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Future GB Power System Stability Challenges and Modelling Requirements

Carlos Ugalde, Nick Jenkins
Cardiff University
Ugalde-LooC@cardiff.ac.uk, JenkinsN6@cardiff.ac.uk

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About this report

The Institution of Engineering and Technology was commissioned by the Council of Science and Technology (CST) to research the emerging challenges for modelling electricity systems and how Britain's capabilities would need to be adapted to assess electricity system resilience as GB makes the transition to a low carbon electricity system.

This project commissioned, and received, fifteen individual papers from GB-based specialists of international standing in power system modelling. The authors of the papers worked with a wide stakeholder base of network companies, academics and others, who provided review and challenge. Professor Graham Ault CEng FIET was contracted to provide technical co-ordination and drafting. The emerging conclusions were further validated by means of an industry and academic workshop sponsored by Government Office for Science. The entire project was conducted under the direction of an independent steering committee composed of senior IET Fellows, two of whom were also CST nominees.

The report is composed of three parts:

- Part 1: Main report
- Part 2: Summary of Commissioned Papers
- Part 3: IET Special Interest Publication – Academic & Industry Papers

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1. BACKGROUND

The stability of an interconnected power system is its ability to maintain equilibrium during normal conditions and to return to normal or stable operation after having been subjected to some form of disturbance [1]. Disturbances, e.g. short circuit faults or changes in load, are inevitable and so the power system is designed and operated to behave satisfactorily during and after disturbances. Instability may lead to blackouts, have disastrous consequences for power system plant and may have massive social, security and economic implications. For instance, following an angle instability event in the form of power swings, voltage instability caused a major blackout in the US and Canada in 2003. This affected more than 50 million people and caused major issues in power generation, water supply, transportation and communications. A more recent event was the 2012 India blackout, affecting around 9% of the world's population. Following a loss of generation, cascaded tripping caused a system overload which resulted in the blackout. This was also a case of angle (transient) instability and as a consequence of angle differences, large variations in voltage and power flows arose in a number of transmission lines.

The simple mechanical analogue of a traditional power system with large synchronous generators connected to a high voltage transmission system is that of a spring-mass system with very little damping. Stability of this underdamped system has been a matter of concern since interconnected power systems were first created in the 1930s.

It is conventional to divide stability into a number of phenomena which, although inter-related, are considered separately and analysed using distinct analytical approaches. Figure 1 shows the conventional classification from a standard textbook.

