## Definitions

<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
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<tbody>
<tr>
<td>Boost</td>
<td>Increase flow of active power in a circuit</td>
</tr>
<tr>
<td>Buck</td>
<td>Reduce flow of active power in a circuit</td>
</tr>
<tr>
<td>Combined Heat and Power (CHP)</td>
<td>Co-generation or use of power station to simultaneously generate electricity and useful heat</td>
</tr>
<tr>
<td>CDM</td>
<td>Construction, Design and Management – regulations used in the construction industry in UK</td>
</tr>
<tr>
<td>DigSILENT</td>
<td>Manufacturer of PowerFactory – a power systems modelling tool used by UK Power Networks</td>
</tr>
<tr>
<td>Distributed Generation (DG)</td>
<td>Electricity generation connected to the distribution network</td>
</tr>
<tr>
<td>EPN</td>
<td>Eastern Power Networks plc, the holder of a distribution licence</td>
</tr>
<tr>
<td>Ellipse</td>
<td>The asset catalogue which contains information on all of UK Power Networks’ electrical assets</td>
</tr>
<tr>
<td>FPP Trial Zone</td>
<td>An area of UK Power Networks’ EPN distribution network that serves approximately 30km diameter (700km²) between Peterborough and Cambridge in the East of England, UK</td>
</tr>
<tr>
<td>Low Carbon Network Fund (LCNF)</td>
<td>A funding mechanism introduced by Ofgem to promote research and development for smart distribution networks</td>
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<tr>
<td>Ofgem</td>
<td>The Office of Gas and Electricity Markets: regulator for the electricity and gas markets in Great Britain</td>
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<tr>
<td>On load tap changer</td>
<td>A connection point selection mechanism along a power transformer winding that allows a variable number of turns to be selected in discrete steps</td>
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<tr>
<td>Point of connection</td>
<td>The interface between the UK Power Networks’ equipment (main fuse, energy meter) and the consumer’s equipment (supply panel)</td>
</tr>
<tr>
<td>Term</td>
<td>Description</td>
</tr>
<tr>
<td>-------------------------------------</td>
<td>---------------------------------------------------------------------------------------------------------------------------------------------</td>
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<tr>
<td>Quadrature-booster</td>
<td>A specialised form of transformer used to control the flow of real power on a three-phase electricity transmission network</td>
</tr>
<tr>
<td>Real Time Digital Simulator (RTDS)</td>
<td>A digital electromagnetic transient power system simulator that operates in real time to provide power systems simulation technology for fast, reliable, accurate and cost-effective study of power systems with complex High Voltage Alternating Current (HVAC) and High Voltage Direct Current (HVDC) networks</td>
</tr>
<tr>
<td>SCADA</td>
<td>Supervisory Control and Data Acquisition – computer controlled systems that monitor and control electricity distribution network</td>
</tr>
<tr>
<td>Standard Running Arrangement</td>
<td>The distribution network configuration under normal network operating conditions</td>
</tr>
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Executive Summary
Executive Summary

Flexible Plug and Play (FPP) is a Second Tier Low Carbon Network Fund (LCNF) project that aims 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 will be trialled to manage constraints and maximise network utilisation. This will enable alternative smart connection solutions to be trialled in order to facilitate, accelerate and cost optimise the connection and operation of DG in a constrained distribution network.

One of the smart devices to be trialled as part of the FPP project is a Quadrature-booster, which has been designed and deployed to balance power flows through parallel circuits supplying a large customer whose ability to export electricity is currently constrained as a result of unbalanced load sharing on two parallel circuits. A key milestone of this project was to install and deploy a Quadrature-booster and demonstrate that this could be used to increase the export capacity of the site. It is reported that power generation on this site achieves the best Combined Heat and Power (CHP) rating under the government CHP environmental quality assurance scheme, further increments of generation exports would therefore contribute to low carbon generation.

This report outlines the design, installation, testing and commissioning of this innovative asset to explain the process which UK Power Networks undertook to successfully meet the project Successful Delivery Reward Criterion (SDRC) for the Quadrature-booster referenced as 9.8 in the Project Direction. In addition to its successful installation, the report also demonstrates how the Quadrature-booster allows 10MW of increased power flow by improving the balance between the circuits.

The Quadrature-booster is designed to shift real power flows from an overloaded circuit to a circuit that is less loaded to achieve improved load sharing and increased network capacity headroom. The Quadrature-booster is equipped with an automatic control system that drives an on-load tap changer to control the power flows in discrete steps.

Based on the available information and references, we understand that this is the first Quadrature-booster to be deployed on a 33kV distribution network in the world. Consequently significant new knowledge has been generated throughout the entire process from concept development, modelling, design, installation, commissioning and ultimately to operations and maintenance.

The Quadrature-booster has been a complex and cutting-edge innovation engineering project delivered in demanding timescales by highly-skilled teams from the various project participants (partners, suppliers and UK Power Networks) working in close collaboration with each other.

The Quadrature-booster project was led by UK Power Networks and delivered in partnership with a team of project partners and suppliers. Wilson Transformer Company designed, built, installed and commissioned the Quadrature-booster and Fundamentals Ltd its control system. Carillion Utility Services was responsible for delivery of the civil and electrical works. Alstom Grid supported the development of the protection scheme while Mott McDonald provided assurance studies on the design of the protection scheme.

