Programme Area: Energy Storage and Distribution

Project: Network Capacity

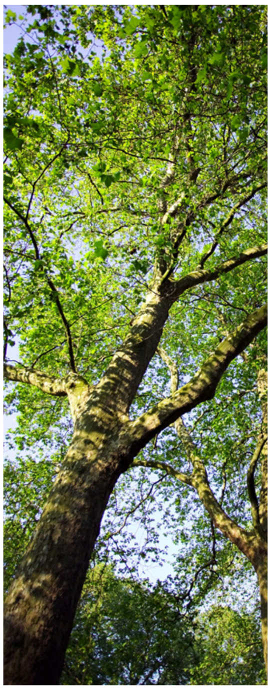
Title: Final Project Summary (Work Packages 1 & 2)

Abstract:

This project has focussed on the feasibility of applying new and existing power electronic technologies to provide enhanced management of network power flows in order to release more capacity within the T&D system. It has also assessed the technical feasibility of multi-terminal HVDC in the context of operation within the existing UK T&D system. The work has been reported on in eleven separate technical reports that address specific areas of the study. This report is the final report for the study; it summarises the previously published reports and presents a summary of all of the key findings in a single coherent document.

Context:

The Network Capacity research project identified and assessed new technology solutions that could enhance transmission and distribution capacity in the UK. It assessed the feasibility and quantified the benefits of using innovative approaches and novel technologies to provide improved management of power flows and increased capacity, enabling the deployment of low carbon energy sources in the UK. The project was undertaken by the management, engineering and development consultancy Mott MacDonald and completed in 2010.

The ETI Energy Storage and Distribution Programme - Network Capacity Project

Work Package 1 Task 8 Final Project Report - Assessment of New Methods of Enhancing the Onshore UK Electricity Transmission & Distribution System to Enable Increased Renewable Energy Connection

December 2010

The Energy Technologies Institute (The ETI)

Mott MacDonald

The ETI Energy Storage and Distribution Programme

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Content

Executive Summary

This project has focussed on the feasibility of applying new and existing power electronic technologies to provide enhanced management of network power flows in order to release more capacity within the T&D system. It has also assessed the technical feasibility of multi-terminal HVDC in the context of operation within the existing UK T&D system. The work has been reported on in eleven separate technical reports that address specific areas of the study. This report is the final report for the study; it summarises the previously published reports and presents a summary of all of the key findings in a single coherent document.

Grid Issues

There are a number of important issues that have to be taken into account when considering the application of FACTS or HVDC technologies that are a function of the Grid network rather than the technologies themselves. These issues are:

- The constraints on the ability of a network link to carry additional power may be the result of stability considerations not just thermal ones. The Grid has to be able to withstand the loss of the enhanced link without exceeding the thermal or stability limits elsewhere in the system.

- The UK Grid has been developed so that the ratings of individual transmission links are compatible with the ratings of surrounding links. Thus, where the Grid network consists of a chain of node to node links, all such links have to be uprated if the whole chain is to be uprated, and this has to include all associated busbars and switchgear not just the transmission lines. In some cases uprating of surrounding parallel links may also be needed.

- The use of an existing AC transmission line or its corridor for conversion to HVDC may be attractive in principle but conversion involves taking the line out of service for a considerable time and that may be unacceptable in practice. Potential increases in capacity from the uprating of a given transmission corridor are more beneficial where there are fewer transmission corridors in parallel with it. However, the fewer transmission corridors that there are in parallel the more operationally disruptive it would be to take one out of service during conversion.

- The post fault HVAC ratings on the UK 400 kV overhead line circuits are already very large, currently in excess of 4 GW, which means that any additional capacity that could be provided by the conversion to an onshore HVDC scheme is very likely to be problematic to the grid. The outage of a high capacity HVDC link that is loaded close to maximum capacity will cause higher-amplitude power flow oscillation across the adjacent HVAC transmission circuits when compared with the loss of the HVAC circuit. The risk of system instability following the loss of the HVDC link is therefore exacerbated unless a curtailed loading schedule is employed for the HVDC link or the transmission capacity of adjacent HVAC is increased to match the rating of the HVDC link. Either solution will involve very significant reinforcement costs that are very likely to make the line conversion uneconomic.

Devices

Only two power electronic device families are used extensively in transmission and distribution applications. These are Thyristors (used in Line Commutated Converters (LCC)) and Insulated Gate Bipolar Transistors (IGBTs) (used in Voltage Source Converters (VSC)). These are both based on silicon technology. At present the voltage ratings of silicon thyristor and IGBT devices are limited to 8.5 kV and

6.5 kV, respectively; there is little scope for significant increase in these figures. For many transmission applications, series connection of devices is required in order to achieve the necessary operating voltage.

New wide band-gap materials such as silicon carbide (SiC) and gallium nitride have the potential to deliver increased voltage ratings, reduce switching losses, and raise operating temperatures. Although low voltage SiC devices are available, major advances would be required in order to achieve the high-voltage, high-power modules necessary for transmission applications.

Converters

Flexible Alternating Current Transmission Systems (FACTS) and High Voltage Direct Current (HVDC) systems are currently implemented using both LCC and VSC technologies. Line commutated FACTS have the advantage of a well established technology but are subject to inherent performance limits. The use of VSC can overcome some of the inherent limitations of LCC based systems, but the IGBT converters used in voltage source FACTS are still in a state of development with relatively limited operation experience, and at present VSC systems have yet to match the established LCC technology in terms of capacity and losses.

In general, power electronic systems for power transmission are required to operate at power levels and voltages significantly above that which may be sustained by a single power device, and they therefore require the use of multiple devices in series. This presents challenges not normally faced in other applications.

Flexible Alternating Current Transmission Systems (FACTS)

All of the FACTS technologies that have been investigated by this study are well established and can be readily implemented, but modern devices offer enhanced performance compared to schemes implemented with older technologies. Particular findings from the study obtained using a verified dynamic model of the UK Transmission & Distribution network are as follows:

- The deployment of Thyristor Controlled Series Compensation (TCSC) on selected transmission corridors in the UK may improve the system's ability to recover to stable operation following selected double contingencies (i.e. the sudden outage of two transmission circuits on the same physical support tower) under certain operational circumstances.

- The deployment of STATic synchronous COMpensators (STATCOMs) may provide benefits to the UK transmission system dynamic response to selected double contingencies under certain operational circumstances. Multiple site deployment of STATCOMs was demonstrated to improve the dynamic behaviour of the system when large disturbances such as loss of transmission corridors are experienced. The rapid reactive power support delivered by adequately tuned STATCOMs plays a major part in the system recovery to stable operation. Coordinated control of the STATCOM devices is not required to achieve the full functionality of the scheme.

- The deployment of Static VAr Compensator (SVC) devices, even at multiple sites, does not have the potential to mitigate the consequences of large perturbations affecting the main transmission corridors in the UK transmission system. The SVC deployment only stabilizes the voltage at weak nodes in the system and improves the voltage profile in areas adjacent to the SVC location.

- Devices of required transmission level rating are not presently available but could be implemented by aggregating sub-modules, although this would incur a significant cost penalty.

HVDC Technology and Schemes

Thyristor based high-voltage DC transmission is a well-established technology with many installations in operation throughout the world and is available from a number of manufacturers including ABB, Areva and Siemens. The limitations of this technology are high reactive power consumption, large harmonic current emissions, and large installation size. It has advantages in terms of DC link fault behaviour (the smoothing inductors in the DC link give resilience against DC side short circuit faults) but is not readily adapted to multi-terminal systems. It is the only option for transmission circuit power capacities greater than 2400 MW utilising individual DC scheme blocks rather than multiple blocks.

The newer Voltage Source Converter (VSC) based HVDC exhibits increased losses relative to thyristor based systems but has important compensating advantages (particularly the lack of dependence on a separate commutating supply source, independent control of active and reactive power, reduced filtering requirements and the ability to provide fast frequency or damping support to AC network through active power modulation). There has been significant use of this technology with subsea links to networks that could not be connected by conventional LCC-based HVDC (most notably offshore renewable generation clusters).

In some circumstances, HVDC transmission provides benefits such as enabling long distance power transmission, eliminating reactive power flows from long HVAC cable circuits and enabling asynchronous system connections. However, these would not be of benefit to the onshore UK transmission system in view of its short transmission distances.

The conversion of selected transmission corridors from AC to HVDC (either LCC or VSC) may improve the system's ability to recover to stable operation following selected double contingencies (such as the simultaneous outage of both transmission circuits on the same towers) under certain operational circumstances. Both the HVDC options can use the fast power controllability inherent to HVDC to boost the power flowing in the converted line by use of a Special Protection System (SPS). Such a system would collect power flow information and status data from adjacent substations interconnected by parallel HVAC transmission circuits and determine, based on automation algorithms, the control settings on the HVDC converters necessary to mitigate the effects of HVAC transmission circuit outages on system stability.

The conversion of some transmission corridors from AC to HVDC may result in post contingency thermal overloads of nearby transmission lines that would not have been overloaded in the AC arrangement. This is because when a neighbouring AC line trips, an AC line automatically adjusts/shares power flow, but HVDC power will stay the same unless changed by its control scheme. The resulting overloads could be mitigated by adjusting the post-contingency power transfer on the HVDC line. However, this would either require an SPS or operator intervention. Both approaches would increase the operation complexity of the transmission system accompanied by amplified requirements for fast multi-directional communication. Such complex operational arrangements that rely on remote data and information transfers are not welcomed by transmission system operators.

For some transmission corridors, installing a back-to-back VSC HVDC link on one circuit of each of the double circuits, while leaving the other circuit unchanged showed similar benefits to the system as those provided by the full conversion to HVDC. This would potentially be an attractive option since it would not require the transmission line itself to be converted to be suitable for HVDC operation.

Multi-Terminal HVDC Schemes

Multi-Terminal HVDC (MT-HVDC) is an HVDC system architecture that enables the injection and distribution of power at several terminals which are interconnected through a network of DC links. Inherent low losses for the DC transmission technology and the wide-range controls of the power accepted/dispatched at each HVDC terminal are essential features that make MT-HVDC attractive for implementation in heavily interconnected HVAC transmission system.

Multi-Terminal HVDC is feasible with both LCC and VSC Technologies. Presently the use of current source converter (LCC) technology in a multi-terminal HVDC system configuration is limited to three terminals due to technical difficulties such as increased control system complexity and DC current balancing between the converters. In principle, a multi-terminal VSC-HVDC transmission system can be extended to any number of terminals without increasing the converter power system complexity significantly. However, a highly co-ordinated control system is required between the converter stations and robust DC circuit breakers are required to improve the possibility of system recovery from DC faults or loss of converters. There are no multi-terminal VSC-HVDC Schemes in commercial operation, although considerable R&D activity is addressing the design and operation of such schemes. Reference was made at the workshop to the possible availability of DC breakers "within a year or two" but no substantiation of this claim has been revealed by any of the investigations carried out under this project. This topic therefore merits further investigation in the future.

Conversion of Existing UK Transmission Lines to HVDC

Although, for a given transmission tower size; significantly more power can be transmitted on a DC circuit than on an AC circuit (typically between approximately 1.5 to 3.5 times depending upon the characteristics of the line concerned and the amount of tower conversion undertaken) to date, there has been only one line in the world where conversion has actually taken place. This indicates that thus far the transmission system operators have not judged the potential advantages of conversion to be sufficiently attractive to them. There is no benefits case for converting individual transmission lines in the UK Grid to HVDC to gain additional transmission capacity or for reasons other than to gain additional transmission capacity (e.g. to implement a multi-terminal scheme) since:

- Conversion to HVDC will, at the very least, entail the replacement of all of the insulators on the line. This conversion would be expensive and would involve taking the line out of service for a considerable time, which may be operationally unacceptable in practice.

- The existing Grid would be unable to cope with the loss of the enhanced capacity transmission line (without the need for additional capacity enhancements in adjacent circuits and the possible need to implement associated special protection schemes). The extent of such required capacity enhancements to adjacent circuits, and the scale of associated costs and system disruption etc during the implementation of the enhancements cannot be addressed generically at this stage since they would be very dependent on the particular transmission line involved. It may be that in the future, enhancements to the ratings of some circuits in the network may happen for other reasons and this may then open up the prospect that lines in the vicinity of these uprated circuits could benefit from conversion to HVDC. The implementation of the Special Protection Schemes will generate increased operation complexity for the transmission system involving the use of remote data collection and selective inter-trips. Reliance on automation using multi-source remote data collection is not welcome practice for transmission operators.

- The ratings of the HVDC circuits that would be required to achieve an improvement on the theoretical thermal transmission capacity of an existing double circuit 400 kV UK HVAC link (approximately 8GW) would depend upon the way in which the replacement was engineered. Assuming that the two equally rated HVAC circuits were replaced by three equally rated HVDC ones (each arrangement thereby making use of the 6 conductors), then the HVDC circuits would each require to be rated at 2.7GW at least. Such a rating is well within the capability of bi-polar LCC converters. With the presently anticipated capability of VSC technology, a practical VSC HVDC scheme could be achieved by the use of three VSC blocks in parallel per converter.

- The converted line does not offer any benefits to the system that cannot be gained by other means, such as the application of FACTS devices.

It should be noted that the above conclusions are in respect of the conversion of an existing AC line to DC. The conclusions do not detract from the potential system benefits which could be derived from the addition of new DC lines in parallel with the existing AC lines. In such circumstances the capacity of the adjacent AC lines would be fully taken into account in the engineering design of the new DC line.

In some circumstances, HVAC to HVDC conversion provides benefits such as enabling long distance power transmission, eliminating reactive power flows from long HVAC cable circuits and enabling asynchronous system connections. However, in view of the short transmission distances involved in the UK these would not be of benefit to the onshore UK transmission system.

Additionally, there may be a business case for the conversion of multiple parallel lines to increase capacity of the system (rather than of an individual line), despite the expense involved, in circumstances where it is not possible to build new lines due to unavailability of way-leaves or where there are no commercially viable alternatives.

HVDC Cables

In general there is a considerable body of experience with the operation of large HVDC transmission schemes using DC cables and so there are no issues associated with HVDC cables that would affect the feasibility of installing multi-terminal schemes in the UK Grid.

General System Interaction Issues

FACTS and HVDC would both introduce local technical issues such as harmonics and control interactions. These are well proven and understood and consequently are not insurmountable and would require specific installation detail design to engineer them out at the design stage. No additional power quality issues are expected to arise from multi-terminal schemes that would affect the feasibility of installing them in the UK Grid.

Social and Environmental Impacts

If FACTS or HVDC were to be implemented on the UK transmission system the significant potential environmental impacts would be the footprint at the substations and the visual impact of the FACTS device installations. In addition conversion of transmission lines to HVDC would have additional environmental impacts associated with the materials, equipment and work needed to change the insulators. The environmental impacts associated with the conversion of an existing line will be considerably less than those associated with the installation of a completely new transmission line, and this should make gaining consent for such conversions commensurately easier.

FACTS and HVDC technologies are not direct sources of CO_2 and their implementation on the UK Grid will have no direct impact on CO_2 reduction. Where such implementation increases the capacity of the grid to carry additional power flows then an indirect affect will be to facilitate the connection of additional generation capacity. This additional capacity could be provided by renewable sources.

Implementation of any of the candidate technologies on the transmission system is unlikely to result in any significant socio-economic impacts. Employment opportunities will be created during the construction phase but these positions will only be short term and no permanent employment will be created. Some minor economic benefits would be felt by the local communities due to spending in the area by construction personnel.

Active Network Management

The potential impacts of Active Network Management technologies on distribution networks has been assessed from the consideration of network planning and operation, likely distributed generation (DG) and network constraints, principally thermal capacity, fault levels and voltage limits. Existing generation connection practice has been reviewed and the potential connection capacity at each of the main distribution voltage levels: 132 kV, 33 kV, 11 kV and low voltage (LV) quantified

The primary limits on the connection of more generation to distribution networks are thermal, fault level and voltage. The balance of limits will vary by location but an assessment of average characteristics indicates that thermal limits or fault level will often place a greater restriction on Distributed Generation (DG) connection than voltage. The restrictiveness of different limits changes with fault level and this emphasises the importance of fault levels in determining the potential generator capacity in any particular circumstance. The inverse relationship between fault level and voltage limits is an important feature of the sensitivity analyses illustrating the conflict around the "strength" of the network. While most of the technologies offer some improvement in thermal limits, power flow management is necessary to overcome limits based on minimum demand.

