Flexible Plug and Play Low Carbon Networks
Quadrature-booster Trial & Learning Report
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References

1. Quad Booster Site Load Test (WTC Reference – P1238) – Wilson Transformer Company
2. Quadrature-booster Final Test Report P1238-01 (Wilson Transformer Company)
5. WS02.P379_FPP_Quadrature-booster Trial Schedule
6. DA.P311_FPP_Quadrature-booster Trial design
7. SDRC 9.8 – Quadrature-booster
## Glossary

<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANM</td>
<td>Active Network Management</td>
</tr>
<tr>
<td>BaU</td>
<td>Business as usual</td>
</tr>
<tr>
<td>CHP</td>
<td>Combined Heat and Power</td>
</tr>
<tr>
<td>DG</td>
<td>Distributed Generation</td>
</tr>
<tr>
<td>DNO</td>
<td>Distribution Network Operator</td>
</tr>
<tr>
<td>DOC</td>
<td>Directional Over-current</td>
</tr>
<tr>
<td>Enmac</td>
<td>Electricity Network Management and Control</td>
</tr>
<tr>
<td>FAT</td>
<td>Functional Acceptance Test</td>
</tr>
<tr>
<td>FPP</td>
<td>Flexible Plug and Play Low Carbon Networks project</td>
</tr>
<tr>
<td>LCNF</td>
<td>Low Carbon Network Fund</td>
</tr>
<tr>
<td>NOP</td>
<td>Normally Open Point</td>
</tr>
<tr>
<td>OLTC</td>
<td>On Load Tap Changer</td>
</tr>
<tr>
<td>PQM</td>
<td>Power Quality Monitor</td>
</tr>
<tr>
<td>PLC</td>
<td>Programmable Logic Controller</td>
</tr>
<tr>
<td>PST</td>
<td>Phase Shifting Transformer</td>
</tr>
<tr>
<td>PV</td>
<td>Photo Voltaic</td>
</tr>
<tr>
<td>QBCS</td>
<td>Quadrature-booster Control System</td>
</tr>
<tr>
<td>RTU</td>
<td>Remote Terminal Unit</td>
</tr>
<tr>
<td>SCADA</td>
<td>Supervisory Control and Data Acquisition</td>
</tr>
<tr>
<td>SDRC</td>
<td>Successful Delivery Reward Criteria</td>
</tr>
<tr>
<td>SRA</td>
<td>Standard Running Arrangement</td>
</tr>
<tr>
<td>TAPCON</td>
<td>Tap Control</td>
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</tbody>
</table>
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1. Executive Summary

1.1 Background

Flexible Plug and Play (FPP) was a Second Tier Low Carbon Network Fund (LCNF) project that aimed to connect Distributed Generation (DG) onto constrained parts of the electricity distribution network without the need for conventional network reinforcement. To achieve this, a number of innovative smart devices and applications were trialled to manage constraints and maximise network utilisation. One of the smart devices trialled was a Quadrature-booster, which was designed and deployed to balance power flows through parallel circuits supplying a large customer at Wissington whose ability to export electricity was constrained as a result of unbalanced load sharing on two parallel circuits.

1.2 Scope and Objectives

This Trial Report outlines the trial experiments, data recording, data analyses and supporting simulations carried out to explain how the Quadrature-booster performed during the trial period. The full information on the initial Quadrature-booster design concept, modelling, installations and commissioning, and lessons learnt from that phase were covered under a separate report SDRC 9.8\(^1\).

The key objective of the trial was to prove the suitability of the Quadrature-booster to create estimated 10MW capacity headroom at Wissington to enable connection of further distributed generation cost effectively. And that the connection of 10MW additional generation around Wissington would be allowable on the interconnected distribution network. The requirements were centred on de-loading the Downham Market No.2 circuit to load levels that closely matched load flows on the corresponding 33kV circuits out of Wissington, that is, the Northwold No.1 and Southery No.3 circuits, in order to create spare capacity headroom and at the same time ensure that all three circuits remained loaded below their seasonal thermal capacity limits (Figure 2, page 12).

1.3 Success Criteria

The following success criteria for the Quadrature-booster trial were identified:

- Successful operation of the Quadrature-booster and the associated control system at Wissington to prove the suitability of this technology on the distribution networks. Based on available information the FPP project believed this was the first Quadrature-booster on the distribution network.
- Uncompromised network integrity, security of supply, and the operations of the Wissington generator throughout the trial period.
- Build confidence of UK Power Networks and other DNOs to adopt the Quadrature-booster technology on distribution networks.

1.4 Trial methodology

The trial was modularised into a set of five hypotheses which were tested through experiments based on actual data from the network and supported by simulations using Power Factory\(^2\). Each hypothesis was set to prove specific elements of the Quadrature-booster operations listed below:

- To confirm that the tap changer operated within the design tap operating range between Tap 10 and Tap 17 positions (specific to the Wissington 33kV network requirements) to buck the power flow in the Downham Market No.2 circuit
- To establish the optimal load balancing achievable between Northwold No.1 circuit and Downham Market No.2 circuit
- To prove the automatic operation of Quadrature-booster control system (QBCS) to carry out automatic load balancing.
- To compare the actual induced voltage phase angle changes that occurred (following a change in tap position) with the specification and design
- To prove that optimal load sharing between Northwold No.1 and Downham Market No.2 parallel circuits would create approximately 10MW additional capacity headroom at Wissington 33kV boundary network, and that an additional 10MW generation export would be allowable on the network.

Actual network power flow, Quadrature-booster tap position and voltage phase angle measurements were recorded using three primary sources (to validate the data) – Power Quality Monitors (PQMs), DR-C50 transformer monitoring equipment, and PI historian data. Simulation studies were also carried out to support the experiments. Excel spreadsheets and graphs were used for visual representation of the results, which were then compared to the design specification and ‘as built’ parameters to establish the findings of the trial.

1.5 Challenges encountered

As a precautionary measure, the Quadrature-booster was temporarily switched out in September and October 2013 due to a number of alarms received at control on the control system and overfluxing respectively. The causes of the alarms were investigated and found to have been related to settings which were then rectified quickly to reduce the time the Quadrature-booster was switched out.

1.6 Main Findings

The Quadrature-booster operated within the design tap operating range (Tap 10 – Tap 17) varying between Tap 10 and Tap 11 in automatic mode during the trial period. Both the experimental and simulation test results showed that the Quadrature-booster shifted power flows from the Downham Market No.2 to Northwold No.1 circuit with some spill over to the Southery No.3 as expected. Simulations showed that while at Tap 10 which was expected to be neutral, the power shifted was approximately 4MW (when the generator export was set at 54MW) which was larger than expected. The recorded maximum power shifted as a result of a change in tap position was 3.6MW which appeared to be a course step change.

\(^2\) Power systems analysis software from DigSILENT, used by UK Power Networks for distribution network studies
Following the commissioning of the Quadrature-booster, the load profiles for Northwold No.1 and Downham Market No.2 circuits were generally closer to each other, which demonstrated that the Quadrature-booster improved the load sharing between the two lines. Utilisation of the additional 10MW capacity would be conditionally allowable subject to the existing automatic generator turndown scheme (Wissington CHP) being maintained and the following post trial requirements necessary to ready the network to accept additional generation are implemented:

1. Upgrade of the QBCS to include remote power flow measurements from Northwold Primary substation end and the Downham Market No.2 circuit T-point, to account for generation connections on the controlled circuits between Wissington and the Downham Market No.2 circuit T-point, and Wissington and Northwold Primary substation. A summary of the required upgrade is discussed in Section 1 (page 56). The trial concept was centred on generation injection on the Wissington 33kV substation which was adequate to prove the Quadrature-booster concept, and therefore the existing control system only monitors power flows on the two lines at Wissington end. It is therefore necessary to include this upgrade as part of future generation application connection charge.

2. Replacement of DOC protection scheme at Swaffham Grid to increase reverse power flow capacity at the site and fully utilise grid transformer capacity.

3. Monitoring potential increase in curtailment of flexible connection generators at March Grid caused by approximately 1.9MW increase in reverse power flow, being a direct spill over of the power shifted by the Quadrature-booster from the Wissington network.

4. Further detailed study at the time of processing any connection request to accommodate any changes on the evolving 33kV network, and ensure costs for upgrading the QBCS are included.

1.7 Lessons Learnt

The key lessons learnt from the trial were the following:

- Functionally, a Quadrature-booster is different to a conventional transformer on the network, but it is just like any other transformer for operations and maintenance purposes. The use of the Quadrature-booster created additional network capacity headroom which would allow increased generation export onto the 33kV distribution network.

- The specified Quadrature-booster phase angle of ±12° was wider than required on the Wissington 33kV network trial case. This resulted in approximately 3.6MW shifted per step tap change recorded with generator export at 43MW, which made it difficult to achieve a finer load balancing between the two lines. The trial results showed that a phase angle of ±6° could have been adequate for the Wissington site. It is recommended that in future applications further simulations are carried out using a phase angle of ±6° for finer tap step, and also place the Quadrature-booster in the Northwold No.1 circuit and use the boost taps. This is expected to give finer phase angle steps under load condition and also avoid overfluxing in the core.

- Innovative trials like the Quadrature-booster require cooperation and participation of customers connected on the network. The ramping of generation export to different export levels for the live tests, and also monitoring the generation protection response to changes in line currents during tap change operations was one of the key elements to the experiments.
1.8 Conclusions

The Quadrature-booster trial results aligned with the requirements to buck power flows on the Downham Market No.2 circuit, and push the shifted power on the Northwold No.1 circuit. The load sharing between the two circuits was found to be closer with the use of the Quadrature-booster. However, a finer MW step tap change would have been more useful, to be able to take smaller steps and more of them than the two recorded during the trial period which would improve load sharing optimisation between the two lines.

The use of the Quadrature-booster will allow approximately 10MW additional generation export to be connected at Wissington 33kV network, subject to upgrading of the QBCS and replacement of the DOC protection at Swaffham Grid. The capability of the Quadrature-booster to create capacity on the Wissington 33kV network is limited to its rating and the line ratings. At some stage the network will ultimately need reinforcement to continue accepting increased levels of generation.

The live tests and full trial experiments were successfully completed without interruption to Wissington generator. It was reported that the CHP generator far field fault monitoring protection scheme detected the step changes in line current measurements when the Quadrature-booster changed tap positions but the generator turndown scheme did not activate, and at all times it appeared stable during tapping. Therefore, the handshake between the QBCS and the generator, where the QBCS sent ‘tap in progress’ signals to the generator to ‘mask’ the protection appeared to have worked successfully.

The trial was successful because the trial hypotheses and Use Cases which the project set out to achieve were all answered and the objectives were met.

1.9 Document structure

The report is structured as follows:

- Section 2 Provides an overview of the trial location and the project drivers,
- Section 3 Describes the Quadrature-booster trial setup,
- Section 4 Provides an analyses of the data gathered or recorded,
- Section 5 Describes the trial outcomes and main findings,
- Section 6 outlines the lessons learnt from the trial, and
- Section 7 Concludes the report.
2. Introduction

2.1 Trial site location

The Quadrature-booster trial at Wissington was primarily driven by a generation export constraint on a CHP generation plant that is located at Wissington British Sugar Factory, Norfolk. Wissington British Sugar is a sugar beet processing factory which also runs a CHP electricity generation plant with an installed turbine capacity of 70MW. Figure 1 below shows the aerial photograph of British Sugar Wissington Factory site and the locations of the CHP, UK Power Networks 33kV substation, and the installed Quadrature-booster.

Figure 1: Aerial photograph of Wissington showing locations CHP, substation and Quadrature-booster

2.2 The Wissington 33kV Network

The existing Wissington 33kV substation is a UK Power Networks’ substation located within the British Sugar site and provides the point of connection for British Sugar to import and export to UK Power Networks distribution network. Under Standard Running Arrangement (SRA), shown in Figure 2, the site connection is provided via three 33kV circuits running interconnected with four 132/33kV grid sites – March Grid, Swaffham Grid, Kings Lynn South Grid and Walsoken Grid (all not shown in the Figure 2).

This network supports British Sugar’s existing CHP installation, which has an overall generator capacity of 95.2MVA, and comprises a 58.8MVA gas turbine generator and a 36.4MVA steam turbine generator with a power factor of 0.85. The installed turbine capacity is 70MW and is reported to be limited by the available export capacity on the distribution lines.

---

\[3\] The distribution network configuration under normal network operating conditions - all three outgoing 33kV circuits are connected and on load
Figure 2: A simplified diagram showing the Wissington 33kV network interconnection under SRA

Generation export is shared across the three circuits according to their electrical impedance which, amongst other factors, is related to their relative circuit lengths shown in Figure 2 above. The Downham Market No.2 circuit (to the T-point) is connected electrically in parallel to the Northwold No.1 circuit, but it is almost half the length of the Northwold No.1 circuit. Due to this difference in length, the Downham Market No.2 circuit has lower circuit impedance, which results in almost twice the amount of power flow through the Downham Market No.2 circuit compared to the Northwold No.1 circuit. Large distributed generators, like the Wissington CHP, can therefore highlight capacity sharing issues with some parallel circuits on distribution networks which had not previously been considered as a constraint on demand customers.

2.3 The network constraint

The constraint conditions usually occur when the CHP runs at full export during the sugar beet campaign months thought to stretch from September to March. The Quadrature-booster was designed and deployed to balance power flows through parallel circuits. During peak export, the thermal capacity of the Downham Market No.2 circuit is reached before that of the two other circuits because the loads are unbalanced across the paralleled circuits. This constraint restricts the seasonal export limit to approximately 54MVA (or 54MW at unity power factor) in winter which is 23% below the installed 70MW generator turbine capacity. The seasonal export limits are shown in Table 2 (page 13) and Figure 5 (page 18). It is reported that Wissington British Sugar generation achieves the best CHP rating under the government CHP quality assurance scheme. As such, further increments of generation export can provide valuable contribution to the electricity generation fleet.

4 About Wissington Factory – British Sugar, page 5 http://www.britishsugar.co.uk/Files/about-wissington-factory-0112.aspx [accessed 24/12/14 12:30pm]
The maximum export for the British Sugar generation site is limited to 54MVA (winter) as any additional generation would risk the Downham Market No.2 circuit breaching its winter maximum thermal rating while the Northwold No.1 is loaded at about 50% of its rating. The output of the CHP generator is, therefore, managed by an existing automatic generator turndown scheme which monitors the loadings on the outgoing 33kV circuits, along with the status of circuit breakers. In the event of a circuit loss, or the combined power flows exceeding the seasonal limits, an automatic generator turndown is activated to reduce generation to within set limits to ensure the restriction is not breached.

