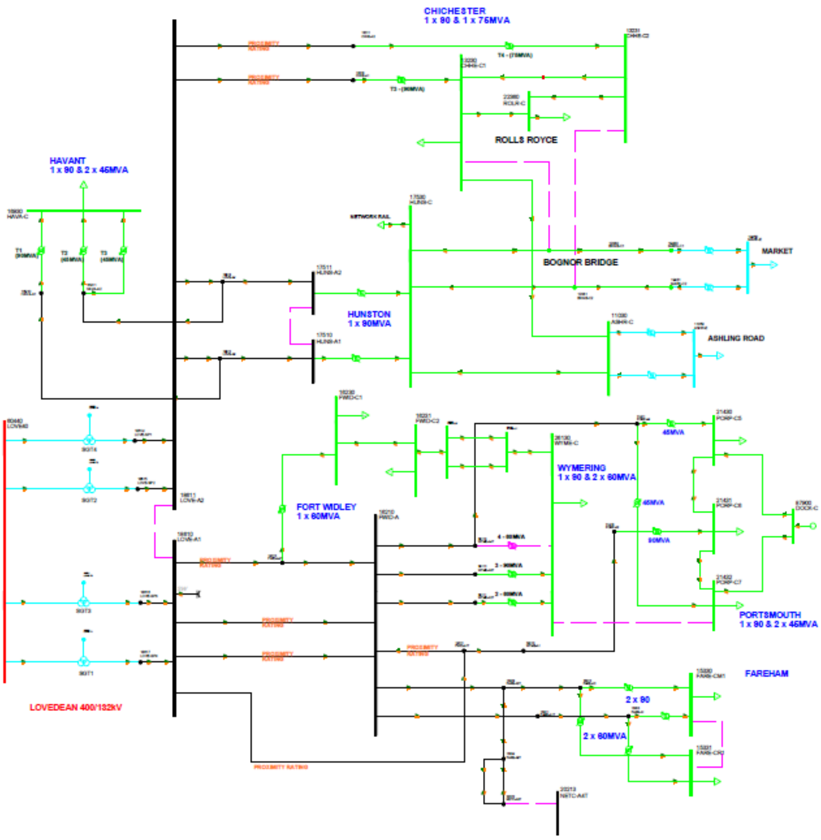

Fig. 15. Single line diagram of Lovedean GSP group.

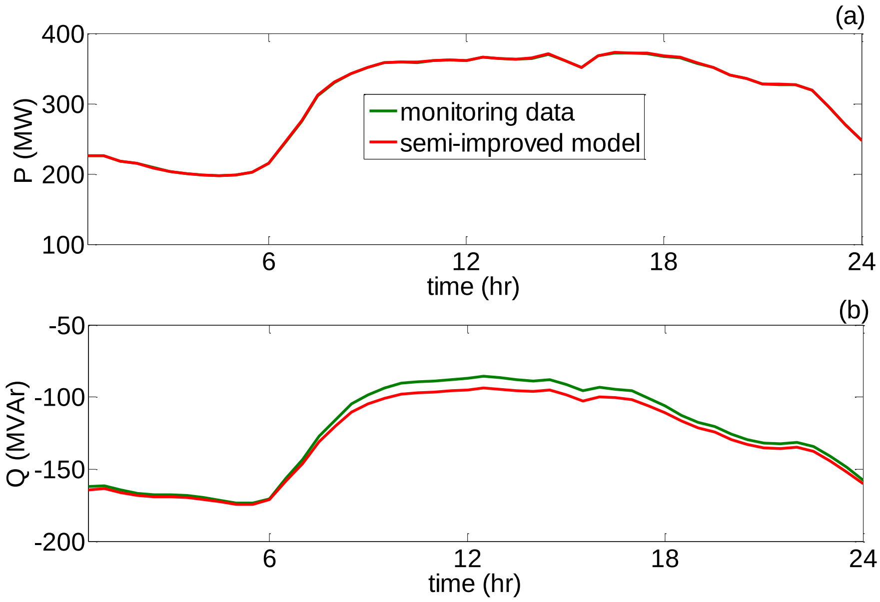

Fig. 16. Simulation results and monitoring data for Lovedean GSP for a) P profile and b) Q profile. Analysis for 18th June 2013.

8.2 Appendix B: Line Parameters of the Improved Network Models

The most important difference between an improved and a semi-improved model is the fact that line susceptances from 132 to 33kV have been updated from their original values and they have been validated in time-series simulations for multiple days.

Emphasis should be given to the fact that these line parameters could be much different from the actual line susceptance values. However, these line susceptances can provide realistic Q gains that allow the improved network models mimic the GSP behaviour during periods of minimum load. Table 5 to Table 7 show the line parameters that have been used in the improved network models of Norton (NP), Kearsley (ENWL) and City Road (UKPN) GSPs.

