OPERATIONAL EXPERIENCE OF USING A QUADRATURE-BOOSTER FROM UK POWER NETWORKS' FLEXIBLE PLUG AND PLAY PROJECT

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ABSTRACT

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 [1]. To achieve this, a number of innovative smart devices and applications were trialled to manage constraints and maximise network utilisation. A Quadrature-booster was one of the smart devices trialled to demonstrate the smart approach to distribution network management.

This paper outlines how the Quadrature-booster trial using the Wissington 33kV trial case was carried out. The paper outlines (1) the network issue, (2) the Quadrature-booster solution, (3) the trial methodology and trial outcomes, (4) the benefits accrued from delivering the Quadrature-booster solution, and (5) the lessons learnt.

INTRODUCTION

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. Figure 1 below shows the aerial photograph of British Sugar Wissington sugar beet factory site and the locations of the CHP, UK Power Networks' 33kV substation, and the installed Quadrature-booster.

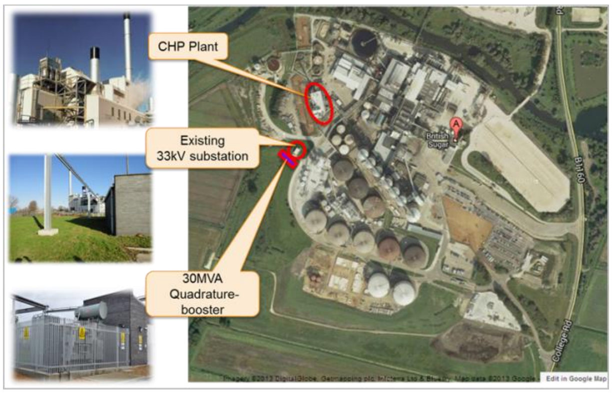

Figure 1: Aerial photograph showing locations of the CHP, 33kV substation and the Quadrature-booster

The existing Wissington 33kV substation provides the point of connection for British Sugar to import and export electrical power to UK Power Networks distribution network.

The Problem

Under Standard Running Arrangement (SRA) the site connection is provided via three 33kV circuits, all rated 30MW (winter), running interconnected with four 132/33kV grid sites as shown in the Figure 2 below.

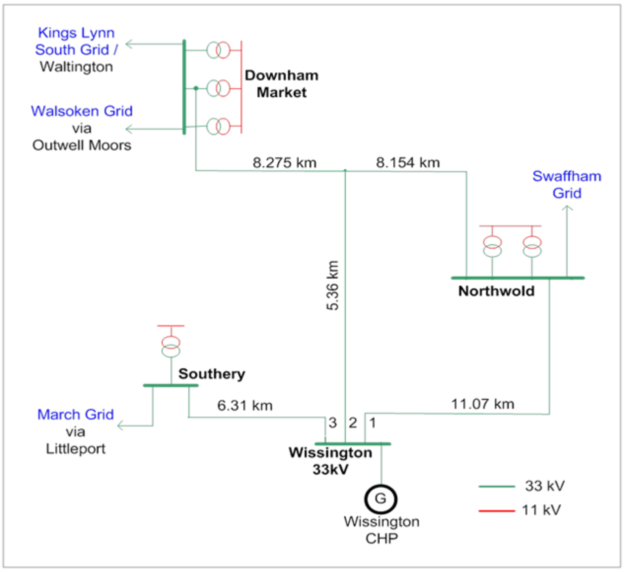

Figure 2: A simplified diagram showing the Wissington 33kV network interconnection under SRA

The CHP comprises a 58.8MVA gas turbine generator and a 36.4MVA steam turbine generator (0.85 PF). The installed turbine capacity is 70MW and is reported to be limited by the available export capacity on the distribution lines. 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.

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. 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 54MW in winter which is 23% below the installed 70MW generator turbine capacity. 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.

Quadrature-booster solution

It is reported that Wissington British Sugar generation achieves the best CHP rating under the UK government CHP quality assurance scheme[1]. As such, further increments of generation export can provide valuable contribution to the electricity generation fleet. The Quadrature-booster was designed and deployed to balance power flows through parallel circuits. A simplified diagram of the trial network, which 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, is shown in Figure 3 below.

