The Design, Manufacture and Operation of a 33kV Quadrature Booster

By

Gilbert Manhangwe, Paul Dyer,
Sotiris Georgiopoulos, Dr Cristiano Marantes
and Mohinder Pannu

SECOND PAGE IS LEFT BLANK

The Design, Manufacture and Operation of a 33kV Quadrature Booster

Gilbert Manhangwe, Paul Dyer, Sotiris Georgiopoulos, Dr Cristiano Marantes UK Power Networks and
Mohinder Pannu, Wilson Transformer Company Pty

ABSTRACT

The 'Flexible Plug and Play Low Carbon Networks' (FPP) project aims to facilitate faster and cheaper connections of distributed generation (DG) onto the distribution network, by using innovative technical and commercial solutions. A number of differing technologies have been identified which have the potential to allow connection of additional DG without the need for reinforcement and assist in lowering carbon emissions. The use of a Quadrature Booster is one of the smart devices to be trialled, and will be installed at UK Power Networks' 33kV substation located within the Wissington British Sugar plc (BSP) site in Norfolk, UK. The FPP will trial the first Quadrature Booster on distribution networks to effectively demonstrate the smart approach to network management.

This paper outlines how the FPP project will adapt the already mature Quadrature Booster technology at transmission networks, to innovatively deploy the first Quadrature Booster at distribution voltage using the Wissington 33kV trial case. The paper discusses (1) the identified network problem, (2) available options to address the problem, (3) how the problem is being addressed, and (4) the benefits accrued from delivering the Quadrature Booster solution.

Introduction

UK Power Networks was awarded funding under Ofgem's (GB Energy Regulator) Low Carbon Networks Fund scheme, for the 'Flexible Plug and Play Low Carbon Networks' (FPP) project. The project aims to facilitate faster and cheaper connection of anticipated growth in distributed generation (DG) onto the distribution electricity network without the need for traditional network reinforcement by, instead, managing network constraints and maximising network utilisation. The project will achieve this through the integration of smart devices, smart applications and smart commercial arrangements. The FPP project is a £10 million project, sited in Cambridgeshire, UK, which commenced in January 2012 and will conclude in December 2014.

It is widely recognised that 'smarter' ways of managing distribution network assets include improved utilisation of existing assets. The intended effect is to defer traditional reinforcement where possible. The FPP project will install 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 BSP substation. The challenge is compounded by the fact that there is no known Quadrature Booster or Phase Shifting Transformer (PST) being used at this rating and voltage.

A Quadrature Booster consists of two separate three-phase transformers specially connected: a shunt connected unit and a series connected unit. The shunt connected transformer is also called the main or exciting transformer and is fitted with an On-Load Tap Changer (OLTC). The series-connected unit is a coupling transformer. Quadrature Boosters are used to control the flow of real power on three phase electricity transmission networks.

Quadrature Boosters are a mature technology at transmission level. 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) [1]. Other examples include Quadrature Boosters on interconnectors between France – Italy and the Netherlands – Germany.

The Problem

UK Power Networks' Eastern Power Networks (EPN) distribution network serves an area of approximately 700km² between Peterborough and Cambridge in the East of England that is particularly well suited to DG and specifically renewable generation. The area between Peterborough and Cambridge is defined as the FPP trial area.

In line with the Government's drive for increased renewables generation to meet the Carbon Emissions Reduction Targets, UK Power Networks has experienced increased activity in renewable generation development in this area over recent years, and a rapid rise in connection applications, with 120MW of wind generation already connected and around 200MW at the planning stage. The connection of these anticipated levels of wind generation is expected to require significant network reinforcement to mitigate network thermal and voltage constraints and reverse power flow issues.

In order for the FPP project to demonstrate the benefits it can deliver, it is paramount that both the technical solution and commercial framework being developed are adopted by the end-use customer - the distributed generation developers.

The FPP Quadrature Booster study case is an interconnected 33kV network with a 70MW rated Combined Heat and Power (CHP) connection within the FPP trial area. Interconnected networks give rise to power flows towards the lowest source impedance, which can result in thermal overloads. Under Standard Running Arrangement shown in Figure 1, the Wissington site connection is via three 33kV circuits running interconnected with four 132/33kV sites – March Grid, Swaffham Grid, Walsoken Grid, and King's Lynn South Grid.