During normal network operating conditions (no circuit outages) the limit at which the output of the generators is constrained is set by the seasonal ratings of the 33kV circuits, which are described within Table 1 below. The three circuits have the same conductor size (200ACSR) and therefore have the same seasonal thermal rating values.

<table>
<thead>
<tr>
<th>Circuit</th>
<th>Summer</th>
<th>Spring / Autumn</th>
<th>Winter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Amps</td>
<td>MVA</td>
<td>Amps</td>
</tr>
<tr>
<td>Northwold No.1</td>
<td>443</td>
<td>25.3</td>
<td>512</td>
</tr>
<tr>
<td>Downham Market No.2</td>
<td>443</td>
<td>25.3</td>
<td>512</td>
</tr>
<tr>
<td>Southery No.3</td>
<td>443</td>
<td>25.3</td>
<td>512</td>
</tr>
</tbody>
</table>

**Source:** Wissington Generation ‘Connection and Use of System Agreement (2007)’

In the current network configuration, the network is constrained as a result of the differences in impedance between the three lines, which results in an imbalance in the power flows through these circuits. The present high loading of the Downham Market No.2 circuit means that seasonal export limits shown in Table 2 below are included in the existing “Connection & Use of System Agreement (2007)”.

<table>
<thead>
<tr>
<th>Season</th>
<th>Maximum seasonal export limits (MVA)</th>
<th>Months [Per Use of System Agreement]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer</td>
<td>46</td>
<td>May, June, July, August</td>
</tr>
<tr>
<td>Spring / Autumn</td>
<td>49.5</td>
<td>March, April, September, October, November</td>
</tr>
<tr>
<td>Winter</td>
<td>54</td>
<td>December, January, February</td>
</tr>
</tbody>
</table>

**Source:** Wissington Generation ‘Connection and Use of System Agreement (2007)’

Combined with these overall network limits, there is also local circuit current limits on the three outgoing 33kV circuits to Northwold No.1, Downham Market No.2, and Southery No.3 with a complex control system to make sure the circuit with the highest electrical load flow is not overloaded (always the Downham Market No.2 circuit). The CHP output is reduced in order to prevent the Downham Market No.2 circuit being overloaded. In addition, the cycle of operation of the British Sugar factory dictates the highest export during winter months and as such the maximum generation export and winter circuit ratings are the condition where the constraint might arise and formed the basis of the network analysis.
2.4 Key Objectives

The Quadrature-booster is a power systems device that can be used to improve the balance of power flows across two parallel circuits on the distribution network and release capacity headroom on the existing assets. This additional capacity can be used by either generation or demand customers for their connection on the distribution network. The objectives of the Quadrature-booster Trial Report are to demonstrate:

- The functionality and reliability over the trial period (August 2013 – September 2014) of what the FPP project believed is the first Quadrature-booster designed and deployed on 33kV distribution network.
- That the Quadrature-booster operated according to design requirements and operated within required tap operating range (to buck power flow in Downham Market No.2 circuit).
- That the Quadrature-booster operated both in manual and automatic modes and balanced the power flows in Northwold No.1 and Downham Market No.2 circuits to optimal load sharing levels.
- That by achieving optimal load sharing between the Northwold No.1 and Downham Market No.2 circuits, use of the Quadrature-booster released additional network capacity headroom of approximately 10MW, and increased the efficient utilisation of Wissington 33kV circuits.
- That the additional 10MW generation export would be allowable on the existing interconnected distribution network.

2.5 Scope of Trial Report

This Trial Report looks specifically at how the Quadrature-booster trial data was used to demonstrate the increase in capacity headroom at the Wissington site by improving load sharing between the Northwold No.1 and Downham Market No.2 circuits through the following:

- The measurement and monitoring of power flows on Northwold No.1, Downham Market No.2, and Southery No.3 circuits and Quadrature-booster voltage phase angle measurements and tap position, and supported by simulation studies.
- The analyses of power flows, voltage phase angles, and other data from monitoring equipment, and PI historian data\(^5\) for answering the Quadrature-booster trial hypotheses on the buck/boost operations and the associated voltage phase angle shifts on the load side of the Quadrature-booster for every tap change operation.
- Assessment of network modelling approach including comparison of modelled versus actual power flow data, identifying areas for improvement in the network model used for, among other Business as Usual functions, the modelling of the Quadrature-booster.

\(^5\) Half hourly historical power flow data recorded from the distribution network and stored in LIMES database
2.6 Previous Work

Quadrature-boosters are a mature technology on electricity transmission networks having evolved in the early 1960’s. Over the years, Quadrature-boosters have been used to control power flows on parallel three phase transmission networks across the world where capacity is constrained by one of the parallel circuits. In the UK, various Quadrature-boosters are connected to National Grid’s network at 275kV (750MVA – 860MVA units) and at 400kV (2000MVA – 2750MVA units). Other examples include Quadrature-boosters on interconnectors between France – Italy and the Netherlands – Germany.

The FPP project adapted the already mature Quadrature-booster technology at transmission networks, and innovatively deployed the Quadrature-booster at distribution voltage using the Wissington 33kV trial case. The FPP project installed a 30MVA rated Quadrature-booster to overcome an existing constraint due to sub-optimal load sharing on 33kV parallel circuits at UK Power Networks’ Wissington 33kV substation. The challenge was compounded by the fact that there was no known Quadrature-booster or Phase Shifting Transformer (PST) being used at this rating and voltage at the time of the FPP trial.
3. Trial Description

3.1 Site Setup

A simplified diagram of the trial network is shown in Figure 3 below. The trial network includes a Quadrature-booster installed in the Downham Market No.2 circuit, and a normally open (NOP) bypass switch used when the Quadrature-booster is switched out of service.

![Diagram of trial network](image)

Figure 3: A simplified Wissington 33kV trial network showing location of Quadrature-booster

And Figure 4 shows the location of the Quadrature-booster at Wissington 33kV substation.

![Image of substation showing Quadrature-booster](image)

Figure 4: Picture of the Wissington substation site showing location of installed Quadrature-booster
The trial sought to address whether or not a distribution network with a typical Quadrature-booster used to control power flows for given levels of Wissington CHP generation export can (i) be characterised, and (ii) its performance predicted with sufficient level of confidence to provide useful insight to Outage Planning and Network Planning tasks. The power flow at Wissington 33kV boundary network was monitored including all three outgoing 33kV circuits from Wissington 33kV bus bar, to ensure none of the circuits exceeded seasonal thermal static ratings. The trial also monitored and captured power flows and voltage phase angle measurements across the Quadrature-booster.

3.2 Trial Methodology

The trial was modularised into five sets of hypotheses which were tested, each focussing on a particular set of functionalities of the Quadrature-booster and its control system as summarised in Table 3 below.

<table>
<thead>
<tr>
<th>Hypothesis</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>QBR001</td>
<td>The tap changer can be raised/lowered between Tap 10 and Tap 17 positions to buck/boost respectively the power flows in the Downham Market No.2 circuit</td>
</tr>
<tr>
<td>QBR002</td>
<td>By raising/lowering the tap position starting from nominal tap, optimal load balancing is achieved between Northwold No.1 circuit and Downham Market No.2 circuit</td>
</tr>
<tr>
<td>QBR003</td>
<td>Quadrature-booster Control System (QBCS) can carry out automatic load balancing to enable capacity sharing between Northwold No.1 and Downham Market teed parallel circuits. The TapCON260 automatically controls the raising/lowering command for the tap changer position to achieve this operation</td>
</tr>
<tr>
<td>QBR004</td>
<td>For every tap change a proportionate phase angle change occurs, which directly correlates the ‘No Load’ test values on the Quadrature-booster nameplate and Factory Test Certificate</td>
</tr>
<tr>
<td>QBR005</td>
<td>Optimal load sharing between Northwold No.1 and Downham Market No.2 parallel circuits would create approximately 10MW additional capacity headroom at Wissington 33kV boundary network</td>
</tr>
</tbody>
</table>

The above hypotheses are discussed in detailed in section 4 and section 5.

3.3 Assumptions:

A number of assumptions were made during the trial, some of which are listed below:

- The trial scenarios were typical of current and future export out of Wissington CHP generator
- Wissington CHP export behaviour was uncontrolled and uninfluenced by their involvement in the trial
- By capturing a year’s data, a complete range of annual load profile characteristics was represented
- Variability of power loading on the network primarily export from the Wissington CHP generator were sufficient to effect tap changing on the Quadrature-booster
- In this report the power factor at Wissington 33kV is assumed to be unity (MVA = MW)
3.4 Monitoring and Data Collection

The trial monitored real power (MW), reactive power (MVar), current, system voltage and voltage phase angle across the Quadrature-booster and the tap position profile for a period of one year. The following data recording systems were used:

- Power Quality Monitors (PQMs)
- DR-C50 transformer management equipment
- PI historian stored in LIMES database

3.4.1 Data recording using PQMs

Initially three PQMs, PQM-1, PQM-2 and PQM-3 were installed in September 2013 (in accordance with HSS 03-037 Connection of Power Quality Monitoring Equipment) by a BaU contractor who was going around installing and removing them and sending the measurements for other BaU sites. All three PQMs were configured to record power flows. PQM-4 was installed in July 2014 and together with PQM-3 the two units were configured to measure voltage phase angles. The locations of the PQMs during the trial are shown in Figure 3 below.

![Figure 5: Extract of the Wissington 33kV network from Enmac showing locations data recording equipment](image)

The PQMs enabled the collection of 10 minute averaged load flow data for each of the three circuits (Northwold No.1, Downham Market No.2 and Southery No.3) that emanate from the Wissington 33kV substation, and 1 minute intervals voltage phase angle data across the Quadrature-booster.
3.4.2 Data recording using DR-C50 Monitoring Equipment

The DR-C50 is a comprehensive transformer online monitoring and management equipment that is configurable to provide an economical solution for monitoring, control and communication. Figure 6 shows the front panel of the DR-C50 cubicle. The DR-C50 was installed together with a Calisto 9 (for online dissolved gas analysis) as part of the enhanced monitoring requirements specified for the Quadrature-booster. Instantaneous power flows (minute granularity) for the Downham Market No.2 circuit and Quadrature-booster tap position analogues were obtained from the DR-C50 equipment. The power flow data was compared to the values recorded by the PQM installed in the same feeder for validation.

Figure 6: Picture showing the front panel of the DR-C50 equipment

3.4.3 PI historian data

PI historian is a database that stores half-hourly network data that can be retrieved for historical analyses. At the time of this trial there were no MW and MVar analogues in Enmac allocated to the 33kV feeders at Wissington. Only current and voltage analogues were used, and the corresponding MW values were calculated assuming unity power factor. As this approach is inadequate to decide the direction of power flow, instances of reverse power (import) into Wissington were cross-checked with the PQM and DR-C50 data.

The methodology included the following:

- Download historical data (feeder loads and CHP export all in amps) from Limes for 2010 – 2013, three years immediately before the commissioning of the Quadrature-booster.
- Download historical data (feeder loads and CHP export all in amps) from LIMES for the period August 2013 to August 2014.
- Compare the loads on the Northwold No.1 and Downham Market No.2 circuits at each tap position. Calculate the power shifted at each tap change.
- Compare the load distribution between Northwold No.1 and Downham Market No.2 circuits (a) network without Quadrature-booster, and (b) network with Quadrature-booster at (i) Tap10 and (ii) Tap11.

A PI tag was created in LIMES system to record the tap position activities of the Quadrature-booster.

For the trial (and perhaps the future operation of the Quadrature-booster) it would be helpful to have these analogues available. It is also assumed that this will form part of the installation on 33kV feeders going forward on other sites. For this trial and from a planning perspective, it would be useful to have the analogues as instantaneous values rather than half hourly averages as currently set up in PI historian.
4. Trial Experiments and Simulations

4.1 Baseline

The following baselines were identified as criteria for a successful Quadrature-booster trial.

- Network power flow distribution over the three circuits over three years immediately before the Quadrature-booster was commissioned was used to ascertain the network trends at each particular season. This was compared with the distribution of the power flows on the three circuits with the Quadrature-booster switched in service and operating at optimal tap position that achieved the best load sharing ratio between the Northwold No.1 and Downham Market No.2 circuits.

- Completion of the live tests and full trial without adverse impact or disruption to the Wissington CHP generator, or compromise to the reliability and security of supply on the Wissington network linked to the Quadrature-booster trial.

- Quadrature-booster specifications and factory test results on voltage phase angles. The phase angle range of ±14.98° as given on rating and diagram plate on the Quadrature-booster under ‘No Load’ condition would be expected to be around ±12° under full load condition due to voltage regulation as indicated by the manufacturer.

- Completion of the trials without interruptions or malfunction of the Quadrature-booster and associated equipment.
4.2 Quadrature-booster Tap Changer Operations

| QBR001 | The tap changer can be raised/lowered between Tap 10 and Tap 17 positions to buck/boost respectively the power flows in the Downham Market No.2 circuit |

Hypothesis QBR001 sought to confirm two objectives:

1. To confirm that the tap changer operates within the required tapping range (Tap 10 – Tap 17) – specific to the requirements of the Wissington 33kV trial network. And by design Tap 1 – Tap 9 inclusive, Tap 18 and Tap 19 are electrically disabled on the Wissington Quadrature-booster.

2. To confirm that the impact of the Quadrature-booster increasing its tap position was to decrease the power in the Downham market No.2 circuit, resulting in an increase in power flow in the Northwold No.1 circuit and, to a lesser extent, in the Southery No.3 circuit.

As a prerequisite to achieving the above objectives, the Quadrature-booster was kept in operation at all times with minimal interruptions for the duration of the trial period. Instantaneous power flows on the three 33kV circuits – Northwold No.1, Downham Market No.2, and Southery No.3 were all recorded by PQMs and the DR-C50 (in the case of the Downham Market No.2).