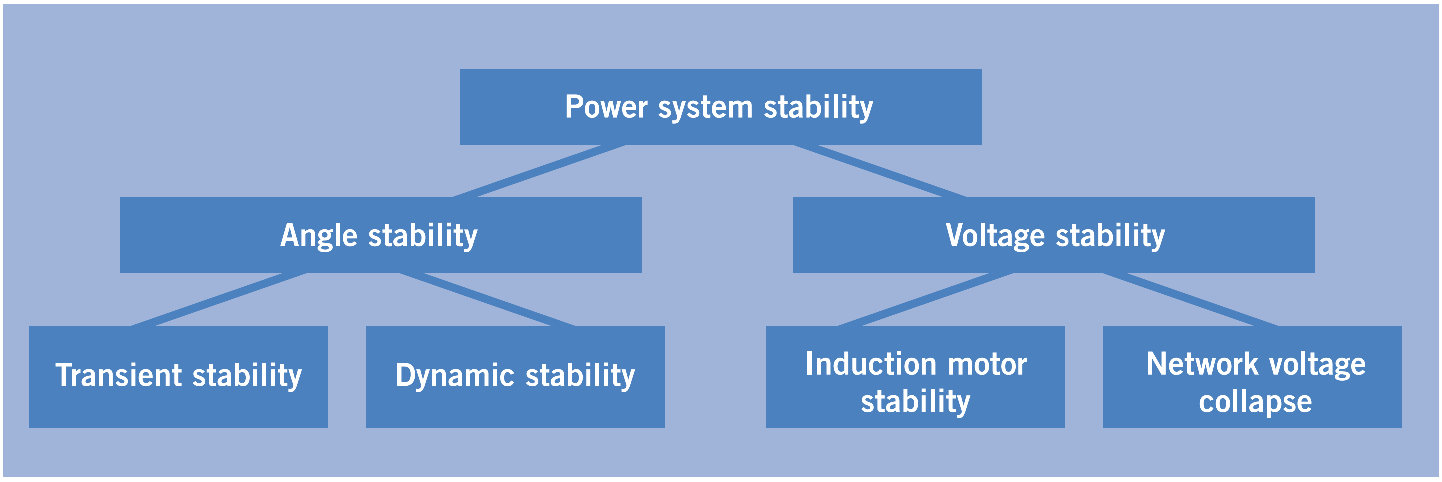


Figure 1: Elementary forms of stability [2].

Angle stability is the ability of interconnected synchronous generators of a power system to remain in synchronism. Equilibrium between the electromagnetic and mechanical torque of each machine and a rotor angle synchronism between the synchronous machines of the power system should be maintained during normal operation or restored following a disturbance. Depending on the type of disturbance, angle stability is classified as either transient or dynamic stability. While transient stability is concerned with severe disturbances such as three-phase faults, dynamic stability is concerned with the effect of small disturbances such as minor changes in load or generation.

Voltage stability is the ability of a power system to maintain steady (or within acceptable boundaries) bus voltages under normal operation and after being subjected to a disturbance.

2. STABILITY

Stability of a large power system is a complex phenomenon. Although it could be argued that current software packages are capable of modelling the system to a high level of detail and fidelity, the model may be too complicated for particular studies, so that a simple representation employing less computational effort may give more understanding. For example, if low frequency oscillations are the subject of study, a complex representation of the transmission lines may not be necessary or desirable. It should be kept in mind that comprehensive time domain simulations giving detailed time series results are computationally expensive and the results difficult to interpret. Conversely, a model may be of a high order, but it may not be suitable for a given application if it fails to reproduce the characteristic behaviour of the phenomenon under study. For instance, a detailed shaft model of the generators should be adopted for the study of torsional interactions, which is usually simplified to a single-mass representation for other studies.

A clear definition of the aspect of stability that is of interest and the techniques to be used is essential before the studies commence. Due to system complexity, the model to be adopted should be simplified as much as possible but with care. There is a fundamental need to clearly understand the potential issues that may arise in future power systems featuring new elements and characteristics.

3. MAIN FORMS OF POWER SYSTEM INSTABILITY IN THE 2030 GB POWER SYSTEM

The GB power system that is anticipated in 2030 has a number of new attributes that unless recognised and mitigated against, may lead to instability.

Reduced system inertia. The increasing connection of converter connected generation plant (e.g. photovoltaic generation) will lead to reduced system inertia. Transient stability will be reduced and require faster clearing times of protection.

Distributed generation (i.e. rotating generators connected to the distribution system). Much distrusted generation is unlikely to be stable after network faults due to its low inertia and the long protection clearing times of distribution networks.

Series compensation. The use of series capacitors on the transmission network increases the risk of sub-synchronous resonance.

Interactions of AC/DC systems. Increasing numbers of DC links are being connected to GB. These links that are either bootstraps connecting two points in GB or international interconnectors (LCC or VSC) have important consequences for the stability of the GB AC power system.

Increase in maximum single loss of power infeed. The increase of the maximum allowable loss of power in-feed from 1320 MW to 1800 MW will require significant additional part loaded generators to be operated in order to maintain stability unless innovative solutions using Demand Side Response are used.

However, recent technical developments offer ways to manage potential instability:

Phasor Measurement Units allow greater visibility of the power system and particularly give early warning of small signal instability.

ICT techniques to acquire and manage very large data sets are being used in other industries and offer the possibility of recording and subsequently analysing system events.