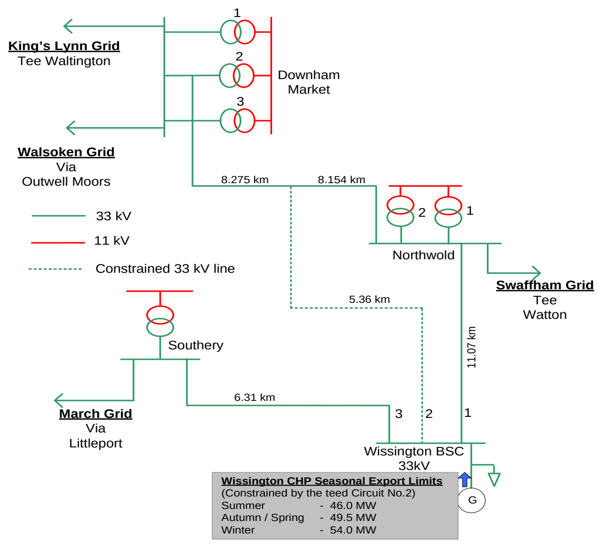

Figure 1: Wissington Site 33kV Circuits Interconnections

The Wissington CHP installed capacity is shown below:

- Generator – 95.2MVA/0.85PF (80.9MW)
- Turbine – 70MW

The Northwold No.1 and Downham market teed No.2 circuits operate in parallel with differing source impedances. Power transfer is limited by the path of least impedance – the teed circuit to Downham Market.

The full capacity of the lines cannot be used because the teed circuit reaches its full capacity limit when the other two lines are loaded to approximately half their full capacity.

The high loading of the teed Downham Market line constrains the Wissington CHP to seasonal export limits, which are at least 23% below the installed turbine capacity. There are also local line current limits on the three outgoing 33kV circuits with a complex generator control system that ensures that the line with the highest electrical load flow is not overloaded (always the teed Downham Market line).

British Sugar plc operates a generator automatic turndown scheme which takes into account the Wissington BSP substation outgoing 33kV feeder circuit breakers status as well as the analogue measurements [2]. The generator automatic turndown scheme is activated to reduce CHP plant output in order to prevent the teed Downham line exceeding thermal limits.

To increase utilisation of the existing 33kV line capacities, it is desirable to force the Northwold No.1 circuit to carry more power regardless of its higher impedance.

The Technical Solution: Quadrature Booster

To increase utilisation of the line capacities, the parallel circuits required to be augmented with series-connected impedance addition/reduction capabilities. The added (or compensated) impedance is chosen such that the current is shared between the parallel lines.

Two possible conventional options were considered:

(1) Use of a series reactor to boost impedance in the lower impedance line. This was discounted because a series reactor would add a predetermined fixed reactance in the lower impedance circuit to limit power flow to a desired level. Series reactors are mainly used as current limiting devices to reduce fault currents to required levels.

(2) Use of series capacitors connected in the higher impedance circuit (to lower the impedance). This was also discounted because, compared to reactors, a number of additional items of equipment are required in series capacitor installations to prevent damaging over-voltages, which can occur during power system faults.

The 'smart' innovative option is the use of a controllable device – the Quadrature Booster. This is the preferred 'smarter' solution. Load balancing is achieved through discrete on-load controllable steps.

This is based on the principle that power flow (P) through a transmission line is proportional to the sine of the difference in voltage phase angle of the sending (V_s) and receiving (V_r) end.

$$P = |Vs|.|Vr|\sin\delta/X_l$$

By manipulating the voltage phase angle using a Quadrature Booster, the circuit impedance and therefore the power flow can be controlled to remain within the constrained rating of the 'weaker' circuit. The Quadrature Booster tap position, and hence the added impedance, is chosen such that the current is shared between the parallel lines.

Figure 2: General view of Quadrature-Booster in test at the factory (January 2013)

Role of the Quadrature Booster

During the FPP trial the Quadrature Booster will monitor and control the network to balance load flows and create additional headroom capacity to accept increased CHP exports to the distribution network.