The SDRC was achieved following the successful deployment of the Quadrature-booster in July 2013 and the FPP project intends to disseminate further information on the operation and performance of the Quadrature-booster at later stages in the project.
2
Introduction
2.1 Flexible Plug and Play

The FPP project, funded under Ofgem’s LCNF Second Tier scheme, aims to facilitate the faster and cheaper connection of DG onto the distribution electricity network without the need for conventional network reinforcement. Rather, the FPP methods achieve this objective by managing network constraints and maximising network utilisation. The FPP project will do this through the integration of smart devices, smart applications and smart commercial arrangements.

One of the smart devices deployed by the project is the Quadrature-Booster. The Quadrature-Booster is a power systems device that can be used to improve balance the power flows across two parallel lines in the distribution network and release headroom in the existing assets. This additional capacity can be used by either generation or demand customers for their connection on the distribution network.

The FPP project, led by UK Power Networks, addresses this requirement in partnership with 10 project partners: Vodafone (formally Cable & Wireless Worldwide), Silver Spring Networks, Alstom Grid, Smarter Grid Solutions, GL Garrad Hassan, University of Cambridge, Imperial College London, the Institute of Engineering and Technology, Fundamentals and GE Power Conversion.

2.1.1 Flexible Plug and Play: The Trial Zone

The location chosen for the FPP project is an area of UK Power Networks’ EPN distribution network that serves approximately 30km diameter (700km²) between Peterborough and Cambridge (the FPP Trial Zone) in the East of England, UK. This area is favourable to DG developers – wind and solar farms in particular – due to geography and favourable weather conditions.

Over recent years UK Power Networks has experienced increased activity in DG development in this area, and a rapid rise in connection applications; existing renewable DG connections total 144MW, with 158MW of DG capacity currently at various stages of the planning process seeking to connect as at July 2013. Using conventional connection approaches, the connection of this anticipated growth in DG is expected to require significant network reinforcement to manage network thermal and voltage constraints and reverse power flow issues.

For this reason, the area between Peterborough and Cambridge serves as an ideal trial area for the FPP project to explore alternative smart connection solutions.

2.1.2 Flexible Plug and Play: The Solution

The FPP project is trialling smart connection solutions, in order to facilitate, accelerate and cost optimise the connection and operation of DG in a constrained distribution network. The project is trialling an alternative to the passive ‘fit and forget’ approach based on conventional network reinforcement – one that considers the active management of network constraints and generation export, driving an innovative active ‘fit and flex’ approach that will avoid or defer network reinforcement. The FPP solution will demonstrate this active ‘fit and flex’ approach through the integration of smart devices, smart applications and smart commercial arrangements:

Smart Devices: The solution will deploy smart devices from various vendors to address and manage specific existing or anticipated network constraints and operational limitations of the network that either restrict DG connections or are introduced by the connection of DG. The range of smart devices include: dynamic line ratings; active voltage management; a Quadrature-booster and associated control system; and generation controllers.

Smart Applications: A smart application will be installed at UK Power Networks’ control centre at Fore Hamlet, Ipswich, providing an Active Network Management (ANM) solution.

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1 The project has also a number of project suppliers: Wilson Transformer Company, Matt McDonald, PA Consulting, Baringa Partners and DNV Kema.
to monitor real time network parameters by the smart devices. The ANM will also manage the generators’ output using the generation controllers, which will allow the DG export to track the real-time export capacity available within the real-time constraints on the distribution network. The ANM will perform these functions while ensuring that the distribution network maintains its reliability and performs within operational limits.

**Smart Commercial Arrangements:** As generators’ export will be actively managed (i.e. their output will be regulated to meet distribution network constraints), new commercial and connection arrangements will be established that define access to the distribution network capacity available in real time. This will be in the form of an ‘interruptible’ connection agreement; the first of which have been presented as part of the connection offers to eligible generation developers within the FPP trial area.
2.2
Scope of report

This report looks to provide evidence to demonstrate the successful completion of the project SDRC for the Quadrature-booster workstream. This SDRC is evidenced by the commissioning of the device and this report.

The report is structured as follows:

Section 3  Outlines the Quadrature-booster concept as adopted by UK Power Networks

Section 4  Provides an overview of the Quadrature-booster specification and design. In this section technical requirements and specifications on the Quadrature-booster, the Quadrature-booster control system, and the Quadrature-booster protection system are discussed.

Section 5  Describes the Quadrature-booster architecture, electrical installation, protection system and the Quadrature-booster control system operating principle to control and regulate active power flow.

Section 6  Outlines the installation activities associated with the Quadrature-booster and the supporting infrastructure.

Section 7  Provides a summary of the testing and commissioning activities and outcomes.

Section 8  Deals with the training for key staff in readiness for the Quadrature-booster deployment on the distribution network.

Section 9  Concludes the report.
Quadrature-booster: Concept
3.1 Project Drivers

The Quadrature-booster trial is 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.

This network constraint is due to the thermal capacity of one of the three outgoing electrical circuits, two of which are connected in parallel. Generation export is shared across the three circuits according to their electrical impedance which, amongst other factors, is related to their relative lengths. Large distributed generators can highlight capacity sharing issues on our network which had not previously been considered as a constraint on demand customers.

During peak export, the thermal capacity of one of the paralleled circuits is exceeded 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 54MW which is 23% below the installed generator turbine capacity (70MW). 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 exports can provide valuable contribution to the electricity generation fleet.

The Wissington British Sugar factory runs the CHP at full export during the sugar beet campaign months from October to March. This is when the constraint conditions usually occur.

Figure 1: Aerial photograph of Wissington site CHP point of connection

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1 http://www.britishsugar.co.uk/files/FacteryPDFs/About-Wissington-Factory-pdf.aspx - accessed 25 July 2013, 1100hours
The concept to deploy a Quadrature-booster at British Sugar’s site at Wissington was investigated as part of the development of the overall FPP project bid submission. This included the high level design of the system, which was developed to enable budget costing for this device.