Converter connected generators and interconnectors offer the possibility of using active control to increase stability.

Reduced Inertia:

The decrease of the carbon intensity of the GB electricity system depends on an increasing penetration of renewable energy sources to displace fossil fuel use. As a consequence conventional fossil fuelled synchronous generators will gradually be phased out. The natural inertia provided by synchronous generators that helps maintain the system frequency will be replaced with generators that are independent of frequency changes [3].

For instance, if at a given time the presence of wind energy is abundant or if demand is low, it is expected that large fossil fuel power plants using large synchronous generators will not be in service. In this case, the system will possess little inertia and will be subjected to rapid fluctuations in system frequency due to supply and demand mismatches. Thus, the system will be more vulnerable to large and small disturbances –having an effect on dynamic and transient angle stability.

A number of questions related to a future low inertia GB system are still unanswered. It is unclear whether a mismatch between supply and demand would lead to excessive RoCoF (Rates of Change of Frequency). It is not known either at what point the reduction of inertia would affect the secure and stable operation of the power system. Additionally, the variations in system inertia will not be uniform, with specific geographical regions being more affected due to their penetration of renewables, e.g. Northern Scotland. This may potentially have an impact on inter-area oscillations.

From a modelling perspective, it is apparent that system representations taking into account the reduction in inertia are necessary. Although effort has been dedicated both in the industry and the academia to create GB-like models for stability studies, their use is not widespread and multiple versions exist for a number of simulation packages. Models featuring an unevenly spread low inertia across the GB are not available. An initial approach would be to reduce system complexity (with a small number of synchronous machines) while keeping an appropriate weighting of the size of generation to ensure an initial understanding of the impact of low inertia in the system. This could be followed by more detailed models featuring a larger amount of generators and power electronics interfaced components.

Distributed Generation [4]:

There is an increasing capacity of generation connected to the distribution system (Distributed Generation) with currently around 10 GW in GB. The capacity of photovoltaic generation is increasing particularly rapidly although there are also significant numbers of onshore wind, biomass and combined heat and power units. The schemes are either small (usually < 10 MW) using synchronous or induction generators directly connected to the power system or with the prime movers interfaced through power electronic units.

The traditional operating philosophy of distributed generation has been to supply energy (kWh) from low carbon sources but to rely on the large fossil fuelled synchronous generators of the power system for stability. This is appropriate as long as distributed generation remains a small fraction of the total generation but is not sustainable as increasing distributed generation is connected.

Distributed generators take a voltage and frequency reference from the power system and are not intended to operate in islanded mode. Distributed generators are fitted with Loss of Mains protection to detect islanding as operation is not permitted without a connection to the normally operating power system. Traditionally distributed generators have not been expected to support the power system in the event of disturbances in frequency and voltage but to trip as soon as a network disturbance is detected. Many use RoCoF protection for Loss of Mains and although the required settings of this protection have recently been relaxed significantly for larger distributed generators and a time delay introduced to increase stability, the basic philosophy of distributed generators being a source of energy only remains.

In addition to instability introduced by Loss of Mains protection, the fundamental technologies of the distributed generators and the desire of equipment manufacturers to minimise costs lead to risks of instability. Power electronic converters are synchronised with the mains frequency through a phase locked loop and this is often designed assuming a stable and benign mains waveform. Small, directly connected rotating distributed generators often have low inertia and so are unstable for the long clearing times of distribution protection. It is technically possible to increase the stability of distrusted generation and even to allow islanded operation but at very considerable increased cost and complexity.