Effective reactive power control is important, in that it has the potential in some circumstances to overcome all voltage limits. However, despite the flexibility and scope of reactive power control, thermal and fault level limits will remain.

A measure of the maximum DG capacity that could be accommodated under typical connection points at different voltages has been produced:

- Based on conventional thermal limits and worst-case planning assumptions, a typical Secondary/Distribution Substation at LV has an estimated DG limit of 0.01 MW. Depending on the circumstances, active power flow management technologies might typically increase that limit to around 1 MW, where fault level limits are reached.
- Based on conventional thermal limits and worst-case planning assumptions, a typical Primary Substation at 11 kV has an estimated DG limit of 1 MW. Depending on the circumstances, active power flow management technologies might typically increase that limit to around 18 MW, where fault level limits are reached.
- Based on conventional thermal limits and worst-case planning assumptions, a typical Bulk Supply Point (BSP) at 33 kV has an estimated DG limit of 5 MW. Depending on the circumstances, active power flow management technologies might typically increase that limit to around 70 MW, where fault level limits are reached.
- Based on conventional thermal limits and worst-case planning assumptions, a typical Grid Supply Point (GSP) at 132 kV has an estimated DG limit of 80 MW, which is equivalent to 16 GW nationally. Depending on the circumstances, changes in operating philosophy to allow reverse power flow and the

application of active power flow management technologies might typically increase that limit to around 296 MW, where fault level limits are reached, which is equivalent to 59 GW nationally. If fault level limits can be overcome then by applying active power flow management technologies some 132 kV networks may be able to accommodate much more DG, although their utilisation factor may be severely limited. Total DG capacity could match the existing capacity of transmission-connected generation.

Power electronic converters are the most comprehensive of the available technologies as they can help to address all limits on DG capacity, including fault level. This is made possible by full four-quadrant control of real and reactive power flows and the decoupling of electrical and mechanical systems or of two AC systems that is achieved with a power electronic converter.

Series compensation and phase shifting transformers may offer solutions in specific circumstances on distribution networks but are not expected to be widely deployed. The topology of distribution networks means that these technologies are likely to be used only at the higher voltages, where the network effectively acts as sub-transmission (132 kV in England and Wales). As such, the advantages and disadvantages of these technologies will be similar to those identified for their use on the transmission network.

DNOs will face a range of challenges in adopting the new technologies, which are likely to be used only if there is a very definite business case for them compared with conventional solutions.

Opportunities

Any research, development or possible investment opportunities that have been identified during the conduct of the study have been identified. These are listed in Section 11.

In general there are more potential opportunities associated with distribution technologies since there are many more such networks, with smaller power requirements, reduced scheme costs and fewer associated technical and commercial risks when compared with transmission scheme options.

1. Introduction

1.1 Background

The ETI is an innovative and unique Limited Liability Partnership between the UK Government and international industrial companies each with a strong focus on energy. The ETI partners work together, sharing expertise and resources to speed up the development and demonstration of energy technologies and shorten the lead times to market. The ETI delivers its Technology Strategy through a portfolio of programmes. These aim to make a major impact on the supply and demand for low carbon energy in the UK, create global business opportunities for its Members, Programme Associates and Project participants, and increase the UK skills base and industrial capacity.

Under its "Energy Storage and Distribution Programme" the ETI has identified the need for important engineering studies to assess innovative approaches and technology solutions that could lead either:

- to the enhancement of the capacity of the existing onshore UK electricity transmission and distribution networks, or
- to the expansion of these networks by means other than the construction of new overhead line infrastructure,

and thereby enable the installation of substantially more renewable energy systems in the UK than the current T&D system can accommodate. Mott MacDonald has been commissioned by the ETI to carry out the "Network Capacity Project" covered by this report.

The Network Capacity Project is aimed at supporting the ETI's overall goal of accelerating the deployment of technologies that will help the UK reduce its greenhouse gas emissions. Specifically the project has assessed the feasibility of two potential areas of development to improve the operation and increase the capacity of the UK onshore T&D systems.

- The first area of the project has focussed on the feasibility of applying new and existing power electronic technologies to provide enhanced management of network power flows in order to release more capacity within the T&D system.
- The second area has concentrated on the technical feasibility of multi-terminal HVDC in the context of operation within the existing UK T&D system.

The work associated with both areas comprises an assessment of the credible options from these technologies in the context of power flow management including the benefits and also associated impediments to their development and deployment, and provides guidance in respect of technology development opportunities. The work has been structured into two packages;

- Work Package 1 concentrates on the novel technologies with the potential to release capacity in the UK T&D networks. The work in this package comprises a literature review and modelling of the various technologies integrated into the networks to determine their effectiveness and requirements for such integration. It also includes an analysis of environmental and social impacts, and of the barriers to development and deployment.
- Work Package 2 concentrates on the use of multi-terminal HVDC transmission and its integration within the existing UK T&D networks. The work in this package comprises a feasibility assessment and

detailed modelling of multi-terminal HVDC to assess its performance, impact and potential interactions arising from its use. It also includes analysis of the requirements for such integration, the benefits case for conversion of existing AC lines, and of the barriers to development and deployment.

1.2 Work Package Details

The two work packages discussed above have been broken down into a number of tasks as follows.

1.2.1 Work Package 1

Work Package 1 (WP1) consisted of eight separate tasks and the work carried out has been reported on separately as detailed in the references below;

- WP1 Task1 - Power Electronic Technologies [1]
- WP1 Task2 - Impact of Active Power Flow Management Solutions [2]
- WP1 Task3 - Transmission System & Integration Studies [3]
- WP1 Task4 - Barriers to Development [4]
- WP1 Task5 - Environmental and Social Impacts [4
- WP1 Task6 - Technology Options, Benefits & Barriers Workshop [5]
- WP1 Task7 - Multi-Criteria Assessment of Technologies [5]
- WP1 Task8 - Final Report for Work Package 1 (See Note)

Note: This report is the final report for WP1. However, as agreed with the ETI, it is presented as a final report for the whole project and so replaces the need for the Work Package 2 Task 5 report listed in the following section.

1.2.2 Work Package 2

Work Package 2 (WP2) consisted of five separate tasks and the work carried out has been reported on separately as detailed in the references below;

- WP2 Task1 - Onshore Multi-Terminal HVDC In UK [6]
- WP2 Task2 - MT-HVDC Integrated Into Existing Network [7]
- WP2 Task3 - Impact of MT-HVDC Onshore [7]
- WP2 Task4 - Technical & Non-technical Barriers [8]
- WP2 Task5 - Final Report for Work Package 2 (See Note).

Note: As discussed in the previous section, this report is the final report for the whole project and so replaces the need for the Work Package 2 Task 5 report.

1.2.3 System Model Validation Task

The work carried out under WP1 Task 3 & WP2 Task 2 involved investigations of the performance of the various technologies when integrated into the UK Grid networks. The purpose of the investigations was to determine the effectiveness of the technologies and the requirements for their integration into the grid. The investigations for these two tasks were carried out using a common, validated model of the UK grid built using the PSS/E modelling software. In view of this, the work on the development and validation of the model used for the studies was reported separately in [9] rather than as part of either or both of the relevant work package reports. Section 7.1.2 gives an overview of the model validation exercise. The PSS/E models used in the studies together with supporting documentation were provided to the ETI under Reference 10.

1.3 Study Constraints

In accordance with the defined scope of work any changes to the UK grid that involve the introduction of additional nodes or links in the network have been excluded from the studies.

With the exception of the WP1 Task1 technology review, the studies have focused on technologies required for the near-medium term reinforcements of the transmission system (assumed to be up to around 2020). Within this time frame, generation and load characteristics may be confidently defined and the established transmission system models remain valid. Beyond this period, the characteristics of the electricity supply network become significantly more uncertain because of the potentially very significant changes that the network must undergo in order to help meet energy demand and 2050 climate change targets. Any such changes would be so large compared to the incremental changes contemplated in these studies as to render any conclusions reached to be meaningless.

1.4 UK Transmission and Distribution Systems

Note that in Great Britain the transmission network includes all 400 kV and 275 kV circuits and all 132 kV circuits in Scotland. All lower voltage circuits are part of distribution networks although they can share some characteristics with the transmission network. For example, in many parts of England and Wales the distribution network operators will run their 132 kV circuits as a sub-transmission network, which can be heavily interconnected and transfer large amounts of power, in a similar manner to the transmission network operated by National Grid.

1.5 Report Overview

As explained above, separate reports have been submitted for the various tasks. These individual task reports contain full details of the work carried out and the findings reached in the area concerned. It was agreed with the ETI that this final report for the project should avoid unnecessary duplication of the contents of the individual task reports. The final report is to provide a clearly presented high level analysis of all of the work carried out and reported in detail in the individual task reports. This will enable the ETI to make informed decisions as to where future work in the programme should be directed. In order to achieve this, the remainder of the document is structured as follows;

- Section 2 gives a high-level *technology overview* of the technologies covered by the study. This section has been included in order to make this report readable in its own right without reference to the separate task reports.

- Sections 3 to 9 cover the following topics. For each one a brief summary of the work carried out is provided and the findings from the work are given;

  - Section 3 covers the review of the *power electronic devices* that underpin many of the technologies discussed in Sections 4, 5 and 6 and in particular relates to the work covered by the WP1 Task 1 report;
  - Section 4 covers the detailed review of the *FACTS technologies* that have been addressed by the study and in particular relates to the work covered by the WP1 Task 1 report;

- Section 5 covers the detailed review of the *Active Network Management technologies* that have been addressed by the study and in particular relates to the work covered by the WP1 Task 2 report;
- Section 6 covers the detailed review of the *HVDC transmission schemes and technologies* that have been addressed by the study and in particular relates to the work covered by the WP1 Task 1, WP2 Task 1 and WP2 Task 3 reports;
- Section 7 covers the assessment of the *performance* of the FACTS and HVDC technologies when applied in selected locations in the UK Grid and in particular relates to the work covered by the WP1 Task 3 and WP2 Task 2 reports;
- Section 8 covers the *social and environmental impacts* that would result from the application of the technologies to the UK Grid and in particular relates to the work covered by the WP1 Task 5, WP2 Task 1 and WP2 Task 3 reports;
- Section 9 covers the *technical and non-technical barriers* that could prevent or limit the deployment of the technologies in the UK Grid and in particular relates to the work covered by the WP1 Task 4, WP1 Task 6 and WP2 Task 4 reports;

- Section 10 discusses the Multi-Criteria Technology Assessment carried out on the technologies covered by this study and in particular relates to the work covered by the WP1 Task 7 report, and finally;
- Section 11 covers the Opportunities that have been identified by the work. As agreed with the ETI no attempt has been made to judge whether or not particular opportunities may be of interest to the ETI. This judgement has been left for the ETI to make.

In view of the fact that this final report summarises the findings of the task reports, a separate conclusions or recommendations section has not been included. High level findings are given in the Executive Summary.

1.6 Study Team

Mott MacDonald's project team for the work was comprised of the University of Strathclyde, the Manitoba HVDC Research Centre, TransGrid Solutions Inc. and Smarter Grid Solutions. The team blends academic research knowledge, world-wide consultancy in power transmission and distribution engineering, strong project management, innovation and world class capability in modelling and analysis of conventional and multi-terminal HVDC and HVAC systems.

1.6.1 Mott MacDonald

Mott MacDonald is a world-class independent international organisation, with 14,000 staff actively working in over 140 countries in all sectors from transport, energy, buildings, water and the environment to health and education, industry and communications. The Transmission and Distribution Division provides a total service for electrical power, transmission and system development including overhead lines, distribution systems, cables, switchgear, transformers, protective relaying, substation control systems and other substation plant. Transmission experience particularly covers HVDC converter stations and associated overhead lines, underground and submarine cables. Mott MacDonald also has a strong power system analysis team who provide all types of modelling of power systems. Experience covers generation, transmission and distribution, industry and all aspects of electrical system analysis and modelling using industry standard and bespoke study tools.

1.6.2 University of Strathclyde

The Power Electronics and Energy Conversion Group has substantial expertise in the field of high voltage/power converter topologies this includes detailed modelling of power converters supported by scaled experimental evaluation. Work has included research into H.V series connection of power semiconductors and a broad range of multi-level converters of the type proposed for advanced FACTs devices and voltage source HVDC.

The Institute for Energy and Environment is the largest group in Europe concerned with electrical power systems, distributed generation and renewables. Comprising of 26 academic staff members, 70 full-time researchers and 130 research students, the Institute has a core expertise covering: power systems; high voltage technologies; wind energy and technology; power systems modelling, simulation and analysis; renewable energy; power electronics, drives and converters; protection and control; and, monitoring and diagnostics.

1.6.3 The Manitoba HVDC Research Centre

The Manitoba HVDC Research Centre, Winnipeg, Canada is a world leader in the technology of electric power system simulation, applied power systems analysis, and related technologies since 1981. The Centre develops and markets an array of products and services worldwide including the renowned power system simulation software PSCAD-EMTDC. PSCAD, commercially available since 1993, embodies years of continuous research and development from 1988 to the present. The Centre has a highly experienced team of power systems and simulation specialists.

1.6.4 TransGrid Solutions

TransGrid Solutions Inc. Winnipeg, Canada is an internationally recognised expert in the area of Power System Services, specialising in Wind Integration, HVDC and FACTS and system planning studies with successful projects spanning the globe. Core services consist of power system simulation including loadflow and transient stability, electromagnetic transients, real time simulation studies including independent control and protection hardware verification, optimization and electricity market analysis, power electronics and their application to ac/dc systems, HVDC and FACTS, and design, development and testing of controls and protections.

1.6.5 Smarter Grid Solutions Ltd

Smarter Grid Solutions Ltd (SGS) delivers new network solutions to help generators connect to the grid and network operators meet connection obligations more quickly and cheaply. This is achieved by providing a range of products, services and consultancy offerings aimed at resolving grid constraints innovatively and cost effectively.

1.7 Acknowledgements

The Electricity Network Investment team of National Grid Electricity Transmission (NGET) are the power system analysis specialist unit employed for planning applications. They have access to an up-to-date dynamic model of the UK transmission system that is based on actual data provided by UK generation owners. The results obtained from the Mott MacDonald model used in the work reported here were submitted for independent assessment by NGET and a statement was issued by NGET confirming the

fitness of the Mott MacDonald model for the purpose for the scope of this project. This contribution from NGET is acknowledged with thanks.

2. Technologies Overview

2.1 Introduction

The purpose of this section is to give a high-level overview of the technologies covered by the study in order to make this report readable in its own right without reference to the separate individual task reports.

2.2 Power Electronic Devices

Power electronics switching devices may be categorised into two principal families, namely;

- Line-commutated devices in which the device can be switched on by a control signal but which can only be switched off by reducing the current through the device to zero;
- Self-commutated devices in which the device can be switched on and off at will by a control signal.

Thyristors are line-commutated devices. They have high power handing capability with low losses and robust overload capability, and have relatively long response times (several power cycles), corresponding to the limits of line frequency switching and the inherent time constant of controlled reactive components. Line frequency switching imposes a requirement for filters and damping networks to eliminate harmonics at low order multiples of the power frequency. The response of such systems allows for compensation of slow transients but lacks the bandwidth necessary for compensation of slow higher frequency disturbances. For line commutated technology a strong AC grid is required.

Self-commutating FACTS act as controlled sources that are capable of injecting voltage or current at the point of common coupling. This provides better decoupling between the compensation function and network conditions. Such FACTS devices employ devices capable of switching at high multiples of the power frequency (typically in the range of 1 to 2 kHz). This eliminates the low order harmonics associated with line-commutated systems. If required the increased bandwidth may be used to achieve active management of harmonics and transients at frequencies above the power frequency (Active Power Filters, APF). Self-commutating FACTS operate as controlled sources that may inject a parallel current (STATCOM) or a series voltage (Dynamic voltage restorers DVR). Combined series and parallel compensation may also be achieved through the integration of parallel and series devices (Unified Power Flow Controller, UPF).

Two device families are extensively used in transmission and distribution applications and these are both based on silicon technology.