Table 5. Line Parameters of the Improved Network Model of Norton GSP

No	From Busbar	To Busbar	Line length (km)	Voltage (kV)	R (Ohm)	X (Ohm)	B (μS)
1	Darlington_Central_GT1_132kV	Norton_DarlCent_Darl6_tee_1	0.391	132	0.08694576	0.19270944	6.920647606
2	Darlington_North_GT1_132kV	Darlington_North_Skeeby_tee	0	132	0	0.00017424	0
3	Darlington_North_GT1_33kV	Darlington_North_33kV	0	132	0	0.017424	0
4	Darlington_North_GT2_132kV	Darlington_North_Skeeby_tee	0	132	0	0.00017424	0
5	Darlington_North_Skeeby_tee	Skeeby_132kV	21.342	132	5.5861344	7.7345136	377.7505402
6	Norton_GT1_132kV	Darlington_North_GT2_132kV	13.898	132	1.280664	5.3770464	245.9927377
7	Norton_GT2_132kV	Norton_Leeming_Hutton_tee_2	0	132	4.27097088	9.52378416	169.1460055
8	Norton_DarlCent_Darl6_tee_1	Darlington_GT1_132kV	0.672	132	0.14914944	0.2230272	11.89430995
9	Norton_DarlCent_Darl6_tee_2	Darlington_Central_GT2_132kV	0.409	132	0.09461232	0.1899216	7.239245194
10	Norton_DarlCent_Darl6_tee_2	Darlington_GT2_132kV	0.605	132	0.0156816	0.0331056	10.70841893
11	Norton_Leeming_Hutton_tee_1	Leeming_Bar_GT1_132kV	10.205	132	1.80791424	4.00943664	180.6271325
12	Norton_Leeming_Hutton_tee_2	Leeming_Bar_GT2_132kV	10.23	132	1.80791424	4.00943664	181.0696292
13	NORTONM1	Norton_GT2_132kV	0	132	0.0052272	0.0156816	0
14	NORTONM1	Norton_DarlCent_Darl6_tee_2	13.438	132	2.317392	5.296896	237.8507993
15	NORTONM1	Norton_Leeming_Hutton_tee_2	25.349	132	4.321152	9.6650928	448.6739032
16	NORTONM1	NORTONM2	0	132	0	0.017424	0
17	NORTONM2	Bowesfield_GT1_132kV	6.382	132	0.5802192	0.688248	112.9605448
18	NORTONM2	Darlington_North_GT1_132kV	13.933	132	1.2771792	5.3718192	246.612233
19	NORTONM2	North_Tees_GT2_132kV	9.345	132	0.77554224	2.45225376	165.4052478
20	NORTONR1	Darlington_North_GT2_132kV	0	132	1.280664	5.3770464	0
21	NORTONR1	North_Tees_GT1_132kV	9.279	132	0.77136048	2.43988272	164.2370566
22	NORTONR1	Norton_GT1_132kV	0	132	0.0121968	0.0191664	4.763544536
23	NORTONR1	Norton_DarlCent_Darl6_tee_1	13.4858	132	2.317392	5.279472	238.6968529
24	NORTONR1	NORTONM1	0	132	0	0.017424	0
25	NORTONR2	Bowesfield_GT2_132kV	6.341	132	0.5871888	0.6952176	112.2348503
26	NORTONR2	Norton_Leeming_Hutton_tee_1	24.998	132	4.27794048	9.54120816	442.4612503
27	NORTONR2	NORTONR1	0	132	0	0.017424	0
28	SGT1S	NORTONM2	0	132	0	0.0017424	0
29	SGT2S	NORTONM1	0	132	0	0.0017424	0
30	SGT3S	NORTONR2	0	132	0	0.0017424	0
31	SGT5S	NORTONR1	0	132	0	0.017424	0
32	sourcebus	SGT1S	0	132	0	0.00017424	0
33	sourcebus	SGT2S	0	132	0	0.00017424	0
34	Bowesfield_T2_66kV	Malleable_T2_66kV	4.088	66	0.2421936	0.3541428	84.2062592
35	Cleveland_Incinerator_66kV	Billingham_Marsh_House_T1_66kV	3.4798	66	0.633798	0.3380256	71.67831232
36	Faraday_Street_66kV	Spencerbeck_Yellow_66kV	4.949	66	0.797148	0.742698	101.9414816
37	Malleable_T1_66kV	Bowesfield_T1_66kV	4.0249	66	0.2430648	0.355014	82.90650016
38	North_Tees_66kV	Cleveland_Incinerator_66kV	1.5307	66	0.3171168	0.1690128	31.52997088
39	North_Tees_66kV	Faraday_Street_66kV	3.518	66	0.39204	0.4460544	72.4651712
40	North_Tees_66kV	Haverton_Incinerator_66kV	1.692	66	0.2169288	0.2321748	34.8524928
41	North_Tees_66kV	Malleable_T1_66kV	2.596	66	0.1411344	0.2182356	53.4734464
42	North_Tees_66kV	Malleable_T2_66kV	2.589	66	0.1659636	0.2208492	53.3292576
43	North_Tees_66kV	Mond_T1_66kV	1.155	66	0.06534	0.08712	23.791152
44	North_Tees_66kV	Mond_T2_66kV	1.156	66	0.06534	0.08712	23.8117504
45	North_Tees_66kV	New_Road_T1_66kV	0.269	66	0.034848	0.030492	5.5409696
46	North_Tees_66kV	New_Road_T2_66kV	0.313	66	0.034848	0.030492	6.4472992
47	North_Tees_66kV	North_Tees_T1_4_66kV	0	66	0	0.0004356	0
48	North_Tees_66kV	North_Tees_T2_3_66kV	0	66	0	0.0004356	0
49	North_Tees_66kV	Seal_Sands_Green_(Saltholme)	5.769	66	0.3306204	0.7727544	118.8321696
50	North_Tees_66kV	Seal_Sands_Red_(Saltholme)	5.682	66	0.3306204	0.7727544	117.0401088
51	North_Tees_GT1_66kV	North_Tees_66kV	0.1	66	0	0.0004356	2.05984
52	North_Tees_GT2_66kV	North_Tees_66kV	0.106	66	0	0.0004356	2.1834304
53	North_Tees_Spencerbeck_Billingham_tee	Billingham_Marsh_House_T2_66kV	4.89752	66	0.8119584	0.4978908	100.881076
54	North_Tees_Spencerbeck_Billingham_tee	North_Tees_66kV	0	66	0	0.0004356	0
55	Spencerbeck_Yellow_66kV	North_Tees_Spencerbeck_Billingham_tee	7.932	66	0.8681508	0.8607456	163.3865088
56	Bowesfield_33kV	Acklam_T1_33kV	5.892	33	0.5441733	0.4577067	132.7822958
57	Bowesfield_33kV	Acklam_T2_33kV	5.929	33	0.5454801	0.4607559	133.616129
58	Bowesfield_33kV	Millbank_Lane_T1_33kV	2.413	33	0.2699631	0.2010294	54.37944329
59	Bowesfield_33kV	Millbank_Lane_T2_33kV	2.417	33	0.2710521	0.2020095	54.46958741
60	Bowesfield_33kV	Rudby_T1_33kV	12.57	33	1.9080369	3.5931555	283.2779122
61	Bowesfield_33kV	Stokesley_T2_33kV	5.046	33	2.1960774	4.1751171	113.7168134
62	Bowesfield_33kV	Urlay_Nook_T1_33kV	6.14	33	0.8432127	1.1209077	138.3712316
63	Bowesfield_33kV	Urlay_Nook_T2_33kV	6.193	33	0.8437572	1.1197098	139.5656412
64	Bowesfield_33kV	Urlay_Nook_T3_33kV	6.059	33	0.8306892	1.2013848	136.545813
65	Bowesfield_GT1_33kV	Bowesfield_33kV	0	33	0	0.0001089	0
66	Bowesfield_GT2_33kV	Bowesfield_33kV	0	33	0	0.0001089	0
67	Catterick_Camp_T1_33kV	Skeeby_Hipswell_Catterick_tee_1	2.198	33	0.4586868	0.3229974	49.53419658
68	Catterick_Camp_T2_33kV	Skeeby_Hipswell_Catterick_tee_2	2.012	33	0.3200571	0.2810709	45.34249477
69	Cowton_T1_33kV	Northallerton_T2_33kV	9.429	33	1.5122943	3.2326965	212.4922382
70	Darlington_Central_33kV	Darlington_East_T1_33kV	2.239	33	0.1632411	0.2235717	50.45817386
71	Darlington_Central_33kV	Darlington_East_T2_33kV	2.245	33	0.1634589	0.224334	50.59339004
72	Darlington_Central_33kV	Darlington_T1_33kV	1.73	33	0.1647657	0.1714086	38.98733398

