Coordination of Phase-Shifting Transformers to Improve Transmission Network Utilisation

M. Belivanis and K. R. W. Bell

Abstract- The location and variability of wind generation along with the difficulty of gaining permits for the construction of new overhead lines are placing increasing pressure on transmission system operators to increase utilisation of existing transmission capacity in as flexible a way as possible. Phase shifting transformers (PSTs) can contribute to this. However, to gain maximum benefit, the settings of a number of PSTs should be coordinated in a ‘smart’ way. This paper presents an overview of PSTs, their technical characteristics and their current use on GB Transmission Network. Issues and challenges for their effective and coordinated operation are raised and discussed with examples from a test network.

Index Terms- power system operation; power system security; phase shifting transformers

I. INTRODUCTION

This paper is concerned with the coordinated operation of phase shifting transformers or, more precisely, “quadrature boosters”, the type of phase shifting transformers installed on the high voltage electricity transmission network of Great Britain (GB).

More effective utilisation of network capacity has become more important since liberalisation of electricity markets and the continuing increase of renewable generation sources in the electricity supply mix. In a liberalised environment, the location and amounts of electricity produced are initially determined by market participants. Subject to trading arrangements, the planned dispatch of generation may not be known to the transmission system operator (TSO) until as little as 1 hour ahead of real time operation [1]. Furthermore, generation coming from renewable energy sources offers no guaranteed output and is often located at distant parts of the network where there may not be sufficient infrastructure to accommodate it or transfer the energy towards the main load centres. With long delays to granting of consents for new or uprated overhead lines, existing network thermal capacity must be utilised as fully and flexibly as possible.

In the context described above, phase shifting transformers (PSTs) or quadrature boosters (QBs) could prove a useful option for controlling the flow of power under different operational circumstances. In particular, they offer the possibility of flexibly increasing utilisation of the thermal capacity of the network under a variety of different conditions, i.e. to use the available network capacity in a ‘smart’ way. A number of QBs or PSTs are already installed in GB [2] and in the interconnected electricity network of continental Europe [3]. However, practical experience suggests that there is room for improvement in the way these units are operated both for day-to-day operation and in the assumptions that may be made about them for long term planning purposes. This mainly concerns the degree to which the settings on multiple PSTs could be coordinated to maximise the network’s power transfer capability without making it unduly vulnerable to differences between the planned operating state of the system and the actual one.

This paper will illustrate the use of PSTs on the GB transmission system and show how network capacity can be more fully utilised when PST tap positions are set appropriately. The respective opportunities and issues concerned with pre-fault ‘preventive’ settings versus post-fault ‘corrective’ settings will be discussed.

II. INCREASING PRE-FAULT UTILISATION OF TRANSMISSION CAPACITY

The requirement for secure operation of transmission systems, i.e. that no one of a particular set of fault outages or ‘secured events’, were it to occur, would cause violation of system limits, often dictates that power transfers should be restricted before the event takes place. This may require the restriction of operation of generation by limiting the output of units in critical exporting areas or constraining units on in importing areas. However, because fault outages are relatively rare whereas preventive actions must be effective at all times, there has also been attention by system operators to corrective actions, i.e. actions taken only after the occurrence of an unplanned event. Depending on the nature of the violation of system limits that the event would cause, the action may be instructed manually by the system operator (for example as a high loading is still within 20 minute ratings but above post-fault continuous ratings) or automatically by, for example, a ‘system to generator inter-trip’, more generally known as a ‘system integrity protection scheme’. These approaches are already used in many places including Britain and depend on real-time information on system conditions.

In terms of economics, the balance of costs between preventive and corrective measures might be expressed as in Fig. 1. On the preventive side, the costs are definitely incurred while, on the corrective side, a cost-benefit analysis might use the expected cost of action, i.e. one that is dependent on the probability of the action being required. However, it should

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also be noted that the scope for adequate corrective actions should be established in advance. For example, the post-fault tripping of generation should be accompanied by a balancing increase in power generated elsewhere. This will require scheduling of sufficient response and reserve. Moreover, in Britain, the ‘arming’ of a system to generator inter-trips generally has a price set by the owner of the affected generator.