- Thyristors. These may turn-on under control but rely on the action of the ac network to turn-off. Such circuits are termed line commutated and are restricted to operation at the frequency of the ac network.
- Insulated Gate Bipolar Transistors (IGBTs). These devices may be controlled to turn-off and turn-on. This allows the use of high frequency (1 to 2 kHz) pulse width modulation to synthesise the voltage or current that is to be applied to the network.

In the long term, new wide band-gap materials such as silicon carbide and gallium nitride have the potential to deliver increased voltage ratings, reduce switching losses, and raise operating temperatures. Although low voltage SiC devices are available, advances are still required in order to achieve the high-voltage, high-power modules necessary for transmission applications.

2.3 Flexible AC Transmission Systems (FACTS)

In a traditional AC power distribution system such as the UK Grid, the power flows and voltages throughout the system depend on the generators and loads connected and on the impedance characteristics of the network interconnections. For any given mix of generation and loads the power flows along any given network link and the voltages at any node are automatically self-determining through the interaction of the individual generator scheduled power, the load and the network impedance characteristics. This behaviour of AC networks is a very powerful advantage since it means that they are to a great extent autonomous, and can automatically self adjust to changing conditions (changes in generation, changes in loads, loss of network links etc) without the need for an overarching intelligence or central control regime. However, the resulting power flows and voltages are not necessarily optimal and so "compensation" may be necessary. Historically this compensation has generally been in the form of passive capacitors or reactors that counteract the natural reactance or capacitance of the network respectively.

Conventional fixed shunts are widely deployed at all voltage levels and are basically capacitors or inductors connected in parallel with the network. Shunt reactors help to reduce voltage by absorbing reactive power. Shunt capacitors help to raise voltage by injecting reactive power. Fixed shunts often provide a cost effective way to correct voltage.

Flexible AC transmission (FACTS) is the name applied to a range of power electronic systems deployed to manage power flow in electrical networks. FACTS have the ability to continuously vary their operating point in response to changing system conditions, and may be used to allow the network infrastructure to be operated closer to its thermal limits by compensating for voltage rise, reactive power, and line reactance. FACTS devices may achieve fast response times making them resistant to stability problems that can be associated with fixed passive compensation. With appropriate control; FACTS devices may be used to damp system oscillations, improving network stability margins and allowing increased utilisation of the transmission infrastructure.

FACTS technology may be split into two principal families, namely shunt devices in which the FACTS is applied at a network node in shunt (parallel) with the system, or series devices in which the FACTS is applied between nodes in line with the network connection between those nodes. FACTS devices can be implemented using line commutated or self-commutated technologies.

Shunt compensation involves connecting a capacitance or inductance in parallel with the network to inject or absorb reactive power. This means reactive power requirements can be addressed locally or flows of reactive power on the network can be controlled, which is an effective way of managing voltage. Fixed shunt compensation has been in use for a long time but more advanced and controllable technologies are now available using power electronic converters.

The family of shunt FACTS devices comprises;

- Static VAR Compensators, SVC: these are parallel connected power electronic devices that can be used to generate or absorb reactive power. This is done using thyristor controlled reactors and capacitors with LCC type power electronics. SVCs are able to adjust their reactive current very quickly (within 100 ms) in response to system voltage changes. They are used when it is necessary to cope with minute-to-minute changes in reactive requirement, and also rapid changes due, for example, to faults on the system.

- STATCOM; A STATic Synchronous COMpensator (STATCOM) is a power electronic device that can be used to inject or absorb reactive power from the AC grid. The operating principle of the STATCOM is based on that of a Voltage Source Converter (VSC) and it can be used as a variable source of reactive power. The capacitive or inductive output current is controlled independently of the AC system voltage.

Series compensation involves connecting a capacitance or inductance in series with the network to modify the impedance of a line. This normally means a series capacitor is inserted to reduce the effective reactance of long overhead lines, which can be used to improve power flow and system stability. New power electronic technologies allow series compensation to be controlled more closely and actively. Series compensation has been deployed widely in other countries but has not been used before in the UK.

The family of series FACTS devices comprises;

- Static VAR Compensators, SVC
- Dynamic Voltage Restorer (DVR)
- Thyristor Switched Series Capacitor (TSSC)
- Thyristor Controlled Series Capacitor (TCSC)
- Quadrature phase shift transformer

FACTS systems are generally based around Pulse Width Modulated (PWM) voltage source converter (VSC) technology, similar to that employed in low and medium voltage variable speed drives. However, since FACTS do not contribute real power to the network, no external power source is required.

2.4 HVDC

High Voltage Direct Current (HVDC) transmission refers to schemes in which an HVDC source is produced by an AC to HVDC converter station, power is transmitted at the HVDC voltage and then it is converted to AC at the receiving end by a second HVDC converter station. It can be used to connect asynchronous AC systems and for the transfer of bulk power over long distances with lower losses than the traditional AC solution. There are three principal technology options for HVDC and these use similar converter technologies to those used in the FACTS devices discussed above. These three options are discussed below.

2.4.1 Line Commutated Converter

A Line Commutated Converter (LCC) uses thyristors and commutation is driven by the AC system voltage. LCC technology is well understood and has been in use for many decades. LCC can be used to control active power flow by adjusting the firing angle of the thyristors. LCC is a proven technology with many installations in operation throughout the world and is available from a number of manufacturers including ABB, Areva and Siemens.

2.4.2 Capacitor Commutated Converter

A Capacitor Commutated Converter (CCC) also uses thyristors and can be used as an alternative to the traditional LCC in HVDC installations. The difference is that a CCC has capacitors between the valve bridge and the converter transformer. Adding these capacitors gives a voltage contribution to the valves and allows the use of smaller firing angles for the thyristors. This reduces the reactive power requirements of the converter eliminating the need for switched shunt capacitor banks on the ac side. This reduction in reactive power also reduces the required MVA rating of the converter transformer.

2.4.3 Voltage Source Converter

A Voltage Source Converter (VSC) uses bi-directional rectifiers/inverters to convert between AC and DC for HVDC transmission. VSC is an alternative to the traditional LCC and alternative CCC current source HVDC and offers more flexibility through the use of Insulated Gate Bipolar Transistors (IGBTs), which are more controllable than the thyristors used in both LCC and CCC.

The benefits of VSC technology include:

- Can control active and reactive power flow
- Can change its power direction without having to swap pole voltages
- Can connect to weak grids
- Smaller footprint and weight when compared to traditional HVDC.

2.4.4 HVDC Scheme Topologies

There are three principal topologies for HVDC schemes;

- Point to point, in which one converter/inverter station is located at one node in the network and another station is located at another node located some distance apart, with the two stations connected by a HVDC transmission line;
- Back to back, in which both inverters/converters stations are located at the same geographical location with the transmission line length between them being essentially zero;
- Multi-terminal, in which there are more than two inverter/converter stations located at different nodes in the network some distance apart with each station having one connection to the HVDC transmission network that connects the stations together.

2.5 Active Power Flow Management

The idea of an active distribution network is one that has emerged over the last two decades, driven by the expansion in distributed generation, distribution automation and supporting technologies. CIGRE working group C6.11 has arrived at the following definition:

> “Active networks are distribution networks with Distributed Energy Resources (DERs) (generators and storage) and flexible loads subject to control. DERs and participating loads take some degree of responsibility for system support, which will depend on a suitable regulatory environment and connection agreements. The Distribution System Operator (DSO) may also have the possibility to manage electricity flows using a flexible network topology.”

The following concepts apply in the area of active distribution networks.

2.5.1 Power flow management

Power flow management is concerned with addressing thermal limits in the connection of additional generation. Less refined approaches involve tripping associated generators when the network reaches certain operating conditions. This might involve a direct inter-trip of generation when a line or transformer goes out of service. Alternatively, power flows might be measured and generation tripped when flows exceed an acceptable level.

More refined approaches will control the power output of generation based on power flow measurements. This is a more attractive solution to the operators of generation plant but requires real-time monitoring and control. Generation is given time to reduce power output in a controlled manner; short term thermal limits can be exploited for a sudden change in power flows that might result from an outage on the system.

2.5.2 Dynamic Thermal Ratings

Dynamic thermal ratings covers a group of technologies and methods aimed at monitoring conditions on the network and calculating component ratings in real time. The conventional approach is to calculate component ratings based on conservative assumptions, particularly for environmental conditions.

Real time power system component temperature is measured directly or estimated through the measurement of indirect parameters such as electric resistance or weather conditions. The software used for managing the system can also take into account each component's thermal behaviour, introducing additional flexibility, especially for electric cables and power transformers.

Dynamic ratings allow improvements in asset utilisation, expanding the power flow transfer capacity according to real environmental conditions and component thermal state. This can allow additional generation capacity to connect without having to reinforce or replace the existing network.

2.5.3 Voltage Management

Upgrading the operating voltage of existing circuits is a conventional solution for improving network capacity. However, there are a number of ways in which the management of voltages can be improved, retaining the same nominal value, to facilitate additional generator connections. The methods differ in the way voltages are measured and the way control actions are determined. Different methods employ different types of calculation or logic, with network operators preferring those methods that are simple, easy to understand and robust to all possible conditions.

The maximum and minimum acceptable voltage or step change in voltage on a distribution network can be a limiting factor on the capacity of generation. Improving voltage management to increase the voltage headroom available to new generators will allow additional capacity to be connected.

2.5.4 Demand Side Management

Demand Side Management (DSM) involves altering or influencing the demand for electricity to achieve a particular objective. That objective might be to shift demand to other times, either to flatten the overall demand profile, make demand coincident with variable supply, or otherwise minimise costs associated with variations in supply and demand. Demand might also be modified to satisfy network constraints such as power flows and voltages. Different types of loads will be better suited to helping to achieve different system management objectives.

Reducing congestion on lines and transformers by levelling loads would facilitate the connection of new loads and generators to the network. This would also reduce voltage problems. DSM is already used in frequency control to some extent (large industrial consumers providing extra reserve, not a fast acting response) and controlling load in correspondence to available renewable energy could contribute to maximising renewable energy contribution.

2.5.5 Special Protection Schemes

Special Protection Schemes (SPSs) are emerging that facilitate the connection and operation of increased amounts of generation. An example of an SPS is an inter-tripping arrangement, ensuring that a single event somewhere on the system will result in the immediate disconnection of a generator. This can add an incremental amount of generator capacity to the network.

2.5.6 Phase shifting transformers

Phase shifting transformers, and the related technology of quadrature boosters, are used to alter the local angle of the network voltage and thereby modify power flows where there are multiple paths on the network. This effectively forces power down one route rather than another and this can be done to make best use of all the available capacity.

The technology is tested and reliable and is on the market from a number of manufacturers. Phase shifting transformers are usually customised because of their large size and their use in the transmission network. They are often used at cross borders connection points. Development work continues on how to co-ordinate their use to maximise network capacity without compromising resilience to disturbances.

There are already twenty quadrature boosters installed on the GB transmission network with more installations planned.

3. Power Electronic Devices

3.1 Summary of Work Carried Out

The work covered by this section was carried out under WP1 Task1 and is reported in detail in Reference 1. This work comprised a literature review of the current state of the art relating to power electronics for transmission and distribution systems.

3.2 Findings

Although there are a wide range of power semiconductor technologies, only two device families are extensively used in transmission and distribution applications and both are based on silicon technology.

- Thyristors. These may turn-on under control but rely on the action of the ac network to turn-off. Such circuits are termed line commutated and are restricted to operation at the frequency of the ac network. Thyristor based systems have a long track record in transmission/distribution applications.

- Insulated Gate Bipolar Transistors (IGBTs). These devices may be controlled to turn-off and turn-on. This allows the use of high frequency (1 to 2 kHz) pulse width modulation to synthesise the voltage or current that is to be applied to the network.

At present the voltage ratings of silicon thyristor and IGBT devices are limited to 8.5 kV and 6.5 kV, respectively; there is little scope for significant increase in these figures. For transmission applications, series connection of devices is required in order to achieve the necessary operating voltage.

New wide band-gap materials such as silicon carbide and gallium nitride have the potential to deliver increased voltage ratings, reduce switching losses, and raise operating temperatures. Although low voltage SiC devices are available, advances are still required in order to achieve the high-voltage, high-power modules necessary for transmission applications. The key benefits that may be achieved are:

- Increased voltage rating leading to decreased device count and possible reliability gains

- Decreased system conduction loss due to reduced numbers of series devices and possible reduction in device on-state voltage. (The realisation of reduced on-state voltage per unit of voltage capability remains to be proven.)

- Increased switching speed may give advantages in terms of reduced switching loss. However the benefits of this for transmission may be marginal since significant increases in dv/dt may prove problematic at these voltage levels. Advances in circuit design have decreased the importance of switching loss in voltage source inverters.

4. Flexible AC Transmission Systems (FACTS) Devices

4.1 Summary of Work Carried Out

The work covered by this section was carried out principally under WP1 Task1 and is reported in detail in Reference 1. This work comprised a literature review of the current state of the art relating to power electronics for transmission and distribution systems and an accompanying discussion of the findings of the review and their relevance to the present study. In particular the discussion covered a comparison of LCC and VSC technologies and the different approaches to designing for scheme operation at power levels and voltages significantly above that which may be sustained by a single power switching device. Additional material relating to practical experience with the technologies was covered under WP1 Task 4 and is reported in detail in Reference 4.

4.2 Findings

4.2.1 Line Commutated Thyristor Systems

The basic steady state operation required of FACTS schemes may be achieved through the use of line commutated thyristor based systems and these have the following advantages:

- Thyristor devices give low losses and are available in robust high-current capacity single-wafer capsules.
- Line commutated FACTS have an established track record at transmission voltage and power levels.
- Thyristor devices tend to fail to a short-circuit condition.
- Thyristor devices have relatively high current overload capability.

There are however limits on the performance/functionality that may be achieved:

- Line commutated systems inject significant low order harmonics which must be eliminated by large (physically and electrically) passive filter arrangements. The presence of these filters may lead to circulating harmonic currents that must be mitigated by damping networks. Filters and damping networks may have to be designed specifically for each location and may not be optimal for all operating conditions. The large passive components that are required lead to systems with large footprints.
- Line commutated systems are inherently limited in their response time (limited to line frequency switching) which limits their control ability.

4.2.2 Voltage Source Converter (VSC) Systems

Voltage Source Converter (VSC) systems are based around self-commutating devices (typically IGBT technology). The use of these devices allows the application of high frequency (>1 kHz) pulse width modulation techniques, which are common in the industrial drives sector, to the control of transmission (and distribution) level power flows. By the use of PWM, the Voltage Source converter may synthesise a fully controlled voltage at its output. This voltage appears as a power frequency fundamental with harmonics at the switching frequency. With appropriate feedback, the voltage source inverter may be controlled to act as a current source.

The principal advantages of VSC technology for FACTS devices are:

- The injection of low order harmonics is reduced, leading to smaller filters, passive energy storage components and damping networks, which all lead to reduced installation size.
- Systems can achieve better levels of control.
- Faster response allows IGBT based converters to attenuate network distortion and transients.

The principal disadvantages of VSC technology for FACTS devices are:

- The IGBT converters used in voltage source FACTS are still in an early state of development with relatively limited operation experience.
- The technology is more complex that LCC technology.
- Improved control is achieved at the expense of increased losses in the power converter as a result of:
  - The move to high frequency switching leads to increased switching loss.
  - IGBT devices exhibit significantly higher on-state voltage drop compared to thyristors with similar voltage ratings. For a given application, this will lead to increased conduction loss.
- IGBT modules have lower power capability than available thyristor packages, leading to increased power component count.
- IGBTs tend to fail to an open-circuit condition.
- IGBT devices have lower current overload capability than thyristor based systems.
- High dv/dt transitions may be present at the output.

4.2.3 Operation at High Voltages

In general, power electronic systems for power transmission are required to operate at power levels and voltages significantly above that which may be sustained by a single power device. This presents challenges not faced in other applications.

In LCC systems this is achieved by series connection of devices, with static and dynamic voltage sharing necessary to ensure that voltage stresses remain compatible with device ratings. Series connection of devices in voltage source converters is more challenging due to the increased operating frequency and switching speed that is required. Recent advances have seen the use of multi-level converters to address the technical limitations of series connected devices in voltage source converters.