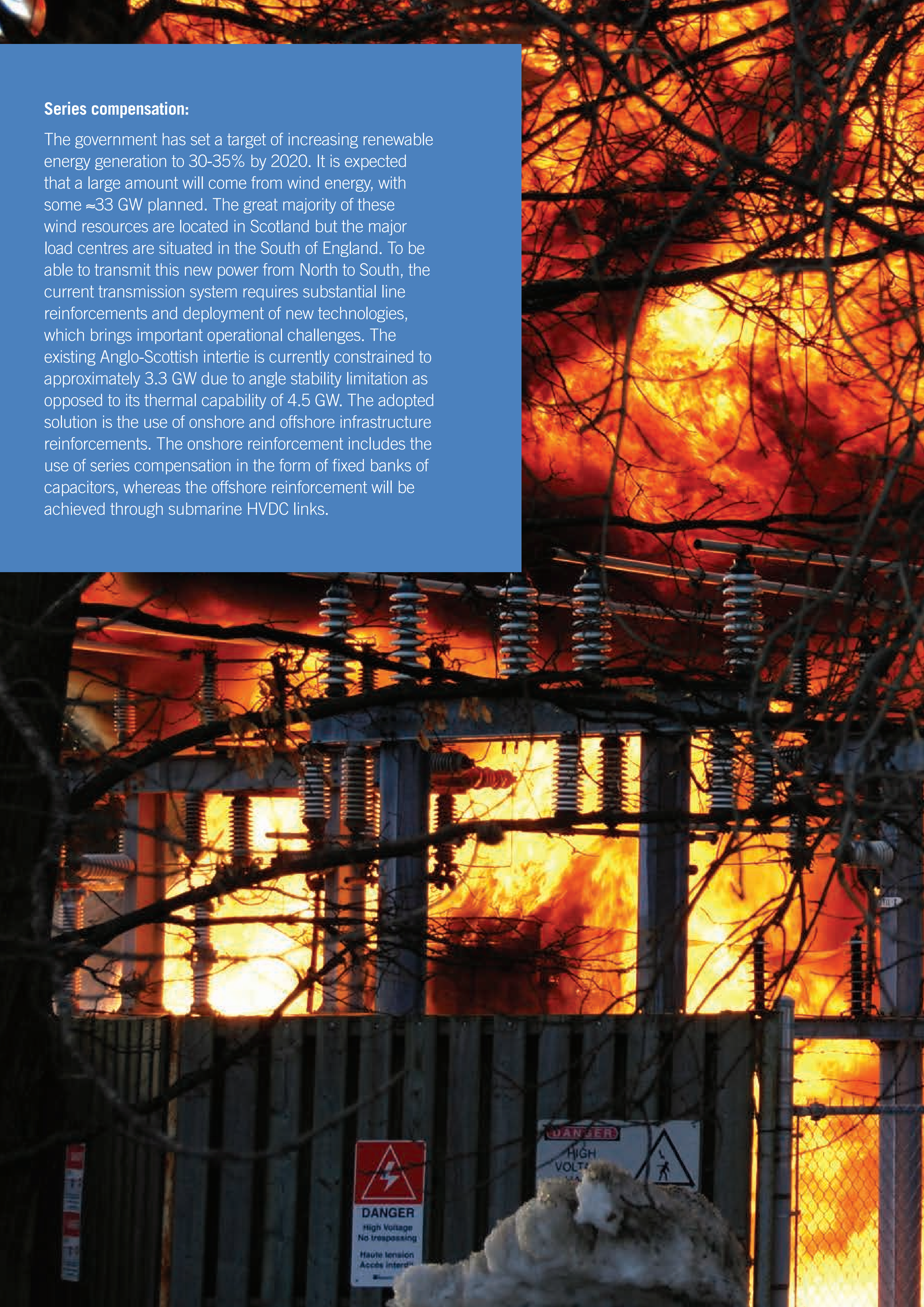
Traditionally the stability of distributed generation has been only an academic study as its impact on the power system, other than as a source of energy, has been ignored. With increasing distributed generation this will change. Studies will be required to investigate:

- Angle stability of larger distributed generators.
- The impact of aggregated distributed generation on small-signal oscillations of the power system.
- The impact of aggregated distributed generation and spinning load on the voltage and frequency stability of the power system.
- The robustness of power electronic converters.
- Islanded operation.