The key activities undertaken during this high level design phase of the project included:
- Verification of the network constraint
- Budget costing for the project
- Identification of the expected benefits of the project

The key output of this phase was a formal technical design review by UK Power Networks. The following sub-sections provide an overview of this high level design, along with the rationale associated with the realisation of these expected benefits.
3.2 Background

The Wissington British Sugar substation is a UK Power Networks’ 33kV 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)¹, shown in Figure 2, the site connection is provided via three 33kV circuits running interconnected with four 132/33kV sites – March Grid, Swaffham Grid, Kings Lynn South Grid and Walsoken Grid (not shown in Figure 2).

Figure 2: The general Wissington 33kV Network Interconnection under Standard Running Arrangement

¹ The distribution network configuration under normal network operating conditions - all three outgoing 33kV circuits are connected and on load
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. The installed turbine capacity is 82.4MVA (or 70MW at 0.85 power factor) and is reported by Wissington British Sugar to be limited by the available export capacity on the distribution lines. The output of these generators 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.

In the past, UK Power Networks has considered enquiries for increasing the export limits, but the local 33kV overhead line was identified as the main restriction to provide a cost efficient solution. The previous solution identified was to connect British Sugar directly to the main connection point at Swaffham Grid, which could be achieved via two options below:

1. A new overhead 33kV line from Wissington to Swaffham at a cost of circa £3.0 million and liable to a Section 37 planning consent, with an expected three year public enquiry.

2. A new fully underground 33kV cable between Wissington and Swaffham at a cost of circa £6.0 million, which would not require Section 37 planning consent.

Neither of the above options were considered a viable cost effective business solution to British Sugar and so the CHP plant continued to operate within the present export constraints.

The Quadrature-booster project spend is forecasted to be approximately £1.6 million including all costs for project management, civil works, the new electrical installation, the device, control and protection systems. The method costs for future replication of the device are expected to be lower but, even at the cost of the project trial, the Quadrature-booster is a more cost effective solution for releasing additional network capacity.
3.3 The network constraint

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. The three circuits have the same conductor size (200SCA) and therefore have the same seasonal thermal rating values as shown in Table 1.

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 line means that seasonal export limits are included in the existing “Connection & Use of System Agreement” between British Sugar and UK Power Networks as shown in Table 2.

Combined with these overall network limits, there is also local line current limits on the three outgoing 33kV circuits to Northwold, Southery and Downham Market with a complex control system to make sure the line with the highest electrical load flow is not overloaded (always the Downham Market line). The Downham Market line (to the Tee point) is connected electrically in parallel to the Northwold line, but it is almost half the length of the Northwold line. Due to this difference in length, the Downham Market line has lower circuit impedance, which results in almost twice the amount power flow through the Downham Market line compared to the Northwold line. The CHP output is reduced in order to prevent the Downham Market line being overloaded.

The network constraint was illustrated through modelling of the network, which was undertaken in PowerFactory modelling software (from DgSILENT) based on the following assumptions:

- The network is operating in its normal configuration
- Wissington CHP generation dispatch is 54.58MVA

### Table 1: Seasonal ratings for circuits within the Wissington 33kV Network interconnection

<table>
<thead>
<tr>
<th>Circuit</th>
<th>Summer Amp</th>
<th>Summer MVA</th>
<th>Spring/Autumn Amp</th>
<th>Spring/Autumn MVA</th>
<th>Winter Amp</th>
<th>Winter MVA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northwold</td>
<td>443</td>
<td>25.3</td>
<td>512</td>
<td>29.3</td>
<td>553</td>
<td>31.6</td>
</tr>
<tr>
<td>Downham Market – Northwold Tee section</td>
<td>443</td>
<td>25.3</td>
<td>512</td>
<td>29.3</td>
<td>553</td>
<td>31.6</td>
</tr>
<tr>
<td>Southery</td>
<td>443</td>
<td>25.3</td>
<td>512</td>
<td>29.3</td>
<td>553</td>
<td>31.6</td>
</tr>
<tr>
<td>Use of System Agreement (2007)</td>
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</tbody>
</table>

### Table 2: Maximum seasonal export limits for the British Sugar, Wissington generation

<table>
<thead>
<tr>
<th>Season</th>
<th>Maximum seasonal export limits (MVA)</th>
<th>Months</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>
• There is an additional 17.5MVA of wind turbine generation connected to the network at 11kV
• The minimum load condition, which occurred on 21 June 2011 at 1421 hours. This information is supplied by National Grid and refers to a time when the national (UK wide) minimum demand was recorded in the summer of 2011, just before the initial modeling of the Quadrature-booster was completed
• There was a discrepancy between the Wissington CHP model dispatch (54.58MVA) and the actual winter export limit, with the UK Power Networks PowerFactory model being updated to reflect the correct information

The system has been modeled under minimum load and maximum generation conditions which correspond to the worst case scenario for the distribution network. This is consistent approach used in planning distribution networks, it is an approach that will yield conservative results.

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 line ratings are the condition where the constraint might arise and form the basis of the network analysis.

The indicative results of the power flow study in Figure 3 show that circuit 2 (Downham Market circuit) approaches the 31.6MVA capacity limit (winter seasonal constraint) while circuits 1 (Northwold circuit) and 3 (Southery circuit) are below their respective capacities.