73	Darlington_Central_33kV	Darlington_T2_33kV	1.734	33	0.1659636	0.1733688	39.0774781
74	Darlington_Central_33kV	Rise_Carr_T1_33kV	3.682	33	0.0684981	0.1319868	82.97766688
75	Darlington_Central_33kV	Rise_Carr_T2_33kV	3.682	33	0.0684981	0.1319868	82.97766688
76	Darlington_Central_GT1_33kV	Darlington_Central_33kV	0	33	0	0.0001089	0
77	Darlington_Central_GT2_33kV	Darlington_Central_33kV	0	33	0	0.0001089	0
78	Darlington_East_T2_33kV	Cowton_T1_33kV	10.2888	33	1.5277581	3.2482692	231.8687178
79	Darlington_North_33kV	Aycliffe_Industrial_T1_33kV	9.178	33	2.33046	3.31056	206.8356944
80	Darlington_North_33kV	Aycliffe_Industrial_T2_33kV	9.569	33	2.3958	3.17988	215.6472826
81	Darlington_North_33kV	DNorth_Rise_Carr_DWest_tee_1	1.182	33	0.1259973	0.1029105	26.63758888
82	Darlington_North_33kV	DNorth_Rise_Carr_DWest_tee_2	1.07	33	0.1259973	0.1029105	24.11355338
83	Darlington_North_33kV	Heighington_T1_33kV	4.57	33	0.74052	1.36125	102.9896626
84	Darlington_North_33kV	Heighington_T2_33kV	4.681	33	0.78408	1.36125	105.491162
85	Darlington_North_33kV	Newton_Aycliffe_South_T1_33kV	7.04359	33	1.0422819	1.6316487	158.734564
86	Darlington_North_33kV	Newton_Aycliffe_South_T2_33kV	6.426	33	0.9285903	1.347093	144.8165365
87	Darlington_North_33kV	Richmond_T2_33kV	22.284	33	5.741208	7.911585	502.1929193
88	Darlington_North_33kV	Rise_Carr_T1_33kV	1.182	33	0.0949608	0.109989	26.63758888
89	Darlington_North_33kV	Rise_Carr_T2_33kV	1.083	33	0.0939807	0.11980089	24.40652179
90	Darlington_North_GT2_33kV	Darlington_North_33kV	0	33	0	0.001089	0
91	DNorth_Rise_Carr_DWest_tee_1	Darlington_West_T1_33kV	3.403	33	0.3899709	0.2959902	76.69011417
92	DNorth_Rise_Carr_DWest_tee_1	Rise_Carr_T1_33kV	0	33	0	0.00001089	0
93	DNorth_Rise_Carr_DWest_tee_2	Darlington_West_T2_33kV	3.403	33	0.3899709	0.2959902	76.69011417
94	DNorth_Rise_Carr_DWest_tee_2	Rise_Carr_T2_33kV	0	33	0	0.00001089	0
95	Leeming_Bar_33kV	Bedale_T2_33kV	5.59	33	1.0829016	2.1244212	125.9764144
96	Leeming_Bar_33kV	Catterick_Camp_T1_33kV	15.619	33	2.6525862	4.8795912	351.9902713
97	Leeming_Bar_33kV	Catterick_Camp_T2_33kV	14.759	33	2.5720002	4.4829774	332.6092845
98	Leeming_Bar_33kV	Leeming_Leeming_RAF_Thirsk_tee	5.324	33	1.1665368	2.0944737	119.9818301
99	Leeming_Bar_33kV	Leeming_Thirsk_Romanby_tee	5.005	33	1.5304806	1.9605267	112.7928362
100	Leeming_Bar_33kV	Leeming_Wensleydale_Bedale_tee	16.742	33	0.3199482	0.6809517	377.2982344
101	Leeming_Bar_33kV	Northallerton_T1_33kV	2.935	33	1.1407275	2.1519729	66.14325157
102	Leeming_Bar_33kV	Northallerton_T2_33kV	6.6573	33	1.026927	1.8241839	150.0291205
103	Leeming_Bar_33kV	Wensleydale_T2_33kV	5.892	33	3.3274395	6.0255459	132.7822958
104	Leeming_Bar_GT1_33kV	Leeming_Bar_33kV	0	33	0	0.001089	0
105	Leeming_Bar_GT2_33kV	Leeming_Bar_33kV	0	33	0	0.001089	0
106	Leeming_Leeming_RAF_Thirsk_tee	Leeming_RAF_33kV	2.11	33	0.5784768	0.51183	47.55102583
107	Leeming_Leeming_RAF_Thirsk_tee	Thirsk_T1_33kV	12.207	33	1.983069	3.55854708	275.0973329
108	Leeming_Thirsk_Romanby_tee	Romanby_33kV	3.875	33	0	0.0001089	87.3271209
109	Leeming_Thirsk_Romanby_tee	Thirsk_T2_33kV	12.562	33	3.7550898	4.8152313	283.0976239
110	Leeming_Wensleydale_Bedale_tee	Bedale_T1_33kV	3.524	33	0.677358	1.2376485	79.41697395
111	Leeming_Wensleydale_Bedale_tee	Wensleydale_T1_33kV	18.173	33	3.3792759	6.1043895	409.547295
112	Richmond_T1_33kV	Skeeby_33kV	1.596	33	0.3225618	0.2339172	35.9675058
113	Rudby_T1_33kV	Rudby_T2_33kV	0	33	0	0.0001089	0
114	Rudby_T2_33kV	Stokesley_T1_33kV	6.44799	33	0.952875	1.976535	145.3121038
115	Skeeby_33kV	Skeeby_Hipswell_Catterick_tee_1	3.565	33	0.58806	1.24146	80.34095123
116	Skeeby_Hipswell_Catterick_tee_1	Hipswell_T1_33kV	0.875	33	0.0279873	0.0509652	19.7190273
117	Skeeby_Hipswell_Catterick_tee_2	Hipswell_T2_33kV	0.84	33	0.0279873	0.0509652	18.93026621
118	Skeeby_Hipswell_Catterick_tee_2	Skeeby_33kV	4.491	33	0.40293	0.86031	101.2093161
119	Stokesley_T2_33kV	Stokesley_T1_33kV	0	33	0	0.0001089	0
120	Aycliffe_Norsk_Sw	Aycliffe_Industrial_11kV	0	11.5	0.13225	0.066125	0
121	Aysgarth_Generation	Wensleydale_11kV	0	11.5	15.803875	65.1728	0
122	Bill_Moreland_s_s	Bill_Pentland_s_s	0	11.5	2.24825	8.133375	0
123	Billingham_Marsh_House_11kV	Bill_Moreland_s_s	0	11.5	0.8768175	0.3795575	0
124	BSC_Chemicals_Sw	Clarence_Gen_Sw	0	11.5	0.13225	0.066125	0
125	Cowpen_Generation_Sw	North_Tees_3_4_11kV	0	11.5	1.3225	0.4761	0
126	Darlington_11kV	Stressholme_STW	0	11.5	3.09465	8.794625	0
127	Darlington_Central_11kV	P_B1	0	11.5	0.298885	0.2102775	0
128	Darlington_Central_11kV	P_B2	0	11.5	0.288305	0.2044585	0
129	Darlington_West_11kV	Darlington_Memorial_Hospital	0	11.5	0.938975	3.35915	0
130	Heighington_11kV	Aycliffe_Fujitsu	0	11.5	0.0357075	0.02645	0
131	North_Tees_3_4_11kV	BSC_Chemicals_Sw	0	11.5	0.833175	0.4761	0
132	Northallerton_T1_11kV	Northallerton_11kV	0	11.5	0	0.00013225	0
133	Northallerton_T2_11kV	Northallerton_11kV	0	11.5	0	0.00013225	0
134	Richmond_11kV	Citadilla_Generation	0	11.5	2.77725	7.0357	0
135	Stokesley_11kV	Nurseries_Gen_Sw	0	11.5	0.34385	0.18515	0
136	Stressholme_STW	Darlington_11kV	0	11.5	3.09465	8.794625	0
137	Norton_11kV	North_Tees_Hosp	0	11	0.3025	0.2057	0
138	Darlington_6kV	Darlington_Brown_6kV	0	6.5	0.0004225	0.232375	0
139	Darlington_6kV	Darlington_Pink_6kV	0	6.5	0.0004225	0.232375	0
140	Darlington_GT1_6kV	Darlington_6kV	0	6.5	0	0.000004225	0
141	Darlington_GT2_6kV	Darlington_6kV	0	6.5	0	0.000004225	0
142	Darlington_Pink_6kV	Darlington_Brown_6kV	0	6.5	0.000004225	0.000004225	0
143	Rise_Carr_T1_6kV	Rise_Carr_6kV	0	6.5	0	0.075205	0
144	Rise_Carr_T2_6kV	Rise_Carr_6kV	0	6.5	0	0.075205	0