Quadrature Booster Design

The 33kV lines out of Wissington substation are 200mm^2 Steel Cored Aluminum (SCA) conductor construction type with static seasonal ratings of 23MVA and 30MVA in summer and winter respectively. It is assumed that the full rated 30MVA (winter) of the line to which the Quadrature Booster is connected flows through one winding of the series-connected transformer. The rating of the shunt-connected transformer is less than rated power as it is required to supply reactive compensation only. The Quadrature Booster rating capacity is therefore 30MVA to match the line rating.

A number of assumptions were also made in the preliminary studies to model the effect of the Quadrature Booster on power flows, fault levels and protection systems using Power Factory Version 14.0 from DigSILENT – power system modelling software. From modelling results the initial Quadrature Booster design parameters – rated impedance, voltage phase angle at maximum tap (buck/boost) etc were also formulated.

The design challenges were compounded by the fact that there were no Quadrature Boosters or Phase Shifting Transformers (PST) being used at this rating and voltage.

The Quadrature Booster (Oil Natural Air Natural (ONAN) cooling) complete with new OLTC will be installed in series on the ‘weaker’ teed line. The intended effect is to buck real power flow from Wissington 33kV and force additional power to flow through Northwold No.1 circuit to achieve a closely balanced load sharing between circuit 1 and 2 without exceeding thermal limits.

Basic principle of application—advanced and retard phase angle[3]

Quadrature Boosters are used to control the power flow in electrical power systems. When power flows between two systems, there is a voltage drop and a phase angle shift between the source and the load that depends upon the magnitude and power factor of the load current. If the systems are connected together in two or more parallel paths so that a loop exists, any difference in the impedances will cause unbalanced line loading.

Figure 3 shows an example with the load-side power factor assumed to be 1 and the system resistances being negligible with respect to their reactances. An arbitrary power flow distribution can be obtained by inserting a PST into one of the branches. Dependent upon whether the PST is installed in the branch with the higher or lower impedance, an advanced or a retard phase angle is needed. Advanced means that the L terminal voltage (VL*) leads the S terminal voltage (VS); retard means that the L terminal voltage (VL*) lags the S terminal voltage (VS).

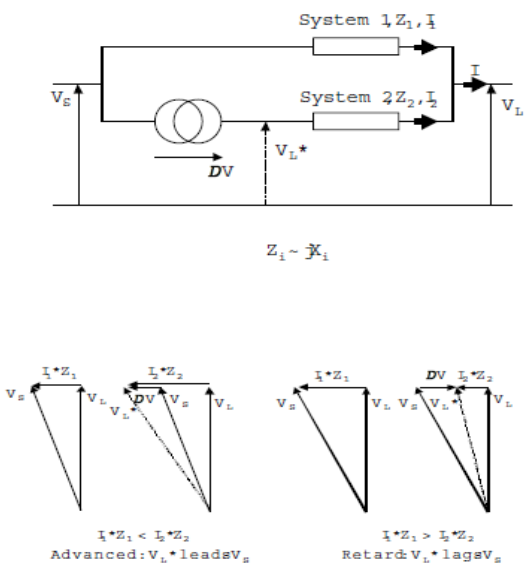

Figure 3: Load-side power factor of 1

Special features of the Quadrature Booster Transformer

Two-core design with its flexibility to control OLTC step voltage and current was adopted. Due to the small MVA and kV rating, the Main and Series units were accommodated in the same tank. “Asymmetric Quadrature Booster” concept was adopted; the physical size is approximately that of a 30MVA transformer.

The windings were designed for the worst short circuit forces at the mean tap position when the main transformer offers negligible reactance. Full type testing has been undertaken, including lightning impulse which was tested with the main and series transformers connected inside the tank and voltage applied in turn to the supply and load terminals.

Specified phase angle shift under load was estimated based on expected percentage regulation under site power factor and load testing was carried out at unity power factor under no load.