Multi-level converters allow the synthesis of an output voltage that is comprised of a number of discrete steps, each of which is within the voltage rating of an individual power semiconductor device. This technique extends the achievable operating voltage, results in significant improvements in waveform quality, reduced filter size, and decreased losses. Intermediate voltage levels are provided by capacitors in a similar manner to the DC link capacitor in a conventional two level inverter. However these capacitors require charge balancing and must be sized according to the principal fundamental current (unlike a conventional two level inverter, where the capacitance experiences only switching frequency and unbalance components). Power circuits and control of multi-level converters are significantly more complex than those of two-level systems.

Since FACTS devices do not contribute to the principal power flow there is the option to use transformers to provide an interface between the network voltage and the voltage ratings of power semiconductors. This allows the use of conventional two-level VSI technology. Raising the operating voltage of self-commutating FACTS has benefits in terms of increased VA capability and direct transformer-less connection.

4.2.4 Summary of FACTS Devices used in Modelling Studies

The review identified numerous types of FACTS devices based on variants of the basic technologies outlined above, with different levels of technology readiness. The principal features and characteristics of all of these FACTS devices are detailed in Reference 1. It was decided to select the following examples for the purposes of the modelling of the performance of FACTS devices when integrated into the UK grid discussed in Section 7;

- Static VAr Compensators (SVCs)
- STATic COMpensators (STATCOMs)
- Thyristor Controlled Series Capacitors (TCSCs)

The selection was based on having examples from the shunt and series families of devices and choosing devices with a realistic prospect of being applied in the timescales and at the ratings required by this project. The principal features and characteristics of the above FACTS devices are summarised in Table 4-1 and the devices are discussed in the following sections.

4.2.4.1 Static VAr Compensators (SVCs)

SVCs have been available since the 1970s and have been successfully applied on the UK transmission system for over 20 years providing an output range of up to 225 MVAr per unit. They can be considered as conventional technology that has been proven practically.

4.2.4.2 STATic COMpensators (STATCOMs)

STATCOMs have been applied commercially for over 20 years, although the scaling up to transmission power levels has only been achieved relatively recently. It is therefore a less mature technology than that applied in SVCs.

Modern day STATCOMs have two basic designs, neither of which has yet gained market domination. One uses pulse width modulation and the other uses a multi level switching approach to produce the intended voltage. The pulse width modulation design is used by ABB in their “SVC Light” device while Siemens use the multi level design and call their device “SVC Plus”. Areva (soon to be Alstom) are developing a multi level device.

4.2.4.3 Thyristor Controlled Series Capacitors (TCSCs)

Thyristor Controlled Series Capacitors (TCSCs) have been applied commercially for 20 years, although the number of developments has been limited. There have been no installations in the UK network. The UK is a relatively small country with a dense population; this has resulted in power stations being located near to one another and relatively near to load centres. This has meant that, by international standards, the UK does not have very long transmission lines and as such there has been no requirement for TCSCs in the UK network.

Table 4-1: Summary of Flexible AC Transmission System (FACTS) Devices

Functionalities	Series Device	Shunt Device	
	TCSC	SVC	STATCOM
Main component	Fixed capacitor plus thyristor	Thyristor, capacitor and reactor	IGBT based voltage source converter
Reactive power compensation	Yes but discrete	Yes but discrete	Yes, continuous
Sub-Synchronous Resonance damping	good	limited	limited
Inter-area oscillation damping	Very good	limited	limited
Active power capability	Very limited	no	no
Active power control capability	yes	no	no
Applications	Transmission system for SSR damping, extending steady-state stability limits and reactive power compensation	Transmission system for dynamic reactive power compensation, improving the fault ride-through capability of wind farms and flicker mitigation	Transmission system for SSR damping, extending steady-state stability limits, improved power quality and reduce voltage variation
Loss minimization	yes	no	no
Harmonic attenuation	no	Is possible, but in this case it called load balancer	Is possible, but in this case it is called APF
Unbalanced Minimization	no	Yes (depends on configuration)	no
Blackout prevention	no	no	no
Voltage instability prevention	limited	yes	yes
Voltage quality improvement	limited	yes	yes
Manufacturers	ABB, SIEMENS, GE	ABB, SIEMENS, AREVA, American Superconductor	ABB, SIEMENS, AREVA, American Superconductor

5. Active Network Management

5.1 Summary of Work Carried Out

The work reviewed by this section was carried out under WP1 Task2 and is reported in detail in Reference 2.

The approach taken in this task was to review and interpret publicly available material to assess the impact of active power flow management on UK networks and collect information to support other tasks. Information was sought on how technologies might enhance network capacity and facilitate the power flows arising from the connection of large volumes of renewable energy generation in the UK context.

A broad range of literature sources has been examined to collect information on the technologies of interest, their potential impact on UK distribution networks and the impact on the transmission networks of technology changes at distribution level. The documents reviewed covered;

- Investigative industry reports such as those produced by the Electricity Networks Strategy Group (ENSG);
- OFGEM reports on Transmission Access Review, Survey of Innovation Projects and Distribution Price Control Review;
- National Grid's Seven Year Statement, Offshore Development Information Statement and report on Operating the Networks in 2020;
- Distribution Network Operators' (DNO) Long Term Development Statements, and their reports on Innovation Funding Incentive (IFI) and Registered Power Zones (RPZ) activities;
- Electricity Industry Documents such as the Distribution Code and Engineering Technical Reports;
- Academic work;
- Manufacturers' information.

A range of active power flow management solutions was identified and categorised. Based on the literature review and informed by the project partners' knowledge and experience, active power flow management solutions and their component technologies have been assessed in terms of:

- Supposed benefits, which have been quantified with approximations of the additional generation capacity that could be connected to distribution networks and the potential increase in network utilisation and discussed in terms of the potential to improve system operation, stability and security;
- Barriers to deployment, including technical, commercial, regulatory, organisational and cultural/momentum barriers specific to the UK context;

- Proposed solutions to the barriers, highlighting development gaps and challenges and opportunities for ETI technology development support;
- Present levels of maturity and risk in being brought to market.

5.1.1 Impact on Distribution Networks

Potential impacts on distributions networks were assessed from the consideration of network planning and operation, likely distributed generation and network constraints, principally thermal capacity, fault levels and voltage limits. Existing generation connection was reviewed and the potential connection capacity at each of the main distribution voltage levels: 132 kV, 33 kV, 11 kV and low voltage (LV) was quantified.

For thermal, fault level and voltage limits some simple characteristics were defined to enable an analysis of maximum generation connection capacity. The simple analysis based on the network characteristics resulted in ten possible thermal, fault level and voltage limits being identified that can be used to quantify the amount of generation that can be connected to a network area. Limits 1-5 are thermal limits that could be applied under different circumstances, Limit 6 ensures that the rating of the switchgear installed on the network is not exceeded, and Limits 7-10 apply a limit to the change in voltage that will result from the connection of the generation when operating at full output power. A sensitivity analysis was carried out to assess how the priority of each limit changes when the parameters of the network are varied. For this analysis the parameters varied were the fault level, the demand and the transformer rating. In each case, the parameter under examination was varied whilst the other parameters were maintained constant. The variability range for the parameters was based on the typical range of values in UK distribution networks.

The conventional and new solutions available for enhancing the ability of a network to accommodate additional generation capacity was reviewed together with the challenges resulting from implementing the new solutions associated with the technologies covered by this study. Finally the challenges and opportunities associated with the following areas were reviewed;

- The transition to active networks
- Network Management Systems
- Protection and Control
- Analysis and Modelling Tools
- The adoption of New Technologies and Methods by DNOs
- Commercial and Regulatory Issues

A measure of the maximum DG capacity that could be accommodated under typical connection points at different voltages has been produced.

- Based on conventional thermal limits and worst-case planning assumptions, a typical Secondary/Distribution Substation at LV has an estimated DG limit of 0.01 MW. Depending on the circumstances, active power flow management technologies might typically increase that limit to around 1 MW, where fault level limits are reached.

- Based on conventional thermal limits and worst-case planning assumptions, a typical Primary Substation at 11 kV has an estimated DG limit of 1 MW. Depending on the circumstances, active power flow management technologies might typically increase that limit to around 18 MW, where fault level limits are reached.

- Based on conventional thermal limits and worst-case planning assumptions, a typical Bulk Supply Point (BSP) at 33 kV has an estimated DG limit of 5 MW. Depending on the circumstances, active power flow management technologies might typically increase that limit to around 70 MW, where fault level limits are reached.

- Based on conventional thermal limits and worst-case planning assumptions, a typical Grid Supply Point (GSP) at 132 kV has an estimated DG limit of 80 MW, which is equivalent to 16 GW nationally. Depending on the circumstances, changes in operating philosophy to allow reverse power flow and the application of active power flow management technologies might typically increase that limit to around 296 MW, where fault level limits are reached, which is equivalent to 59 GW nationally. If fault level limits can be overcome then by applying active power flow management technologies some 132 kV networks may be able to accommodate much more DG, although their utilisation factor may be severely limited. Total DG capacity could match the existing capacity of transmission-connected generation.

5.1.2 Impact on Transmission Networks

Potential impacts on transmission networks from the technologies covered by the project were assessed at a very high level, particularly from the point of view of interfaces with the distribution systems. In addition, the impact on the transmission network of additional DG enabled by the deployment of new technologies was assessed in terms of the following issues that the system operator has responsibility for.

- Power Flows
- System Balancing
- Protection
- Stability
- Complexity

5.2 Findings

The literature review shows that there is a lot of effort going into considering and testing active power flow management solutions for the connection of DG. Industry working groups and individual DNOs are addressing the challenges and identifying the technologies that are best suited to specific circumstances. New technologies are available on the market now and barriers to deployment are mostly concerned with cost or with specific deployment considerations. Network operators are concerned with how new technologies might be integrated with their existing infrastructure without affecting customer supplies. The more conceptual research work concerned with future grids is less important to network operators working with five to ten year planning horizons.

The primary limits on the connection of more generation to distribution networks are thermal, fault level and voltage. The balance of limits will vary by location but an assessment of average characteristics indicates that thermal limits or fault level will often place a greater restriction on Distributed Generation (DG) connection than voltage. Even where the most restrictive limits can be overcome, whether by conventional solutions or with new technologies, other limits will remain and continue to impose a limit on generation capacity. The potential value of new technologies in each circumstance will depend on which limits are most restrictive, the additional generator capacity that can be connected before other limits are reached, and the ability of the technologies to address multiple limits.

The analysis demonstrated that the restrictiveness of different limits changes with fault level and this emphasises the importance of fault levels in determining the potential generator capacity in any particular circumstance. The inverse relationship between fault level and voltage limits is an important feature of the sensitivity analyses as it illustrates the conflict around the “strength” of the network. Fault level limits persist with most of the new technologies with only power electronic converters offering a solution. The limits on DG capacity caused by fault level will, however, depend on the DG technology being connected. This dependence on DG technology is different for fault level than for thermal or voltage limits, where the limits are a function of power output rather than the means of conversion or interface to the network.

While most of the technologies offer some improvement in thermal limits, power flow management is necessary to overcome limits based on minimum demand. Power flow management might be combined with other technologies. Dynamic thermal ratings can only be exploited fully if there is some form of active management to use additional capacity when it is available. HVDC, series compensation or phase shifting transformers might be controlled according to the requirements or opportunities identified by a power flow management scheme.

The analysis demonstrates the value of effective reactive power control, in that it has the potential in some circumstances to overcome all voltage limits. It also illustrates that no matter the flexibility and scope of reactive power control, thermal and fault level limits will remain. Voltage limits can be addressed with power electronic converters, shunt compensation and active voltage management but will persist with other technologies.

Power electronic converters are the most comprehensive technology of those reviewed as they can help to address all limits on DG capacity. This includes fault level, which is highlighted by a number of DNOs as the most pressing limit and is not addressed by any of the other technologies – except where series compensation might be used to increase rather than decrease network impedance. While HVDC offers the broadest solution it is also likely to prove the most expensive and offers limited gains because of the thermal capacity of existing distribution network equipment. The most promising use at distribution level may come as an interface between network areas that cannot be interconnected by conventional means. The manufacturers already have a range of products available and continue to develop new offerings.

Shunt compensation is already an attractive solution for voltage problems associated with the connection of DG. The use of this technology is likely to expand as more DNOs become familiar with its use and prices fall as the equipment is manufactured more widely. There may be scope for establishing a supply chain for this type of technology that is based more in the UK rather than relying on imported equipment.

Series compensation and phase shifting transformers may offer solutions in specific circumstances on distribution networks but are not expected to be widely deployed. The topology of distribution networks means that these technologies are likely to be used only at the higher voltages, where the network effectively acts as sub-transmission. As such, the advantages and disadvantages of these technologies will be similar to those identified for their use on the transmission network.

Active network management promises to provide distribution networks with some of the functionality and capability already used on the transmission network. The use of established communication and control technologies, albeit in a different setting, means that the technical barriers are not great. By exploiting the capabilities of DG, in real or reactive power control, and linking DG operation to network constraints, ANM makes the source of problems part of the solution. ANM is already being deployed and further developed on distribution networks in the UK and is emerging as a key element of future network designs, which will definitely contain conventional equipment like cables and transformers but may not incorporate advanced power electronics. The primary barriers to the further use of ANM arise in commercial and regulatory frameworks and in the standardisation and productisation of ANM technologies. There are opportunities for specific ANM technologies to be fully tested and then developed into products that can more easily be rolled out more widely.

DNOs will face a range of challenges in adopting the new technologies, which are likely to be used only if there is a very definite business case for them compared with conventional solutions. Assuming the cost-benefit analysis favours the new technology, DNOs may remain hesitant for reasons of standardisation, maintainability and complexity. Distribution networks are extensive, covering large areas and supplying millions of customers. Wherever possible it is advantageous for the DNO to settle on standard approaches that can be deployed widely. This makes it quicker and cheaper to install new pieces of network but also supports ongoing maintenance and operation, which must be achieved within strict cost restrictions. The literature review and discussion with stakeholders also points to a problem with skills in DNOs, where the drive for cost savings and efficiencies has driven out some of their capacity to assess and incorporate new technologies into their business. This is now being addressed to some degree with new incentive mechanisms and an acknowledgement that capabilities must be expanded, but the DNOs continue to face problems in being allowed to spend money on research, development and deployment of new technologies.

This review of ANM did not consider some of the more detailed or esoteric issues associated with power system operation such as protection design, dynamic stability or harmonic distortion. From the assessment performed, no significant barriers or negative impacts were identified in terms of the impact on the transmission network of deploying these new technologies at distribution level. If the technologies are successful in increasing the capacity of distributed generation then this will pose various challenges in system operation but all should be within the bounds of what is already being planned for on the transmission network.

Table 5-1 presents a high level summary of the technologies considered at distribution level, in terms of technology readiness, barriers to deployment and solutions to those barriers, the potential to facilitate generator connections at distribution level, and the broader impacts on DNOs and the transmission system.

Table 5-1 Summary of technology characteristics

Technology	Technology Readiness	Barriers to Deployment	Solutions to Barriers	Potential to Enhance Capacity	Broader Impacts
Power Electronic Converters	LCC = 9 CCC = 8 VSC = 9	Cost Losses	Cheaper and more efficient components	Address thermal, fault level and voltage limits	Significant new technology for DNOs Impacts similar to those of HVDC at transmission level
Shunt Compensation	SVC = 9 STATCOM = 9	Cost Losses	Developments in materials, assembly or greater competition	Address voltage limits and relax slightly any thermal limits	No significant challenges for DNOs Benefit transmission network by reducing demand for reactive power
Series Compensation	TCSC = 8 DSSC = 6	Extensive system modelling required	Improved analysis tools and skills	Address thermal and voltage limits	Challenges for DNOs in network operation, modelling and analysis No significant impact on transmission
Phase Shifting Transformers	TRL = 9	Coordination of multiple units	Ongoing research	Address thermal limits	No significant challenges for DNOs No significant impact on transmission
Power Flow Management	TRL = 8	Established commercial and technical approaches	Pilot projects, flexible standards, new tools	Address thermal limits	DNO challenges in establishing the commercial and regulatory frameworks No significant impact on transmission
Dynamic Thermal Ratings	TRL = 8	Technical complications and cost	Commercial development of solutions	Address thermal limits	DNOs must understand technologies and modify operational practices No significant impact on transmission
Voltage Management	Single location = 9 Multiple resources = 7	Technical restrictions	Improvements in technologies for measurement, computation, communications, and faster and more flexible reactive compensation devices	Address voltage limits and thermal limits to a small degree	DNO challenges in establishing the commercial and regulatory frameworks Benefit transmission network by reducing demand for reactive power
Demand Side Management	Small island systems = 9 System balancing = 9 To enhance distribution network operation = 6	Contractual agreements between the network operator and the user Lack of suitable loads	Economic incentives Development of appliances and industrial processes with flexibility in energy consumption	Address thermal limits and voltage limits to a small degree	DNO challenges in establishing the commercial and regulatory frameworks No significant impact on transmission

6. HVDC Transmission Technology and Multi-Terminal Schemes

6.1 Summary of Work Carried Out

The work covered by this section was carried out under WP1 Task1, WP2 Task 1 and WP2 Task 3 and is reported in detail in References 1, 6 and 7 respectively.