Table 6. Line Parameters of the Improved Network Model of Kearsley GSP

No	From Busbar	To Busbar	Line length (km)	Voltage (kV)	R (Ohm)	X (Ohm)	B (μS)
1	agecro_132_gt1	freder_132_gt1	3.54	132	0.30631392	0.3763584	114.791763
2	agecro_132_gt2	freder_132_gt2	3.57	132	0.31206384	0.38054016	115.7645746
3	agecro_132_ju1	freder_132_gt3	9.79	132	0.1838232	0.20002752	317.4608362
4	athert_132_te1	athert_132_gt1	0.14	132	0.01202256	0.01585584	4.539787239
5	athert_132_te1	westho_132_gt1	6.02	132	0.40266864	1.1569536	195.2108513
6	athert_132_te2	athert_132_gt2	0.06	132	0.00505296	0.00679536	1.945623102
7	athert_132_te2	westho_132_gt2	6.02	132	0.40197168	1.15643088	195.2108513
8	bolton_132_gt1	bolton_132_gt3	0	132	0	0.017424	0
9	bolton_132_gt1	bolton_132_gt4	0	132	0	0.017424	0
10	bury_132_gt2	radcli_132_te2	7.69	132	0.56140128	2.56550976	249.3640276
11	kea_1005	kearsl_132_mb3	0	132	0	0.017424	0
12	kea_1005	kearsl_132_rb3b	0	132	0	0.017424	0
13	kea_105	kearsl_132_mb1	0	132	0	0.017424	0
14	kea_105	kearsl_132_rb1b	0	132	0	0.017424	0
15	kea_150	kea_151a	0	132	0	0.017424	0
16	kea_150	kearsl_132_mb2	0	132	0	0.017424	0
17	kea_150	kearsl_132_rb2	0	132	0	0.017424	0
18	kea_151a	kea_151b	0	132	0	0.017424	0
19	kea_151a	kea_151c	0	132	0	0.017424	0
20	kea_180	kearsl_132_mb1	0	132	0	0.017424	0
21	kea_180	kearsl_132_rb1b	0	132	0	0.017424	0
22	kea_205	kearsl_132_mb2	0	132	0	0.017424	0
23	kea_205	kearsl_132_rb2	0	132	0	0.017424	0
24	kea_280a	kearsl_132_mb3	0	132	0	0.017424	0
25	kea_280a	kearsl_132_rb3b	0	132	0	0.017424	0
26	kea_305	kearsl_132_mb1	0	132	0	0.017424	0
27	kea_305	kearsl_132_rb1b	0	132	0	0.017424	0
28	kea_380a	kearsl_132_mb1	0	132	0	0.017424	0
29	kea_380a	kearsl_132_rb1b	0	132	0	0.017424	0
30	kea_405	kearsl_132_mb3	0	132	0	0.017424	0
31	kea_405	kearsl_132_rb3b	0	132	0	0.017424	0
32	kea_480	kearsl_132_mb3	0	132	0	0.017424	0
33	kea_480	kearsl_132_rb3b	0	132	0	0.017424	0
34	kea_505	kearsl_132_mb1	0	132	0	0.017424	0
35	kea_505	kearsl_132_rb1b	0	132	0	0.017424	0
36	kea_605	kearsl_132_mb3	0	132	0	0.017424	0
37	kea_605	kearsl_132_rb3b	0	132	0	0.017424	0
38	kea_705	kearsl_132_mb1	0	132	0	0.017424	0
39	kea_705	kearsl_132_rb1b	0	132	0	0.017424	0
40	kea_780	kea_781	0	132	0	0.017424	0
41	kea_780	kearsl_132_mb2	0	132	0	0.017424	0
42	kea_780	kearsl_132_rb2	0	132	0	0.017424	0
43	kea_805	kearsl_132_mb3	0	132	0	0.017424	0
44	kea_805	kearsl_132_rb3b	0	132	0	0.017424	0
45	kea_1005	athert_132_te2	12.78	132	0.67518	4.81268304	414.4177208
46	kea_105	athert_132_te1	12.8	132	0.69417216	4.89858336	415.0662619
47	kea_205	agecro_132_ju1	6	132	0.73076256	1.70511264	194.5623102
48	kea_305	agecro_132_gt1	6.29	132	0.92364624	2.26512	203.9661552
49	kea_505	bolton_132_gt1	10.17	132	0.63911232	3.0936312	329.7831159
50	kea_605	bolton_132_gt4	10.44	132	0.63754416	3.10286592	338.5384198
51	kea_705	radcli_132_te1	1.68	132	0.1141272	0.54084096	54.47744687
52	kea_805	agecro_132_gt2	5.97	132	0.69713424	1.62879552	193.5894987
53	kearsl_132_mb1	kearsl_132_mb2	0	132	0	0.017424	0
54	kearsl_132_mb2	kearsl_132_mb3	0	132	0	0.017424	0
55	kearsl_132_rb1b	kearsl_132_mb1	0	132	0	0.017424	0
56	kearsl_132_rb1b	kearsl_132_rb2	0	132	0	0.017424	0
57	kearsl_132_rb2	kearsl_132_rb3b	0	132	0	0.017424	0
58	kearsl_132_rb3b	kearsl_132_mb3	0	132	0	0.017424	0
59	kearsl_132_sgt1	kea_180	0	132	0	0.017424	0
60	kearsl_132_sgt1	sourcebus	0	132	0	0.00017424	0
61	kearsl_132_sgt2a	kea_280a	0	132	0	0.017424	0
62	kearsl_132_sgt2a	sourcebus	0	132	0	0.00017424	0
63	kearsl_132_sgt3a	kea_380a	0	132	0	0.017424	0
64	kearsl_132_sgt3a	sourcebus	0	132	0	0.00017424	0
65	kearsl_132_sgt4	kea_480	0	132	0	0.017424	0
66	kearsl_132_sgt4	sourcebus	0	132	0	0.00017424	0
67	radcli_132_gt1	radcli_132_te1	0	132	0.04634784	0.2317392	0
68	radcli_132_gt2	radcli_132_te2	0	132	0.05645376	0.26170848	0
69	radcli_132_te1	bury_132_gt1	7.71	132	0.55983312	2.56324464	250.0125687
70	radcli_132_te2	kea_405	1.73	132	0.1123848	0.53526528	56.09879945