Figure 3: PowerFactory Load Flows
Following further investigation of the historical load profiles for these three circuits, as shown in Figure 4, it can be seen that circuit 2 (Downham Market circuit shown in red) is generally loaded approximately twice as much as circuits 1 (Northwold circuit shown in teal) and 3 (Southery circuit shown in purple).

Figure 4: Historical circuit loadings
3.4 Quadrature-booster solution

Based on this initial network assessment it was clear that there is value in trialling a solution that would enable improved load sharing on the Downham Market and Northwold 33kV circuits. The proposed solution was to investigate the installation of a new Quadrature-booster complete with an on load tap changer.

3.4.1 What is a Quadrature-booster?

Quadrature-boosters are phase shifting transformers used to control the flow of active power in electricity transmission networks. They consist of two transformer units; a shunt transformer and a series transformer as illustrated in Figure 5. The shunt transformer is fitted with tap changer to extract a component of the system voltage, typically in the range of ±20% of the nominal system voltage (33kV, 132kV or 400kV). The series transformer is connected in series with the main transmission circuit and should have ratings equivalent to the circuit rating. The voltage component from shunt transformer is induced in quadrature i.e. 90 degrees to the system base voltage in the series transformer to affect the voltage angle.

The overall output voltage of the Quadrature-booster is therefore the vector sum of the supply voltage and the 90° quadrature component. The output voltage is approximately equal to the input voltage but with a (variably) shifted phase angle. This shift in phase angle enables the control of power flow across two parallel lines, with the circuit containing the Quadrature-booster said to be “Boosting” power flow where the power flow through the circuit is increased (boost tapping), or “Bucking” power flow, where the power flow through the circuit is reduced (buck tapping).

The Quadrature-booster is a mature technology and has been used by transmission companies like National Grid and across continental Europe since the 1970s, and pictures of typical units are shown in Figure 6. One of the major differences with the unit designed for the distribution network is its size.

Figure 5: General symbol representation of a Quadrature-booster

![General symbol representation of a Quadrature-booster](image)

Figure 6: General views of typical Quadrature-boosters used on transmission networks

![General views of typical Quadrature-boosters used on transmission networks](image)
Based on available information, the FPP Quadrature-booster is the first to be designed specifically for a distribution network, and the general overview of this unit is shown in Figure 7.

### 3.4.2 How was it be deployed?
The Quadrature-booster is series-connected in circuit 2, as shown in Figure 8, to “buck” real power flow to achieve a closely balanced load sharing between circuit 1 and 2.

### 3.4.3 Expected benefits
The results obtained from the modelling are such that balancing the load through lines 1 and 2 would increase available export capacity headroom by 10MW. In addition to this, the delivery of the Quadrature-booster is expected to achieve the following benefits:

- Improving utilisation of existing assets
- Smarter network with improved controllability
- Deployment of the first Quadrature-booster on the 33kV distribution network

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**Figure 7:** General view of the Wissington Quadrature-booster: 3D design, and during construction
Figure 8: Schematic illustration of existing distribution network around the Wissington British Sugar substation
Quadrature-booster: The Journey
Following the completion of the design review, the project moved into the definition stage, in which UK Power Networks developed specifications describing the performance requirements for the Quadrature-booster, along with the associated control and protection systems, necessary for the successful deployment on to the distribution network. This enabled project partners, Wilson Transformer Company and Fundamentals, along with UK Power Networks contractor, Carillion Utility Services, to agree on scope and deliverables for the project.

The key activities undertaken during this phase included:
- Production of specifications for the systems
- Agreement of project costs and contractual arrangements
- Development of a project implementation plan

The key outputs of this phase were:
- Engineering Design Standard for the Quadrature-booster
- Protection and Control design brief for the Quadrature-booster installation
- Fixed priced quotation for the design, delivery, installation and commissioning of the Quadrature-booster and the associated control system
- Target price for overall electrical design, civil works and electrical infrastructure works
- Project agreement with Wilson Transformer Company
- Project agreement with Fundamentals Limited
- Work package order for Carillion Utility Services
- Project Implementation Plan
4.1 Requirements Specification

The requirements specifications describe the performance requirements for Quadrature-boosters and the associated control and protection systems necessary for the successful deployment on the network. Specifications were produced for the Quadrature-booster, control system and the protection system.

**Quadrature-booster requirements**
The Quadrature-booster was designed as a dual core unit consisting of interconnected series and shunt transformers. Its nominal rating is 30MVA and has a maximum impedance of 2.3 ohm (6.34% on 30MVA base), so as to ensure that the existing protection scheme can remain functional. To achieve the necessary control of the power flow between the two lines, the Quadrature-booster has been designed to provide a phase shift in the voltage between the ranges of ±12°.

**Quadrature-booster control system requirements**
The Quadrature-booster control system is designed for automatic control of the On Load Tap Changer (OLTC) to optimise the load sharing between the Northwold and the Downham Market Teed Northwold circuits. This will be achieved by monitoring active power flow down each of the lines and issuing controls to the Quadrature-booster, to tap up or down, and control the phase shift, which affect the power flow. The system also contains appropriate auto-switching and interlocking so as to prevent mal-operation during planned and/or unplanned network reconfiguration.

**Protection system requirements**
The protection of the Quadrature-booster consists of fast acting main protection, Inverse Definitive Minimum Time (IDMT) backup protection and mechanical protection devices. The protection system is also designed to be immune to inrush currents and is suitable for the range of tap positions used in the scheme to interface with existing protection schemes.
Quadrature-booster: Implementation – detailed design
The detailed design for the Quadrature-booster system was completed in accordance with the aforementioned performance requirements identified by UK Power Networks and was subject to a review by individuals from UK Power Networks, Fundamentals and Wilson Transformer Company. The final design is such that the deployment of the Quadrature-booster has not adversely affected the operation of the network, and that safety of personnel and plant that may be affected by its operation has been assured.