The work carried out under WP1 Task1 comprised a literature review of the current state of the art relating to power electronics for transmission and distribution systems and an accompanying discussion of the findings of the review and their relevance to the present study. The work presents a review of high-voltage DC (HVDC) transmission systems with the main focus on their capabilities and limitations. It also discusses the current state of the art of the converter stations of HVDC transmission systems and their potential influence on power system operation in terms of voltage and power system stability, reactive power support, and resilience to AC and DC faults. A comparison is presented of the features of different HVDC transmission system technologies, such as, line commutated HVDC, capacitor commutated HVDC, and voltage source converter HVDC (VSC-HVDC) based on two-level voltages, neutral-point-clamped and modular converters. The strengths and weaknesses of each technology are highlighted. Examples of recent projects, covering most of the HVDC technologies, are given in order to show the maturity of each technology. Also discussed is the potential use of point-to-point HVDC and multi-terminal HVDC transmission systems to relieve network congestion, improve system stability and reliability against system blackout, and provide ancillary functionality such as damping support and frequency stabilisation of the AC networks.

The work carried out under WP2 Task1 covered topics associated with assessing the feasibility of onshore multi-terminal HVDC in the UK. The assessment covered the power quality issues at HVDC terminals, technical issues associated with conversion of ac overhead lines to dc, a high level discussion of dc cable technology, and a review of multi-terminal HVDC control regimes. Note that the assessment of the feasibility of conversion of ac overhead lines to dc was limited to considerations of the practicalities of converting the line itself. Impacts on the system such as its ability to accept associated increased power flows were not considered in this task. These system issues were addressed in the work carried out under WP2 Task3 on the impacts of Multi-Terminal HVDC on the UK Grid, which also covered the lifecycle cost comparison between HVAC and HVDC schemes, and the impact on CO_2 reduction covered elsewhere in this report.

6.2 Findings

6.2.1 Literature Review

The basic devices used to construct HVDC systems are generally similar to those used for the FACTS devices discussed in Section 4. Therefore the findings given in Section 4 covering the comparison of LCC and VSC technologies and the different approaches to designing for scheme operation at power levels and voltages significantly above that which may be sustained by a single power device also apply here.

Conventional, thyristor based high-voltage DC transmission is a well-established technology with many installations in operation throughout the world and is available from a number of manufacturers including ABB, Areva and Siemens. The limits of this technology are well-known, namely high VAr (reactive power) consumption, large harmonic current emissions, and large installation size. Conventional HVDC transmission is based on current source principles; giving advantages in terms of DC link fault behaviour but is not readily adapted to multi-terminal systems. Example deployments of LCC HVDC schemes include:

- ABB – NorNed (Norway-Netherlands) A 580 km, 700 MW, 450 kV link connecting Norway to Netherlands (the longest sub-sea LCC scheme in the world)
- Areva – Cross-Channel Scheme (UK-France) A 2000 MW link operating at ±270 kV between UK and France
- Siemens – Basslink (Australia) A 500 MW link between Australia and Tasmania operating at 400 kV

Suitable FACTS devices (such as SVC or STATCOM) are used on both AC sides of conventional HVDC schemes to reduce the impact on the local network and improve fault ride-through capability.

Voltage source converter HVDC is a more recent development. Voltage source HVDC exhibits increased losses relative to thyristor based systems but is suited for connection to weak networks where conventional thyristor technology would not be technically practical. There has been significant use of this technology with subsea links to circuits that could not support conventional HVDC (most notably offshore renewable generation clusters). Unlike conventional HVDC, voltage source converter systems do not require a DC link voltage reversal in order to change the power flow direction; this allows the use of robust and flexible polymer insulated cables. Voltage source converter HVDC operates from a common DC bus with fixed polarity, permitting more complex multi-terminal architectures.

With the presently anticipated capability of VSC technology the rating of a VSC HVDC scheme that could be achieved by the use of single VSC blocks per converter is approximately 1200MW based on a bi-pole arrangement and HVDC voltage of +/-320kV. Practical schemes with higher ratings can be achieved by the use of multiple VSC blocks per converter pole.

A VSC-HVDC transmission system can provide all the ancillary functionality available on conventional generating units based on synchronous machines, such as frequency support, local and inter-area oscillations damping, and voltage support as required in the GB Grid Code, at no additional cost. The functionality, such as power reversal, frequency support, AC voltage control, and recovery from DC fault within 0.5 s, have been demonstrated in the Caprivi link (Namibia) based on the overhead line VSC-HVDC transmission system. In the case of an overhead line VSC-HVDC transmission system, a reduction in construction cost will be achieved compared to the cases where underground cable is used.

The power electronics presently used in voltage source inverter circuits cannot block current flowing from the AC supply into a suppressed DC link voltage during DC faults. For point-to-point installations, protection may be on the AC in feed, but the low overload capability of power electronic components adds to the difficulty of providing protection in this way.

DC link control is required to manage transient power flow during a disturbance in either the ac and dc sides without imposing the risk of device failure in the converters. This becomes of increased importance where HVDC is applied to overhead lines due to the increased likelihood of temporary DC side faults. For multi-terminal systems this control is necessary in order to minimise the risk of system collapse and total loss of power resulting from temporary dc line faults or permanent faults on individual sections.

6.2.1.1 High-Voltage DC Circuits

The high-voltage DC circuit breaker is an important system component, the availability of which is key to the exploitation of multi-terminal DC transmission systems, especially since an increased number of terminals and lines increase the risk of a DC fault. An unavoidable consequence of a DC side fault is that the power transfer in the whole system will be interrupted and therefore fast dc fault clearance is essential. DC systems have no natural current zero at which the fault current may be extinguished. Circuit breakers must therefore provide sufficient voltage to drive the current to zero and absorb the fault energy. This must be achieved without incurring excessive steady state losses in the protection device. Circuit breaker technology for VSC based multi-terminal HVDC faces additional challenges resulting from the low impedance DC bus architecture and in-feed from the converter stations (which currently lack reverse blocking capability). In these systems the circuit breaker may be subjected to high fault levels and must achieve clearance times compatible with protection of the semiconductors in the converter stations.

Academic and industry research approaches to these issues use passive or active circuits in parallel with the actual current interruption circuit to create an artificial zero crossing in order to minimise the resulting over-voltage following the interruption. The first prototype of a 500 kV DC circuit breaker was developed by Brown Boveri (BBC) (now part of ABB) in 1984. Practical DC circuit breakers have been reported for use with LCC based HVDC schemes but circuit breakers for use in VSC-HVDC remain at the development stage (including state funded programs e.g. E.U. FP7 'Twenties Project') with no clear consensus on technical solutions. The use of reverse blocking converter technology is being actively investigated as a means of controlling DC faults. Reference was made at the workshop to the possible availability of DC breakers "within a year or two" but no substantiation of this claim has been revealed by any of the investigations carried out under this project. This topic therefore merits further investigation in the future.

6.2.2 Feasibility Assessment

6.2.2.1 Power Quality

The most significant power quality issue associated with the operation of HVDC schemes is the harmonic voltages and currents that are produced by the ac-to-dc and dc-to-ac conversion process. All HVDC scheme conversion technologies produce harmonics to a varying degree. The harmonics can produce undesirable effects such as extra heating in transformers, control system inaccuracies and interference with communication circuits. These effects are well-known and appropriate supply authority standards and regulations have been developed to ensure that equipment connected to the system does not produce adverse effects on the system and its users.

In HVDC systems, harmonic filters are used on the ac and dc sides to prevent the harmonics generated by the converter from propagating into the ac or dc system. The processes that lead to the production of harmonics and the methods for designing suitable filters are well understood and are readily amenable to analysis. The filter creates a low impedance path (for shunt filter) or a low admittance path (for a parallel filter) at a specific frequency. If designed properly, this will act as a local "sink" for any generated harmonics and prevent them from entering the associated ac or dc network. When considering harmonics for HVDC, the effects, mitigation and performance indices are the same irrespective of the conversion technology. These considerations apply equally to multi-terminal HVDC schemes as to two terminal schemes and so no additional power quality issues are expected to arise from multi-terminal schemes that would affect the feasibility of installing them in the UK Grid.

6.2.2.2 Line Conversion

It is well understood that for a given transmission tower size; significantly more power can be transmitted on a dc circuit than on an ac circuit. The potential additional transmission capacity of the dc circuit arises as a result of a number of technical differences associated with dc transmission when compared to ac transmission. These differences include:

- Continuous operation at the rated peak voltage rather than a sinusoidally varying voltage
- The absence of skin effect in the current in the conductor
- The lack of a requirement to carry reactive current
- Higher operational voltage resulting from less demanding overvoltage design requirements.

The achievable increase for any given specific transmission line will depend on how the above features apply to the line concerned. The increase can range from approximately 1.4 (assuming no increase other than that resulting from continuous operation at the peak voltage) to up to approximately 3.5 (if all of the characteristics are favourable and the tower layout is modified so as to be optimal for dc transmission. The conversion of an existing AC transmission line to HVDC is therefore potentially attractive to transmission system operators in that it offers the prospect of increasing the power that can be transmitted through the existing right of way. To date however there has been only one line where conversion has actually taken place. This was the HVDC national project in India which involved a 220 kV double circuit ac line of 196 km length and rated at 240 MW. One circuit was converted to a ±100 kV dc line and this resulted in an increase in total transmission capacity to 400 MW. Given that there are many thousands of transmission lines worldwide it is noteworthy that there has only been one line conversion to HVDC operation since this indicates that thus far the transmission system operators have not judged the potential advantages of conversion to be sufficiently attractive to them.

It is important to note that the insulators for dc lines are made with specific dielectric materials, and that additionally their string length and characteristics, such as leakage distance, have to be adjusted for the prevailing contamination conditions. For these reasons it is technically not possible to use the existing AC lines unchanged for HVDC. At the very least it is necessary to replace the AC insulators with appropriate dc ones.

In principle it would be feasible to convert any existing UK Grid ac overhead transmission line to dc. If serious consideration was to be given to such conversion then detailed, line specific, studies would have to be carried out to determine the suitability of the existing transmission line especially with respect to tower cross arms, insulators and the conductor configuration. The required design principles and criteria that would be applied are understood in general but would require to be formalised into codes that apply to the UK Grid. In addition, studies would need to be performed to determine whether the towers needed any structural changes and to confirm the capability of foundations to accept any increased loads.

6.2.2.3 DC Cables

As with AC transmission, the majority of HVDC transmission schemes use overhead transmission lines. However, the number of HVDC projects using long HVDC cables is on the increase, mostly for submarine power transmission. HVDC systems utilising dc cables have been in service since 1954 and the number of systems in the planning stage is increasing. Table 6-1 contains a summary of some of the major HVDC cable schemes presently in operation.

The economic design of dc cables is very important, because the cost of the dc cables is a high proportion of the total cost of the HVDC project. The feasibility and economic viability of HVDC cable projects can improve if HVDC cables can be made at lower costs or the transmission capacity of the HVDC cables is increased.

There are two factors that affect the design of an HVDC cable, the current carrying capacity which is related to the thermal stresses on the cable, and the voltage capability of the cable which is related to the voltage gradient on the insulation. There are technical challenges in improving both these factors and there is ongoing research in both fields.

There are presently two types of cable that would be used in new multi-terminal HVDC projects:

- Mass impregnated (MI)
- Solid extruded, cross-linked polyethylene insulation (XLPE)

Mass impregnated cables are the most widely used type in HVDC transmission systems. The Sweden-Gotland HVDC link used this type of cable in 1954 for the first time. MI cable ratings have increased over the years in both voltage and current. Presently, cables rated for 600 kV DC voltage have been successfully type tested and are available now. The maximum dc current rating is presently up to about 1700 A and there are indications that it will climb to 1800 A in the near future. This means a power rating of approximately 1100 MW per cable or 2200 MW per bipolar link. MI cables are utilised with LCC thyristor converters mainly because of the higher ratings and their capability to withstand dc polarity reversal. The dc polarity reversal is essential in LCC thyristor converters mainly to changing power direction and also during HVDC disturbances. MI cables can be also used with VSC converters; however, for most applications the cost will be higher compared to XLPE alternatives. The use of MI cable with VSC converter is justified in cases where the dc voltage rating is too high for XLPE cable.

XLPE cables have been applied in HVDC since 1997. Their voltage rating has increased to 325 kV and their current rating to 1500 A. XLPE cables have been used in HVDC applications with VSC converters that utilise Insulated Gate Bipolar Transistor (IGBT) valves. Both two and three level converters as well as multi-module converters have been used with XLPE cables. There are also reports that a 350 kV cable has been type tested. Note that the highest voltage XLPE cable presently in testing and commissioning is 200 kV (Transbay project). The technology to produce extruded cables is the technology needed to produce mass impregnated or oil filled cables and therefore production costs are considerably lower. Extruded insulation cables can operate at higher temperatures than MI cable. Despite these advantages the use of XLPE cables is somewhat hampered by its sensitivity to polarity reversal. When an XLPE cable is under DC voltage for a relatively long time (hours) and fully charged, its voltage polarity cannot be changed quickly. This is due to the presence of the space charge trapped within cable insulation due to its high resistivity. As a result, this type of cable cannot be used together with conventional thyristor based line commutated HVDC converters as the DC voltage polarity reverses quickly in these converters during a power reversal and some transients. The application of XLPE cables in HVDC is suitable for the Voltage Source Converter (VSC) technology since in this application the change in power direction does not require a voltage polarity reversal, it is the current that reverses.

The increasing demand for the transmission of large amounts of power from renewable energy resources, combined with the increased limitations on building new overhead transmission lines are the major development drivers for HVDC cables. MI cable technology has been improved to allow transmission of up to 2200 MW through one bipole and MI submarine cables have been installed at a depth of one mile. Further development in increasing the voltage and current ratings, reducing weight and reducing the number of joints is expected to continue. It is anticipated that a rating of 3000 MW per bipole will be achieved within a few years. Lower cost and better mechanical properties have also increased the interest in the XLPE cables and so development of this type of cable is also anticipated to continue in the future towards higher power ratings.

In general there is a considerable body of experience with the operation of large HVDC transmission schemes using dc cables and so there are no issues associated with HVDC cables that would affect the feasibility of installing multi-terminal schemes in the UK Grid.

Table 6-1 **Existing HVDC cable systems in operation**

Name	Commissioning year	Voltage (kV)	Power (MW)	Insulation	Length (km) L= land S=Sea	Converter Line commutated (LCC) Voltage source (VSC)
Gotland 1	1954	100	20	MI	100	Decommissioned
Gotland 2&3	1983 and 1987	+/-150	260	MI	92+0.9/ 92+6 (L+S)	LCC
Gotland HVDC Light	1999	+/- 60	50	XLPE	70	VSC
Cross Channel	1986	+/ 270	2000	MI	71	LCC
SACOI	1992	+ 200	300	MI	221	LCC
The Baltic Cable	1994	450	600	MI	261	LCC
Direct Link	2000	+/- 80	3X60	XLPE	59	VSC
Fenno-Skan	1989	400	500	MI	200	LCC
GRITA	2001	400	500	MI	163 +43	LCC
Haenam-Cheju	1996	+/-180	300	MI	101	LCC
Hokaido-Honshu	1993	+/- 125	600	OF	43	LCC
Kontiscan 1	1965	250	250	OF+MI	87	LCC
Kontiscan 1	1988	285	300	OF+MI	87	LCC
Kontek	1995	400	600	MI	171 (L+S)	LCC
Leyte-Luzon	1998	350	440	MI	23	LCC
New Zealand	1965-1992	270/-350	1240	MI	40	LCC

Name	Commissioning year	Voltage (kV)	Power (MW)	Insulation	Length (km) L= land S=Sea	Converter Line commutated (LCC) Voltage source (VSC)
Skagerrak	Bipole 1976 Monopole 1993	Two mono poles @ 250/ and one monopole @ 350	275x2 and 500	MI	127 127	LCC
SwePol	2000	450	600	MI	239+14.8	LCC
Norned	2008	+/-450 Mid point ground	700	MI	580	LCC
Cross Sound	2002	+/- 150	330	XLPE	40	VSC
Murray Link	2002	+/- 150	220	XLPE	180	VSC
Transbay Cable	2010	+/- 200	400	XLPE	80	VSC
Bass link	2006	400	500	MI	295+1.7	LCC
Neptune	2007	500	650	MI	80	LCC
Kai Channel	1998 Currently operating only at 250 kV	500	2800	OF	50.7	LCC

6.2.2.4 Multi-Terminal Schemes

Presently the use of current source converter (LCC) technology in a multi-terminal HVDC system configuration is limited to three terminals due to technical difficulties such as increased control system complexity and DC current balancing between the converters. Examples of constructed multi-terminal HVDC transmission systems using the LCC current source approach are summarised in Table 6-2.