4.2.1 QBR001 Methodology

To prove this hypothesis and Quadrature-booster operation on the ‘live’ network, this test:

- Monitored the tap position and recorded the time at each tap change
- Used 10 minute interval sampling rate to show power flow variations at each tap change
- Used 1 minute interval sampling rate to show time of tap change

The circuit power flow data on the three Wissington 33kV circuits was recorded using three data sources:

1. Power Quality Monitors (PQM),
2. DR-C50 transformer monitoring equipment – used without change
3. PI historian data measurements from the RTU (LIMES database) – which was used to support the above two primary data sources

The tap change profile and power flows were plotted on graphs.

- Tap change profile was plotted from DR-C50 data recorded at 1 minute interval
- Power flows on the three circuits were plotted from PQM data sampled at 10 minute intervals, and PI historian data sampled at half-hourly intervals

Enmac alarm schedule for Wissington 33kV substation was utilised to corroborate the dates and times at which a tap change occurred. This source was utilised as the primary source of data for time synchronisation – the RTU is connected to a time server and can therefore be assumed to be accurate.
### 4.2.2 Recorded Tap Change Operations

The recorded power flows and Quadrature-booster tap position profile (using 1 minute data intervals) were plotted on a scatter diagram to provide a visual means of presenting the impact of the Quadrature-booster during periods when the Quadrature-booster changed tap. The month by month plots are shown in Appendix 1. Figure 7 below shows the overall recorded tap positions over one year trial period.

![Graph showing the Quadrature-booster tap position profile during the trial period](image)

Figure 7 – Graph showing the Quadrature-booster tap position profile during the trial period

Figure 7 shows that few tap change operations were recorded during September 2013, October 2013 and February 2014. Increased tap operations were recorded for the period March – August 2014. The tap change operations followed what appeared to be a cyclic routine on almost daily basis – the Quadrature-booster changed tap from Tap 10 to Tap 11 around/between 07:00 – 10:00 hours and changed tap again from Tap 11 to Tap 10 around/between 16:00 – 19:00 hours. From this observation, it appears that the tap changes followed the general daily load profile pattern. It is also possible that the increased tap change was a response to the changing network running arrangements during planned works on the interconnected 33kV networks which were carried out during the outage period (March – August 2014).

The Quadrature-booster was switched out of service from 15 June 2014 to 23 July 2014 to carry out planned works:

- Update the Quadrature-booster protection settings to prevent spurious over fluxing alarms
- Update the TAPCON260 control software used for the Quadrature-booster control system
- Installation of cable boxes to cover power cable terminations, and surge diverters on the Quadrature-booster to complete outstanding works

A summary of the overall time the Quadrature-booster was observed have spent at a given tap position for the trial period is shown in Table 4 below.

---

6 Control relay used by the QBCS to regulate power flows
Table 4: Summary of time Quadrature-booster was on given at a tap position

<table>
<thead>
<tr>
<th>Tap Position</th>
<th>Proportion of annual Time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Minutes</td>
</tr>
<tr>
<td>Tap 10</td>
<td>490,435</td>
</tr>
<tr>
<td>Tap 11</td>
<td>34,978</td>
</tr>
<tr>
<td>Tap 12</td>
<td>119</td>
</tr>
<tr>
<td>Tap 13</td>
<td>8</td>
</tr>
<tr>
<td>Tap 14</td>
<td>0</td>
</tr>
<tr>
<td>Tap 15</td>
<td>0</td>
</tr>
<tr>
<td>Tap 16</td>
<td>0</td>
</tr>
<tr>
<td>Tap 17</td>
<td>0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>525,540</td>
</tr>
</tbody>
</table>

The results in the table show that the Quadrature-booster was at Tap 10 (including periods when offline) for approximately 93.32% of the time, and at Tap 11 for approximately 6.66% of the time during the trial period. Tap 12 and Tap 13 were reached during live tests for short periods of times in August and September 2013 and the time spent at these tap positions are reflected as negligible compared to one year trial period. A single operation at Tap 12 was also recorded in October 2013.

An example of the variation of power flows in the three circuits when the Quadrature-booster changed tap (in automatic mode) from Tap 10 to Tap 11 and from Tap 11 to Tap 10 is shown in Figure 8 below.

The example in Figure 8 shows that:

- The Quadrature-booster changed tap position from Tap 10 to Tap 11 on 21 September 2013 at approximately 11:31am as recorded on SCADA alarms – extract of the filtered alarms is shown in Table 5 below.
Table 5 - Extract of recorded Quadrature-booster tap change alarms

<table>
<thead>
<tr>
<th>DATE</th>
<th>ALARM</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>03/10/2013</td>
<td>11:17</td>
<td>WISSINGTON BSC QUAD BOOST TAP CHANGE ON LOCAL RESET</td>
</tr>
<tr>
<td>24/09/2013</td>
<td>10:39</td>
<td>WISSINGTON BSC QUAD BOOST TAP CHANGE ON LOCAL OPERATED</td>
</tr>
<tr>
<td>23/09/2013</td>
<td>09:00</td>
<td>WISSINGTON BSC QUAD BOOST TAP CHANGE IN PROGRESS RESET</td>
</tr>
<tr>
<td>23/09/2013</td>
<td>09:00</td>
<td>WISSINGTON BSC QUAD BOOST TAP CHANGE IN PROGRESS OPERATED</td>
</tr>
<tr>
<td>21/09/2013</td>
<td>11:31</td>
<td>WISSINGTON BSC QUAD BOOST TAP CHANGE IN PROGRESS RESET</td>
</tr>
<tr>
<td>21/09/2013</td>
<td>11:31</td>
<td>WISSINGTON BSC QUAD BOOST TAP CHANGE ON LOCAL OPERATED</td>
</tr>
<tr>
<td>11/09/2013</td>
<td>03:16</td>
<td>WISSINGTON BSC QUAD INTERCONNECTOR ISOL F EARTH SELECTOR OFF</td>
</tr>
<tr>
<td>11/09/2013</td>
<td>03:16</td>
<td>WISSINGTON BSC QUAD INTERCONNECTOR ISOL F EARTH SELECTOR ON</td>
</tr>
<tr>
<td>10/09/2013</td>
<td>14:37</td>
<td>WISSINGTON BSC QUAD BOOST TAP CHANGE ON LOCAL RESET</td>
</tr>
<tr>
<td>10/09/2013</td>
<td>14:37</td>
<td>WISSINGTON BSC QUAD BOOST TAP CHANGE ON LOCAL OPERATED</td>
</tr>
</tbody>
</table>

Before this tap change the power flow in the Downham Market No.2 circuit was approximately 5MW higher than the power flow in the Northwold No.1 circuit. After the change from Tap 10 to Tap 11, the power flow in the Downham Market No.2 circuit decreased, with the power flow in the Northwold No.1 circuit increasing accordingly – rising above the power flow in the Downham Market No.2 circuit. The Southery No.3 circuit was switched out of service at the time.

- On 23 September 2013 at approximately 09.00am the load on the Southery No.3 circuit increased from about 1MW to approximately 10MW as the circuit was switched back in service leading to a decrease in load on the other two circuits. The Quadrature-booster responded by changed tap from Tap 11 to Tap 10 resulting in the power flow in the Northwold No.1 circuit decreasing accordingly to below the power flow in the Downham Market No.2 circuit.

4.2.3 Analysis of DR-C50 data logs

To illustrate the relationship of power flows (MW) in Downham Market No.2 circuit with Quadrature-booster tap change an extract of the data recorded at one minute granularity by the DR-C50 monitoring equipment in May 2014 is graphed and shown in Figure 9 below.

![Figure 9 Graph showing power flow and tap position profiles](image)

Figure 9 above shows that a change in tap from Tap 10 to Tap 11 resulted in approximately 4MW decrease (buck) of power flow in the Downham Market circuit. Also, when the tap changed from Tap 11 down to Tap 10, there was an increase (boost) of power flow in Downham Market No.2 circuit of approximately 4MW.
To validate variation of power flows with tap change, DR-C50 data curve was compared with equivalent curves based on the PQM 10 minute averaged data and 30 minute averaged PI historian data as shown in Figure 10 below.

![Comparison of recorded power flow data from various trial data sources for validation](image)

**Figure 10 – Graphs showing comparison of recorded power flow data profiles**

Figure 10 shows that there is strong correlation between power flow and voltage data recorded by the DR-C50, PQM data and the PI historian data. The PI curves are smoother because of the 30 minute averaging intervals compared to the 10 minute averaging intervals used for the PQM data and the 1 minute averaged DR-C50 data. This result was replicated in every other instance at which the Quadrature-booster changed its tap position. The recorded DR-C50 and PQM data sets were therefore validated, and the PQM data was used in the comparison of the Northwold No.1 and Downham Market No.2 power flow variation with change in tap position.

### 4.2.4 Summary of Results

Based on the results above the Quadrature-booster operated as envisaged:

- The monitored and recorded data show that the Quadrature-booster operated within its operating range, mainly varying between Tap 10 and Tap 11 during the trial period.

- In all instances where an increase or decrease in tap position was recorded, a corresponding decrease or increase respectively in the power flow on the Downham Market No.2 circuit was recorded.

- The Quadrature-booster operated in auto mode at Tap 10 and Tap 11 only which was limited by available levels of power flows on the network. Tap 13 was reached in manual mode during ‘live’ tests. The Quadrature-booster operated within the expected tap range of Tap 10 to Tap 17. Tap 14 – Tap 17 positions inclusive were unused during the trial period.

- The Quadrature-booster was on Tap 10 for 93.32% of the time and on Tap 11 for 6.66% of the time during the trial period. Time spent at Tap 12 and Tap 13 was negligible.
4.3 Optimal Load Balancing

| QBR002 | By raising/lowering the tap position starting from nominal tap, optimal load balancing is achieved between Northwold No.1 circuit and Downham Market No.2 circuit |

Hypothesis QBR002 sought to confirm the following objectives:

1. To prove that the effect on power flows on the Northwold No.1 and Downham Market No.2 circuits was in opposition between raise/lower directions of tap change operations.

2. To prove that the difference in load flowing through the Downham Market No.2 and the Northwold No.1 parallel circuits will be reduced to smallest value to give optimal load sharing with the use of the Quadrature-booster. Without the Quadrature-booster the Downham Market No.2 circuit was generally loaded to approximately twice as much as the Northwold No.1 circuit.

As a prerequisite to achieving the above objectives, the Quadrature-booster was kept in operation at all times with minimal interruptions for the duration of the trial period. Instantaneous power flows on the three 33kV circuits – Northwold No.1, Downham Market No.2, and Southery No.3 were all recorded by PQMs.

4.3.1 QBR002 Methodology

The Quadrature-booster can adjust the load sharing across two circuits by adjusting its tap position based on measurements taken locally to the Quadrature-booster. This is done to share power flows in proportion to the thermal ratings of the two circuits. To prove this hypothesis and Quadrature-booster operation on the ‘live’ network, the circuit power flow data on the three Wissington 33kV circuits was recorded using three sources:

- ‘Live tests’ recorded data – read from instrument protection relays and recorded manually
- PQMs – time series data recorded over a period of one year,
- PI historian data measurements from the RTU – used without change to support the above primary data source
- Power flow simulations – using Power Factory software (DigSILENT)

Power flows were plotted using the recorded data.

4.3.2 Experiment Live Tests

The Quadrature-booster trial commenced with the initial ‘live tests’ which were carried out on 5th August 2013 and 6th September 2013. These tests were carried out in coordination with British Sugar. The tests involved tapping the Quadrature-booster in manual mode and automatic mode respectively, and the generation export was ramped in steps from 10MW, 24MW to 40MW – which was the applicable maximum export which was reported to have been limited by CHP generator configuration at the time of tests. Event logs available from the RTU and local mimic which provide chronological site events with timestamps were captured, together with readings from instrument relays and Enmac displays. The objectives of the live tests were threefold:
1. Proving the **manual mode** tapping function, and the impact of the Quadrature-booster on the power flows on the three 33kV circuits starting with the Quadrature-booster at nominal tap, and manually tapping up when generation export was at 10MW, 24MW and 40MW.

2. Proving the **automatic mode** function of the Quadrature-booster Control System (QBCS). The results also fed into a planned TAPCON260 relay software upgrade and ensured that any shortcomings were addressed at the same time.

3. Proving the CHP generation protection stability (by British Sugar) following changes to the protection scheme to accommodate the operations of the Quadrature-booster. This required proving that the ‘Quadrature-booster ‘tap in progress’ signal was received by CHP generator control to mask generator protection. This test was carried out with the QBCS set to automatic mode, for generation export at 40MW, which was crucial to confirm before the sugar beet campaign commenced in middle of September 2013.

Table 6 below shows the list of sample tests carried out.

**Table 6: List of 'live tests' - part of Quadrature-booster trial**

<table>
<thead>
<tr>
<th>Item</th>
<th>CHP export (MW)</th>
<th>Tests</th>
</tr>
</thead>
</table>
| 1    | 10              | 1.1 By-pass test (Quadrature-booster by-passed). Downham Market No.2 feeder out for a brief period for switching.  

1.2 Quadrature-booster in circuit and set at nominal tap (Tap 10), and QBCS in manual mode  

1.3 Tap Quadrature-booster in manual mode from Tap 10 to Tap 11 (maximum permissible – reverse power flow in Downham Market No.2 circuit) |
| 2    | 24              | 2.1 Quadrature-booster in circuit and set at nominal tap (Tap 10), and QBCS in manual mode  

2.2 Tap Quadrature-booster in manual mode from Tap 10 to Tap 13 (maximum permissible – reverse power flow in Downham Market No.2 circuit) |
| 3    | 43              | 3.1 * By-pass test (Quadrature-booster by-passed). Downham Market No.2 feeder out for a brief period for switching.  

3.2 Quadrature-booster in circuit and set at nominal tap (Tap 10), and QBCS in manual mode.  

3.3 Tap Quadrature-booster in manual mode from Tap 10 to Tap 12 (maximum permissible – cautious approach to reduce risk)  

3.4 Whilst at Tap 12 switch the QBCS to Automatic mode and let it correct the power flow distribution |

* Restricted export before switching ~ 20MW

A sample of the recorded test results (for item 3) are shown in Table 7 below. The current and voltage measurements were recorded from protection relay readings on the Quadrature-booster control panel and the 33kV feeder control panels. The MW values were then calculated assuming unity power factor.
The results in Table 7 show that:

- The generation output appeared not to equate to the distribution of power in the three feeders, for which it was assumed to follow basic Kirchhoff's law. The small differences can be attributable to other power flow factors such as voltage angles which need to be considered in this case.