A key challenge is the very large number of distributed generators, which implies that studies of individual distributed generators must be automated and aggregate models developed for system studies. Also, expertise in studying stability tends to be concentrated in transmission companies and the larger consultancies.

Series compensation:

The government has set a target of increasing renewable energy generation to 30-35% by 2020. It is expected that a large amount will come from wind energy, with some ≈33 GW planned. The great majority of these wind resources are located in Scotland but the major load centres are situated in the South of England. To be able to transmit this new power from North to South, the current transmission system requires substantial line reinforcements and deployment of new technologies, which brings important operational challenges. The existing Anglo-Scottish intertie is currently constrained to approximately 3.3 GW due to angle stability limitation as opposed to its thermal capability of 4.5 GW. The adopted solution is the use of onshore and offshore infrastructure reinforcements. The onshore reinforcement includes the use of series compensation in the form of fixed banks of capacitors, whereas the offshore reinforcement will be achieved through submarine HVDC links.



Although series compensation is not a novel topic of study, it is being used in the GB power system for the first time. Series compensation is recognised as an efficient approach to increase the power transfer capacity and stability margin between large interconnected regions by partially compensating the inductive impedance of the transmission line. Let the power transfer between two arbitrary points in a system be described as

$$P = \frac{V_1 V_2}{X} \sin \delta$$

where P is power, V_1 and V_2 stand for the voltage at either end, *X* is the circuit reactance, and δ is the angular difference between voltages V_1 and V_2. By installing series compensation between the two points, the reactance between the line ends is reduced and the power transfer capability is increased.

The use of series compensation alters the characteristics of the compensated line and its transient behaviour. In addition to an increased short circuit level, reduced line impedance, introduction of harmonics and transient recovery voltage, it is also accompanied by a form of angle (both transient and dynamic) instability termed sub-synchronous resonance (SSR). In particular, stress, fatigue, shaft failure and damage on turbogenerators connected to series-compensated transmission lines have been traced to SSR. If left unattended, it can lead to catastrophic consequences.

SSR is defined as an electric power system condition where the electric transmission network exchanges energy with a turbogenerator at one or more of the natural frequencies of the combined system below the synchronous frequency [5]. It mainly occurs in series-capacitor compensated transmission networks. Although SSR is not a new phenomenon, it has been observed predominantly in countries with long transmission lines and relatively low fault levels. Conversely, the GB network is tightly meshed with high fault levels. In addition the GB system has large thermal and nuclear generation near the Anglo-Scottish intertie and so the effect of series compensation needs to be evaluated within this context [6].

The study of SSR and its mitigation requires a detailed representation of the turbogenerators close to the series-compensated transmission lines. For example, if torsional interactions are of interest, a detailed model of the shaft is required. This requires knowledge of the inertia constants, self and mutual damping coefficients and torsional stiffnesses of the masses representing the shaft. These data is usually not available. Independently of the approach followed for the study of SSR (ranging from frequency scanning techniques, eigenvalue analysis or time domain simulations), a high level of expertise is required. Unfortunately the degree of know-how is limited in GB and the analysis may be obscured by the lack of reliable plant data. The analysis is expected to be further complicated by the landing of DC links.

Increasing DC links being landed in GB:

The connection and integration of offshore wind power into the GB grid and the interconnection with other grids in Europe has been recognised as fundamental to fulfil environmental targets. It is expected that approximately 33.5 GW of offshore wind power will be connected to the grid by 2020; foreseen to increase to 83 GW by 2030. However, the development of the offshore grid infrastructure connecting remote offshore wind generation to load centres remains a great challenge.