In principle, a multi-terminal VSC-HVDC transmission system can be extended to any number of terminals without increasing the converter power system complexity significantly. However, a highly co-ordinated control system is required between the converter stations along with robust DC circuit breakers to improve the possibility of system recovery from DC faults or loss of converters. The common DC bus architecture of VSC-HVDC is fundamentally different from previous LCC based multi-terminal HVDC. This architecture requires protection and fault management systems to protect un-faulted converter stations and to ensure rapid recovery of the network. The recovery strategy for a VSC-HVDC multi-terminal transmission system from a dc side fault will require the ability to interrupt the DC fault current, isolate the faulted line sections, and re-energise the line. These special requirements would require the equipment to have additional functionality including, dc fault blocking converter stations, dc breakers, and fault location systems.

Table 6-2 Examples of multi-terminal HVDC transmission system in operation

Project	Rating	Length	Configuration	Commissioning year
SACOI Italy/France	250 MW 200 kV DC link	406 km	Three monopolar terminals in series (extension of existing two terminal monoploar HVDC)	1967 and 1986
Pacific Intertie USA	3100 MW, ±500 kV DC link	1360 km	Four bipolar terminals in parallel, rated at 2×2000 MW and 2×1100 MW (built in three stages, 1600 MW 2 bipolar terminals with ±400 kV using Mercury arc valve, upgrading of existing terminals by 400 MW and DC link voltage is increased to ±500 kV using thyristor valve converter, and 1100 MW 4 bipolar terminals at ±500 kV)	1970, 1984 and 1989
Hydro Quebec-New England Hydro Canada/USA	2250 MW, ±450 kV DC link	1480 km	Three bipolar terminals in parallel rated at 2250 MW, 2130 MW and 1800 MW (constructed in three stages)	1990 1991 1992

6.2.3 Impacts of HVDC on the Grid

6.2.3.1 System Losses

The change of an existing ac transmission line to an HVDC one would result in an increase in system losses. The actual increase would depend on the line converted and the selected HVDC technology. Table 6-3 gives a comparison of typical losses for various transmission scheme options.

Table 6-3 Comparison of Typical Losses for Different Transmission Scheme Options

		CONVERTER	TOTAL			Conductor Information
Transmission Method	Voltage		100 km	300 km	600 km	
Single Circuit Overhead Line	HVAC 500 kV	N/A	3000 MW	3000 MW	2000 MW	3 x ACSR "Falcon" per phase
		-	1.6 %	4.7 %	6.3 %	
Double Circuit Overhead Line	HVAC 500 kV	N/A	6000 MW	6000 MW	4000 MW	3 x ACSR "Falcon" per phase
		-	1.6 %	4.7 %	6.3 %	
Bipole LCC Overhead Line	HVDC ± 500 kV	3000 MW	3000 MW	3000 MW	3000 MW	2 x ACSR "Bluebird" per pole
		1.4 %	2.2 %	3.8 %	6.1 %	
Bipole VSC Overhead Line	HVDC ± 200 kV	600 MW	600 MW	600 MW	600 MW	2 x ACSR "Falcon" per pole
		3.0 %	4.3 %	7.0 %	11.0 %	
Bipole LCC Overhead Line	UHVDC ± 800 kV	6400 MW	6400 MW	6400 MW	6400 MW	5 x ACSR "Curlew" per pole
		1.4 %	1.9 %	3.0 %	4.6 %	

6.2.3.2 Reliability

The reliability of an HVDC scheme depends on the reliability of its critical components listed below and can be improved at the design phase by incorporating redundancy in the following critical components:

- Thyristor/IGBT valves
- Control system
- Cooling system
- Auxiliary power supplies
- AC harmonic filters

The reliability of the overhead line itself would remain the same after HVDC conversion since the conversion does not by itself introduce additional failure modes given the general similarity between HVAC and HVDC insulator strings. Table 6.4 gives typical reliability statistics for LCC (Bipole) and LCC HVDC Converters.

Table 6-4 Typical HVDC Converter Reliability Statistics

Reliability Criteria	LCC (Bipole)	VSC
Forced outage rate	6 outages per year (100% power) 0.05 outages per year (minimum of 50% power)	1 - 2 outages per year (100% power)
Forced unavailability	0.6% to 1.0% (100% power) 0.003% (minimum of 50% power)	0.3% to 0.5% (100% power)
Scheduled unavailability (mostly due to maintenance)	< 2.0% (100% power) < 0.1% (minimum of 50% power)	< 0.4% (100% power)
Availability	> 97% (100% power) 99.9% (minimum of 50% power)	> 99.0% (100% power)
Life Expectancy	40 years	40 years

6.2.3.3 Security of Supply

The National Electricity Transmission System Security and Quality of Supply Standard (SQSS) (Reference 11 defines the security and quality of supply requirements for the UK Grid and these requirements would have to be met by any link in the existing system that was to be converted to HVDC.

The post fault HVAC ratings on the UK 400 kV overhead line circuits are already very large, currently in excess of 4 GW, which means that any additional capacity that could be provided by the conversion to an onshore HVDC scheme is very likely to be problematic to the grid. The outage of a high capacity HVDC link that is loaded close to maximum capacity will cause higher-amplitude power flow oscillation across the adjacent HVAC transmission circuits when compared with the loss of the HVAC circuit. The risk of system instability following the loss of the HVDC link is therefore exacerbated unless a curtailed loading schedule is employed for the HVDC link or the transmission capacity of adjacent HVAC is increased to match the rating of the HVDC link. Either solution will involve very significant reinforcement costs that are very likely to make the line conversion uneconomic.

Furthermore, a significant requirement is that for the Average Cold Spell (ACS) peak demand (i.e. in winter conditions), the transfer capacity of the link must be planned such that, starting with an intact system, following the secured event of a fault outage of a double circuit line there shall be no unacceptable overloading of any primary transmission equipment. In practice, the NG transmission system is often operated such that the post-fault loading on the overhead line circuits exceeds the long-term post-fault capability. In this case the short term overload capacity of the HVAC system is exploited after the fault has occurred to allow power transfers to be reduced (e.g. by automatic tripping of generating plant through an 'Operational Tripping' scheme or instructing reductions in generation output). This sort of capability is not possible with HVDC technologies in view of their limited overload capacity.

Thus, although a converted HVDC transmission line itself may have a higher power handling capability than the AC line it replaces it may be difficult to incorporate the uprated line into the system because its loss could cause overloading of the associated primary transmission equipment such as adjacent transmission lines. It would be feasible to overcome this problem by uprating the affected primary transmission equipment as well but this would have significant cost implications. The extent of such required enhancements to adjacent circuits, and the scale of associated costs and system disruption etc during the implementation of the enhancements cannot be addressed generically at this stage since they would be very dependent on the particular transmission line involved. It may be that in the future, enhancements to the ratings of some circuits in the network may happen for other reasons and this may then open up the prospect that lines in the vicinity of these uprated circuits could benefit from conversion to HVDC. In addition, providing converter stations to match the enhanced capability of the new transmission line would be problematic because of the limited overload capability of the converters, and at present only LCC schemes would have the necessary maximum ratings.

6.2.3.4 Costs

Given the generic nature of the study that has been carried out it has only been possible to identify cost implications at a very high level. Table 6-5 below provides estimated capital costs for converter stations based on the ratings shown (costs are from a CIGRE document that quotes figures in US$ for international comparison purposes).

Table 6-5 Typical LCC Converter Station Costs (Rectifier plus Inverter)

Voltage [kV]	Bipolar Rating [MW]	Total Cost [US$ million]
± 500	1000	170
± 500	2000	290
± 500	3000	420
± 500	4000	680
± 600	3000	450 – 460
± 800	3000	510

Source: Impacts of HVDC lines on the economics of HVDC projects, Cigré

The existing maximum VSC HVDC converter station rating is 1000 MW. Based on this, it is estimated that a ± 320 kV VSC HVDC converter station pair (rectifier plus inverter) would cost approximately US$277 million. This estimate covers equipment directly related to the converter station (i.e. DC converter, transformers and AC filters), but not costs associated with additional HVAC switchyard equipment. It includes installation and civil work and a 20% addition to allow for project management and engineering.

The overhead line conversion cost is estimated to be approximately 75% of a new overhead line cost. For example, if a UK 400 kV HVAC double-circuit overhead line was converted to a bipole HVDC overhead line, this conversion would cost approximately US$1.13 million per km (a new 400 kV HVAC double-circuit overhead line costs approximately US$1.58 million per km).

Typically the annual operational and maintenance (O&M) costs of an HVDC scheme are approximately 2% of the total scheme cost. When analysing the O&M costs of a HVAC to HVDC conversion, the overhead line O&M costs are likely to remain the same but there will be additional O&M costs due to the addition of the converter stations.

6.2.3.5 Benefits Case for Conversion of HVAC Onshore to HVDC

The post fault HVAC ratings on the UK 400 kV overhead line circuits are already very large, currently in excess of 4 GW, which means that any additional capacity that could be provided by the conversion to an onshore HVDC scheme is very likely to be problematic to the grid. The outage of a high capacity HVDC link that is loaded close to maximum capacity will cause higher-amplitude power flow oscillation across the adjacent HVAC transmission circuits when compared with the loss of the HVAC circuit. The risk of system instability following the loss of the HVDC link is therefore exacerbated unless a curtailed loading schedule is employed for the HVDC link or as discussed elsewhere in this report the transmission capacity of adjacent HVAC is increased to match the rating of the HVDC link. Either solution will involve very significant reinforcement costs that are very likely to make the line conversion uneconomic

There is no benefits case for converting individual transmission lines in the UK Grid to HVDC to gain additional transmission capacity since:

- Conversion to HVDC will, at the very least, entail the replacement of all of the insulators on the line. This conversion would be expensive and would involve taking the line out of service for a considerable time, which may be operationally unacceptable in practice.

- The existing Grid would be unable to cope with the loss of the enhanced capacity transmission line (without the need for additional capacity enhancements in adjacent circuits and the possible need to implement associated special protection schemes). The extent of such required enhancements to adjacent circuits, and the scale of associated costs and system disruption etc during the implementation of the enhancements cannot be addressed generically at this stage since they would be very dependent on the particular transmission line involved. It may be that in the future, enhancements to the ratings of some circuits in the network may happen for other reasons and this may then open up the prospect that lines in the vicinity of these uprated circuits could benefit from conversion to HVDC.

There is no benefit case for converting individual transmission lines in the UK Grid to HVDC for reasons other than to gain additional transmission capacity (e.g. to implement a multi-terminal scheme) since:

- Conversion to HVDC will require the replacement of the line insulators.

- The converted line does not offer any benefits to the system that cannot be gained by other means, such as the application of FACTS devices.

It should be noted that the above conclusions are in respect of the conversion of an existing AC line to DC . The conclusions do not detract from the potential system benefits which could be derived from the addition of new DC lines in parallel with the existing AC lines. In such circumstances the capacity of the adjacent AC lines would be fully taken into account in the engineering design of the new DC line.

Other than the potential additional capacity, a conversion to HVDC could provide the following benefits that are not offered by the existing HVAC transmission overhead lines:

- Real and reactive power flow control: power flow in HVDC systems can be predetermined and is independent of phase relationships, avoiding inadvertent overloading or under-utilisation as may occur in HVAC systems.
- Loss of HVAC transmission lines can be automatically compensated by reduction in power through the HVDC link, to match the capability of the remaining in-service HVAC transmission network.
- Damping of electro-mechanical oscillations.
- Suppression of AC network / generator rotor sub-synchronous resonances.
- Following a load rejection on the network, a limitation of temporary over-voltage can be achieved by the HVDC link by the rapid absorption of reactive power.
- Frequency limit control can be initiated, if normal operating limits are exceeded.
- HVDC links provide negligible contribution to the short circuit levels in the connected systems. This may be desirable depending on the application.
- HVAC Faults and oscillations do not transfer across HVDC interconnections.

In some circumstances, HVAC to HVDC conversion provides benefits such as enabling long distance power transmission, eliminating reactive power flows from long HVAC cable circuits and enabling asynchronous system connections. However, in view of the short transmission distances involved in the UK these would not be of benefit to the onshore UK transmission system.

Additionally, there may be a business case for the conversion of multiple parallel lines to increase capacity of the system (rather than of an individual line), despite the expense involved, in circumstances where it is not possible to build new lines due to unavailability of way-leaves or where there are no commercially viable alternatives.

7. Performance of Technologies Integrated into UK Grid

7.1 Summary of Work Carried Out

The work reviewed by this section was carried out under WP1 Task 3 and WP2 Task 2 and is reported in detail in References 3 and 7 respectively. The investigations for these two tasks were carried out using a common, validated model of the UK grid built using the PSS/E modelling software. The work on the development and validation of the model used for the studies was reported separately in Reference 9.

The system performance during transients caused by the occurrence of secured events (i.e. the loss of a double circuit transmission connection or of a section of the transmission network) is usually analysed through dynamic simulations of the system response. It is during the transient studies that the impact caused by the FACTS devices or the inherent rapid flexibility provided by the control of HVDC links becomes more apparent by helping the system to recover to stable operation. The transient studies therefore demonstrate the range of benefits that may be provided by the informed use of FACTS devices, their location, ratings and associated controls and are instrumental in realising the full potential of the devices.

7.1.1 System Model

An existing steady-state (load flow) model of the UK transmission system, representing the network for the winter 2013/14 peak demand (Average Cold Spell - ACS) as forecast in the National Grid Electricity Transmission (NGET) Seven Year Statement (SYS) 2007, formed the basis of the model. The model represented all generators connected to transmission assets and the transmission circuits owned by the three transmission system operators, i.e. National Grid Company (NGC), Scottish Power Transmission (SPT) and Scottish and Hydro Electric Transmission (SHETL). The model was revised in order to correspond to the most recent NGET load demand forecasts. The main change was associated with the modified forecast of the 2013/14 ACS peak demand of approximately 61.9 GW (67.5 GW estimated in the NGET SYS 2007). The 61.9 GW forecast demand for 2013/14 excludes station demands and the power exports to Northern Ireland (the Moyle interconnector) and the Republic of Ireland across (the East/West interconnector). Note that power exchanges less than an aggregate 0.6 GW are anticipated with Northern Ireland and Republic of Ireland during the 2013/14 ACS peak demand. This is considered a negligible proportion of the total GB load demand and these interconnectors were therefore not included in the UK transmission system model).

The static load-flow model was transformed into a dynamic model by the addition of appropriate dynamic features such as the transient impedances, transient time constants, magnetic saturation effects and mechanical inertia characteristics for the various types of generators, with appropriate governor and excitation system controllers. A review of the composition of existing power stations in terms of individual generators demonstrated that a large number of different transient data sets and the associated controllers would have been required. The number was considered too large to be practical for this particular exercise and so a reduction in numbers was implemented by grouping the thermal units (steam-turbine or gas-turbine driven) and the hydro units (hydro-turbine driven) separately into classes of their own, based on selected ranges of the machine rating. A representative rating of a synchronous machine was then selected for each class. Ten classes of thermal units and seven of hydro units were used.

The scheduling of the generation was carried out according to accepted principles considering typical loading levels of the grid generators. The loading levels were based upon operational experience and engineering judgement so as to provide reasonable spinning reserve for stable and robust operation of the system.