The key activities undertaken during this phase of the project included:
  • Completion of the detailed design

The key outputs of this phase of the project included:
  • Installation, Operating and Maintenance manual for the Quadrature-booster
  • Installation, Operating and Maintenance manual for the Control System
  • Construction issue drawings

A summary of the Quadrature-booster architecture is shown in Figure 9 below.

Figure 9: Quadrature-booster architecture
The Quadrature-booster control system controls the MW flows in order to achieve improved power flow sharing between line 1 and line 2 (see figure 9), by comparing the power flow of line 1 and line 2 and tapping up or down to minimise the power difference between the circuits. The current reference will be provided by looping into the instrumentation single phase current transformer (CT) circuit on each of the lines. The voltage reference is provided by tapping into the non-protection part of the voltage transformer (VT) circuit on each of the lines – installed on the load side of the Quadrature-booster. If the current or voltage value is missing from any one of the controlled circuits 1 and/or 2, the Quadrature-booster control system is programmed to revert to fail safe mode by returning the OLTC to nominal tap where it has no effect on power flows on the circuits.

The Quadrature-booster control system can be operated in either auto mode or manual model, although the system is designed to ensure single mode operation, and can be selected locally and remotely. In manual mode it can be operated locally via the front panel, or remotely via hard wired inputs and IEC 61850 based communications network. In auto mode the Quadrature-booster is controlled automatically by the TAPCON 260 (Quadrature-booster control system) relay.

The Quadrature-booster control system settings can be accessed and modified via a dial in user interface to the TAPCON260 relay by remote access for configuration. This access can be password protected. The Quadrature-booster control system scheme is capable of being disabled while the Quadrature-booster is in bypass mode.

The Quadrature-booster is equipped with enhanced monitoring functions through the Calisto 9 and DR-C50 systems. The Calisto 9 monitors dissolved gases inside the Quadrature-booster tank, and the DR-C50 provide dynamic rating management of the OLTC and the Quadrature-booster unit. The monitoring activities of the Calisto 9 are fed into the DR-C50, and both are accessible from remote via a web interface for download and further analyses.

A number of commands, indications and alarms are provided to UK Power Networks’ control room via SCADA.
5.1 Electrical installation

The Quadrature-booster is connected via a new five panel switchboard located in a new brick switch house adjacent to an enclosure that contains the Quadrature-booster. The alterations to the existing network, necessary to accommodate the Quadrature-booster, are illustrated in the single line diagram shown in Figure 10.

The new 33kV switchgear for the Quadrature-booster, including the aforementioned five-panel switchboard, is equipped with a bus section circuit breaker which is used as a by-pass over the Quadrature-booster. The by-pass is normally OPEN during normal operating conditions. It can be closed under planned or emergency conditions, keeping the circuit connected to the network.

Various safety interlocking schemes and restrictions apply to reduce risk to plant and operator. The by-pass circuit breaker and the two Quadrature-booster related circuit breakers operate in an OPEN before CLOSE logic. Network Control Engineers are responsible for operations of the Quadrature-booster and its associated equipment.

Figure 10: Single Line Diagram showing 33kV Network re-configurations
5.2 Protection system

The protection of the Quadrature-booster and its connection can be split into the following schemes:
- Quadrature-booster primary windings unit protection
- Quadrature-booster secondary windings unit protection
- Over fluxing protection
- Gas and oil operated protection
- Quadrature-booster earth fault backup protection
- Busbar unit protection
- Overall Quadrature-booster and busbar backup protection

These schemes overlap with each other and with the existing line and switchgear protection schemes to create the necessary cross over as well as discrimination required for 33kV protection schemes.

The Quadrature-booster primary and secondary windings unit protection schemes and the earth fault back up scheme are based on recommendations within the IEEE Standard C57.135-2001.4

Over fluxing protection was applied to reduce the risk of damage caused by core flux going out of limit under certain running condition. This is an issue that is likely to be present if operating on the extremities of the tapping range and under load imbalance or open circuit faults on the 33kV network.

The gas and oil operated protection schemes applied, such as Buchholz and Pressure Relief Device, are in line with standard practice for primary and grid transformers. An additional scheme was also introduced to carry out online condition monitoring through the bespoke Dynamic Rating Management for transformers (DR-C50) and online dissolved gas analyses by Morgan Schaffer Calisto 9 device. This will help in assessing the suitability of the Quadrature-booster design in this trial project.

The busbar unit protection scheme comprises of two zones of circulating current protection to detect and discriminate for fault in the 33kV switchgear.

The overall Quadrature-booster and busbar backup protection is a differential scheme using IDMT protection. This provides a specific zone backup scheme for both when the Quadrature-booster is in service or being bypassed.
5.3 Quadrature-booster design

The final design for the Quadrature-booster satisfies UK Power Networks’ performance requirements and can be illustrated by the transformer nameplate, a copy of which is shown in Figure 11.

As per the schematic in Figure 11, circuit 2 (low impedance circuit) draws increasing active power (MW) when the Quadrature-booster is operated from tap 10 to tap 1 which is associated with advance phase angle, and decreasing MW from tap 10 to tap 19 for retard phase angle change. Circuit 1 (high impedance circuit) behaves in an opposite manner. This is in line with Quadrature-booster theory\(^1\) that “advanced” phase angle results in active power “boost” and “retard” phase angle results in active power “buck” in a transmission line. When power flows between two parallel systems with different impedances, a Quadrature-booster placed in the branch with lower impedance needs to operate in “retard” phase angle mode to buck the power in that branch.