- At nominal tap the Quadrature-booster shifted approximately 3.51 MW with export level of 42 MW from the generator as shown in Test 3.1 (By-pass test).

- The Quadrature-booster buck/boost operation worked as expected. As the tap was raised from Tap 10 to Tap 11 there was a reduction in load on the Downham Market No.2 circuit and an increase in loading on the Northwold No.1 circuit as shown in ∂MW columns. A slight increase in load was also seen on the Southery No.3 circuit.

- At approximately 43 MW export, a single tap change from Tap 10 to Tap 11 shifted 3.59 MW (61A) from the Downham Market No.2 circuit to Northwold No.1 (2.96 MW) and Southery No.3 (1.15 MW). The MW step change per tap change appears more ‘course’ than expected so much that the Northwold No.1 circuit was more loaded than the Downham Market No.2 circuit whilst at Tap 11. Achieving a closer line balancing appears difficult because of the large MW shifts per tap change. From Tap 11 to Tap 12 resulted in 3.31 MW shifted from Downham Market No.2 circuit.

- Indications were that the CHP generator far field fault monitoring detected the step changes in line current on the 33 kV feeders but did not activate, and at all times it was reported that the protection appeared stable when the Quadrature-booster changed tap positions.

---

### Table 7: Quadrature-booster ‘live test’ results - manual and automatic tapping (06/09/13)

#### Test 3.1: By-pass Test - Tap control in manual mode

<table>
<thead>
<tr>
<th>CHP Export MW</th>
<th>Tap</th>
<th>Northwold No.1</th>
<th>Downham Market No.2</th>
<th>Southery No.3</th>
<th>Recorded</th>
<th>Calculated</th>
</tr>
</thead>
<tbody>
<tr>
<td>42</td>
<td>By-pass</td>
<td>209 33.04 12.0 0.00</td>
<td>370 32.91 21.1 0.00</td>
<td>169 32.97 9.7 0.00</td>
<td>Amps kV MW ∂ MW</td>
<td></td>
</tr>
<tr>
<td>42</td>
<td>10</td>
<td>258 33.10 14.8 2.83</td>
<td>307 33.06 17.6 -3.51</td>
<td>185 33.08 10.6 0.95</td>
<td>Amps kV MW ∂ MW</td>
<td></td>
</tr>
<tr>
<td>Q8@Tap10 - Bypass</td>
<td>49</td>
<td>2.8 -63 -3.5</td>
<td>16 0.9</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Tests 3.2 & 3.3: Tap control in manual mode - starting from Tap 10 up to Tap 12

<table>
<thead>
<tr>
<th>CHP Export MW</th>
<th>Tap</th>
<th>Northwold No.1</th>
<th>Downham Market No.2</th>
<th>Southery No.3</th>
<th>Recorded</th>
<th>Calculated</th>
</tr>
</thead>
<tbody>
<tr>
<td>42.3</td>
<td>10</td>
<td>258 33.10 14.8 0.00</td>
<td>307 33.06 17.6 0.00</td>
<td>185 33.08 10.6 0.00</td>
<td>Amps kV MW ∂ MW</td>
<td></td>
</tr>
<tr>
<td>43.1</td>
<td>11</td>
<td>310 33.06 17.8 2.96</td>
<td>245 32.97 14.0 -3.59</td>
<td>205 33.10 11.8 1.15</td>
<td>Amps kV MW ∂ MW</td>
<td></td>
</tr>
<tr>
<td>43.0</td>
<td>12</td>
<td>359 33.06 20.6 2.81</td>
<td>187 32.97 10.7 -3.31</td>
<td>206 33.02 11.8 0.03</td>
<td>Amps kV MW ∂ MW</td>
<td></td>
</tr>
</tbody>
</table>

#### Test 3.4: Tap control in Auto mode - starting from Tap 12 down to Tap 10

<table>
<thead>
<tr>
<th>CHP Export MW</th>
<th>Tap</th>
<th>Northwold No.1</th>
<th>Downham Market No.2</th>
<th>Southery No.3</th>
<th>Recorded</th>
<th>Calculated</th>
</tr>
</thead>
<tbody>
<tr>
<td>30.0</td>
<td>10</td>
<td>183 32.69 10.4</td>
<td>215 32.64 12.2</td>
<td>140 32.67 7.9</td>
<td>Amps kV MW ∂ MW</td>
<td></td>
</tr>
<tr>
<td>43.0</td>
<td>11</td>
<td>308 33.06 17.6 -2.92</td>
<td>244 32.97 13.9 -3.26</td>
<td>206 33.02 11.8 0.00</td>
<td>Amps kV MW ∂ MW</td>
<td></td>
</tr>
<tr>
<td>43.0</td>
<td>12</td>
<td>359 33.06 20.6 0.00</td>
<td>187 32.97 10.7 0.00</td>
<td>206 33.02 11.8 0.00</td>
<td>Amps kV MW ∂ MW</td>
<td></td>
</tr>
</tbody>
</table>
The graphs below show the actual power flows plotted against the CHP generation output (10MW, 24MW and 43MW).

Figure 11: Graph showing circuits loadings (Tap 10) against CHP generation export

Figure 11 shows that with the Quadrature-booster at Tap 10, the Downham Market No.2 circuit carried more load than the Northwold No.1 circuit for generation export exceeding 15MW. The tests showed that this was reversed when the tap was raised from Tap 10 to Tap 11 as shown Figure 12 below.

Figure 12: Graph showing circuits loadings (Tap 11) against CHP generation export

Looking at the above results it can be seen that the Quadrature-booster operated as expected. From inception the aim of the Quadrature-booster trial was to ideally achieve a 50:50 sharing of the power between the Northwold No.1 and the Downham Market No.2 circuits. It was however observed that the results showed that a significantly higher level of power flow was flowing down the Northwold No.1 circuit when the Quadrature-booster was at Tap 11, that is, a single tap change from nominal (Tap 10). Based on these results it appeared that the nominal tap (Tap 10) seemed to give a better load sharing than Tap 11.
4.3.3 Power flow simulations

The simulations were carried out using Power Factory software (DigSILENT) in three scenarios as follows:

- Before the installation of the Quadrature-booster,
- Quadrature-booster operating at nominal Tap 10,
- Quadrature-booster operating at Tap 11.

Figure 13 presents the modelled loading of the three circuits under different generation export levels. The three Wissington 33kV circuits all have a winter thermal rating of 30MW and the graph in Figure 13 illustrates the sub-optimal distribution of the power flow across the three circuits.

![Modelled circuit loadings - without Quadrature-booster](image)

**Figure 13 – Graph showing circuits loading Vs generation export - without Quadrature-booster**

The simulations showed that the Downham Market No.2 circuit reached its thermal capacity limit when the generation export was approximately 55MW. Figure 14 below shows the equivalent modelled loading of the three circuits under the same generation export levels (shown in Figure 13) with the Quadrature-booster at Tap 10.

![Modelled circuit loadings - with Quadrature-booster at Nominal Tap (Tap 10)](image)

**Figure 14 – Graphs showing circuits loading Vs generation export - with Quadrature-booster at Tap 10**

It can be seen from the above graphs that the difference in load carried by the Downham Market No.2 and Northwold No.1 circuits was reduced from approximately 8MW (Figure 13) to approximately 4MW (Figure 14 with the Quadrature-booster at Tap 10). There was a reduction in loading on Downham Market No.2 and a corresponding increase in loading on the Northwold No.1.
Figure 15 below shows the modelled loading of the three circuits under the same generation export levels as above with the Quadrature-booster now set at Tap 11.

![Figure 15 - Circuits loading Vs generation export - with Quadrature-booster at Tap 11](image)

Figure 15 shows that with the Quadrature-booster at Tap 11 the difference in loading carried by the Downham Market No.2 and Northwold No.1 was reduced to a minimum approximating 2MW.

### 4.3.4 Summary of Results

Both the experimental and simulation results show that the Quadrature-booster introduced significant impact on the load sharing between the Northwold No.1 and Downham Market No.2 circuits.

- A general trend was observed. At tap 10 – the load on the Northwold No.1 circuit was less than the load on the Downham Market No.2 circuit. At tap 11 – the load on the Northwold No.1 circuit is more than the load on the Downham Market No.2 circuit.
- Figure 11 and Figure 12 (on page 29) shows that the optimal load sharing was achieved at nominal Tap 10 at low CHP generator export less than 40MW.
- Figure 13 to Figure 15 show that the difference in load flow through Downham Market No.2 and Northwold No.1 circuits was reduced with the introduction of the Quadrature-booster and as the tap position was raised from Tap 10 to Tap 11. Tap 11 was considered the optimal tap position because the load sharing was the closest that could be obtained, and the load on the Northwold No.1 circuit increased above the loading of the Downham Market No.2 circuit.
- The live test results showed that a significantly higher level of power flow was flowing down the Northwold No.1 circuit when the Quadrature-booster was at Tap 11, that is, a single tap change from nominal (Tap 10). It therefore appeared that the nominal tap seemed to give a better load sharing than Tap 11 for a generation export level of 43MW.
- The largest step change of current recorded was 61A for a tap change from Tap 10 to Tap 11 with generator exporting 43MW. The setting on this protection is a 100A change in current in less than 1 second on both the Northwold No.1 and Downham Market No.2 circuits. Although the step change of current was within limits and the protection on the Wissington generator did not trip during this test, it appears that the step size could be significant enough when generator export increases above 43MW (to say 54MW on existing arrangements) to cause a potential risk of future mal operation.
These results align with the requirements of the Quadrature-booster design. However, it can be concluded that a finer step tap change would have been more useful, to be able to take smaller steps and more of them.

It is recommended that the impedance/tap design and permissible voltage phase angle required at extreme tap positions of the Quadrature-booster could take into account such simulation results in the future to further reduce the difference between line loadings.
4.4 QBCS Automatic Operations

The QBCS monitors the power flows in the Northwold No.1 and Downham Market No.2 circuits and the TAPCON260 relay regulates the active power of the Quadrature-booster. Using the analogue measurements, the TAPCON260 calculates the active power flow in Northwold No.1 ($P_1$) and Downham Market No.2 ($P_2$). The difference in loading between the Downham Market No.2 circuit and the desired target is then compared to the set bandwidth only if both lines are in service.

Power flow deviation from the desired 50:50 target load sharing was calculated using the equation below.

$$\delta P = P_2 - \frac{(P_1 + P_2)}{2}$$

Where,
- $\delta P$ – the power flow deviation
- $P_1$ – power flow on Northwold No.1 circuit
- $P_2$ – power flow on Downham Market No.2 circuit

Results from live tests showed that the biggest power step change per tap was about 3.6MW. The smallest bandwidth setting that could be set was $\pm$1.9MW. During the trial period the bandwidth was set to $\pm$2.25MW (total bandwidth of 4.5MW) which was considered comfortably higher than the biggest step change of 3.6MW. Increasing the bandwidth setting affects how closely the scheme is able to optimise the power share between Downham Market No.2 and Northwold No.1 circuits but ensures a stable operation and would reduce the frequency of tap change operations to minimise wear and tear of the tap changer and prolong its economic lifecycle.

Hypothesis QBR003 sought to confirm two objectives:

1. To calculate the difference in power flow in real time between the Northwold No.1 and Downham Market No.2 circuit and compare it to the set control bandwidth of $\pm$2.25MW.
2. To observe the action taken by the QBCS to change tap position in the event of excursions outside the control bandwidth of $\pm$2.25MW

As a prerequisite to achieving the above objectives, power flow data was recorded using PQMs on the Northwold No.1 and Downham Market No.2 33kV circuits at Wissington.

4.4.1 QBR003 Methodology

Using Excel spreadsheet, recorded PQM power flow data was used to calculate power flow deviations in real time and this value was compared to the set control bandwidth of $\pm$2.25MW. The desired sharing target between Northwold No.1 and Downham Market No.2 circuits was taken as 50%.

- If the magnitude of the power flow deviation fell within $\pm$2.25MW the Quadrature-booster was expected to remain at the same tap position.
• If the magnitude of the power flow deviation exceeded ±2.25MW and sustained for a period exceeding the set time delay, the Quadrature-booster was expected to change tap to correct the power flow difference to fall within bandwidth.
• Tap change operation was calculated from power flow deviation data and compared with tap position profile recorded by the DR-C50 at 1 minute interval.

4.4.2 Comparison of Power Flows and power flow deviations

The PQM data was plotted for the period September 2013 – June 2014 as shown in Figure 18 below.

![Figure 16 - Graph showing PQM-recorded power flows (Sept 2013 - June 2014)](image)

The Northwold No.1 circuit was switched out of service from October – November 2013. Also, as discussed in section 4.2.2 above it can be seen that more frequent tap operation occurred between March and June 2014, and that the Quadrature-booster was switched out of service from June to July 2014 for planned works.

Figure 17 below shows a graph of the calculated power flow deviations from the recorded PQM power flow measurements, and periods where excursions outside the control bandwidth were recorded.

![Figure 17 - Graph showing the deviation of power flows on Northwold No.1 and Downham Market No.2 circuits](image)
The bandwidth is defined by an upper threshold value and a lower threshold value. If the measured active power share is outside the bandwidth, the TAPCON 260 emits a switching pulse after a time delay $T_1$ (60 seconds) – being the time between detecting deviation, which permanently stays outside the bandwidth, and the initiation of the tap operation in TAPCON260. The switching pulse triggers an OLTC to change tap position to correct the Quadrature-booster active power.

Figure 17 above shows that excursions above the upper bandwidth threshold (+2.25MW) were recorded that triggered tap change operation. However, except for the 6 September 2013 when live tests were carried out on the Quadrature-booster with the tap change on manual mode, it initially appeared that the tap change operations from Tap 11 to Tap 10 consistently occurred before the lower bandwidth threshold (-2.25MW) was reached. Further analyses showed mismatches between the PQM and QBCS data which appeared to have been caused by differences in P and Q measurements (real time versus average), and therefore calculation of $\delta P$. The PQM measurements were then adjusted to correspond to QBCS measurements.

Figure 18 and Figure 19 below show a more detailed sample graph of the typical power flows and power flow deviations respectively for tap operations recorded on 24\textsuperscript{th} and 25\textsuperscript{th} March 2014.