Where the main actions concern re-dispatch of generation, the rewards for use of corrective actions instead of preventive are clear. However, in the context of import constraints, the only corrective action that is available may be reduction or shedding of load. Furthermore, an operator may view dependency on corrective actions as risky – will the corrective action succeed when it is needed? If the consequences of an action’s failure might be a cascade of outages or a voltage or frequency instability, an operator is likely to prefer preventive actions. This is particularly true when the weather is forecasted to be bad and there is an increased likelihood of one or more fault outages in quick succession that prevent re-securing of the system after each event. In the long-term, in order to avoid demand reduction, load shedding or the risk of extensive or costly curtailment of generation, the only viable option may be to increase the capacity of the network by investment in new or uprated overhead lines, HVDC links, transformers, reactive compensation and so on.

Actions, whether preventive or corrective, that do not involve re-dispatch of generation and the costs associated with it are understandably attractive. The ability to reduce or increase the power flowing on branches of a network by means of changing the tap positions on phase shifting transformers in a ‘smart’ way adapted to the current state of the system is one example that is discussed below.

III. PRINCIPLES OF OPERATION OF PHASE-SHIFTING TRANSFORMERS

Phase shifting transformers are devices that are able to exercise control on the flow of power across a transmission line and consequently on the network, by means of redistributing the power across the different circuits of the network.

The flow of active and reactive power over a long distance, high voltage transmission line in steady state conditions is described by the following equations [4],

\[ P = \frac{|V_s||V_r|}{X} \sin \delta \]  
\[ Q = \frac{|V_s||V_r|}{X} \left( \cos \delta - \frac{|V_r|}{|V_s|} \right) \]

where the subscript \( s \) stands for the sending end of the transmission line, \( r \) for the receiving end, \( X \) is the reactance and \( \delta \) is the load angle, the angular difference of the voltage phasors on either end of the line.

A phase shifting transformer’s principle of operation is that it manipulates \( \delta \) by inserting a phase shift angle \( \alpha \) that can increase or decrease the original angle \( \delta \) and consequently the flow of active power on the line. The flow of reactive power is also influenced but to a lesser extent. The phase shift angle can be acquired either by the appropriate connection (Y-D or D-Y) of the windings of a single three-phase transformer [5] or by using two separate transformers.

In the latter case, the transformer consists of a parallel (shunt) branch and a series branch. Power is extracted from the network through the parallel branch and injected back to the transmission line by injection of a voltage through the series branch. One can distinguish between two different design options. In the first one, the Phase Angle Regulator (PAR), the injected voltage is of the same magnitude as the line’s voltage but not in phase. This has the effect of introducing a controllable phase shift angle into the line. In the second design option, the Quadrature Booster transformer (QB), the injected voltage is always shifted by 90° with respect to the line voltage. The magnitude of the injected voltage is the controlled variable [6]. (All the PSTs installed on the transmission network of GB belong to the second category).

Quadrature boosters and phase angle regulators have some differences in their operational characteristics. The most important one comes from the fact that a QB changes the magnitude of its outgoing terminal voltage, so its operation has a greater effect on the reactive power flow on the line and the nodal voltage than that of PARs. For the same reason, while the location of a PAR on either end of a line will make no difference to the transmission characteristics or to the voltage profile of the network, this is not the case with the location of a QB [6].

Other important design characteristics of a phase shifting transformer are the through MVA ratings (nominal and short term) and the phase shift angle range at no load and at rated load operation [7].

In the rest of this paper, in view of their similar behaviour in a system context, PSTs will be referred to rather than QBs or PARs.

IV. CURRENT PRACTICE IN USE OF PSTS

By 2010, there were fifteen PSTs installed on the GB high voltage transmission network. Nine of them are connected to 400 kV circuits, five having nominal ratings of 2000 MVA and four rated at 2750 MVA. At the same time, six are connected in 275 kV circuits having nominal rating of 750 MVA [2]. They are owned and operated by National Grid Electricity Transmission that is also the Great Britain System Operator (GBSO).