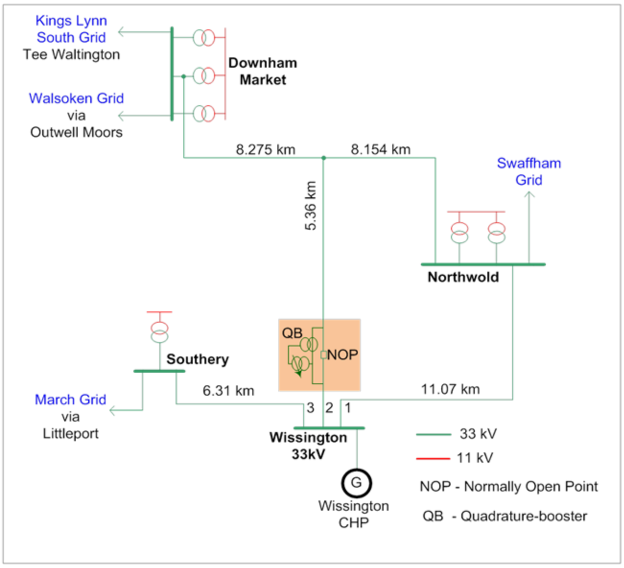

Figure 3: A simplified Wissington 33kV trial network showing location of Quadrature-booster

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

1 About Wissington Factory – British Sugar, page 5 http://www.britishsugar.co.uk/Files/about-wissington-factory-0112.aspx [accessed 05/01/15 16:30pm]

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.

QUADRATURE-BOOSTER TRIAL

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 below.

Table 1: List of Quadrature-booster Trial Hypotheses

Hypothesis	Description
QBR001	The tap changer can be raised / lowered between Tap 10 and Tap 17 positions to buck/boost respectively.
QBR002	By raising/lowering the tap position starting from nominal tap, optimal load balancing is achieved between the two circuits.
QBR003	Quadrature-booster Control System (QBCS) can carry out automatic load balancing to enable load sharing between two parallel circuits.
QBR004	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
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

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)

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 [2]. For the FPP project the optimal load sharing was intended to release capacity headroom on the existing assets which can be used by either generation or demand customers for their connection on the distribution network. The objectives of the Quadrature-booster Trial were to demonstrate:

- The functionality and reliability over the trial period (August 2013 – September 2014).
- That the Quadrature-booster operated according to design requirements and operated within required tap operating range.
- That the Quadrature-booster operated both in manual and automatic modes and achieved optimal load sharing levels on the two parallel circuits.
- 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.
- That the additional 10MW generation export would be allowable on the existing interconnected distribution network.

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

Initially three PQMs, PQM-1, PQM-2 and PQM-3 were installed in September 2013 and 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 5 below.

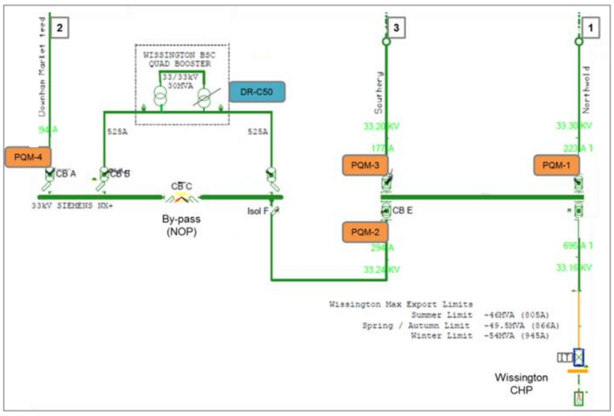

Figure 5: Extract of the Wissington 33kV network from Enmac showing locations data recording equipment

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), and 1 minute intervals voltage phase angle data across the Quadrature-booster.

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. 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.

PI historian is a database that stores half-hourly network data that can be retrieved for historical analyses. 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, and 2013 to 2014.

Trial Findings

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. 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 at the Wissington site as expected. The key finding was the capacity headroom created by use of the Quadrature-booster. Prior to the Quadrature-booster the Downham Market No.2 circuit reached its thermal capacity limit of

30MW when the generation export was approximately 55MW as shown in Figure 6 below.