![Figure 18](image1.png)

**Figure 18 – Graph showing typical power flow variation with tap change**

![Figure 19](image2.png)

**Figure 19 – Graph showing typical power deviation triggering a tap change**

31/03/2015
Figure 19 above shows there were two tap change operations of Quadrature-booster per day in automatic mode which occurred on 24 and 25 March 2014 at around 10:00 and 18:00 on both days – that appear to be a response to a typical daily load pattern. On both occasions when the tap changed from Tap 10 to Tap 11, Figure 19 shows evidence of the power deviation exceeding the upper bandwidth threshold, but the same cannot be said about the lower bandwidth threshold when the tap changed from Tap 11 to Tap 10. Since the PQM data used was 10 minute interval samples, it is possible that the time when the deviation reached/exceeded the lower bandwidth could have been missed, and was smoothened by the 10 minute averaging.

4.4.2.1 Summary of Results

The Quadrature-booster successfully operated in automatic mode during the trial period changing tap position from Tap 10 to Tap 11 and vice versa.

Based on the results shown in Figure 19 the tap change operations from Tap 10 to Tap 11 were triggered when the power deviation exceeded the upper bandwidth of ±2.25MW. The PQM measurements were adjusted to correspond to QBCS measurements.

Minute by minute data granularity would have provided more accurate data to capture power variation to the minute timescales which would be lost when 10 minute averaged data or PI historian half hourly data is used.
4.5 Induced Voltage Phase Angle across Quadrature-booster

| QBR004 | For every tap change a proportionate voltage phase angle change occurs, which directly correlates the ‘No Load’ test values on the Quadrature-booster rating and diagram plate and the specified angles at full load condition |

The initial Quadrature-booster design requirements specified a tap range of ±12° at the extreme tap ends and assumed a symmetrical variation with 0° at nominal tap (Tap 10) under full load condition.

‘No load’ tests at all tap positions were carried out at the Factory in Australia and are shown on the Quadrature-booster rating & diagram plate in Figure 20 below. The test results were considered sufficient, and therefore the same tests were not repeated on site. The trial focused on testing the Quadrature-booster ‘under load condition’.

Hypothesis QBR004 sought to:

1. Confirm that the simulated ‘no load’ induced voltage phase angles using Power Factory would compare favourably with the equivalent design ‘no load’ voltage phase angle values shown on the rating and diagram plate – to validate the Quadrature-booster template used in Power Factory.

2. Record actual voltage phase angle measurements and confirm that the ‘no load’ phase angles shown in Figure 20 would come within the specified ±12° under load condition due to voltage regulation.

Figure 20 – Extract of Quadrature-booster rating & diagram plate showing phase angles against tap position

Figure 20 above shows a maximum/minimum voltage phase angle of ±14.982° under ‘no load’ condition at the extreme tap positions, which would be expected to be around ±12° under ‘full load condition’ due to voltage regulation, as indicated by the manufacturer.

Photograph of extract from Quadrature-booster ‘as built’ Rating & Diagram Plate (Also refer to Part No. 665 0976E10 – Dwg No. 720-1238C-A_RevB, Wilson Transformer Company)
4.5.1 QBR004 Methodology

The voltage phase angle changes from the bus bar side to the line side of the Quadrature-booster against the tap position were recorded using the following cases:

1. Case 1 – Experiment: the induced voltage phase angle data was recorded on all three phases (R,Y,B) using two (2) PQMs at 1 minute intervals – one PQM connected on the bus bar side and the other on the line side of the Quadrature-booster. The results were displayed on Tables and plotted on curves and scatterplots (Tap position Vs phase angle) to establish the pattern.

2. Case 2 – Simulation: simulations were carried out using Power Factory (DigSILENT). Load angles on both input and output side of the Quadrature-booster were recorded, from which the induced voltage angle across the Quadrature-booster was calculated.

4.5.2 Case 1 – Phase Angle Data Measurements

The objective of this experiment was to establish the induced voltage phase angle changes that occurred at the corresponding times a tap change occurred. Four (4) PQMs were available for the trial and three of these units were already being used to record power flows on the three 33kV circuits. PQM-2 and PQM-4 were re-assigned to measure and record voltage phase angles across the Quadrature-booster (see Figure 5, page 18), and PQM-1 and PQM-3 continued to record power flows on the Northwold No.1 and Southery No.3 circuits respectively. This experiment was carried out from 21 July 2014 to 5 September 2014, a period that was assumed would provide adequate sample data necessary to carry out this analysis and prove the hypothesis. Power flow data for the Downham Market No.2 circuit was obtained from the online DR-C50 data records.

The tap change operations as seen from the PQM and DR-C50 power flow data variations were validated using PI historian power flow profiles before and after the tap change operation, and Enmac SCADA alarm schedule. An example of tap change operation validation is shown in Appendix 3. Figure 21 below shows the recorded power flow and the tap operations that occurred from 21 July 2014 to 5 September 2014.

![Power flows and Tap position profile](image)

**Figure 21 – Graph showing time series load flows and tap position profile**
The Quadrature-booster was switched into service on 23 July 2014, and from 24 July to 6 August 2014 there was negligible export from the generator. Figure 22 below shows the average induced voltage phase angle across the Quadrature-booster plotted against the corresponding tap position profile.

![Induced voltage phase angle Vs tap position profile](image)

**Figure 22 – Graph showing variation of average voltage phase angle with tap position**

Figure 21 and Figure 22 above show that the induced voltage phase angle across the Quadrature-booster followed both the level of power flow loading and the tap position of the Quadrature-booster. A scatter plot showing the relationship between the load, phase angle and tap position is shown in Figure 23 below.

![Quadrature-booster measured voltage phase angle against load](image)

**Figure 23 - Scatter plot showing relationship between load and phase angle and tap position**

Based on the above results the following observations were made:

- Generally, when the load on the Quadrature-booster approached zero and while the Quadrature-booster was at Tap 10 as shown for the period 25 July – 6 August 2014 (Figure 21), the phase angle seen on the line side of the Quadrature-booster ranged from 0° to 0.2° (Figure 22).

- When the load on the Quadrature-booster was above 10MW, the phase angle fluctuated between approximately -0.5° to -2.8°, and varied between these two values depending on whether the Quadrature-booster was on Tap 10 or Tap 11.
For load above 10MW and with the Quadrature-booster at Tap 10, the voltage phase angle ranged from approximately -0.5° to -1.2°, compared to the expected 0° angle at nominal tap.

When the load was above 10MW and the Quadrature-booster was at tap 11, the voltage phase angle was found to be approximately -2.4° to -2.8°, which are higher (in magnitude) than the expected values of between -1.2° and – 1.3° at Tap 11 and at full load of 30MW (Table 10, page 42).

The results are summarised in Table 8 below.

<table>
<thead>
<tr>
<th>Tap Position</th>
<th>Load (MW)</th>
<th>Voltage Phase Angle (degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tap 10</td>
<td>~ 0</td>
<td>~ 0</td>
</tr>
<tr>
<td>Tap 10</td>
<td>&gt; 10</td>
<td>-1.2 to -1.6</td>
</tr>
<tr>
<td>Tap 11</td>
<td>&gt; 10</td>
<td>-2.4 to -2.8</td>
</tr>
</tbody>
</table>

From the above results it appears the Quadrature-booster was bucking at a faster rate than anticipated.

4.5.3 Case 2 – Voltage Phase Angle Simulations

Simulations were carried out on two scenarios using Power Factory software from DigSILENT: (1) ‘No load’ – achieved by opening the Quadrature-booster line side circuit breaker, (2) ‘Model base load’ – as configured in Power Factory.

The following methodology was followed.

- Load flows were run at each tap position, Tap 1 through to Tap 19 inclusive. Although Tap 1 – Tap 9 inclusive and Tap 17 – Tap 19 inclusive are not utilised on the Wissington Quadrature-booster, they were used in the simulation for information only for complete comparison with the Quadrature-booster rating & diagram plate.

- The per unit voltage, voltage phase angles at busbar side and line side of the Quadrature-booster, and power flows on the Downham Market No.2 circuit was recorded onto a spreadsheet.

- At each tap position, Tap 1 through to tap 19 inclusive, the phase angle difference across the Quadrature-booster was calculated.

- The ‘model base load’ phase angles and the phase angles recorded by the PQMs from site experiment were compared.

- The ‘no load’ phase angles and the ‘built’ voltage phase angles shown on the Quadrature-booster rating & diagram plate (Figure 20 above) was also compared.

4.5.3.1 Model base ‘No Load’ scenario

In this simulation the line side circuit breaker was OPENED. The Quadrature-booster was energised from the Wissington bus bar side. The ‘no load’ voltage phase angle on the ‘as built’ Quadrature-booster rating and diagram plate (Figure 20) were uploaded into the Power Factory (DigSILENT) Quadrature-booster template. Table 7 below shows comparative simulated induced voltage phase angles under ‘no load’ condition carried out at each tap position, Tap 1 through Tap 19 inclusive.
The results in Table 9 show that the simulated 'no load' voltage phase angles were found to corroborate the design voltage phase angles shown on the Quadrature-booster rating & diagram plate as shown in Figure 20 above, and were symmetrical around the nominal tap. The Quadrature-booster template built within Power Factory was validated as representative enough to accurately approximate the behaviour of Quadrature-booster on the network.

### 4.5.3.2 Model ‘Load Condition’ scenario

The simulation in section 4.5.3.1 was repeated with the Quadrature-booster on full load. The load on the Quadrature-booster was regulated and set to 30MW at nominal Tap 10, and maintained at the same level for the rest of the tap positions by adjusting the output from the Wissington generators. Table 10 below shows the simulated results under model base full load condition, with the last column showing the initial specification phase angles.
Based on the simulated results in Table 10 above, the simulated phase angles at nominal and extreme tap positions under 30MW load condition were found to be -2.20°, and +11.24° (Tap 1) and -18.73° (Tap 19) respectively. These results compared closely with equivalent measurements shown in Table 11 below (which show phase angles of -2.3°, +6.4° and -17.4° at Tap 10, Tap 1, and Tap 19 respectively) which were recorded during network simulations that were carried out on site by the manufacturer using low voltage source and dummy loads.

Table 11 - Power factor and phase angle measurements from on-site network simulations

<table>
<thead>
<tr>
<th>TAP POSITION</th>
<th>POWER FACTOR – CIRCUIT – 1 ( COS Ø1 )</th>
<th>POWER FACTOR – CIRCUIT – 2 ( COS Ø2 )</th>
<th>PHASE ANGLE BETWEEN Vs2 &amp; Vi2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Us - lu</td>
<td>Vs - lv</td>
<td>Ws - lw</td>
</tr>
<tr>
<td>1</td>
<td>0.986</td>
<td>0.986</td>
<td>0.986</td>
</tr>
<tr>
<td>7</td>
<td>0.991</td>
<td>0.991</td>
<td>0.981</td>
</tr>
<tr>
<td>9</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>10</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>13</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>19</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

+ = Quad booster : load voltage leads Supply voltage
- = Quad booster : load voltage lags Supply voltage

At nominal tap (Tap 10) the Quadrature-booster was already in ‘buck’ mode (retard angle of -2.20°).

---

8 Table 3 from Wilson Transformer Report ‘Quad Booster Site Load Test (WTC Ref – P1238)’ dated 07/06/2013
4.5.3.3 Comparison of measured and simulated phase angles

To further understand the deviation of voltage phase angles between load and ‘no load’ conditions, random samples of data were taken on the Downham Market No.2 circuit which included:

- Calculated induced voltage phase angle (from measured values)
- Measured thermal loading in MW
- Quadrature-booster tap position

Simulations were carried out in Power Factory. The Quadrature-booster tap position was fixed to the tap position recorded at the time of the sample data. The thermal loading on the Downham Market No.2 circuit was regulated to the measured sample thermal load level by adjusting the output of the Wissington CHP generators. The simulated results were then compared to the measured voltage phase angle. The results are shown in Table 12 below.

Table 12 - Comparison of measured and simulated phase angles at a given load and tap position

<table>
<thead>
<tr>
<th>Downham Market No.2 circuit</th>
<th>25/07/14 08:00</th>
<th>26/07/14 08:30</th>
<th>28/07/14 14:00</th>
<th>05/08/14 08:30</th>
<th>10/08/14 04:30</th>
<th>11/08/14 14:00</th>
<th>12/08/14 06:30</th>
<th>12/08/14 11:30</th>
<th>13/08/14 19:00</th>
<th>14/08/14 12:30</th>
<th>15/08/14 18:00</th>
<th>16/08/14 15:30</th>
<th>18/08/14 13:00</th>
<th>19/08/14 19:30</th>
<th>22/08/14 16:30</th>
<th>31/08/14 17:30</th>
<th>01/09/14 14:00</th>
<th>04/09/14 14:00</th>
</tr>
</thead>
<tbody>
<tr>
<td>QB Tap Position</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Measured load (MW)</td>
<td>-1.54</td>
<td>-2.07</td>
<td>-2.1</td>
<td>-1.6</td>
<td>15.2</td>
<td>16</td>
<td>13.5</td>
<td>17.3</td>
<td>13.6</td>
<td>12</td>
<td>14.9</td>
<td>12.4</td>
<td>11.2</td>
<td>12.5</td>
<td>15.8</td>
<td>15</td>
<td>11.9</td>
<td>12.2</td>
</tr>
<tr>
<td>Measured phase angle (deg.)</td>
<td>0.13</td>
<td>0.13</td>
<td>0.17</td>
<td>0.13</td>
<td>-1.1</td>
<td>-1.2</td>
<td>-2.7</td>
<td>-1.3</td>
<td>-2.8</td>
<td>-2.6</td>
<td>-1.1</td>
<td>-2.7</td>
<td>-2.6</td>
<td>-1.2</td>
<td>-1.1</td>
<td>-2.6</td>
<td>-2.6</td>
<td>-0.03</td>
</tr>
<tr>
<td>Simulated phase angle (deg.)</td>
<td>0.12</td>
<td>0.14</td>
<td>0.16</td>
<td>0.13</td>
<td>-1.3</td>
<td>-1.4</td>
<td>-2.9</td>
<td>-1.5</td>
<td>-2.9</td>
<td>-2.8</td>
<td>-1.3</td>
<td>-2.8</td>
<td>-2.7</td>
<td>-1.4</td>
<td>-1.3</td>
<td>-1.3</td>
<td>-2.7</td>
<td>-2.8</td>
</tr>
</tbody>
</table>

It can be seen from the results in Table 12 that the induced voltage phase angle depends on the tap position and the thermal loading on the Quadrature-booster.