The control of the quadrature voltage and thus of the phase shift angle is achieved by mechanical on load tap-changers in...
discrete steps that are tele-operated from the control centre. A protection control and alarm system is installed on each PST that restricts the tap positions available to the operator when certain tap positions would lead to the device exceeding its thermal or flux limits [7].

From the perspectives of both geography and system operation, most GB PSTs belong to one of two groups. The first group consists of the transformers located around London area and the second consists of the transformers located across the North - Midlands boundary of England.

PSTs can also be found on the interconnected European electricity network. One of the most well studied cases concerns those installed on the interconnectors across the German/Dutch border [4].

Although optimisation software was used at the investment planning stage to identify the potential benefits of PSTs in terms of maximisation of boundary transfer capability [8], there is currently no overall coordination of the operation of the PSTs on the GB transmission network [9]. In steady state, pre-fault conditions, the PSTs are generally operated close to their nominal tap settings. After a fault has occurred, the PSTs may participate in post-fault corrective actions based on scenarios studied in advance off-line that take into account a credible set of contingencies. Usually the scenarios anticipate that only PSTs located at one particular site will be used as part of the corrective action. There is no automatic response by PSTs to changes in network flows; instead, they are operated manually from the control centre.

V. RISKS AND CHALLENGES FOR COORDINATED OPERATION OF PSTS

The restriction in operation of the GB system of changes to PST tap settings to just one transformer at a time means that, in many instances, pre-fault constraint of generation or post-fault re-Dispatch of generation will be necessary. Such action on generation comes at a cost incurred through the acceptance of ‘offers’ to increase the output of one or more generators and balancing ‘bids’ to reduce it at others [1]. In future when Britain’s wind generation capacity has been more fully developed, this may mean failure to utilise the available wind power or a need to reinforce the system. The former can attract a very high cost, both in terms of recompense to wind farm operators for loss of income under the British renewables obligation and in acceptance of offers for replacement output on other plant with the net cost being in excess of £100/MWh, perhaps as high as £1000/MWh [10]. Meanwhile, system reinforcement is something that is increasingly difficult to achieve in a timely fashion whenever consents are required for overhead lines.

The coordination of PSTs in future system operation promises a fuller utilisation of the available thermal capacity of the network but raises concerns among operators. One of the key challenges is the interaction between the control actions at one PST device and other parts of the network.

Any action taken on one part of an interconnected network has an effect, albeit sometimes small, on every other part of it. This is particularly true of actions that, in effect, change the series reactance characteristics of the network and shift large amounts of power onto other branches. For instance, Kling et al mention in [11] that during pre-commissioning tests of the phase shifters installed at the Meeden substation close to the Dutch/German border, it was realised that changing the tap settings of the devices at Meeden has a significant effect on the power flow on the interconnectors between Netherland and Belgium as well as those between Belgium and France.

It is clear from the Dutch experience that control actions enforced on PSTs that belong to the same network or at least in the same group should be coordinated so that the overall configuration of the network is optimised for any particular situation and the objectives set by the TSO are met.

Another challenge comes from the nature of control actions on PSTs. It is reported in [9] that use of PSTs on the GB network is limited to a maximum of 15 tap positions at one site within 20 minutes. Indeed, in the GBSO’s operational planning for the management of system constraints, PSTs are considered in a time phase that involves manual operations and takes place 20 minutes after the original fault has been cleared. A contributor to this policy is system operators’ concerns that an intended, coordinated optimised state may be highly sensitive to errors in implementation of the full set of PST tap changes that might arise from communication or tap changer failure. (The need for changes to settings on a number of different devices within a short time period is what operational staff in GB tend to mean by ‘complexity’ of a control action. This is articulated, for example, in the British ‘Security and Quality of Supply Standard’ with respect to the number of circuit ends that must be operated to isolate a fault [12]).