71	walmsl_132_tee	bolton_132_gt1	1	132	0.156816	0.4024944	32.42705171
72	walmsl_132_tee	sctmor_tee	0	132	2.27749104	5.74486704	0
73	walmsl_132_tee	walmsl_132_gt1	0	132	0	0.017424	0
74	agecro_33_a	agecro_33_b	0	33	0	0.001089	0
75	agecro_33_b	swinto_33_t12	0.95	33	0.35852058	0.33597828	24.18476517
76	agecro_33_gt1	agecro_gt1	0	33	0	0.001089	0
77	agecro_33_gt2	agecro_gt2	0	33	0	0.001089	0
78	agecro_gt1	agecro_33_a	0	33	0	0.001089	0
79	agecro_gt2	agecro_33_b	0	33	0	0.001089	0
80	ancnor_33_tee	blafri_33_a	0.1	33	0.11123046	0.12561615	2.545764755
81	athert_33_a	athert_33_b	0	33	0	0.001089	0
82	athert_33_gt1	athert_gt1	0	33	0	0.001089	0
83	athert_33_gt2	athert_gt2	0	33	0	0.001089	0
84	athert_gt1	athert_33_a	0	33	0	0.001089	0
85	athert_gt2	athert_33_b	0	33	0	0.001089	0
86	athetc_33_t11	athert_33_a	2.257	33	0.19997307	0.17775747	57.45791052
87	athetc_33_t12	athert_33_b	2.52	33	0.24626646	0.29523879	64.15327182
88	athetc_33_t12	hindly_33_b	5.486	33	0.62862525	0.91366011	139.6606544
89	barbar_33_t11	bolton_33_d	5.081	33	0.6357582	0.4740417	129.3503072
90	bedford_33_t12	athert_33_b	2.747	33	0.31934925	0.22385484	69.93215781
91	bedford_33_tee	athert_33_a	0	33	0	0.001089	0
92	bedford_33_tee	bedford_33_t11	3.005	33	0.30476754	0.26518239	76.50023088
93	blafri_33_a	blafri_33_b	0	33	0	0.001089	0
94	blafri_33_b	freder_33_a	0.1	33	0.1127115	0.24846624	2.545764755
95	blafri_33_t11	freder_33_b	0.1	33	0.22310343	0.19419048	2.545764755
96	bolton_33_a	bolton_33_d	0	33	0	0.001089	0
97	bolton_33_a	uniord_33_t11	0.145	33	0.01537668	0.0140481	3.691358894
98	bolton_33_a	wordsw_33_t11	1.931	33	0.15131655	0.15107697	49.15871742
99	bolton_33_b	bolton_33_a	0	33	0	0.001089	0
100	bolton_33_b	coxgre_33_t12	5.019	33	0.64549386	0.57903219	127.771933
101	bolton_33_b	uniord_33_t12	0.135	33	0.01626966	0.01486485	3.436782419
102	bolton_33_b	wordsw_33_t12	3.425	33	0.30145698	0.2707254	87.19244285
103	bolton_33_c	bolton_33_d	0	33	0	0.001089	0
104	bolton_33_c	prinst_33_a	1.398	33	0.1472328	0.1298088	35.58979127
105	bolton_33_gt1	bolton_gt1	0	33	0	0.001089	0
106	bolton_33_gt3	bolton_gt3	0	33	0	0.001089	0
107	bolton_33_gt4	bolton_gt4	0	33	0	0.001089	0
108	bolton_gt1	bolton_33_c	0	33	0	0.001089	0
109	bolton_gt3	bolton_33_b	0	33	0	0.001089	0
110	bolton_gt4	bolton_33_a	0	33	0	0.001089	0
111	bolwas_33_a	kealoc_33_c	6.342	33	0.61906383	0.742698	161.4524007
112	bradga_33_t11	bolton_33_d	2.99	33	0.38269638	0.29576151	76.11836617
113	bradga_33_t12	barbar_33_t12	2.22	33	0.17633088	0.17345592	56.51597756
114	bradga_33_t12	bolton_33_c	2.66	33	0.21810492	0.20282625	67.71734248
115	bradsh_33_a	bolton_33_a	2.212	33	0.19033542	0.16918704	56.31231638
116	bradsh_33_a	harwoo_33_t11	1.55	33	0.13701798	0.121968	39.4593537
117	bury_33_a	rock_33_tee	0	33	0	0.001089	0
118	bury_33_b	bury_33_a	0	33	0	0.001089	0
119	bury_33_b	rock_33_t12	2	33	0.15288471	0.14880096	50.9152951
120	bury_33_gt1	bury_gt1	0	33	0	0.001089	0
121	bury_33_gt2	bury_gt2	0	33	0	0.001089	0
122	bury_gt1	bury_33_a	0	33	0	0.001089	0
123	bury_gt2	bury_33_b	0	33	0	0.001089	0
124	butoct_33_a	bury_33_a	1.081	33	0.09047412	0.09991575	27.519717
125	butoct_33_b	butoct_33_a	0	33	0	0.001089	0
126	butoct_33_tee	bury_33_b	1.899	33	0.15979986	0.1691217	48.34407269
127	butoct_33_tee	butoct_33_b	0	33	0	0.001089	0
128	butoct_33_tee	heabri_33_b	2.607	33	0.22214511	0.20073537	66.36808716
129	carrst_33_t11	kealoc_33_c	5.08	33	0.54356346	0.45191322	129.3248495
130	carrst_33_t12	kealoc_33_b	5.083	33	0.54246357	0.4514994	129.4012225
131	chambe_33_t11	rock_33_tee	0.08	33	0.00890802	0.00814572	2.036611804
132	chambe_33_t12	bury_33_b	0.08	33	0.009801	0.00896247	2.036611804
133	chehil_33_t11	agecro_33_a	6.157	33	0.59648886	0.51906096	156.742736
134	chehil_33_t12	fredrd_33_tee	3.37	33	0.34301322	0.29846223	85.79227224
135	clijun_33_t11	clijun_33_tee	0.95	33	0.18751491	0.10598148	24.18476517
136	clijun_33_tee	agecro_33_a	0.994	33	0.09796644	0.08524692	25.30490166
137	clijun_33_tee	swinto_33_t11	1.81	33	0.2546082	0.24733368	46.07834206
138	coxgre_33_t11	bradsh_33_a	2.995	33	0.45754335	0.28652679	76.24565441
139	crownl_33_t11	westho_33_b	6.427	33	0.90022185	1.8073044	163.6163008
140	crownl_33_t12	westho_33_a	3.451	33	1.01704977	1.78910721	87.85434169
141	dumlan_33_a	dumlan_33_b	0	33	0	0.001089	0
142	dumlan_33_a	dumlan_33_t11	0	33	0	0.001089	0
143	dumlan_33_b	bury_33_a	3.908	33	0.32717916	0.29761281	99.48848662
144	dumlan_33_t11	heabri_33_a	4.417	33	0.45918774	0.71586504	112.4464292