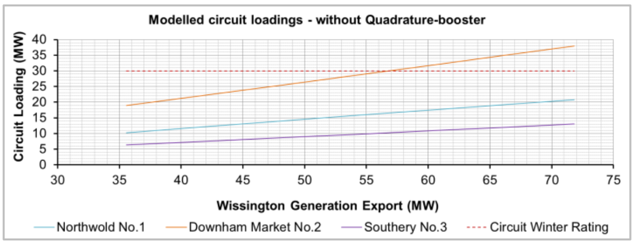

Figure 6: Graph showing circuits loadings against generation export prior to Quadrature-booster

The recorded PQM data was sampled into 10 minute intervals and 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. Figure 7 below shows a scatterplot of the recorded circuit loads against CHP export for periods the Quadrature-booster was at Tap 11.

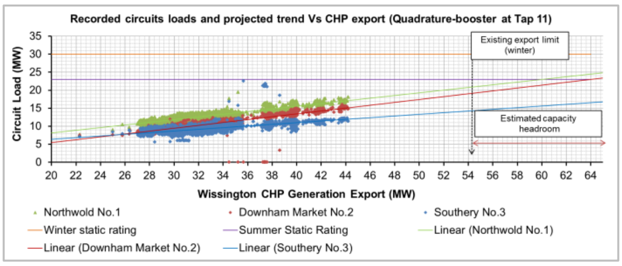

Figure 7: Scatter graph showing recorded circuit loadings at Tap 11

The graphs in Figure 7 above were extrapolated by increasing CHP export by a further 10MW from 54MW to 64MW (winter). 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-year generation export profile and the corresponding loading profiles on the Wissington 33kV circuits from 2012 to 2014 are shown in Figure 8 below.

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.

Figure 8 shows that the 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.

It is clear from Figure 8 that in August 2013 (following the commissioning of the Quadrature-booster) 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 due the control and load equalising effect of the Quadrature-booster. 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. These results demonstrated that the Quadrature-booster improved the load sharing between the two lines, and that additional 10MW capacity headroom was possible.

Simulation network studies were then carried out to establish if the additional 10MW export would be allowable on the existing 33kV and 132kV network under both normal running arrangement and various possible abnormal running arrangements – including planned

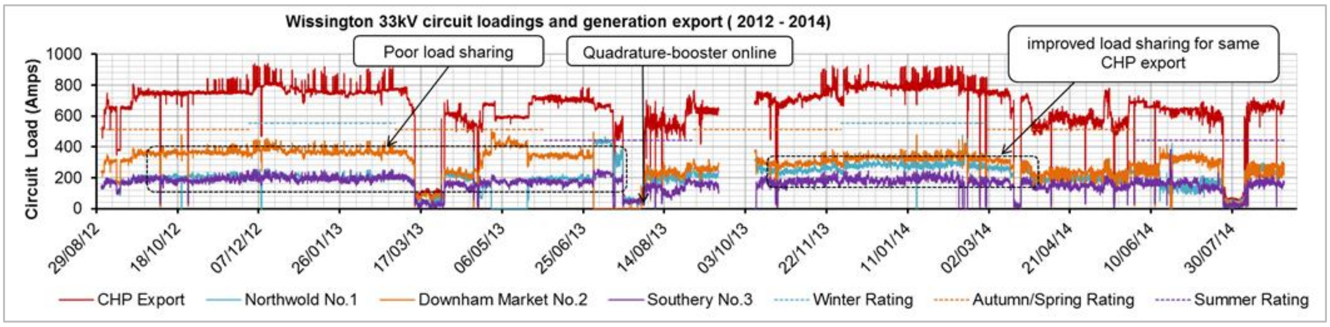

Figure 8: Graph showing recorded PI data on Wissington 33kV circuit loadings and generation export

network outages and emergency conditions. The results showed 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.

LESSONS LEARNT

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. 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 $\pm 12^o$ 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. The trial results showed that a phase angle of $\pm 6^o$ 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.

The required Quadrature-booster control system (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 solar 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.

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.

CONCLUSION

The trial was successful because the trial 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 and the loadings on the two circuits were closer to each other with the Quadrature-booster in use.

Based on experimental data and supported by network simulation studies the 10MW additional capacity headroom was proved. 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. This was achieved.

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 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.

MISCELLANEOUS

Acknowledgments

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