Policy regarding PSTs, whereby the setting of only one PST is changed at a time and then only slowly, clearly limits PSTs’ effectiveness as a system control facility. For example, where changes to a number of different PSTs would achieve a maximum secure power transfer with minimum dependency on bid or offer acceptances, the dynamic nature of the system would present risks since a number of independent state variables may have changed significantly by the time the full set of coordinated PST settings is fully implemented, and that combination of settings may no longer provide a secure system.

Finally, although phase shifting transformers are able to influence the flow of power on a transmission line, they are not able to determine it completely. The flow of power on a transmission line is determined by the circuit parameters of all the transmission lines of the network as well as the disposition of generation and demand across the network. Indeed Kling et al. in [11] mention that only to a certain extent is it possible to control the power flows of the German/Dutch boundary with the phase shifters installed at Meeden. The effectiveness of the phase shifter’s operation is influenced by the amount of generation dispatched in the immediate vicinity of the devices. The more generation deployed, more influence on the power flows can be exercised by the phase shifters.

VI. COORDINATION OF PSTS: WORK TO DATE

Investigations are ongoing at a number of universities, TSOs and system coordinating bodies to determine how PSTs might best be used. This section will refer to the published results of some of them.

The case of two PSTs on the German/Dutch border has already been mentioned. In [11], the rationale behind the
decision to utilise PSTs is reported as being to increase the securely available cross-border transfer capacity and avoid or at least defer the construction of new transmission lines. The specification of the design parameters and the necessary agreements between the neighbouring TSOs are discussed as well as pre-commissioning simulation and operational results.

A new European organisation – Coreso – aims to enhance the coordination of TSOs of Central-Western Europe by proposing optimised coordinated remedial actions (regarding network topology, generation values or PST settings) that will help the TSOs avoid possible security risks that would not normally be visible to them as they are focused only on their own system. The centre was incorporated in December 2008 by the French and Belgian TSOs and shares its operation with the German, Dutch, Luxemburg and GB TSOs [13].

Marinakis et al. in [14] propose algorithms to form a tool for the coordinated control of several phase shifters by one transmission system operator. First, the authors explain that within an interconnected AC power system in which a number of TSOs are responsible for operation of different areas, power flows can alter from what is planned due to fault outages, changes in demand, changed availability of renewable generation or new energy trades. The unscheduled power flows that happen as a consequence could endanger the security of the system. One of the ways this might be dealt with is by utilising phase shifters. The control objective adopted is to re-secure the system with minimum reduction of the unscheduled power flows. Consequently, the problem is formulated as a simplified and linearised corrective Security Constrained Optimal Power Flow (SC-OPF) problem. Application of the algorithm is demonstrated on a test system inspired by a part of the UCTE interconnected network.

In [15], the authors of [14] propose a framework for the coordination of control actions of several TSOs that operate PSTs within the same interconnected network. The settings imposed on a single PST may have profound effect on distant parts of the network and since the different TSOs operating them may be operating with different objectives, conflicts can occur that endanger the security of the whole system. Their approach is to model a Nash equilibrium where every TSO has a non public individual control objective but their control actions are shared between the participants. Every TSO will take its control action in sequence respecting operating constraints relevant to the whole system and knowing the control actions already taken by the other participants.

Verboomen et al. in [16] are concerned with the problem of maximizing the net transfer capacity across a boundary that can be offered to market participants for inter-area trading. The total transfer capacity also serves as an indicator of the degree of coordination achieved. The boundary consists of more than one interconnecting transmission line. As a case study the systems of Netherlands and Belgium are used where one can find six PSTs installed (or expected to be installed) within a small area. The problem is formulated as an optimisation problem and a “particle swarm” approach is used. Different parameters for the algorithm are considered and its performance is studied.

Reference [17] follows a similar approach to find the optimal set of pre-fault settings for the PSTs so that the probability of congestion of the lines of the system is minimized. A 39 bus system with two PSTs is used as a study case. Monte Carlo Simulation is used to quantify uncertainty and to calculate the probability of congestion for every line taking into account the available settings of every PST device. Particle swarm optimisation is then used to calculate the set of settings that satisfy the objective of minimum congestion risk.