With the Quadrature-booster installed in circuit 2 (with its lower line impedance compared to Circuit 1), the Quadrature-booster needs to be operated between taps 10 – 19, that is, in retard mode. However, the higher taps 18 and 19 are likely to cause a risk of over-fluxing the Quadrature-booster. To avoid over-fluxing (due to load phase angle adding to the no load phase shift), it must be operated between taps 10 – 17. Taps 18 and 19 are electrically blocked. Taps 9 – 1 are also blocked as shown in Figure 11.

Figure 11: Quadrature-booster nameplate
5.4 Quadrature-booster control system

The Quadrature-booster control system uses a TAPCON260 relay. A picture of typical TAPCON260 relay is shown in Figure 12, and is manufactured by MR in Germany.

This control system:
- provides a local display of all pertinent Quadrature-booster operational information
- provides facility to manually tap the Quadrature-booster locally on site, or in the event of SCADA failure
- ensures that the Quadrature-booster on-load tap changer is only used when it is safe to do so
- inhibits operation below tap 10 to prevent the Quadrature-booster boosting the power and overloading line. inhibits operation above tap 17 to avoid over-fluxing of the Quadrature-booster
- provides appropriate alarms and indications to UK Power Networks via SCADA to the distribution network management system

5.4.1 Operating Principle – Regulation of power flow

The TAPCON260 relay regulates the active power of the Quadrature-booster through an on load tap changer. This is achieved by monitoring the single phase analogue measurements of the voltage and current on the Downham Teed circuit (LINE 2) and the Northwold circuit (LINE 1). Using these analogue measurements, the TAPCON260 calculates the total active power flow in LINE 1 (P1) and LINE 2 (P2) and adjusts the tap position to achieve improved power sharing between the Northwold (LINE 1) and Downham Teed (LINE 2) circuits to within approximately 5% of each Line 1 and Line 2, unless system operating constraints decree smaller variations. This comparison includes a set MW bandwidth to ensure stable alterations to the tap position. If the measured active power share is outside this bandwidth, the TAPCON260 emits a switching pulse after a defined delay time after which the switching pulse triggers an on-load tap-changer tap change which corrects the Quadrature-booster’s active power.

Standard operation mode for the Quadrature-booster TAPCON 260 relay is Auto/Remote mode. In this mode the relay controls the Quadrature-booster, and SCADA control is enabled. If the Quadrature-booster is required to operate manually from the control panel the relay needs to be switched out of Remote mode (switched to “Local” mode). When manual operation is completed the relay must be switched back to Remote.

5.4.2 Interface with British Sugar

As previously mentioned, British Sugar currently operate automatic turndown scheme on their generation which takes into account the Wissington British Sugar substation outgoing 33kV feeder circuit breakers status as well as analogue measurements on from the feeders. In order for this scheme to incorporate the Quadrature-booster operations it was necessary to provide ‘tapping in progress’ status information for the Quadrature-booster, to trigger the masking of the generation turndown scheme and ensure the generator ignores any changes on line currents for which it would normally initiate a reduction in generation output.

Figure 12: TAPCON 260 relay (Source: TAPCON260 Operating Manual)
6 Quadrature-booster: Implementation – Installation
The overview of highlights of the programme is shown in Figure 13.

Construction works, including the preparation activities, took approximately eight months. The key activities undertaken during this phase of the project included: Production and maintenance of health and safety documentation Procurement of all materials and equipment Installation, testing and commissioning of the system

The key outputs of this phase of the project included:
• Construction Phase Health and Safety Plan
• Protection Programmable Scheme Logic (PSL) and settings files
• Commissioning plan

The construction activities associated with the installation of a Quadrature-booster are very similar to that for a transformer of a similar size and included:
• The erection of a new switch house and transformer bund
• Manufacture and installation of the Quadrature-booster
• Manufacture and Installation of the Quadrature-booster control system panel & scheme
• Manufacture and Installation of the Quadrature-booster protection panel & scheme Installation of Panel Board with voltage transformer
• Manufacture and installation of a new Remote Terminal Unit at Wissington
• Modification of the existing circuit protection Telemetry to UK Power Networks SCADA
• Telemetry to British Sugar
The installation phase of the project was successfully completed, and Figure 14 to Figure 16 shows the installed equipment.

Figure 14: Installed Quadrature-booster

Figure 15: Installed 33kV Switchboard

Figure 16: Installed Quadrature-booster control system
Quadrature-booster: Testing and commissioning
Whilst undertaking during the implementation phase of the project, the testing and commissioning elements of the project were key to the demonstration of the SDRC and, as such, have been recorded as a separate section of this report. The section documents key commissioning activities which were completed and provides evidence that the Quadrature-booster operates in accordance with its design and releases the appropriate levels of headroom at maximum generation export conditions, expected to be approximately 10MW.

7.1 Pre-installation testing

The factory acceptance testing for the Quadrature-booster was undertaken in Melbourne, Australia during the second week of January 2013, with snagging rectified in time for its dispatch on 21 January 2013.

Before commencing the tests, a test programme was prepared and discussed between UK Power Networks and Wilson Transformer Company prior to confirm the suitability of the tests. All components for the Quadrature-booster were installed for the type testing at the factory to ensure that they could be fitted and are of the correct type for the project to ensure a satisfactory onsite installation. The DR-CS0 was initially bench tested at the DR laboratory and was brought to the Quadrature-booster and connections made to the tap changer, gas monitor and temperature sensor.