1. Tap 10 and load ~ 0MW

This scenario included conditions when the real power loading on the Quadrature-booster tended to zero and to a reverse power flow from the Quadrature-booster line side to the Wissington busbar side, and the results showed that:

- The measured and simulated phase angles ranged from -0.03° to +0.17° and from -0.05° to +0.16° respectively – which were typically of the same order.
- For approximately zero export the measured and simulated induced voltage phase angles -0.03° and -0.05° respectively, which compared favourably with the ‘no load’ phase angle of 0° at Tap 10. For reverse power (import) up to 2MW the phase angle ranged from +0.12° to +0.17° (advance) as expected.
2. **Tap 10 and load > 10MW**

This scenario included conditions when the real power loading was above 10MW and the Quadrature-booster was at nominal tap position. The results showed that:

- The induced voltage phase angle fluctuated between approximately -1.1° to -1.3° (measured) and between -1.3° to -1.5° (simulated) – which were typically in the same order.
- An increase in phase angle change of approximately -1° occurred when the load increased from near zero to approximately 10MW and above. This showed that the Quadrature-booster was already operating in ‘bucking’ mode with the tap changer still at Tap 10, which was expected to be neutral.
- This result agreed with findings from the live tests carried out during commissioning that showed that the Quadrature-booster shifted approximately 3.6MW from the Downham Market No.2 circuit when it (Quadrature-booster) was switched into circuit while the tap changer was at Tap 10.

3. **Tap 11 and load > 10MW**

This scenario included conditions when the real power loading was above 10MW and the Quadrature-booster tap position changed from Tap 10 to Tap 11. The results showed that:

- The induced voltage phase angle ranged from -2.6° to -2.8° (measured) and from -2.7° to -2.9° (simulated) – which were typically in the same order.
- An increase in phase angle change of approximately -1.5° occurred when the Quadrature-booster changed tap from Tap 10 to Tap 11 – ‘bucking mode’, which compared favourably to the expected phase angle change of -1.7° in the draft specification (Table 9).

4.5.3.4 **Summary of results**

Under ‘no load’ condition the simulation model corroborated the design and ‘as built’ phase angle data. Under ‘load condition’, the induced phase angle change across the Quadrature-booster appeared to lose the expected symmetrical pattern about the nominal (Tap 10). The point of symmetry appeared to shift to between Tap 8 and Tap 9 under full load condition. At nominal tap (Tap 10) the Quadrature-booster was already in ‘buck’ mode (retard angle of -2.20°). From ‘live’ tests it was found that while at Tap 10 the Quadrature-booster shifted approximately 3.6MW from the Downham Market No.2 circuit which could be because of series winding impedance and the retard phase angle of -2.20°.

A significant difference between the simulated phase angles and the expected phase angles under load condition was apparent. It appears that the centre of symmetry for the induced voltage phase angle was shifted from mid Tap 10 to between Tap 8 and Tap 9. The simulation was repeated three times under different network load scenarios and yielded similar results.

It also appears that the factory ‘no load’ tests were carried using a constant voltage source 1pu (33kV nominal) on the Quadrature-booster for all tests at each tap position, Tap 1 through to Tap 19 inclusive, compared to 1.06pu voltage for the simulation case. Also the experiment measurements were based on actual ‘load condition’ on ‘live’ 33kV network with variable voltage/power flows. These different conditions were taken into account when a comparison of the results was made.
4.6 Network Capacity Headroom Created

| QBR005 | Optimal load sharing between Northwold No.1 and Downham Market No.2 parallel circuits would create approximately 10MW additional capacity headroom at Wissington 33kV boundary network |

As part of the SDRC 9.8 and the original FPP project deliverables, one of the key benefits of delivering the Quadrature-booster was the estimated increase in capacity headroom of approximately 10MW on the Wissington 33kV boundary network. The key milestone of the Quadrature-booster trial was therefore to prove this hypothesis.

QBR005 and to confirm three objectives:

1. The use of a Quadrature-booster would optimise the load sharing between the Northwold No.1 and Downham Market No.2 circuits – and thereby improve the utilisation of existing 33kV circuits. Pre-Quadrature-booster, the Northwold No.1 to Downham Market No.2 load sharing ratio was approximately 1:2, which would be improved to approximately 1:1 with the use of the Quadrature-booster.

2. To demonstrate that the improved load sharing between the Northwold No.1 and Downham Market No.2 circuits would create additional capacity headroom of approximately 10MW at the Wissington 33kV boundary network by diverting power flows from the Downham Market No.2 circuit towards the Northwold No.1 circuit with some spillovers to the Southery No.3 circuit.

3. To demonstrate that the estimated additional 10MW would be allowed on the existing interconnected 33kV and 132kV network by show that the connection of 10MW additional generation export on the Wissington 33kV network would not create new ‘pinch points’ or cause existing network constraints to breach set limits.

The prerequisite for achieving these objectives was keeping the Quadrature-booster in operation and recording its operational performance during the trial period. Detailed simulations were also carried out to show that no pinch points would be created on other parts of the interconnected 33kV network as a direct result of any additional power infeed on the Wissington 33kV network.

4.6.1 QBR005 Methodology

The QBR005 hypothesis analysis was carried out in four cases:

- Test Case 1 – studied PI historian data and compared the pre to post Quadrature-booster power flow distributions across the three Wissington 33kV feeders.
- Test Case 2 – used PQM data and produced scatterplots of the 33kV circuit loadings plotted against the generation export to demonstrate capacity headroom created by use of the Quadrature-booster.
- Test Case 3 – used Power Factory (DigSILENT) simulations and demonstrated capacity headroom created and was compared with Test Case 2 (to validate the model). This simulation and analysis was discussed under hypothesis QBR002 [section 4.3.3, page 30].
- Test Case 4 – used Power Factory (DigSILENT) simulations to study the network thermal loadings, reverse power flow at grid sites, and voltage levels on the network to demonstrate that injecting an
additional 10MW generation export on the Wissington 33kV network would be allowable on the interconnected network without breaching existing network constraints or creating other ‘pinch points’ on the network.

### 4.6.2 Test Case 1 – Analysis of PI Historian Data

PI historian data was used to compare the loading on the three 33kV circuits emanating from Wissington and the CHP export profiles for a period of two years:

- 2012 to 2013 – pre Quadrature-booster period
- 2013 to 2014 – post Quadrature-booster period

The general trend of the profiles was also compared to establish consistency of seasonal pattern of the export from the Wissington CHP generator. The two-year generation export profile and the corresponding loading profiles on the Wissington 33kV circuits from 2012 to 2014 are shown in Figure 24 below.

**Figure 24:** Graph showing recorded PI data on Wissington 33kV circuit loadings and generation export

There was a planned outage on the Downham Market No.2 circuit in July 2013 for connecting and commissioning the Quadrature-booster, which was brought online on 26 July 2013. The break in the curves (16 September – 10 October 2013) was due to the unavailability of PI data records within LIMES database possibly due to technical issues relating to the SCADA communications, RTU or the data storage. The increase in the load in the Downham Market No.2 circuit for the period 15 June 2014 to 23 July 2014 was because the Quadrature-booster was switched out of service and the Downham Market No.2 circuit placed on by-pass in order to carry out planned improvement works on the Quadrature-booster as discussed in section 4.2.2.

Figure 24 above shows that:

- The seasonal export profile from the Wissington CHP generator was generally consistent from year to year, with peak export occurring from September to March – which is thought to be associated with the sugar beet campaign season when the factory is reported to operate at its peak production, which also results in peak generation export.
- Downham Market No.2 circuit was loaded approximately twice as much load as was on each of the Northwold No.1 and Southery No.3 circuits for the period September 2012 to June 2013 as expected. With an average of approximately 800A delivered by the CHP generator, the Downham Market No.2 circuit was loaded at approximately 400A with both the Northwold No.1 and Southery No.3 circuits carrying approximately 200A each on average. This resulted in load sharing ratio of 1:2 between the Northwold No.1 and Downham Market No.2 circuits.

- Following the commissioning of the Quadrature-booster, it is clear from Figure 24 above that in August 2013 with generation export at approximately 700A, the load profiles for Northwold No.1 and Downham Market No.2 circuits are generally closer to each other. These results demonstrate that the Quadrature-booster has had the intended effect on improving the load sharing between the two lines. The Northwold No.1 circuit load averaged 250A while the load on the Downham Market No.2 reduced to an average of 300A resulting in an improved load sharing ratio of 5:6.

4.6.3 Test Case 2 – Analysis of recorded PQM Data

The recorded PQM data was sampled into 10 minute intervals for the period September 2013 to July 2014. The data was further filtered into two groups: (1) Quadrature-booster at Tap 10, and (2) Quadrature-booster at Tap 11. It was assumed that the CHP export was equal to the aggregate of the loads on the three 33kV circuits. Two scatter graphs of loads on the three 33kV circuits against the CHP export power flows were plotted to show the variability of the circuits’ loads at the two tap positions. Figure 25 below shows a scatterplot of the recorded circuit loads against CHP export for periods the Quadrature-booster was Tap 10.

![Figure 25: Scatter graph showing recorded circuit loadings at Tap 10](image)

And Figure 26 below shows a comparative graph with the Quadrature-booster at Tap 11.
The graphs in Figure 25 and Figure 26 above were extrapolated by increasing CHP export by a further 10MW from 54MW to 64MW (winter). It was assumed that the Quadrature-booster was fixed at Tap 11 for purposes of this illustration. The scatterplots show a definite relationship between circuit loading and CHP export. The correlation coefficients are shown in Table 13 below. ‘Lines of best fit’ were also plotted to show the general trend lines.

Table 13 - Pearson's correlation coefficient of circuit load Vs generation export

<table>
<thead>
<tr>
<th></th>
<th>Northwold No.1</th>
<th>Downham Market No.2</th>
<th>Southery No.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tap 10</td>
<td>0.822968</td>
<td>0.918688</td>
<td>0.853128</td>
</tr>
<tr>
<td>Tap 11</td>
<td>0.913198</td>
<td>0.825871</td>
<td>0.638985</td>
</tr>
</tbody>
</table>

Pearson’s correlation coefficient is a statistical measure of the strength of a linear relationship between paired data – circuit load and generation export. From Figure 25, Figure 26 and Table 13, it can be seen that:

- There is a positive correlation between the circuit loadings and the CHP generation export – and a linear relationship between the two variables. The variance of the data is low as shown by a high density of scatter points concentrated along the line of best fit – which provides confidence in the recorded data.

- As the tap position was raised from Tap 10 to Tap 11, the correlation coefficient for the Northwold No.1 load to the CHP export increased from 0.82 to 0.91, and that for the Downham Market No.2 decreased from 0.92 to 0.83 respectively. This proved that as the generation export increased the Quadrature-booster was most likely to raise tap position thereby push additional power through the Northwold No.1 circuit more than it pushed power through the Downham Market No.2.

- Based on the extrapolated circuit load trend lines, it is projected that with the CHP export approaching 54MW (winter) the load on the Downham Market No.2 circuit would be approximately
23MW – which is 7MW below the winter static rating. Without the Quadrature-booster the load would normally approach 28 - 30MW for this level of export.

- The two graphs (Figure 25 and Figure 26) compare favourably to modelled results shown in Figure 14 and Figure 15 (on page 31). The modelled data for the circuit loads with the Quadrature-booster in service and the actual data show similar trend with minimal difference between them. Both simulation and experiment data show that with generation export set at 64MW, the predicted circuit loads from the Wissington end would be 25 – 27MW (Northwold No.1), 23 – 25MW (Downham Market No.2), and 14 – 16MW (Southery No.3). The actual allowable power flows would have to include any generation connected downstream of Wissington on the Northwold No.1 and Downham Market No.2 circuits. This would require the QBCS to be upgraded as discussed in section 1 (on page 56). The consistency between actual data and simulation validates the Power Factory (DigSILENT) model data and the extrapolation methodology to estimate the capacity headroom.

4.6.3.1 Case for extrapolation of graphs

Historical PI data shows that Wissington generation export generally fall within seasonal export limits as shown in Figure 27 below.

![Graph showing the Wissington CHP generator export profile for period 2012 – 2013](image)

Figure 27: Graph showing the Wissington CHP generator export profile for period 2012 – 2013

As stated earlier in this report, at the time when the ‘live’ test experiments were carried out (August/September 2013) the maximum generator export was limited to 40MW due to the configuration of the CHP generator at the time of the tests. Extrapolation was then used to prove the estimated 10MW increment in capacity headroom.

The ideal test case was to increase the applicable seasonal export by 10MW, and using the Quadrature-booster load balancing act to ensure the load on all three 33kV circuits remained within static seasonal rating. This however, would have meant exploring the possibility of arranging for generation export above the existing arrangements by increasing the applicable seasonal static ratings by 10MW for a short period of time adequate to cover the test in order to make the relevant comparison. The test could have been done in autumn/spring, winter or summer. The test was designed to follow a sequence of graduated and build-up tests, assessing the effect and operation of the network on each and every progression. The ideal test could not, however, be carried out fully within the trial timeframe because of a number of issues that could have
taken longer to resolve within the trial period, and/or navigate within the existing regulatory framework. Some of the key issues considered included the following:

1. Establishing the technical capability of the generator to deliver the increased export and how the cost of the increased generation involved was to be covered. Additional export would have meant running the heat oriented generator at full tilt, which could have potentially required a mechanism of matching the high generation output to heat demand. This required further investigation on how much steam dumping the process could do if the energy transfer/steam cooling from processes was not there or the pressure relief system being inadequate to dispel the unused heat energy.

2. Need for an agreement, temporary in nature, to cover export in excess of the existing contracted maximum export capacity for the Wissington site and to spell out the terms and liabilities for generation usage above the agreed export capacity within the connection agreement. Additionally, such an agreement could have been potentially difficult to administer within the existing regulatory framework post the test.