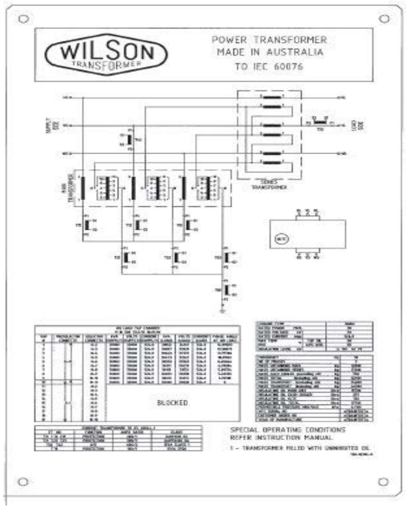

Figure 4: Rating and diagram plate

The installation of a Quadrature Booster on existing 33kV network at Wissington had a number of implications to content with – system protection, control, and space requirements.

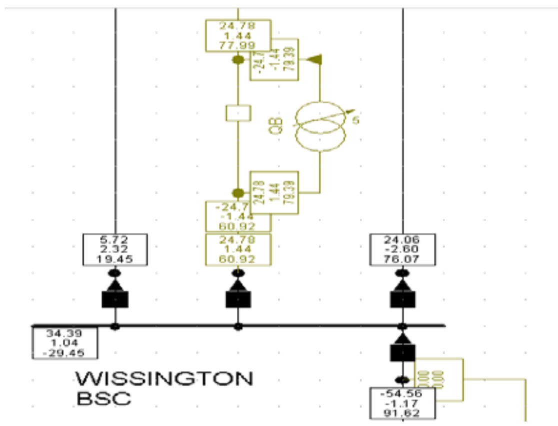

Figure 5: Load Flows with Proposed Quadrature Booster

Protection

The prospect of installing a Quadrature Booster on the interconnected 33kV network required a protection rethink. The load flows are subject to changes in voltages and impedances. The network already has many issues with protection setup. Protection studies showed that a Quadrature Booster could be connected to the teed circuit using the existing distance protection settings.

In order to build an interface with the existing Wissington generator protection, volt-free signals were provided to British Sugar plc that indicates when the Quadrature Booster is IN or OUT of service, or changing tap.

A number of operational restrictions were built into the Quadrature Booster Engineering Operating Standard. For example, it is necessary to set the Quadrature Booster to mid tap, when the Northwold No.1 circuit is out of service, leaving a low fault level in-feed to the teed circuit from Wissington.

Control of the phase shifting is to be accomplished using a Maschinenfabrik Reinhausen 260 (MR) relay configured specifically for the operation at Wissington.

The protection of the Quadrature Booster shall consist of fast acting main protection, IDMT backup protection and mechanical protection devices. The protection used shall be immune to inrush currents and shall be stable for the full range of tap positions. The Quadrature Booster protection must interface with existing protection on site at Wissington.

Project delivery

The Quadrature Booster delivery is carried out business as usual by UK Power Networks' Capital Programme team. Civil works on site commenced January 2013. The Quadrature Booster was shipped from Australia in January 2013 and will be delivered on site in March 2013. Installation commences thereafter. Project milestone agreed with Ofgem for the Quadrature Booster commissioning is the end of June 2013.

The Partners

The FPP Quadrature Booster with a Maschinenfabrik Reinhausen (MR), type OLTC is designed and manufactured by Wilson Transformer Company Pty Ltd in Melbourne, Australia. The Quadrature Booster Control System is based on MR's Tapcon 260 relay and is designed and supplied by Fundamentals in conjunction with MR.

Project Outcome

Throughout the project, there has been significant collaboration between Wilson Transformer Company Pty, Fundamentals, British Sugar plc and UK Power Networks. This collaboration has provided key learning points to introduce the first known Quadrature Booster on the distribution network. The Quadrature Booster trial case has already provided significant technological and reputational enhancement to the project partners, suppliers and collaborators.

By using a Quadrature Booster, a smarter and active management of load sharing between the parallel 33kV circuits at Wissington will provide capability for improving utilisation of the existing lines – resulting in over 10MW additional capacity headroom available to potentially increase the CHP power export. British Sugar plc confirmed that there are opportunities across the year when they could operate their highly efficient CHP plant at higher generation capacity but cannot do so because of the restriction from the electrical load flow along the teed Downham Market circuit. The 'Business as Usual' options that could have traditionally been offered were:

1. A new overhead 33kV line from Wissington to Swaffham Grid at a cost of £3 million. This was liable to a planning consent (Section 37) and a likely 3 year public enquiry.