It is not clear from [14-17] whether the proposed algorithms have been discussed with system operators to establish the degree to which they would be prepared to trust the outputs from ‘black boxes’, or whether a method such as particle swarm optimisation can be relied on during rapidly changing emergency conditions.

It may be argued that operation of PSTs already installed in GB, which does not currently exploit results of computer based optimizations such as those in [14-17], under-utilises their capability. Future work by the authors of the present paper will attempt to address this. However, the use of a ‘smart’ coordinated PST control system will depend on an adequate appreciation of the current state of the system (which depends on accurate and timely measurements), the forecast state of independent variables and of the effect of PST tap change actions. These actions must be found quickly and reliably and to be robust against uncertainties in the initial system state and the reliability of implementation of identified actions. One way to achieve this may be by providing some margin against ‘credible’ errors, the considered set of which may be adapted to conditions prevailing on the system such as adverse weather, or by limiting the complexity of actions.

VII. ILLUSTRATION OF THE OPERATION OF PSTS ON THE GB TRANSMISSION SYSTEM

In order to illustrate the use of PSTs on the transmission network of GB and to study the effect of their operation on active power flows across the country, a simple representative model of GB transmission system has been constructed. The version of the model used hereafter consists of 24 nodes that represent the electricity system of England and Wales (Fig. 2).

The topology of the model and the layout of the nodes are consistent with the “SYS Study Zones” as published in National Grid’s annual “Seven Year Statement” (SYS) [2]. However this is not the case in the central-east part of England (SYS zones 10 and 12) where the layout chosen is more complex so as to better represent that meshed part of the network and the PSTs’ functionality. The main generation groups and demand centres are represented in each zone so that power flows across the main boundaries are similar to those that would arise on the full network under comparable demand and generation conditions. Four pairs of PSTs are modelled representing those installed on the high voltage transmission system. In common with real system in GB, all main transmission routes use 400 kV double circuit lines. For the examples in the following section the power flow results are calculated using DC load flow (DCLF) analysis. Initially the load flow is executed with all the PSTs set to neutral settings (zero degrees phase angle).

A. Sensitivity of the Power Flows to PSTs Control Actions

While operating the network with the PSTs it is clear that tap position changes on one PST will result to changes in the
flows of active power across every line of the network. The power flow on the line in which a PST is installed is directly and strongly related to the tap position of the PST. However, the effect of that tap position on the flow on other circuits depends on the disposition of demand and generation prevalent at the time. In other words, while the ‘line shift factor’ for the line in which the PST is installed is quite large and, in a DC approximation, constant, that for other lines varies with the initial system state.

**B. Preventive Control by the PSTs**

We will now consider a case study where there is an increased export of electricity from Scotland to England and examine its effects on the transmission system of England, the possible resulting constraints and the options available to the system operator. On the GB electricity system, Scotland has a significant surplus of installed generation capacity over peak demand including two nuclear stations and a growing number of wind farms [2]. Both of these technologies have low marginal cost leading to them being initially dispatched when available, but tend to be costly for the GB system operator to constrain off should it be necessary to respect a network export limit [1].

In our case study the transmission system operator expects a very high export of electricity from Scotland due to the forecasted wind conditions and the operation of nuclear power stations in the north west of Britain. This results in the loading of the western interconnector (Harker) between the two countries to levels up to 84% of its nominal thermal rating (that is the typical limit for pre-fault continuous operation [18]) but, as the simulation shows, if the initial generation dispatch were to take place, also results in the overloading of the circuit connecting the nodes “Drax” and “Daines” in England up to 103% of its pre-fault continuous rating as well as the increased loading of other circuits, e.g. those connecting the nodes “Keadby” and “Sundon”.

This is not a sustainable situation and the system is insecure against future unscheduled events such as fault outages. The system operator has to take measures to establish secure operation. Simulation shows that, for the overloading to be avoided, the total export from Scotland would have to be constrained at least by 1100 MW. In the scenario studied, much of this would be implemented on low carbon generation the output of which would have to be replaced by use of fossil fuelled plants in the south. (In GB, there is no obligation on the system operator to dispatch wind generation at its full available level).