In view of the above challenges, it appeared the available alternative was to prove the additional capacity by extrapolation of actual power flow measurements, supported by simulation. Therefore the 10MW additional capacity was proved by extrapolating trend lines on actual power flow measurements recorded during the trial period. This was the preferred approach which also had no countenance of putting demand on the relevant 33kV circuits on single circuit risk in order to load or de-load the Wissington 33kV test circuits to make the test easier.

4.6.4 Test Case 3 – Simulations: Capacity Headroom

The simulations were carried out using Power Factory (DigSILENT) and were covered under QBR002 (section 4.3.3, page 30).

4.6.5 Test Case 4 – Simulations: Allowable additional export

The simulation test case was carried out to establish if the additional 10MW export would be allowed on the existing 33kV and 132kV network under both normal running arrangement and various possible abnormal running arrangements – including planned network outages and emergency conditions. The simulated conditions are shown in the results tables in Appendix 4, Appendix 5, and Appendix 6.

The following assumptions were made for the simulation studies.

- Maximum generation and minimum load scenario. All connected generators and all accepted generation (firm) offers known at the time of this study were connected and were all generating at full rated output. All ANM controlled generators were excluded because their impact would be curtailed (potentially down to zero) as dictated by network loading at the controlled constrained points. A minimum summer load scenario was generated using National Grid’s declared time of national minimum demand for 2012 summer period, which occurred on 01 July 2012 at 5:30am. The network loads were uploaded and applied to the scenario.
• Power Factory (DigSILENT) ratings for circuits (cables, conductors and transformers) were all set to summer rating (Hot weather).

• Baseline Wissington CHP export was set to 46MW summer. This was achieved by setting the Wissington CHP generator No.2 to 16.854MW (down from the rated output of 25.474MW). The test export was set to 56MW, which is equivalent of additional 10MW export connected onto the network. This was achieved by disconnecting Wissington factory load CB_88_92_1 and IM_10 (in Power Factory model).

• Key network performance elements to check from the simulation were thermal loading on 33kV and 132kV circuits, and reverse power flows from 33kV to 132kV at 132/33kV grid sites within the interconnected Walpole Supergrid network, and voltage levels.

• Quadrature-booster Tap was set on manual throughout the simulation. The optimal tap positions to balance lines was set at Tap 10 for 46MW export, and Tap11 for CHP export of 56MW

• Because an 11kV model was unavailable in Power Factory at the time of this study, all known generators connected (including accepted connections) at 11kV and LV including micro-generations were built into the model as separate network variations, and connected at the 11kV busbar of the feeding primary substation. It was assumed this would provide adequate representation of the generators on the modelled network and improve the estimates for the results of the simulation.

• The directional over-current (DOC) protection at March Grid was replaced by load blinding protection. The reverse power flow was limited by grid transformer rating to 45MVA. It was also assumed that Active Network Management (ANM) control was fully operational and monitored and controlled levels of reverse power flow from 33kV to 132kV side at March Grid. The simulation also assumed the ANM applied a 10% operating margin, and hence the reverse power flow limit was 41.5MVA (or 90% of 45MVA).

• It was also assumed the reverse power flow capacity at Swaffham Grid limited to 600A by existing DOC protection, was exhausted. If DOC protection was replaced the reverse power flow capacity would be increased by 200A to 800A limited by the least rated grid transformer (45MVA).

• A worst case scenario of the Peterborough Central – March Grid 33kV network split at Funtham’s Lane primary via the RMUs was assumed. In this case Glassmoor Extension wind farm and Whittlesey Primary were fed from March Grid. Under the expected standard running arrangement however, Glassmoor Extension would be expected to export towards Peterborough Central.

• Under outage conditions specific considerations of reduction in output of specific generators would still be required, including any generation connected to utilise the additional 10MW capacity created on the Wissington 33kV network.
4.6.6 Summary of results

Based on experiment and simulation results, it can be seen that for 10MW additional generation export on the Wissington 33kV network, the predicted circuits loading would be 25 – 27MW (Northwold No.1), 23 – 25MW (Downham Market No.2), and 14 – 16MW (Southery No.3) from the Wissington end. The actual allowable power flows would have to include any generation connected downstream of Wissington on the Northwold No.1 and Downham Market No.2 circuits.

Results on baseline simulation tests on existing network (intact condition, summer minimum load, maximum output from all generators) showed that:

- All 33kV circuits would be loaded below their thermal rating. The results also indicate that the Wissington – Downham Market No.2 (to the T-point) section and from the T-point to Downham Market would have the highest loading of approximately 79% and 74% respectively.
- At 132kV, the results show that all circuits would be loaded way below their thermal ratings except for the Peterborough Power Station – Peterborough Central 132/11kV GT3 circuit which appeared to be already loaded at approximately 115% before connection of additional generation export at Wissington. However, this loading was not impacted by the effect of the Quadrature-booster or the 10MW additional power injection on the Wissington 33kV network.
- When the Wissington CHP export was increased from 46MW to 56MW the loading on the Northwold No.1 and Downham Market No.2 circuits increased from 74% to 85% and from 79% to 83% respectively under intact network condition, with negligible increment on loading on the rest of the 33kV and 132kV network.
- 10MW additional generation on the Wissington 33kV network increased reverse power flow at March Grid and Swaffham Grid by approximately 1.9MW and 2.8MW respectively under intact network condition, with no apparent impact on the rest of the grid sites within Walpole Supergrid network.

Under outage conditions:

- The greatest impact would be felt when the Southery No.3 33kV feeder is out of service – which would result in estimated loadings of up to 105% and 113% on the Northwold No.1 and Downham Market No.2 circuits respectively. However, under normal operations the Wissington generator would automatically reduce output under current arrangements, and therefore overload would be avoided.
- The reverse power flow limit will be reached at Swaffham Grid under certain circuit outages. It is assumed all connected generator export will be managed under current arrangements for the periods when works to normalise the network would be carried out.
- No adverse loading directly related to additional 10MW export on the Wissington 33kV network was apparent on the 132kV network.
5. Trial Outcome

The following are the key trial findings.

5.1 Operational performance

The Quadrature-booster operated within the design tap operating range (Tap 10 – Tap 17) specific to the requirements of the Wissington 33kV network, varying between Tap 10 and Tap 11 in automatic mode during the trial period. In all instances where an increase or decrease in tap position was recorded, a corresponding decrease or increase respectively in the power flow on the Downham Market No.2 circuit was recorded as expected.

Both the experimental and simulation test results showed that the Quadrature-booster shifted power flows from the Downham Market No.2 to Northwold No.1 circuit with some spill over to the Southery No.3 as expected at the Wissington site. While at nominal tap (Tap 10), the power shifted was approximately 3.5MW (for a generation export of 42MW) due to the Quadrature-booster series transformer winding impedance, and the measured negative voltage phase angle (retard) of -2.20° under load. The recorded maximum power shifted was 3.6MW for a single step change from Tap 10 to Tap 11 (and vice versa) under 43MW generation export. From simulations the power shifted by the Quadrature-booster while at Tap 10 was approximately 4MW for a generation export of 54MW.

Because of the limited generation export available at the time of the trials and the large step change of 3.6MW, it was only possible to operate the tap changer from Tap 10 to Tap 13 inclusive during live tests to avoid drawing large negative power flows in the Downham Market No.2 circuit. The optimal load sharing was achieved at Tap 10 (generator export less than 40MW), and at Tap 11 for higher export levels above 40MW (under simulation). Generally, at Tap 10 the load on the Northwold No.1 circuit was less than the load on the Downham Market No.2 circuit, and when at Tap 11 the load on the Northwold No.1 circuit exceeded the load on the Downham Market No.2 circuit. This result means that at the Wissington trial site, it appears only Tap 10 and Tap 11 would be used, and it is possible that Tap 12 – Tap 17 inclusively are unlikely to be used.

The Quadrature-booster operated reliably throughout the trial period with minor issues reported on the Calisto 9 monitoring and erroneous over fluxing alarms generated – all issues were rectified quickly and no recurrences were recorded. The Quadrature-booster oil and winding temperature and voltage profiles recorded during the trial period appear satisfactory as shown in Appendix 2.

5.2 Quadrature-booster Control System (QBCS)

The TAPCON260 relay was customised to function as the QBCS and successfully operated in both manual mode and automatic mode. To accommodate the biggest power step change per tap of 3.6MW the smallest bandwidth setting that could be set was ±1.9MW. During the trial period the bandwidth was set to ±2.25MW for a total bandwidth of 4.5MW which was comfortably higher than the biggest step change of 3.6MW.

Increasing the bandwidth setting affects how closely the scheme was able to optimise the power share between Downham Market No.2 and Northwold No.1 circuits but ensured a stable operation and reduced tap changer operations to minimise wear and tear of the tap changer and prolong its economic lifecycle.

The QBCS operated correctly when the deviation in power flows reached the upper bandwidth threshold of +2.25MW and send tap change signal to the tap changer to raise the tap position from Tap 10 to Tap 11. For the lower bandwidth threshold of -2.25MW the results show that tap changes appeared to have occurred before the power flow deviation reached the lower bandwidth threshold. Since 10 minute averaged data was...
used in this trial, it is possible that the deviations that caused the tap change operations from Tap 11 to Tap 10 were averaged and smoothened within the 10 minute averaged sample – and the moment the threshold was reached could have been missed.

One of the elements of the trial was to monitor the generation response when the Quadrature-booster changed tap position which would result in step changes in amperes loading on the 33kV lines. Throughout the trial period no issues were reported on the generator protection scheme that monitors the rate of change of current on the three 33kV circuits. It can therefore be concluded that the ‘tap change in progress’ signals sent from the QBCS to the generator to mask protection appeared to have operated successfully.

### 5.3 Induced voltage phase angles

The recorded induced voltage phase angle across the Quadrature-booster was dependent on both the level of load and the tap position. The results are summarised in the Table below.

<table>
<thead>
<tr>
<th>Tap Position</th>
<th>Load (MW)</th>
<th>Voltage Phase Angle (degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tap 10</td>
<td>~ 0</td>
<td>~ 0</td>
</tr>
<tr>
<td>Tap 10</td>
<td>&gt; 10</td>
<td>-1.2 to -1.6</td>
</tr>
<tr>
<td>Tap 11</td>
<td>&gt; 10</td>
<td>-2.4 to -2.8</td>
</tr>
</tbody>
</table>

A change in tap from Tap 10 to Tap 11 induced a negatively increasing voltage phase angle (retard/buck mode), and a change of tap position from Tap 11 to Tap 10 resulted in a positively increasing phase angle (advance/boost mode). The Quadrature-booster operated as expected. The measured phase angles were recorded at Tap 10 and Tap 11 only – as the Quadrature-booster operated at these two tap positions only during the trial period. It would have been useful if actual measurements were recorded at more tap positions to enable a full scale comparison through the operating tap range from Tap 10 to Tap 17 inclusive.

The simulated voltage phase angles under ‘no load’ condition were found to be the same as the design and ‘as built’ ‘no load’ voltage phase angles. Under load condition, the induced phase angles appeared to deviate from the expected or specified ±12° range. The results show voltage phase angles that ranged from +11.24° (at Tap 1) to -18.73° (at Tap 19). It also appeared that while at Tap 10 the Quadrature-booster was already in ‘buck’ mode (retard angle of -2.20°). These results are consistent with similar network simulation test measurements carried out on site by the manufacturer during commissioning.

### 5.4 Capacity headroom created

Following the commissioning of the Quadrature-booster, the load profiles for Northwold No.1 and Downham Market No.2 circuits were generally closer to each other due the control and load equalising effect of the Quadrature-booster. These results demonstrated that the Quadrature-booster improved the load sharing between the two lines. As the Quadrature-booster tap position was raised from Tap 10 to Tap 11, the correlation coefficient for the Northwold No.1 load to the CHP export increased from 0.82 to 0.91, and that for the Downham Market No.2 decreased from 0.92 to 0.83 respectively. This proves that as the generation export increases the Quadrature-booster is most likely to raise tap position thereby pushing additional power through the Northwold No.1 circuit more than it would push power through the Downham Market No.2.
Based on extrapolations of scatterplots on both measured and simulated data, the results showed that, at the existing maximum export of 54MW (winter) the loading on all three lines would be below 25MW when the Quadrature-booster was switched in service. For 64MW export (with additional 10MW), the loading on the 33kV lines would be under 30MW capacity limit (winter). The loads on all three circuits remained under the respective seasonal static rating when 10MW was added to each seasonal export limit.

Network study results, which assumed that all connected generators and known accepted generation connection offers at the time of study were generating and exporting maximum contracted power showed that, under intact condition, the worst circuit loadings caused directly by the additional 10MW at Wissington would be 85% on the Northwold No.1 33kV circuit. Under emergency conditions the worst loaded line would be the Downham Market No.2 circuit (113%) for an outage on the Southery No.3 circuit. This overload condition is unlikely to occur as it is managed by the Wissington generator turndown scheme under the existing arrangements. An estimated increase in reverse power flow of approximately 1.9MW and 2.8MW would be seen at March Grid and Swaffham Grid respectively under intact conditions.

The capacity headroom on the Wissington 33kV network would ultimately be based on a number of variables across the network – including load magnitude and distribution, load power factor and reactive power flows, and voltage profile on the 33kV network. Before connecting additional generation on the 33kV lines between Wissington and Northwold or Wissington and the Downham Market T-point to utilise the 10MW capacity, the following observations need to be taken into account in order to ready the network to accept the additional generation:

- Upgrade the QBCS to include remote power flow measurements from Northwold Primary end and the Downham Market T-point, to account for generation export connecting on the controlled circuits between Wissington and Downham Market No.2 circuit T-point, and Wissington and Northwold Primary (on the Northwold No.1 circuit). A summary of the required upgrade is discussed in section 1 on page 56.
- Replace the DOC protection scheme at Swaffham Grid to increase reverse power flow capacity at the site and fully utilise grid transformer capacity, in order to accommodate an estimated 2.8MW increase in reverse power at the site attributable to the connection of 10MW additional generation export on the Wissington 33kV network.
- Monitor the potential increase in curtailment levels of generators on flexible connection arrangements feeding into March Grid, caused by an estimated 1.9MW increase of reverse power flow as a result of the spill overs of the power shifted by the Quadrature-booster that is forced onto the Southery No.3 circuit.
- Further detailed study at the time of processing any connection request to accommodate any changes on the evolving 33kV network.