The electrical type and routine tests were satisfactory and all within the tolerance of the specification. The Quadrature-booster was prepared for despatch and shipped on time in accordance with the programme of works.

The factory acceptance testing for the Quadrature-booster Control system TAPCON 260 relay was successfully completed in May 2013, at Fundamentals’ factory in Swindon.
7.2 Cold Commissioning

Cold commissioning, which consists of a number of off-load tests designed to confirm correct installation and configuration of the system prior to the final connection, commenced in early June 2013 and were successfully completed in July 2013. The tests included, among others, the following key activities:

- **Drawing checks** – all wiring in the protection panels and circuit breakers, Quadrature-booster etc were checked with reference to relevant wiring drawings, and all terminations checked to ensure that they were correctly terminated. The drawings were also checked against the relay standard drawings to ensure that standard schemes were correct to the manufacturer’s standard schemes. All wiring was subjected to Insulation tests with a Megger type Instrument with no less than 500 Volts.

- **CT Checks** – all current transformers (CT) on circuit breakers were tested with an Omicron CT analyser test set. The CT analyser measures the CT secondary resistance, ratio, polarity and magnetising curve. The CT circuits for the Quadrature-booster and switchgear have been tested with the CT analyser and also primary injected to prove stability and operation for in Zone and out of Zone faults.

- **Functional tests** of the 33kV vacuum circuit breakers were undertaken, including open/close inhibits, in the correct operational sequence. The Quadrature-booster protection was proved to ensure correct alarms and trips, intertripping and all the electrical interlocking operations. Correct operation of the tap changer and control circuits was also proven to confirm correct operation.

The above show some of the key tests only. Many other relevant tests not discussed here were carried out in accordance with the test plan.

7.3 Final Commissioning

The final commissioning for the project was undertaken and the Quadrature-booster was energised in July 2013. A dynamic type commissioning plan included three stages:

- **Soak stage** – the Quadrature-booster was energised and left running without load for a period of 24 hours.

- **Load stage** – the Quadrature-booster was put on load carrying current as part of the live network, with the Wissington generator offline.

- **Generation stage** – the Wissington generator was then switched on with the Quadrature-booster in circuit.

During these stages checks were made on the function and response of Quadrature-booster to the network and the British Sugar generation.
7.4 Demonstration of improved balance between the circuits allowing increased power flow of 10MW

Figure 17 presents the modelled loading of the three circuits under different generation export scenarios. The modelling methodology and assumptions are detailed in section 3.3.

All lines have a winter thermal rating of 31.6MVA and the graph below illustrates the sub-optimal distribution of the export across the three lines. As discussed in section 3.3, the maximum export for the British Sugar generation site is limited to 54.58MVA as any additional generation will result to the Downham Market line breaching its winter maximum thermal rating while the Northwold line is loaded at about 50% of its rating.

Figure 18 shows the modelled loading of the three circuits under different generation export scenarios with the Quadrature-booster in-service in the Downham Market line. For consistency, the graph data presented in all graphs in this section are based on the Quadrature-booster set at tap 11.

![Figure 17: Circuit Loadings – Modelled without the Quadrature-booster](image1)

![Figure 18: Circuit Loadings – Modelled with the Quadrature-booster (at tap 11)](image2)
In order to prove the capacity headroom created on the 33kV circuits, current measurements (amps) on the three circuits were recorded from the protection relays on the local control panel. These were then compared with the modelled data.

Measurements of the power flows across the three incoming feeders were taken at different generation export levels (10MW, 24MW, 40MW) with the Quadrature-booster in service at nominal tap 10 and also at taps 11 and 12.

Due to generator maintenance currently being underway at the Wissington site, the maximum available export generation during the tests was approximately 40MW and hence some of the results had to be extrapolated in order to achieve like-for-like comparison with the modelled circuit loadings at 54MW. The actual observation of the system under 54MW of export will be possible from September onwards when the full generation capacity will be operational.

The following graphs compare the modelled data with the actual measured on site for each of the lines and discuss the operation of the Quadrature-booster.

**Downham Market Tee Northwold line**

Figure 19 presents the modelled and actual values for the loading of the Downham Market Tee Northwold line. The Downham Market is the line where the Quadrature-booster has been installed. By operating it, it is expected that it will move power flow from the Downham Market line to the other two lines. This effect is demonstrated in Figure 19 by the actual measured values of the power flow across the line. It is observed that by introducing the Quadrature-booster at Tap 11, power shifts away from the Downham Market line. The measured data demonstrate the same trend and track very closely to the modelled ones.

This behaviour demonstrates that the Quadrature-booster operates as designed and has the desired effect on the line.

The measurements and overall system analysis have also confirmed the linear nature of the relationship between the Wissington generator export and the circuit loadings. This provides the ability to extrapolate the actual measurements curve and demonstrate the loading of the line for higher export levels (54MW and 64MW).
Figure 19 shows that with the Quadrature-booster in service the line will stay within limits (loaded at approximately 27MVA) when the generation export is increased at 64MW.

It can be seen in Figure 19 that an error between the modelled data for the circuit loadings with the Quadrature-booster in service and the actual data has been introduced. This is expected as the software model has been set up using a specific set of assumptions while the measured data represent a snapshot of the network which corresponds to different network conditions. Further work will be undertaken to calibrate the model against the actual data and gain insights in the data and the system power flows.

It is worth noting that both modelled and actual data have assumed low demand (summer) conditions. It is therefore expected that during winter conditions and in the presence of higher demand in the network, the lines will be able to accommodate even higher amounts of generation before reaching their limits.