Following the successful validation of the initial version of the dynamic model two more refined versions were created in order to improve the opportunities to observe the system dynamic behaviour. The first refined version replaced all the simplified models of wind farms with the equivalent dynamic models based on open-access, generic models of Wind Turbine Generators (WTG). The equivalent was constructed by using the appropriate generic WTG model combined with the corresponding controllers (electrical control module, mechanical system and pitch controller).

A second, further refined version of the dynamic model was created to ensure that the loss of the Western Interconnector across system boundary B6 (between Scotland and England) caused a separation of the systems across the boundary. (This separation of the UK transmission system was considered an outcome that could be successfully prevented by the application of FACTS/HVDC technologies and so it was important that the model could be used to investigate this). This was achieved by raising the power exchange across boundary B6 from 4.2 GW to 4.7 GW through re-dispatching of the generation. The resulting second refined version of the model formed the base case that was used for the system studies.

7.1.2 Model Validation

The validation of the model for the dynamic studies was achieved by liaising with the Electricity Network Investment team of National Grid Electricity Transmission (NGET). They are the power system analysis specialist unit employed for planning applications with access an up-to-date dynamic model of the UK transmission system that is based on actual data provided by UK generation owners. (This data is confidential and not available in the public domain).

The results obtained from the Mott MacDonald model for several contingencies assuming different planned power flows and clearance times were submitted for independent assessment by NGET. The analysis of the comparison of these results with the benchmark responses was concluded by a statement issued by NGT confirming the fitness for purpose of the Mott MacDonald model for the scope of this project.

7.1.3 Contingency Events

System studies have been completed using the verified Mott MacDonald model in order to demonstrate the benefits that may be provided by the insertion of the FACTS devices or HVDC links in the existing UK transmission system. The selection of the type of system studies that are needed for this demonstration has to consider the effects of the FACTS device or HVDC link upon the steady-state and dynamic behaviour of the power system. The UK transmission system response to stresses caused by selected fault events (termed “contingencies”) has to be compliant with the requirements set in the National Electricity Transmission System Security and Quality of Supply Standard (NETS SQSS).

The NETS SQSS requirements concern the system performance prior to and after the occurrence of secured events (the loss of a double circuit transmission connection or of a section of the transmission network) in the main interconnected transmission system assuming loading conditions that ought reasonably to be experienced during the ACS peak demand. The NETS SQSS requires the minimum transmission capacity of the interconnected transmission system to be planned such that, prior to any fault, there are no unacceptable operation conditions (equipment loading and voltage profile) and there is no system instability. The minimum transmission capacity should be planned such that the secured event of a fault outage does not cause unacceptable operating conditions, loss of supply capacity and system instability. The outage of a double circuit overhead line on the 400 kV supergrid has been used as the basis for the faults investigated using the model since this is the most onerous secured event against which sufficient transmission capacity has to be planned.

The selected secured events for which the benchmark dynamic responses were established consisted of 14 double contingencies. The events that were selected were driven by the locations selected for deploying the FACTS devices for technology demonstration purposes. The deployment of the FACTS devices was co-ordinated with the deployment of potential Multi-Terminal or Point-To-Point HVDC links so that the selected locations would enable a comparison to be made of the benefits that may be provided by the use of either FACTS devices or HVDC links. The selected double contingencies were therefore those that potentially affect circuits located along the main North-South transmission corridors at positions where the contingencies are expected to cause the most onerous conditions for the system recovery to stable operation. These are shown in Figure 7.1.

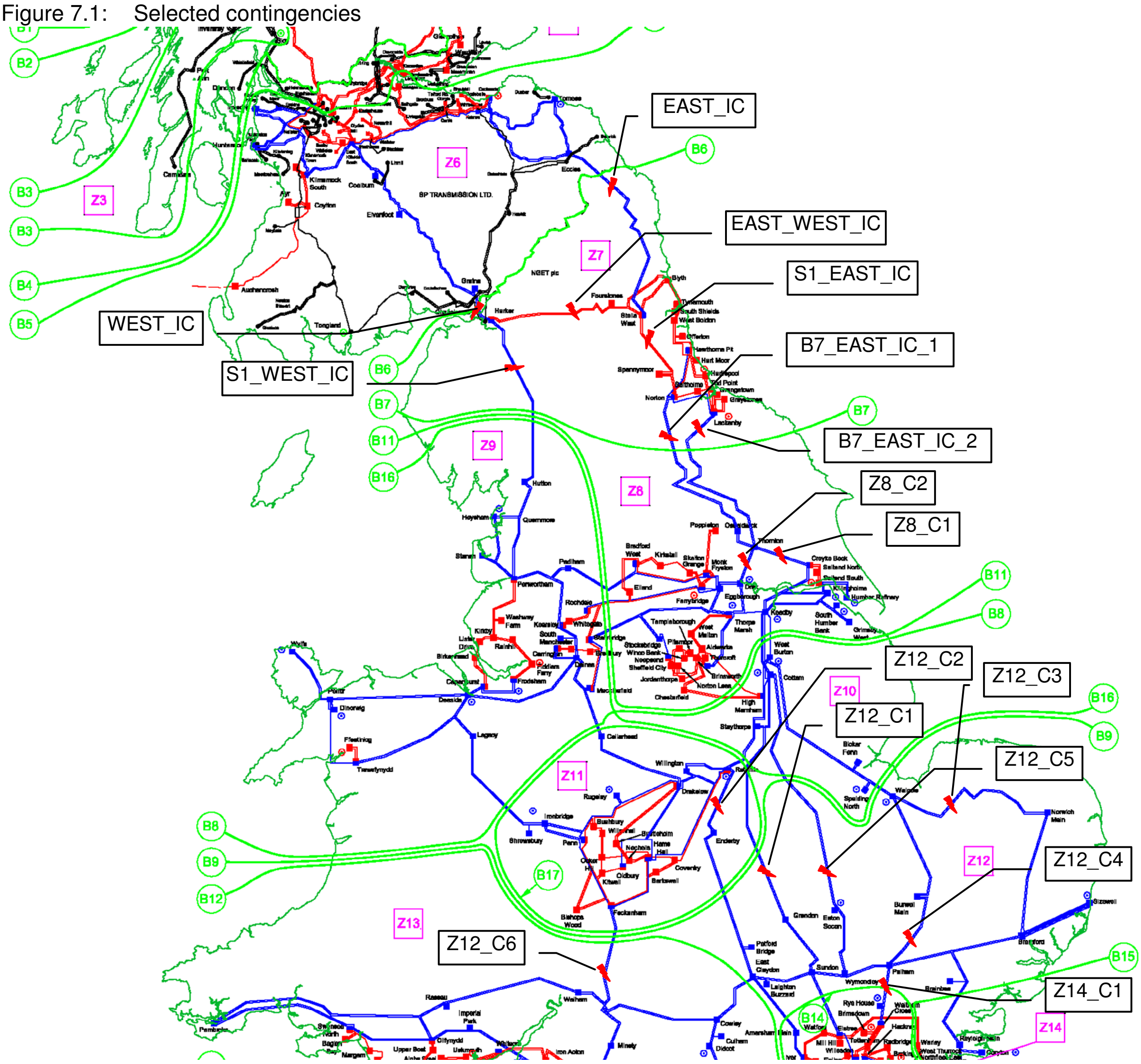
Contingencies 1 and 2 simulate the loss of the Western and Eastern inter-connectors, respectively. During the validation phase of the dynamic model, these contingencies were demonstrated to cause the separation of the UK transmission system into two non-coherent sub-systems.

Contingencies 3, 5, 6 and 7 were chosen for investigating double contingencies affecting the North-South transmission corridors in the region south of the B6 boundary (Scottish Power - NGET boundary) and across the B7 boundary (See Figure 7.1).

Contingency 4 simulates the loss of the double circuit tie between the Eastern and the Western Interconnectors immediately below the B6 boundary. Along these sections of the transmission network the introduction of FACTS devices or indeed the conversion of the AC circuits into point-to-point HVDC links may demonstrate to a fuller extent the benefits these technologies may provide from the point of view of enhancing the transmission capacity.

Contingencies 8 and 9 were chosen to investigate the system response to double faults on circuits located in system zones with more than two North-South transmission corridors. Contingencies 10, 11, 12 and 13 simulate the loss of double circuits in the UK system zone 12 where five main North-South transmission corridors can be identified that supply the main 400 kV ring surrounding London area). In this zone a suitable candidate for the deployment of a Multi-Terminal HVDC link through conversion of an existing AC transmission double circuit was identified. This is the 400 kV double circuit Cottam-Eaton Socon-Wymondley. Finally, contingency 14 simulates the loss of a double circuit immediately below the integral 400 kV ring surrounding the greater London area.

Figure 7.1: Selected contingencies



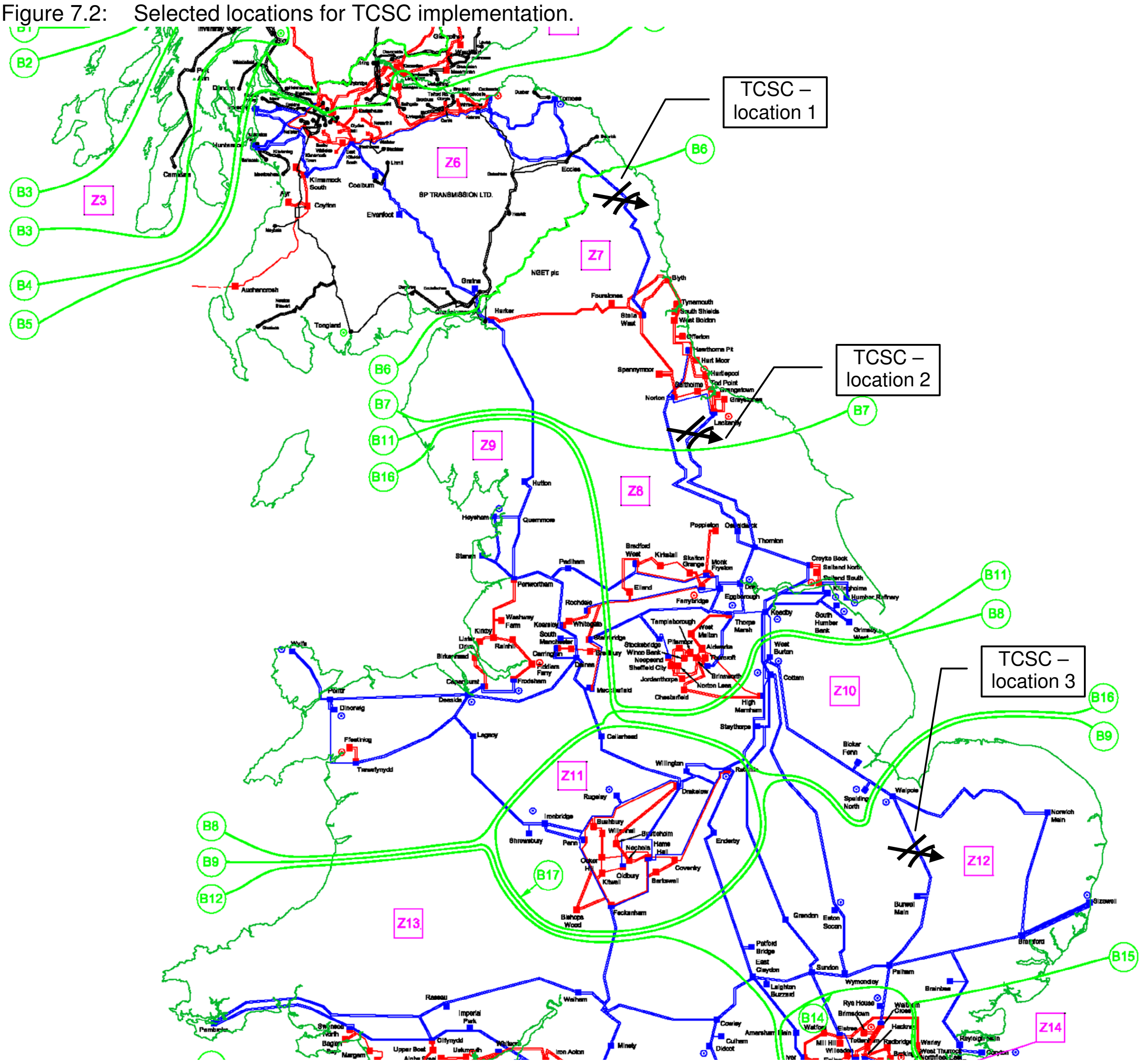
7.1.4 FACTS Studies

The following locations (See Figure 7.2) were chosen for the investigation of the performance of Thyristor Controlled Series Capacitors (TCSCs):

- **Location 1:** Double circuit Eccles - Stella West (along the Eastern Interconnector crossing boundary B6). The location is the same as that used in Scenarios 1A and 1B for the HVDC studies described below;
- **Location 2:** Double circuit Lackenby - Thornton (along the Eastern Interconnector crossing boundary B7). The location is the same as that used in Scenario 2 for the HVDC studies described below;

- **Location 3:** The double circuits along the Walpole-Burwell Main-Pelham corridor in Zone 12. The location is parallel with the location of the lines used in Scenario 3 for the HVDC studies described below;

Figure 7.2: Selected locations for TCSC implementation.



The selection of these locations for the TCSC studies was influenced by the desire to co-ordinate the FACTS device investigations with those being carried out for the implementation of Multi-terminal HVDC links. The implementation of the HVDC links took a leading role in the selection because the AC circuits suitable for conversion to HVDC were more challenging to identify. Locations 1 and 2 cover known transmission capacity constraints in the UK system. The third location was selected along one of the five North-South transmission corridors crossing the Midlands to South system boundary B9 (See Figure 7.2); this double circuit is especially suited for investigation of the potential deployment of a three-terminal HVDC link.

The selection of locations for investigation of Static VAr Compensators (SVCs) and STATic synchronous COMPensators (STATCOMs) was carried out by using PSS/E load flows to implement an analytical technique based on introducing supplementary injections of reactive power at selected nodes and re-solving the load flow with a view to calculate the voltage magnitude variation compared with the original scenario. The voltage sensitivity to reactive power could then be calculated as the voltage magnitude variation dV divided by the injected reactive power dQ. Since an objective of the study was to investigate the transfer capacity of the Grid, forty 400 kV buses in the west and east corridors (zone 6, 7, 8 and 9) and in the major load areas of zones 10 and 12 were selected for the sensitivity analysis.

The test results showed that the weaker buses are in zone 6, 7, 8 and 9 and that the buses in zone 10, 11, 12, and 14 are generally very strong, and that the east corridor is stronger than the west corridor. From the test results 4 buses were selected as prospective locations of SVC and STATCOM implementations. They are:

- 25770 COAL4
- 5920 HUTT4N/4M
- 5895 HARK2J/K
- 760 FOUR20

Based on the above reactive power sensitivity analysis the following initial study cases were used for the performance evaluation of STATCOMs and SVCs.

STATCOMs:

- Case 1. STATCOMs on both Harker 275 kV busbars (HARK2J, HARK2K)
- Case 2. STATCOMs on both Harker 275 kV busbars (HARK2J, HARK2K) and Coalburn 400 kV busbar (COAL40).
- Case 3. STATCOMs on both 400 kV Hutton busbars (HUTT4M, HUTT4N) and Coalburn 400 kV busbar (COAL40).

SVCs:

- Case 1. One SVC implementations at 5895 HARK2J
- Case 2. Two SVC implementations at 25770 COAL40 5920 HUTT4N
- Case 3. Two SVC implementations at 5895 HARK2J 760 FOUR20

The results from the FACTS simulation studies are discussed in Section 7.2 together with those from the HVDC studies.

7.1.5 HVDC Studies

Transient stability and power flow analysis were performed to assess and compare the performance of the HVDC and AC schemes for the scenarios described below. The analyses were performed for Voltage Source Converter (VSC) HVDC and Line-Commutated Converter (LCC) HVDC schemes. In addition, the

Unit Interaction Factors (UIF) were calculated for generators nearby to the HVDC links to assess the potential for oscillatory interactions in the form of sub-synchronous resonance (SSR). Finally, a brief study was performed to investigate the impact of HVDC lines on neighbouring AC lines.

The four scenarios were chosen for the investigation of the performance of HVDC schemes. The corresponding positions in the UK transmission system where the HVDC links were located to replace or enhance controllability of HVAC transmission circuits are shown in Figure 7.3.