145	farnwo_33_t11	campst_33_t11	1.696	33	0.1477773	0.13534092	43.17617024
146	farnwo_33_t11	kealoc_33_c	3.325	33	0.26056503	0.27455868	84.6466781
147	farnwo_33_t12	campst_33_t12	2.477	33	0.24996906	0.2228094	63.05859298
148	farnwo_33_t12	kealoc_33_b	3.278	33	0.26900478	0.27308853	83.45016866
149	freder_33_a	chapew_33_t11	2.431	33	0.14851782	0.26360334	61.88754119
150	freder_33_a	freder_33_b	0	33	0	0.001089	0
151	freder_33_a	robhal_33_t11	1.987	33	0.20989386	0.19145709	50.58434568
152	freder_33_a	trinit_33_t11	1.75	33	0.09663786	0.17513298	44.55088321
153	freder_33_a	weaste_33_t12	3.993	33	0.44385462	0.31490613	101.6523867
154	freder_33_b	freder_33_c	0	33	0	0.001089	0
155	freder_33_c	chapew_33_t12	2.434	33	0.14851782	0.26360334	61.96391413
156	freder_33_c	freder_33_t12	0.1	33	0.0060984	0.00670824	2.545764755
157	freder_33_c	trinit_33_tee	0	33	0	0.001089	0
158	freder_33_c	weaste_33_t11	4.005	33	0.44897292	0.31970862	101.9578784
159	freder_33_gt1	freder_gt1	0	33	0	0.001089	0
160	freder_33_gt2	freder_gt2	0	33	0	0.001089	0
161	freder_33_gt3	freder_gt3	0	33	0	0.001089	0
162	freder_33_t11	freder_33_b	0.1	33	0.00626175	0.00687159	2.545764755
163	freder_gt1	freder_33_a	0	33	0	0.001089	0
164	freder_gt2	freder_33_b	0	33	0	0.001089	0
165	freder_gt3	freder_33_c	0	33	0	0.001089	0
166	fredrd_33_tee	agecro_33_b	1.106	33	0.25479333	0.22170951	28.15615819
167	fredrd_33_tee	freder_33_b	0	33	0.11100177	0.09658341	0
168	harwoo_33_t12	bolton_33_b	3.002	33	0.2139885	0.21708126	76.42385794
169	heabri_33_b	heabri_33_a	0	33	0	0.001089	0
170	heabri_33_b	heahil_33_b	1.702	33	0.11537955	0.13029885	43.32891613
171	height_33_t11	agecro_33_a	2.23	33	0.33501996	0.21222432	56.77055403
172	height_33_t12	agecro_33_b	2.02	33	0.33597828	0.21287772	51.42444805
173	hiltop_33_b	hiltop_33_a	0	33	0	0.001089	0
174	hiltop_33_t13	kealoc_33_c	3.918	33	0.58017564	0.32912847	99.74306309
175	hindly_33_a	hindly_33_tee	0.1	33	0.441045	0.799326	2.545764755
176	hindly_33_b	hindly_33_a	0	33	0	0.001089	0
177	hindly_33_t11	hindly_33_a	0	33	0	0.001089	0
178	hindly_33_t13	bedford_33_tee	0.1	33	0.66691449	0.6321645	2.545764755
179	hindly_33_tee	wigan_33_b	0	33	0	0.001089	0
180	holtst_33_a	holtst_33_b	0	33	0	0.001089	0
181	holtst_33_a	woolfo_33_a	6.07	33	0.757944	0.54006777	154.5279206
182	holtst_33_b	bury_33_a	6.364	33	0.83971701	1.42129746	162.012469
183	kealoc_33_b	clijun_33_t12	5.016	33	1.155429	1.40436351	127.6955601
184	kealoc_33_b	hiltop_33_b	4.3	33	0.322344	0.21145113	109.4678845
185	kealoc_33_b	kealoc_33_c	0	33	0	0.001089	0
186	kealoc_33_b	kealoc_sgt2	0	33	0	0.001089	0
187	kealoc_33_b	lithul_33_b	5.692	33	0.8523603	0.55405053	144.9049298
188	kealoc_33_b	moslan_33_a	7.719	33	1.07891586	1.41650586	196.5075814
189	kealoc_33_c	hiltop_33_a	4.394	33	0.32832261	0.2161665	111.8609033
190	kealoc_sgt3	kealoc_33_c	0	33	0	0.001089	0
191	kirkha_33_t11	athert_33_b	1.334	33	0.19893852	0.1302444	33.96050183
192	kirkha_33_t12	athert_33_a	1.401	33	0.14360643	0.12934053	35.66616421
193	knomil_33_b	blafri_33_a	1.5	33	0.1931886	0.16833762	38.18647132
194	leigh_33_t11	leigh_33_tee	2.663	33	0.26022744	0.31196583	67.79371542
195	leigh_33_tee	athert_33_b	0	33	0	0.001089	0
196	lithul_33_b	leigh_33_tee	0	33	1.5149079	0.98656866	0
197	lithul_33_t11	kealoc_33_c	6.242	33	0.91968228	0.60891435	158.906636
198	lostoc_33_t11	westho_33_b	2.878	33	0.1635678	0.2964258	73.26710964
199	lostoc_33_t12	westho_33_a	3.25	33	0.23374296	0.22243914	82.73735453
200	moslan_33_b	moslan_33_a	0	33	0	0.001089	0
201	moslan_33_t11	kealoc_33_c	5.65	33	0.86512338	0.54992322	143.8357086
202	moslan_33_t11	moslan_33_a	0	33	0	0.001089	0
203	musgrd_33_t11	bolton_33_d	3.112	33	0.32311719	0.28231236	79.22419917
204	musgrd_33_t12	prinst_33_a	1.863	33	0.193842	0.1692306	47.42759738
205	newhea_tee	redban_33_c	0.1	33	0.40402989	0.3777741	2.545764755
206	pendle_33_t11	freder_33_b	1.107	33	0.08405991	0.07693785	28.18161584
207	pendle_33_t12	trinit_33_tee	1.118	33	0.08564985	0.07833177	28.46164996
208	ppg_33_a	hindly_33_t11	2.312	33	0.17747433	0.20290248	58.85808113
209	ppg_33_t11	athert_33_a	3.685	33	0.28903149	0.3066624	93.81143121
210	ppg_33_t11	ppg_33_a	0	33	0	0.001089	0
211	ppg_33_t12	athert_33_b	3.623	33	0.20597346	0.37327653	92.23305707
212	ppg_33_t12	ppg_33_a	0	33	0	0.001089	0
213	prestw_33_t11	agecro_33_a	3.484	33	0.20258667	0.30157677	88.69444406
214	prestw_33_t12	agecro_33_b	3.514	33	0.20759607	0.30580209	89.45817348
215	prestw_33_t12	moslan_33_b	2.553	33	0.08465886	0.15324408	64.99337419
216	redban_33_b	harpur_33_a	0.2	33	0.40201524	0.37567233	5.09152951
217	redban_33_b	redban_33_c	0	33	0	0.001089	0
218	redban_33_c	ancnor_33_tee	0	33	0	0.001089	0