Figure 19: Quadrature-booster Capacity Headroom (Downham Market) at tap 11
Northwold line

The results for the Northwold line are shown in Figure 20. The actual measured data with the Quadrature-booster track very closely the modelled data and demonstrated the desired behaviour. In this instance, the loading of the line is increasing by using the Quadrature-booster as the load is shifted away from parallel line (Downham Market).

By extrapolating linearly the actual values from the 40MW level to the 64MW level, we are able to demonstrate that for a 64MW generation export the Northwold line will remain within its seasonal limits.

Figure 20: Quadrature-booster Capacity Headroom (Northwold) at tap 11
**Southery line**

The Southery line receives the lower percentage of the load that is being shifted away from the Downham Market by the use of the Quadrature-booster. The modelled behaviour of the circuit and the actual site measurements demonstrate consistent behaviour.

The actual measurements presented in Figure 21 show a higher than forecasted power transfer to Southery and this will be subject to further analysis. However, the actual results confirm the expected outputs and the validity of the model.

---

**Figure 21: Quadrature-booster Capacity Headroom (Southery) at tap 11**

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<thead>
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<th>Winter Line Thermal Rating</th>
<th>Circuit Loading (MW)</th>
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<td></td>
</tr>
<tr>
<td>35</td>
<td></td>
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</tbody>
</table>
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**Key**
- Model - Southery circuit with Quadrature-booster
- Model - Southery circuit without Quadrature-booster
- Actual - Southery circuit with Quadrature-booster
- Winter Line Thermal Rating
- Linear (Actual - Southery with Quadrature-booster)
Conclusions

The actual measurements and their comparison with the modelled and forecasted effect of the Quadrature-booster have confirmed that:

- the Quadrature-booster has the desired effect on the line that has been installed in, by bucking power away from it the lines will be able to accommodate additional 10MW of generation export (total 64MW) when the Quadrature-booster is in circuit and set at tap 11 (illustrated in Figure 22)
- there is an improved balancing of the lines can be demonstrated. As shown in Figure 22, the Quadrature-booster balances significantly the lines at 64MW of generation export in order to be able to accommodate the additional 10MW.
- there is a potential for more than 10MW of headroom release. The projected figures for loading of the lines at 64MW of generation export are 27MW and 29MW respectively for Downham Market Tee Northwold and Northwold respectively. Given that the winter limit for the lines is 31.6MVA and that these values have been calculated under low summer demand conditions, there is potential for additional generation export to be accommodated by the lines.

Figure 22: Quadrature-booster Capacity Headroom
8

Quadrature-booster: Training
As part of introducing the Quadrature-booster and its control system to the operational network staff, one day classroom sessions were arranged for selected UK Power Networks key technical staff expected to work on the Quadrature-booster, and control engineers and managers from the control centre. These training sessions included presentations by Wilson Transformer Company and Fundamentals with the objective of providing sufficient information to prepare key staff before the arrival of the Quadrature-booster and its control system for installation. Three presenters, one facilitator and a total of twenty three participants received training and were drawn from UK Power Networks’ Capital Programme, Network Operations, Health & Safety, and Carillion Utility Services.

The training presentations covered:
- What is a Quadrature-booster/Quadrature-booster control system
- How does a Quadrature-booster/Quadrature-booster control system work
- What it can and cannot do
- Installation/commissioning/operations/control/maintenance brief
- Case studies or applications elsewhere
- Training handouts to participants
- Question and answer session

On-site inductions at Wissington British Sugar substation were subsequently undertaken to provide a live demonstration of how the Quadrature-booster works; along with the controls, operations and maintenance regimes. Going through details of measured, alarms and indications – what they mean and actions to be taken in an emergency etc.

Finally, Engineering Operating Standards (EOS) were produced for both the Quadrature-booster and the associated control system to provide a single point of reference for operational and control staff responsible for carrying out safe operations and maintenance of the Quadrature-booster. These documents supplement the user manuals for the equipment and will be made available to other DNOs for their own use. Figure 23 shows the set of documents available for reference.

Figure 23. Engineering Standards and Manuals
Learning and next steps
As part of the FPP project, the first Quadrature-booster in the world for a 33kV distribution network application was designed and installed. The Quadrature-booster was successfully commissioned on the distribution network in July 2013.

This was approximately a month later than initially planned due to technical challenges faced in cold commissioning and during the design and commissioning of its protection scheme. These challenges are described in the FPP project six-monthly report (June 2013).

Significant knowledge was generated as part of the design, construction and testing process. Key learning has been produced across all stages of the lifecycle of the project with particular focus in the areas of modelling and specification for Quadrature-booster transformers for distribution networks and protection scheme design and implementation.

The learning generated will support and improve any further implementations of a Quadrature-booster by UK Power Networks and any other Distribution Network Operators.

The operation of the Quadrature-booster and its ability to control the power flow, balance the lines and create 10MW headroom within the network has been demonstrated.

A trial plan is currently being developed in order to test the Quadrature-booster under various operational scenarios and conditions. These trials will take place during 2014.

The learning will be disseminated through a learning report, a learning event, academic papers and bilateral engagement with DNOs and interested parties. In addition, UK Power Networks is working on a guidance note for modelling of Quadrature-boosters in PowerFactory software with the software providers.

The Quadrature-booster implementation has been a complex and challenging engineering feature that has developed knowledge, skills and a new solution for maximising the utilisation of distribution networks.
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**Table 1:** Seasonal ratings for circuits within the Wissington 33kV Network interconnection

**Table 2:** Maximum seasonal export limits for the British Sugar, Wissington generation