2. A new underground 33kV cable from Wissington to Swaffham Grid at a cost of £6 million, but would not need planning consent (Section 37).

None of these were considered cost effective business opportunity to British Sugar plc and therefore British Sugar plc continue to run the CHP plant within the prevailing export constraints.

The FPP Quadrature Booster forecasted project cost is circa £1.8 million. This is the total forecasted cost for the project including design, construction and installation costs for the Quadrature Booster, the new 33kV switchger adn switch room and all associated control and protection systems.
This cost is expected to reduce significantly for future installations as R&D costs are eliminated.

In the example of Wissington British Sugar plc, the Quadrature Booster solution at distribution level is attractive as the estimated costs are clearly favourable compared to the cost of conventional network reinforcement options.

Conclusion

The FPP Quadrature Booster trial case provides both technological and reputational advantage to all involved. As an innovation project a number of challenges are being encountered. Diligent bespoke design requiring continuous liaison between parties involved is one of the success factors. Although a Quadrature Booster provides a smarter way of managing load sharing constraints, it also introduces two lots of transformer losses – series and shunt transformers, although these losses are less than a conventional 30MVA transformer.

British Sugar plc would be in a position to take advantage of the increased export limits if the Quadrature Booster trial proved a success. However, the amount of increased generation levels to use some of the increased export potential would vary across the year, and would be dependent on economics – the current day gas and electricity prices.

There is great potential for replication of the Quadrature Booster scheme. Future costs are expected to fall significantly as costs for research and development are eliminated.

Acknowledgements

The authors would like to acknowledge Tim Golden and Chris Young from British Sugar plc, Azzam Al-Riyami and Jonathon Ratsey from UK Power Networks for their contribution to the work presented. UK Power Networks is also grateful to Ofgem for financial support from the Low Carbon Network Fund.

References

[1]. National Grid, Seven Year Statement 2008 - http://www.nationalgrid.com/uk/sys_08/dddownloaddisplay.asp?sp=sys_TableB_4b (accessed 20/12/12)

[2]. Connection And Use of System Agreement (Wissington Sugar Factory), dated 14/05/98, document reference JW12421IBSWIS4, DCC (as revised 06/11/07).

[3]. C57.135-2001 – IEEE Guide for the Application, Specification and Testing of Phase-Shifting Transformers - Clause 4.2

Biography

Gilbert Manhangwe is Low Carbon Networks Planning Manager for UK Power Networks. He is responsible for the power systems planning and modelling for network development strategies to facilitate increased renewable generation connections on UK Power Networks' regulated public electricity distribution networks business.
Gilbert holds an MBA, Bachelor of Science Honours Degree in Electrical Engineering, and he is also a Certified International Project Manager (CIPM). He is a Chartered Engineer and a Member of the UK Institution of Engineering and Technology. He is also a fellow of the American Academy of Project Management.

Paul Dyer is responsible for formulation of specifications and approval of switchgear and transformers in UK Power Networks. He has been involved in many aspects of a distribution network operation, particularly with maintenance policies for network equipment. He is involved with IEC and National working groups for the specification and care of equipment. Paul is a Chartered Electrical Engineer and a Fellow of the Institution of Plant Engineers.

Sotiris Georgiopoulos is the Low Carbon Senior Project Manager at UK Power Networks with responsibility for developing and delivering smart grid projects. He is the project manager of "Flexible Plug and Play Low Carbon Networks" Sotiris has previously worked in a number of project engineering and management roles in the UK electricity generation and distribution industry
Sotiris received his BEng (Hons) in Electrical & Electronic Engineering from University of Manchester's Institute of Science and Technology in 2003 and his MSc in Energy Systems and Management from the University of Dundee in 2004.

Dr. Cristiano Marantes is the Low Carbon Networks Development Manager at UK Power Networks and has the overall responsibility for developing 'low carbon' smart grid networks. He is the project director of "Flexible Plug and Play Low Carbon Networks". Dr. Marantes sits on several industry forums such as the Smart Grid GB and the Energy Network Future Group within the UK Energy Networks Association. He has also written several scientific papers and a book. Dr Marantes received his PhD from the University of Manchester's Institute of Science and Technology in 2005. He is also an invited lecturer at City University London.