Although a topology is yet to be defined, countries in Europe have agreed to develop an integrated North Sea grid, with HVDC being the key enabling technology [7]. Two alternatives are available, namely line commutated converter (LCC) and voltage source converter (VSC) HVDC. LCC HVDC is a mature and well developed technology that has been conventionally employed for bulk power transfer. On the other hand, VSC HVDC offers black start capability and an independent control of active and reactive power [8]. Since VSC HVDC provides the possibility to change the direction of its power flow without reversing the polarity of the voltage of the DC cables, it is expected that multi-terminal HVDC (MTDC) grids based on VSC technology will be developed across the North Sea. MTDC grids will increase the flexibility, redundancy and economic viability of offshore wind power transmission.

HVDC technologies are based on power electronic converters. These converters have also been widely used for wind power and other types of distributed generation to meet Grid Codes for their integration into AC grids. As more and more conventional synchronous generators are decommissioned and more HVDC links are landed into the GB grid, this will become dominated by generation with a power electronic interface. Such a scenario presents a series of challenges for AC system operation such as the potential impact on existing relaying protection, voltage instability, and frequency instability and commutation failure of LCC HVDC.

The increase of HVDC connections should be carried out with care as they do not inherently provide inertia or add large short-circuit currents to AC grids. As synchronous generators are increasingly phased out, system inertia as well as short-circuit level, will drop significantly. More spinning reserve would be required to maintain the level of inertia and this entails higher costs. HVDC converters do not increase the short-circuit level of AC grids greatly but can provide voltage support through proper reactive power control. It is also expected for there to be inertia contribution from HVDC converters through real power control. This requires coordination of the sources connected to the HVDC links in order to maintain stable operation of the AC grids.

LCC HVDC can provide artificial inertia but requires high short-circuit ratio of the grid to work properly. During AC fault and post-fault restoration, the inertia support capability of the LCC would be limited at the very time it is most needed. VSC HVDC control is less dependent on the behaviour of AC grids. However a DC fault can be easily propagated across a whole HVDC grid due to the very low resistance of DC circuits, which in turn affects the AC sides of all terminals. During the DC fault, the real power injected into AC grids as well as the inertia support from VSC HVDC grids would be lost at the very moment it is much needed to maintain the system frequency. At the same time, reactive power support to AC grids from VSC HVDC grids would also be lost completely or partially depending on converter topologies.

The problem is complex from a modelling point of view, as a number of VSC HVDC technologies and topologies have been proposed and may coexist in the future. For instance, an MTDC grid connecting offshore wind farms to the GB system may feature a combination of two and three-level converter topologies and modular multi-level converters (MMCs). The MMC in turn could be based on H-bridge or half-bridge modules. The possible dynamic AC/DC interactions or the impact of DC system faults on system stability remain unclear.

4. RECOMMENDATION

The dynamic characteristics and hence the stability of the GB power system is changing as new forms of generation displace conventional steam units. Although there is considerable academic research being undertaken on the stability of the “smart grid” much of it is not directly relevant to GB as much of the necessary machine data is confidential to the generating companies. A “quick win” would be to complete an agreed open access simplified GB dynamic model and ask UK researchers to test their ideas on that rather than IEEE models as is done at present. A regular annual day colloquium could be held of studies undertaken on the GB model.

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IET Offices

London*
Savoy Place
2 Savoy Place
London
WC2R 0BL
United Kingdom
www.theiet.org

Stevenage
Michael Faraday House
Six Hills Way
Stevenage Herts
SG1 2AY
United Kingdom
T: +44 (0)1438 313311
F: +44 (0)1438 765526
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www.theiet.org

Beijing
Suite G/10F
China Merchants Tower
No.118 Jianguo Road
Chaoyang District
Beijing China
100022
T: +86 10 6566 4687
F: +86 10 6566 4647
E: china@theiet.org
www.theiet.org.cn

Hong Kong
4412-13 Cosco Tower
183 Queen's Road
Central
Hong Kong
T: +852 2521 2140
F: +852 2778 1711

Bangalore
Unit No 405 & 406
4th Floor, West Wing
Raheja Towers
M. G. Road
Bangalore 560001
India
T: +91 80 4089 2222
E: india@theiet.in
www.theiet.in

New Jersey
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