It is expected that these conditions will be taken into account when processing generation applications to utilise the 10MW capacity created by the Quadrature-booster, and the related costs would be treated as part of the connection cost. It is also assumed that the output of the Wissington CHP generator will continue to be managed by the existing automatic generator turndown scheme which monitors the loadings on the outgoing 33kV circuits, along with the status of circuit breakers. In the event of a circuit loss, or the
combined power flows exceeding the seasonal limits, an automatic generator turndown is activated to reduce generation to within set limits to ensure that the restriction is not breached.

5.4.1 Case to upgrade QBCS

At the inception of the FPP project in 2011/12, the QBCS was based on a network drawing shown simplified in Figure 28 below and the following assumptions:

- Only power flow measurements at Wissington side 33kV on the Northwold No.1 and Downham Market No.2 circuits would be used to regulate the power sharing between these two circuits. This was considered adequate to prove the Quadrature-booster concept and satisfy the project objective.
- The controllable power flow was the power passing through the Quadrature-booster (Downham Market No.2 circuit).
- Power flow on Southery No.3 or possible impacts on Southery No.3 was not considered by the control system.

The QBCS regulates the OLTC in the Quadrature-booster to achieve optimal load sharing between Northwold No.1 and Downham Market No.2 circuits by comparing the power flow of Northwold No.1 and Downham Market No.2 at Wissington end. The trial concept was centred on generation injection on the Wissington 33kV substation which was adequate to prove the Quadrature-booster concept, and therefore
the existing control system only monitors power flows on the two lines at Wissington end. It was also not envisaged at the time the project was initiated that other new generation plants would be connected on these two lines between Wissington and Northwold or Wissington and Downham Market T-point during the trial period. The existing QBCS and the current version of the associated Engineering Operating Standard (EOS 04-8003) are based on Figure 28 and the assumptions above.

The 33kV network has since changed from what it was at the inception of the project. A new 5MW solar farm generation was connected on the Northwold No.1 circuit, and has been operational since 2013. When both the Wissington CHP generator and the solar farm are exporting it is clear that the power flow at Northwold Primary end would be higher than the power flow out of Wissington end on the Northwold No.1 circuit. Although there is currently no envisaged circuit overloading under this condition given the existing seasonal export limits arrangement with Wissington CHP generator, the installed QBCS algorithm would require upgrading in order to accommodate further generation connection. Figure 29 below shows the additional remote power flow measurements which will be required as inputs to upgrade the QBCS. It is therefore necessary to include this upgrade as part of future generation connection application connection charge.

**Figure 29 – Single line drawing showing required additional remote measurements to upgrade QBCS**

One possibility is to input the four power flow measurements into a PLC client server to run a set of algorithms to determine the appropriate load sharing factor between the two lines. The idea of the algorithm would not only be sharing the power through the lines equally, but also to account for any generation
connected to any of the monitored lines. The algorithm would detect any generation between the local (Wissington end) and remote measurements and de-rate the line on which generation is connected before deciding the appropriate power sharing factor.

It should be noted that the controllable power is the one that passes only through the Quadrature-booster (Downham Market No.2 circuit at Wissington substation end). Any generation that pushes power at any point between the two ends of any of the circuits would be considered to be forced rather than controllable, hence the corresponding circuit would deal with this power regardless of the power flowing through from the Wissington substation end. The seasonal static thermal ratings of the lines will be used in order to prevent any overloading conditions, and ensure true equal power sharing between the lines. It is therefore critical that this upgrade is carried out as part of any additional generation export on the Northwold No.1 and/or Downham Market No.2 circuits.

A high level of the scope of work required to upgrade the QBCS includes the following:

- Implementation of the QBCS algorithm on IEC 61850 client and server enabled PLC device (with additional Ethernet switch with fibre)
- Installation of the P and Q measurements on the 33kV feeders and connection to RTU (at Northwold Primary)
- Installation of optical CTs at the Downham Market T-point, and to include feasibility of collecting the data as there is no substation/building to house an RTU.
- Installation of communication links to carry the remote measurements to Wissington 33kV substation.
- Installation of the PLC device at Wissington and commissioning of the scheme
6. Lessons Learnt

The key lessons learnt from the trial included the following:

6.1 Load balancing

The key learning generated was the demonstration of the capability of Quadrature-booster to actively manage thermal loading constraints by achieving optimal load sharing on parallel 33kV circuits at Wissington. When the Quadrature-booster was commissioned the loading on the Northwold No.1 and Downham Market No.2 was closer to each other compared to pre-Quadrature-booster era for the same Wissington generation export. The use of the Quadrature-booster created additional network capacity headroom which would allow increased generation export onto the 33kV distribution network.

6.2 Phase angle specification

The specified Quadrature-booster phase angle of ±12° was wider than required on the Wissington 33kV network trial case. This resulted in approximately 3.6MW per step tap change being shifted, which appears ‘course’ and made it difficult to achieve a finer load balancing between the two lines. Because of this large MW step change the Quadrature-booster operated at Tap 10 and Tap 11 only which meant that the trial was unable to evaluate the operation of the Quadrature-booster on the full tap operating range (Tap 10 – Tap 17 inclusive). The trial results showed that a phase angle of ±6° could have been adequate for the Wissington site. This lesson will inform future assessments and specification for the required Quadrature-booster phase angle range on other networks. It is recommended that in future applications further simulations are carried out using a phase angle of ±6° for finer tap step, and also place the Quadrature-booster in the Northwold No.1 circuit and use the boost taps (Tap 9 – Tap 1). This is expected to give finer phase angle steps under load condition and also avoid overfluxing in the core.

6.3 Deviation of phase angle under load

The deviation of measured phase angles under load conditions from specification showed that for new plant that has not been deployed on the distribution network before, like the Quadrature-booster, it is imperative that the Factory Acceptance Tests included a detailed simulation of the plant on a setup that depicts the application to which the plant will be operating on site under full load conditions. The difficulty with the Quadrature-booster FAT appeared to have been that transformer factories are not normally equipped to provide the necessary reactors/load banks to simulate real network tests. It is recommended that the tests required are confirmed at the design review, to ensure that sufficient suitable equipment can be made available for the FAT.

6.4 QBCS logic upgrade

The required QBCS logic could vary as the distribution network configuration evolves, which is possible mainly with more distributed generation connecting on the controlled circuits. Although there was a connection of 5MW PV generator on the Northwold No.1 circuit during the trial period which was not taken into account by the QBCS control scheme, there was no apparent risk on thermal overload on the circuit given the existing export arrangements with Wissington CHP generator. However, it is preferable to upgrade the QBCS logic to reflect the connection of a PV generator on the Northwold No.1 circuit.

31/03/2015
6.5 Calisto 9 monitoring equipment

Isolated issues experienced with the Calisto 9 alarms during the trial period showed that it is important to have specialised support skills local to UK for quick response. The Calisto 9 was supplied by Morgan Schaffer with support services provided by personnel from Canada which took longer to resolve the alarms issues than it is estimated would have taken were the support services based locally in UK. This forced the Quadrature-booster to be switched off for cautionary reasons as the cause of the alarms was initially not apparent. It should be noted that the Calisto 9 is a very new piece of monitoring equipment and was the first of its type in the UK, thus there were some initial operational issues with the installation and setup.

6.6 Collaboration with stakeholders

Innovative trials like the Quadrature-booster require cooperation and participation of customers connected on the network. The ramping of generation export to different export levels for the live tests, and also monitoring the generation protection response to changes in line currents during tap change operations was one of the key elements to the experiments.
7. Conclusion

The Quadrature-booster trial results aligned with the requirements of the Quadrature-booster design. However, it can be concluded that a finer step tap change would have been more useful, to be able to take smaller steps and more of them than the two recorded during the trial period. This would have made the control smoother to achieve a better optimisation of the load sharing between the two circuits.

The use of the Quadrature-booster at Wissington created spare capacity of approximately 10MW at Wissington 33kV network, which can be available subject to upgrading the QBCS and replacement of the DOC protection at Swaffham Grid. The QBCS control algorithm require to be upgraded to include power flow analogue measurements at the Downham Market No.2 circuit T-point and Northwold Primary to take account of any generation likely to connect on the two controlled lines.

The capability of the Quadrature-booster to create capacity on the Wissington 33kV network is limited to its rating and the line ratings. If the level of generation export on the Wissington 33kV network continues to rise, the installed Quadrature-booster would be a temporary solution. At some stage the network will ultimately need reinforcement to continue accepting increased levels of generation. However, the Quadrature-booster project will allow approximately 10MW additional generation export to be connected to the Wissington 33kV network that may otherwise would have involved costly infrastructure reinforcement.

The trial was successful because the Hypotheses and Use Cases were all answered and the following objectives were met:

- The trial set out to achieve optimal loading sharing between the Northwold No.1 and Downham Market No.2 circuits. The Quadrature-booster balanced power flows by tapping up/down to optimal tap position, and showed that loading on the Northwold No.1 and Downham Market No.2 circuits were closer to each other than prior to the installation of the Quadrature-booster.

- The trial also estimated that 10MW additional capacity headroom would be created on the Wissington 33kV network. Based on experimental data and supported by network simulation studies the 10MW additional capacity headroom was proved, and that it would be conditionally allowable to connect additional generation export up to 10MW.

- As a ‘first’ Quadrature-booster on 33kV network, the trial set out to ensure a smooth operation of the Quadrature-booster trial on a live network without compromising security of supply or existing network plant, for example, the Wissington generator with sensitive protection. Over the trial period the overall stability of operation of the Quadrature-booster was confirmed with enhanced monitoring from the DR-C50 and Calisto 9 data, and no adverse impact was reported on the Wissington generator during the trial period.
Appendices

Appendix 1 – Quadrature-booster tap and load profiles for selected months

DR-C50 Data: Power Flows and Tap Position profile (August 2013)

DR-C50 Data: Power Flows and Tap Position profile (September 2013)

DR-C50 Data: Power Flows and Tap Position profile (October 2013)
Appendix 1 continued

DR-C50 Data: Power Flows and Tap Position profile (November 2013)

DR-C50 Data: Power Flows and Tap Position profile (December 2013)

DR-C50 Data: Power Flows and Tap Position profile (January 2014)
Appendix 1 continued

DR-C50 Data: Power Flows and Tap Position profile (May 2014)

DR-C50 Data: Power Flows and Tap Position profile (June 2014)

DR-C50 Data: Power Flows and Tap Position profile (July 2014)
Appendix 2 – Quadrature-booster temperature and voltage profiles

Quadrature-booster temperature profiles as recorded by DR-C50 Equipment

Quadrature-booster voltage profiles as recorded by DR-C50 equipment
The PQM was in time synch with the RTU, but the DR-C50 appeared to have lagged the PQM and the RTU.

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### Appendix 4 – Table showing simulated 33kV circuits thermal loadings under various scenarios

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<th>Scenarios</th>
<th>Summer Current Rating (kA)</th>
<th>Baseline intact condition + Accepted gen connections (CHP export = 46MW)</th>
<th>Test intact condition + Accepted gen connections (CHP export = 56.10MW)</th>
<th>March Grid GT1 outage + Littleport 33kV bus section opened</th>
<th>Wissington - Southery 33kV circuit outage</th>
<th>Northwold - Swaffham 33kV circuit outage</th>
<th>Kings Lynn South GT1B outage</th>
<th>Peterborough Central Grid GT1B outage</th>
<th>Hempton Grid GT1 outage</th>
<th>Kings Lynn - Swaffham GT1B outage</th>
<th>Northwold Local T1 - Narborough 33kV circuit outage</th>
<th>Swaffham - Hempton 33kV circuit outage</th>
<th>Swaffham - Narborough 33kV bus section opened</th>
<th>Swaffham - Walsoken 33kV circuit outage</th>
<th>Swaffham - Watton 33kV circuit outage</th>
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31/03/2015
## Appendix 5 – Table showing simulated reverse power flows at grid sites under various scenarios

| Scenarios | Summer Current Rating (kA) | Baseline Intact condition existing network (CHP export = 46MW) | Test Intact condition + Accepted gen connections (CHP export = 64MW) | Test Intact condition + Accepted gen connections (CHP export = 64MW) | March Grid GT1 outage + Littleport 33kV bus section opened | Walsoken Grid GT1 outage | Swaffham Grid GT1 outage | Kings Lynn GT1 outage | Kings Lynn South GT1B outage | Peterborough Central Grid GT1B outage | Wissington - Southery 33kV circuit outage | Northwood - Swaffham 33kV circuit outage | Swaffham - Hempton 33kV circuit outage | Swaffham Local T1 - Narborough 33kV circuit outage | Swaffham - Hempton 33kV circuit outage | Swaffham - Narborough 33kV circuit outage | Swaffham - Hempton 33kV circuit outage | Downham Market - Kings Lynn South/Waltington 33kV circuit outage | Kings Lynn - Fairstead - Narborough 33kV circuit outage | March - Upwell Lakes End 33kV circuit outage |
|-----------|----------------|-------------------------------------------------|------------------------------------------------------------------|------------------------------------------------------------------|-----------------------------------------------------------------|----------------|----------------|----------------|----------------|----------------|--------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|
| s0        | Reverse Power Flow (% of DOC) | 0.60 | 40% | 70% | 78% | 85% | 79% | 60% | 82% | 76% | 78% | 78% | 92% | 65% | 68% | 75% | 73% | 84% | 97% | 79% | 84% | 102% | 87% |
| Swaffham Grid | 0.85 | 0% | 66% | 69% | 72% | 56% | 71% | 69% | 69% | 74% | 69% | 74% | 73% | 70% | 69% | 69% | 59% | 68% | 70% | 72% | 68% | 73% |
| March Grid (Load blinding + ANM) | 0.80 | 82% | 90% | 90% | 90% | 90% | 90% | 90% | 90% | 90% | 90% | 90% | 90% | 90% | 90% | 90% | 90% | 90% | 90% | 90% | 90% | 90% |
| Walsoken | 0.58 | 0% | 34% | 35% | 35% | 35% | 41% | 30% | 31% | 35% | 35% | 36% | 34% | 34% | 41% | 36% | 33% | 35% | 35% | 33% | 36% |
| Hempton | 0.40 | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| Kings Lynn | 0.50 | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
## Appendix 6 – Table showing simulated reverse power flows at grid sites under various scenarios

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<td>Quadrature-booster Trial &amp; Learning Report</td>
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