The above actions come with an increased cost, especially since the type of generation to be constrained is primarily wind. Wind generators have no fuel related operating cost and they are unwilling to see their production constrained because not only do they not make any savings from the fuel not used but they also have to make up for the lost value of renewable obligation certificates (ROCs). This is reflected in the highly negative average price of bids that wind generators submit to the balancing mechanism [1, 10]. The same fact regarding the average bid prices is also true for nuclear energy generators, although to a lesser extent.

An alternative option for the system operator would be to utilise the PSTs, an action that lies completely within its jurisdiction and comes with zero cost. Indeed simulation results show that by using the PSTs and introducing preventive phase shift angles of +30 degrees for the devices 5 and 6 (installed on the line connecting the nodes (“Deeside” and “Feckenham”) as well as +30 degrees for the devices 3 and 4 (between “Ratcliffe” and “Staythorpe”) and -4 degrees for PSTs 1 and 2 (“Keadby” – “Cottam”), the situation is solved. Under the same generation and demand disposition as before, there would be no overloading in the circuits in England.

**C. Coordinated Corrective Control by the PSTs**

In this case study, the double circuit fault outage between the nodes “Ratcliffe” and “Staythorpe” is considered. According to the simulation this will lead to the transmission lines that connect the nodes “Staythorpe” and “Sundon” to be overloaded up to 105% of their post-fault continuous rating. At the same time, the lines connecting the nodes “Drax” and “Daines” will be loaded up to 93% of their ratings.

The above situation with a marginal overload does not represent an immediate threat to the system. However, it is now much more vulnerable to further faults outages, unplanned changes to the generation dispatch or unforeseen changes to demand. Action should therefore be taken to restore the system to a secure state.

The overloading can initially be reduced by increasing the phase shift angle of the PSTs 1 and 2 installed between “Keadby” and “Cottam”. However the extent of control that can be exercised with these devices is limited by the fact that other lines (“Drax” – “Daines” and, to a lesser extent, “Keadby” – “Sundon”) will soon start to increase their loading. The simulation results show that one solution would be to utilise the PSTs installed on the lines connecting “Deeside”...
and “Feckenham” and representing the devices installed at Legacy substation on the real network. Their operation has a greater effect on the lines between “Drax” and “Daines” and a lesser effect on the originally overloaded pair of lines (“Ratcliffe” - “Staythorpe”). With the coordinated operation of both sets of devices, however, the overloading of “Ratcliffe” - “Staythorpe” can be removed while at the same time reduce the loading of “Drax” - “Daines”.

The final result is one set of feasible settings for all four PSTs so that the network is returned to a secure state without the need for re-dispatch of generation. In this case the combination of settings is neither unique nor optimal. For coordinated control to be fully trusted by system operators, optimisation algorithms and techniques have to be developed that will determine not only the optimal combination of settings but also a secure way to reach them. This means taking into account the dynamics of the system while it is being shifted from one intermediate state to the next one. At the same time the possibility of secondary failures, like the failure of individual phase shifting actions or failure of communication, should be considered [19].

VIII. CONCLUSIONS

The location and variability of wind generation along with the difficulty of gaining permits for the construction of new overhead lines are placing increasing pressure on transmission system operators to increase utilisation of existing transmission capacity in as flexible a way as possible. Phase shifting transformers are devices that can effectively exercise control on the transmission lines in which they are installed and change the distribution of power between different branches of a network. A number of these devices are already installed on the GB transmission network. However, their operation is not currently done in a coordinated way and thus there may be scope for them to make a greater contribution to system operation and the minimisation of actions to constrain generation.

In this paper, some of the risks and challenges that the coordination of tap settings of PSTs presents have been discussed and illustrations of their operation on a test network representing the GB transmission system have been presented. More comprehensive work that will follow by the same authors will aim to address operators’ concerns about the complexity and robustness of actions and tackle the coordination of tap settings problem as an appropriate mathematical security-constrained optimisation problem.

REFERENCES