219	*redban_33_tee*	*bloost_33_tee*	0.2	33	0.5138991	0.41121729	5.09152951
220	*redban_33_tee*	*redban_33_b*	0	33	0	0.001089	0
221	*redban_gt2*	*redban_33_b*	0	33	0	0.001089	0
222	*redban_gt3*	*redban_33_c*	0	33	0	0.001089	0
223	*rinpry_33_t11*	*kealoc_33_c*	1.15	33	0.12246894	0.10872576	29.27629468
224	*rinpry_33_t12*	*kealoc_33_b*	1.29	33	0.13834656	0.12340548	32.84036534
225	*robhal_33_t12*	*robhal_33_tee*	0.306	33	0.0317988	0.02781306	7.79004015
226	*robhal_33_tee*	*freder_33_b*	0.1	33	0.08318871	0.15076116	2.545764755
227	*robhal_33_tee*	*salqua_33_t12*	1.461	33	0.14490234	0.17371728	37.19362307
228	*rock_33_tee*	*rock_33_t11*	0	33	0.15288471	0.14880096	0
229	*salqua_33_t11*	*freder_33_c*	3.008	33	0.31048479	0.32118966	76.57660382
230	*sparod_33_t11*	*bolton_33_a*	2.391	33	0.13616856	0.24615756	60.86923529
231	*sparod_33_t12*	*bolton_33_b*	2.569	33	0.14270256	0.25828902	65.40069655
232	*sparod_33_t13*	*prinst_33_a*	1.138	33	0.128502	0.117612	28.97080291
233	*trinit_33_tee*	*trinit_33_t12*	0	33	0.168795	0.20235798	0
234	*westho_33_a*	*westho_33_b*	0	33	0	0.001089	0
235	*westho_33_gt1*	*westho_gt1*	0	33	0	0.001089	0
236	*westho_33_gt2*	*westho_gt2*	0	33	0	0.001089	0
237	*westho_33_tee*	*greens_33_t11*	0	33	0.04506282	0.05448267	0
238	*westho_33_tee*	*westho_33_a*	0.1	33	0.92862297	1.5880887	2.545764755
239	*westho_gt1*	*westho_33_a*	0	33	0	0.001089	0
240	*westho_gt2*	*westho_33_b*	0	33	0	0.001089	0
241	*wigan_33_b*	*westho_33_tee*	0	33	0	0.001089	0
242	*wigan_33_b*	*wigan_33_a*	0	33	0	0.001089	0
243	*woolfo_33_a*	*bury_33_a*	2.037	33	0.15719715	0.15117498	51.85722806
244	*woolfo_33_a*	*woolfo_33_b*	0	33	0	0.001089	0
245	*woolfo_33_b*	*bury_33_b*	2.213	33	0.18249462	0.1728243	56.33777402

Table 7. Line Parameters of The Improved Network Model of City Road (GSP)

No	From Busbar	To Busbar	Line length (km)	Voltage (kV)	R (Ohm)	X (Ohm)	B (µS)
1	BACA1T4A	BACH1TP8		132	0	0.00017424	0
2	BACH1TP7	BACH1TP8		132	0	0.00017424	0
3	BACH1TP7	CITY1TP1	2	132	0.069696	0.209088	176.7676768
4	BACH1TP8	BACK1T4B		132	0	0.00017424	0
5	BACK3RB1	BACK3RB2		33	0	0.00001089	0
6	BACK3RB1	BACK3T4B		33	0	0.00001089	0
7	BACK3RB1	FISH3T1_	1.31	33	0.111078	0.09801	220.3856749
8	BACK3RB1	FISH3T2_	1.3	33	0.109989	0.096921	220.3856749
9	BACK3RB2	FISH3T3_	1.32	33	0.112167	0.09801	220.3856749
10	BACK3RB2	FISH3T4_	1.33	33	0.113256	0.099099	220.3856749
11	BEEA3T3_	BEEA3TP3		33	0	0.00001089	0
12	BEEA3T4_	BEEA3TP4		33	0	0.00001089	0
13	BEEA3TP1	FINC3FB1	0.91	33	0.040293	0.063162	211.2029385
14	BEEA3TP1	PATE3T1_	1.38	33	0.114345	0.124146	266.2993572
15	BEEA3TP2	FINC3FB1	0.91	33	0.040293	0.063162	202.020202
16	BEEA3TP2	PATE3T2_	1.37	33	0.113256	0.123057	257.1166208
17	BEEA3TP3	FINC3RB2	0.92	33	0.040293	0.063162	211.2029385
18	BEEA3TP3	PATE3T3_	1.36	33	0.112167	0.121968	257.1166208
19	BEEA3TP4	FINC3RB2	0.93	33	0.040293	0.064251	211.2029385
20	BEEA3TP4	PATE3T4_	1.35	33	0.112167	0.121968	257.1166208
21	BEEB1T1	CITY1FB3	2.19	132	0.69696	1.04544	207
22	BEEB1T2_	MANS1TP1	2.19	132	0.69696	1.04544	207
23	BEEB1T3_	CITY1FB1	2.19	132	0.69696	1.04544	207
24	BEEB5BB3	BEEB5T2B		11	0	0.00000121	0
25	BEEB5BB3	BEEB5TB3		11	0	0.00000121	0
26	BEEB5T3A	BEEB5BB2		11	0	0.00000121	0
27	BEEB5T3B	BEEB5TB3		11	0	0.00000121	0
28	BEEB5TB1	BEEB5BB1		11	0	0.00000121	0
29	BEEB5TB1	BEEB5TB2		11	0	0.00000121	0
30	BEEB5TB2	BEEB5T2A		11	0	0.00000121	0
31	BEEB5TB2	BEEB5TB3		11	0	0.00000121	0
32	CITB1T1_	CITY1TP1		132	0	0.00017424	0
33	CITB1T2_	CITY1TP2		132	0	0.00017424	0
34	CITB1T3_	CITY1TP3		132	0	0.00017424	0
35	CITB5FB2	CITB5T1B		11	0	0.00000121	0
36	CITB5FB4	CITB5T2B		11	0	0.00000121	0
37	CITB5FB6	CITB5T3B		11	0	0.00000121	0
38	CITB5RB1	CITB5T1A		11	0	0.00000121	0
39	CITB5RB3	CITB5T2A		11	0	0.00000121	0
40	CITB5RB5	CITB5T3A		11	0	0.00000121	0
41	CITC5FB2	CITC5T4B		11	0	0.00000121	0
42	CITC5RB2	CITC5T4A		11	0	0.00000121	0
43	CITY1FB2	CITY1TP1		132	0	0.00017424	0
44	CITY1FB2	CITY1TP2		132	0	0.00017424	0
45	CITY1FB2	CITY1TP3		132	0	0.00017424	0
46	CITY1FB2	MANS1TP1		132	0	0.00017424	0
47	CITY1FB3	BANF1RB2	2.75	132	0.0923472	0.3449952	191.3449839
48	CITY1FB3	BANF1TP1	2.75	132	0.0923472	0.3449952	191.3449839
49	CITY1FB3	BANF1TP3	2.75	132	0.0923472	0.3449952	191.3449839
50	CITY1RB1	DEVO1TP1	3.12	132	0.139392	0.400752	296
51	CITY1RB1	DEVO1TP2	3.13	132	0.139392	0.400752	296
52	CITY1RB1	DEVO1TP3	3.14	132	0.139392	0.400752	296
53	CITY1RB2	FINE1T2		132	0	0.00017424	0
54	DEVO1T1_	DEVO1TP1		132	0	0.00017424	0
55	DEVO1T2_	DEVO1TP2		132	0	0.00017424	0
56	DEVO1T3_	DEVO1TP3		132	0	0.00017424	0
57	DEVO1TP1	FINE1T1		132	0	0.00017424	0
58	DEVO1TP2	CITC1T4_		132	0	0.00017424	0
59	DEVO1TP3	FINE1T3		132	0	0.00017424	0
60	DEVO5BB1	DEVO5T1B		11	0	0.00000121	0
61	DEVO5BB2	DEVO5T3A		11	0	0.00000121	0
62	DEVO5BB3	DEVO5T3B		11	0	0.00000121	0
63	DEVO5T1A	DEVO5TB1		11	0	0.00000121	0
64	DEVO5T2A	DEVO5TB2		11	0	0.00000121	0
65	DEVO5T2B	DEVO5TB3		11	0	0.00000121	0
66	FINA1T1A	FINA1TP1		132	0	0.00017424	0
67	FINA1T2A	FINA1TP2		132	0	0.00017424	0
68	FINA1T3A	FINA1TP3		132	0	0.00017424	0
69	FINA1TP1	FINC1T1C		132	0	0.00017424	0

70	*FINA1TP1*	*FINM1TP1*		132	0	0.00017424	0
71	*FINA1TP2*	*FINC1T2C*		132	0	0.00017424	0
72	*FINA1TP2*	*FINM1TP2*		132	0	0.00017424	0
73	*FINA1TP3*	*FINC1T3C*		132	0	0.00017424	0
74	*FINA1TP3*	*FINM1TP3*		132	0	0.00017424	0
75	*FINA5LB1*	*FINA5T4_*		11	0	0.00000121	0
76	*FINB1T1B*	*FINM1TP1*		132	0	0.00017424	0
77	*FINB1T2B*	*FINM1TP2*		132	0	0.00017424	0
78	*FINB1T3B*	*FINM1TP3*		132	0	0.00017424	0
79	*FINB3FB1*	*FIND3T5D*		33	0	0.00001089	0
80	*FINB3FB1*	*WHSR3T1*	2.73	33	0.117612	0.191664	642.7915519
81	*FINB3FB2*	*FINB3T2B*		33	0	0.00001089	0
82	*FINB3FB2*	*FINB3T4_*		33	0	0.00001089	0
83	*FINB3FB2*	*FIND3T6D*		33	0	0.00001089	0
84	*FINB3FB2*	*FIND3T7D*		33	0	0.00001089	0
85	*FINB3RB1*	*FINB3T3B*		33	0	0.00001089	0
86	*FINB3RB1*	*OSBN3T1_*	1.44	33	0.139392	0.165528	128.5583104
87	*FINB3RB1*	*OSBN3T2_*	1.43	33	0.091476	0.15246	156.1065197
88	*FINB3RB2*	*FINB3T1B*		33	0	0.00001089	0
89	*FINB3RB2*	*OSBN3T3_*	1.42	33	0.14157	0.164439	128.5583104
90	*FINB3RB2*	*OSBN3T4_*	1.41	33	0.091476	0.149193	156.1065197
91	*FINC3FB1*	*FINC3T2C*		33	0	0.00001089	0
92	*FINC3RB1*	*FINC3T1C*		33	0	0.00001089	0
93	*FINC3RB2*	*FINC3T3C*		33	0	0.00001089	0
94	*FINE1T1*	*FINM1TP1*		132	0	0.00017424	0
95	*FINE1T1C*	*FINE5FB1*		11	0	0.00000121	0
96	*FINE1T1C*	*FINE5RB1*		11	0	0.00000121	0
97	*FINE1T2*	*FINM1TP2*		132	0	0.00017424	0
98	*FINE1T2C*	*FINE5RB2*		11	0	0.00000121	0
99	*FINE1T2C*	*FINE5RB3*		11	0	0.00000121	0
100	*FINE1T3*	*FINM1TP3*		132	0	0.00017424	0
101	*FINE1T3C*	*FINE5FB2*		11	0	0.00000121	0
102	*FINE1T3C*	*FINE5FB3*		11	0	0.00000121	0
103	*FINE5FB1*	*FINE5FB2*		11	0	0.00000121	0
104	*FINE5FB1*	*FINE5RB1*		11	0	0.00000121	0
105	*FINE5FB3*	*FINE5FB2*		11	0	0.00000121	0
106	*FINE5FB3*	*FINE5RB3*		11	0	0.00000121	0
107	*FINE5RB1*	*FINE5RB2*		11	0	0.00000121	0
108	*FINE5RB2*	*FINE5RB3*		11	0	0.00000121	0