- Scenario 1A: This scenario looked at converting the Eccles - Stella West 400 kV AC double circuit (the Eastern Interconnector) into two two-terminal bi-polar HVDC links. The scenario investigated the potential for transmission capacity improvements in zones 6 and 7 across system boundary B6. The converted line is the same as that used in Location 1 for the FACTS studies described above.

- Scenario 1B: This scenario looked at installing a back-to-back VSC HVDC link at Stella West on one circuit of the 400 kV double circuit AC Eastern interconnector, and a second back-to-back VSC link at Harker on one circuit of the 400 kV double circuit AC Western Interconnector. As for Scenario 1A, this scenario also investigated the potential for transmission capacity improvements in zones 6 and 7 across system boundary B6.

- Scenario 2: This scenario looked at converting the 400 kV double circuit AC line from Lackenby to Thornton into two two-terminal bi-polar VSC or LCC based HVDC links. The scenario investigated the potential for transmission capacity improvements in zones 6, 7 and 8 across system boundary B7. The converted line is the same as that used in Location 2 for the FACTS studies described above.

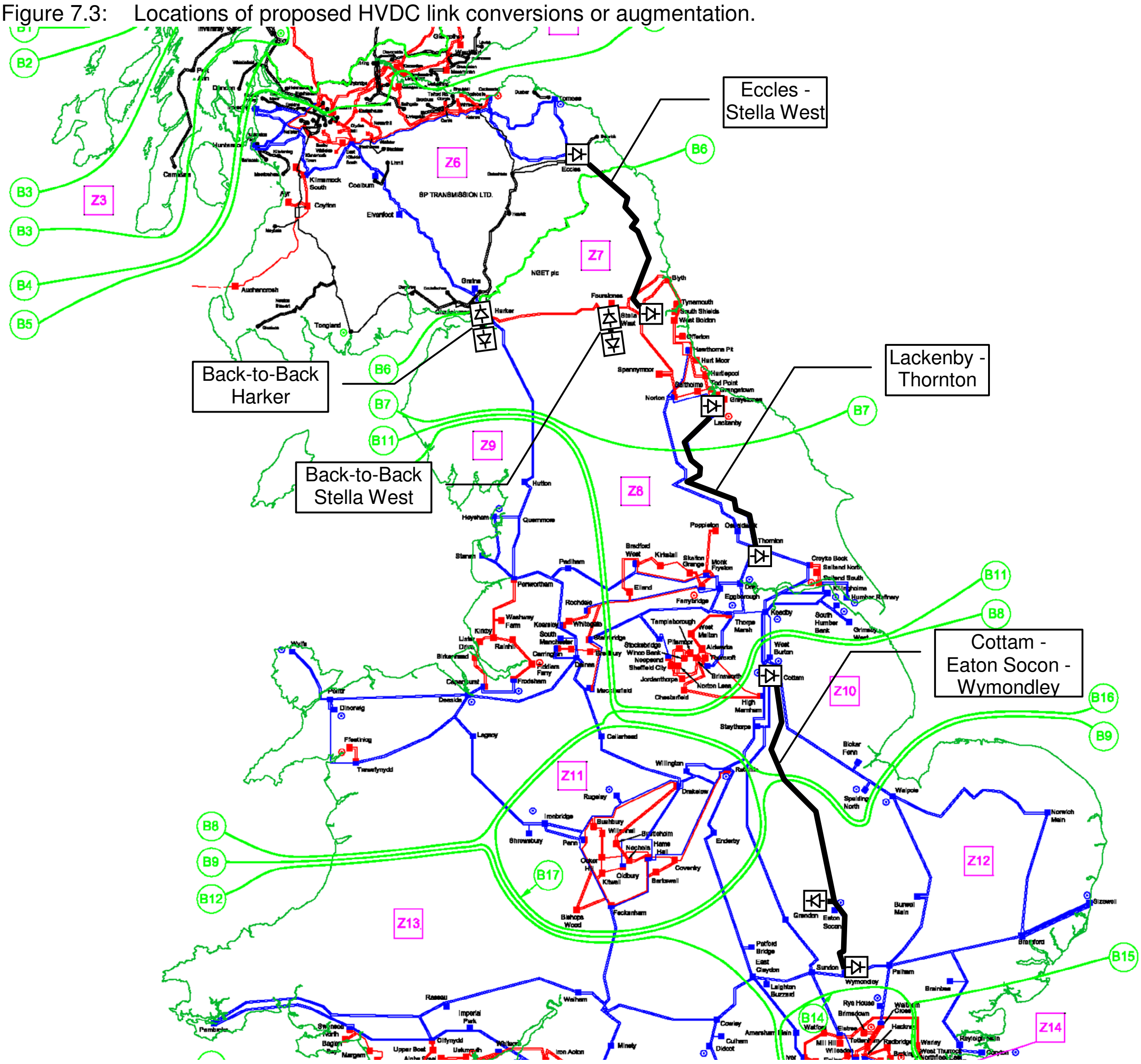
- Scenario 3: This scenario looked at converting the 400 kV double circuit AC line from Cottam to Eaton Socon to Wymondley into two three-terminal bi-polar VSC/LCC based HVDC links. The scenario investigated the potential for transmission capacity improvements in zones 10, 11 and 12 across system boundary B9. The converted line operates in parallel with that used in Location 3 for the FACTS studies described above.

The results from the HVDC simulation studies are discussed in Section 7.2 together with those from the FACTS studies.

7.1.6 Controllers

The control techniques used in the studies are simple and robust techniques and are referred to as conventional control. They are the most commonly used control algorithms in the transmission industry. This proven approach is also used to control the FACTS devices. The parameters of the controller are determined iteratively by “trial and error” using multiple simulations. The controller parameters are tuned at a given operating condition. The parameters remained unchanged when the operating condition changes. However, the non-linear nature of FACTS devices and the other power system elements as well as the uncertainties that exist in the system make it difficult to design an effective controller for the FACTS that guarantees fast and stable regulation under all operating conditions. This problem has led to academic and research studies of other novel control techniques such as adaptive controllers and non-linear controllers for power system stability control. These are discussed in the study report, Reference 3.

Figure 7.3: Locations of proposed HVDC link conversions or augmentation.



7.2 Findings from System Integration Studies

7.2.1 Thyristor Controlled Series Capacitor (TCSC) Conclusions

The deployment of TCSCs on selected transmission corridors may improve the system's ability to recover to stable operation following the system's dynamic response to selected double contingencies under certain operational circumstances. The rapid control of circuit impedance within carefully engineered limits was shown to mitigate the loss of significant transmission capacity across critical boundaries of the UK transmission system.

The selection of the TCSC rating has to be adapted to the insertion location through engineering judgement. A low set point for the line reactance compensation may not yield enough damping to stabilise the system after a large disturbance. A higher set point value close to the upper reactance limit can saturate the TCSC. The TCSC tuning for selected locations across the UK transmission system indicated that a middle range of the initial set point, that is 45-50 % compensation, seemed to work well.

The parameters of the TCSC controller require careful tuning which is usually carried out through dynamic simulations. The controller gain is particularly sensitive to the location of the TCSC installation. Improper gain setting can easily saturate the TCSC controller thereby losing dynamic control.

The TCSC capability is however limited by the characteristics of the transmission circuit into which it is inserted. Therefore the system may not always benefit from their presence in the case of some large perturbations.

TCSCs can directly facilitate the increase of power flows closer to the AC line's thermal capability realising an improved usage ratio while providing improvement of the transient stability margin and means of damping power oscillations. The last two features of TCSCs are especially relevant in situations when system stability is the constraining factor against higher power flows across main transmission corridors.

7.2.2 Static Synchronous Compensator (STATCOM) Conclusions

The deployment of STATCOMs may provide benefits concerning the UK transmission system dynamic response to selected double contingencies assuming certain operational circumstances. Multiple site deployment of STATCOMs was demonstrated to improve the dynamic behaviour of the system when large disturbances such as loss of transmission corridors are experienced. The rapid reactive power support delivered by adequately tuned STATCOMs plays a major part in the system recovery to stable operation. The coordinated control of the STATCOM devices is not required to achieve the full functionality of the scheme.

STATCOM controllers require location-specific tuning of the gain and some time constants so as to realise the full potential of the devices. Faster reactive power support and a gain that avoids the saturation of the output signal, when the input signal is 'large', are the preferred tuning options.

STATCOMs do not directly increase the transmission capacity but they have the potential of unlocking unused transmission capacity due to stability limits. The lack of available power transfer capacity within the areas adjacent to a section of the UK transmission system crossed by critical transmission corridors may not be mitigated by STATCOM deployment even at multiple sites.

7.2.3 Static VAR Compensator (SVC) Conclusions

The deployment of SVC devices, even at multiple sites, does not have the potential to mitigate the consequences of large perturbations affecting the main transmission corridors in the UK transmission system. The SVC deployment only stabilizes the voltage at weak nodes in the system and improves the voltage profile in areas adjacent to the SVC location during transient system conditions that impact the system transfer limits.

The SVC characteristics were tuned following best practice procedures. In order to achieve a reasonably fast response with low overshoot, the time constant was selected so that a phase angle of 110 -120 degrees was present at the cross over frequency. The dynamic simulations showed that the even with tuned parameters, the effect of SVCs is very limited when compared with the performance of STATCOM and TCSC devices at the same locations.

7.2.4 HVDC Conclusions

The conversion of selected transmission corridors from AC to HVDC (either LCC or VSC) may improve the system's ability to recover to stable operation following the system's dynamic response to selected double contingencies under certain operational circumstances. Both the HVDC options can use the fast power controllability inherent to HVDC to boost the power flowing in the converted line by use of a special protection system (SPS). By using automation algorithms an SPS processes power flow information and status data from adjacent substations that are interconnected by parallel HVAC transmission circuits to determine the control settings on the HVDC converters necessary to mitigate the effects of HVAC transmission circuit outages on system stability.

The conversion of some transmission corridors from AC to HVDC may result in post contingency thermal overloads of nearby transmission lines that would not have been overloaded in the AC arrangement. This is because when a neighbouring AC line trips, an AC line automatically adjusts/shares power flow, however HVDC power will stay the same unless changed by its control scheme. The resulting overloads could be mitigated by adjusting the post-contingency power transfer on the HVDC line; however this would either require an SPS or operator intervention. Both approaches would increase the operation complexity of the transmission system accompanied by increased requirements for fast multi-party bi-directional communication. Such complex operational arrangements that rely on remote data and information transfers are not welcomed by transmission system operators.

For some transmission corridors, installing a back-to-back VSC HVDC link on one circuit of each of the double circuits, while leaving the other circuit unchanged showed similar benefits to the system as those provided by the full conversion to HVDC. This would potentially be an attractive option since it would not require the transmission line itself to be converted to be suitable for HVDC operation.

8. Social and Environmental Impacts

8.1 Summary of Work Carried Out

The majority of the work covered by this section was carried out under WP1 Task 5 and is reported in detail in Reference 5. In accordance with the scope of work, with the exception of consideration of CO_2 implications, the assessment of the environmental impacts was limited to FACTS devices. However note that many of the findings apply equally to HVDC schemes. The potential impacts of HVDC schemes were addressed under WP2 Task 3 (Reference 7).

A review was made of the following areas relevant to the assessment of the social and environmental impacts of the FACTS devices:

- The planning and consenting requirements for traditional means of increasing the capacity of the grid (new overhead lines or cables) and those that would be required by use of the FACTS technologies.
- Any particular requirements associated with special sites such as world heritage sites or sites of special scientific interest.
- National Grid's site selection guidelines, including the Holford Rules for the routing of overhead lines and the Horlock rules for the location of substations.
- The requirements of the Scottish Network operators.

The environmental issues associated with the FACTS technologies during the construction and operational phases of the proposed infrastructure projects were assessed covering ecology and nature, landscape and visual impact, planning policy, traffic and transport, cultural heritage, electromagnetic field intensity, air quality, hydrology, land and land use, and noise.

Consideration was given to the potential impacts of FACTS schemes on the carbon balance. This took the form of the development of a basic concept diagram of a generation/transmission system and the use of the diagram as a framework for discussion of the possible impact of the FACTS devices covered by the study on CO_2 emissions. In Reference 10 a CO_2 emission reduction figure of 430g CO_2/kWh quoted by Renewable UK (previously known as BWEA) was used to provide an estimate of the CO_2 savings that might be achieved per additional GW of wind generation capacity.

8.2 Findings

All the FACTS options considered are similar in that they involve an increase in substation size but do not require any retrofit of overhead conductors, pylons or insulators. (Note that the FACTS options are different to the HVDC schemes in this respect since the HVDC schemes, which involve the conversion of an existing AC line to DC, require the insulators of the existing transmission line to be replaced). Options 1, 2 and 3a (SVC, STATCOM and a TCSC when located at an existing substation) all involve additional equipment to be installed adjacent to existing substations although the footprint of that equipment varies.

Option 3b (TCSC when located at a new site in the midpoint of an existing transmission line) requires equipment to be installed at a new site to be constructed midway along the line. **Table 8-1** provides a summary of the potential impacts associated with each technology type, however note this is provisional and will ultimately depend on site specific considerations.

Table 8-1 Summary of Potential Environmental Impacts

Aspect	Option 1 SVC	Option 2 STATCOM	Options 3a TCSC	Options 3b TCSC
Ecology, Cultural Heritage, Hydrology, Contaminated Land, Land use.	Largest footprint of options involving substation extensions and therefore the greatest potential to impact on habitats		Smallest footprint and therefore the least potential to impact on habitats	Requires development of previously undeveloped site. Also likely to require new access road in addition to substation site. Overall this is the option with the greatest potential for damage.
Operational Noise	Not Likely to be significant for any of the options under consideration			
Construction Noise	All options under consideration are comparable			
Landscape and Visual	Largest footprint which will require the greatest level of screening	Significant proportion of equipment housed indoors which is preferable visually	Smallest footprint however unusual equipment may be more noticeable by general public if not suitably screened.	As for Option 3a
Air quality	Not Likely to be significant for any of the options under consideration			
Waste	All options under consideration are comparable			
Access	May be some upgrading to existing access	May be some upgrading to existing access	May be some upgrading to existing access	Likely to require a new access road. Access for construction vehicles less certain. Overall this is option has the greatest potential for access issues
Traffic Management	All options under consideration are comparable			
Socio-economics	All options under consideration are comparable			
EMF	Dependant on site configurations but in all situations mitigations would be put in place to ensure public and occupations exposure meets guidelines.			

From an environmental perspective FACTS options are a significantly more attractive way of providing additional capacity than the traditional means of capacity expansion by building a new line. A new line will include a new substation with equivalent impacts to those associated with the FACTS options. However, there would be also be the construction and operation of the overhead line or underground cable. For similar reasons the FACTS options have advantages over the HVDC options since the impacts associated with re-insulating the transmission line are avoided. Table 8.2 gives the differences between the two traditional options, new overhead line and new underground cable compared to the impacts associated with the implementation of a FACTS solution.

Table 8-2 Environmental Impacts of Overhead Lines and Underground Cables Relative to FACTS Impacts

Aspect	Overhead Line	Underground Cable
Ecology	Additional impacted areas along line route mainly during construction but also impacts on birdlife during operational life.	Additional impacted areas along cable route. Mainly temporary impacts during construction but some permanent on sensitive habitats such as peat or wetlands.
Operational Noise	Some additional impact due to corona hum	Similar to FACTS technology
Construction Noise	Additional impacted areas along line route	Additional impacted areas along cable route
Landscape and Visual	Very significant increase in impacts	Greater potential impacts than FACTS options
Air quality	Larger construction area but not significant	Larger construction area but not significant
Cultural Heritage	Additional potential for impacts along line route	Significantly higher potential for impacts along cable route
Hydrology	Greater impacts due to additional water crossing. Provided pylons are located away from riversides the additional impact should be minimum	Greater impacts due to additional water crossings. Cable crossing have the potential to disturb river and river ecology.
Contaminated Land	Additional potential for impacts along line route	Significantly higher potential for impacts along cable route
Land use	Additional land take for pylon locations.	Additional impacted areas along cable route. Route corridor sterilised from building permanent structures, and restricted planting ie. no trees or shrubs
Waste	Significant increase in excavated spoil volumes during construction	Very significant increase in excavated spoil volumes during construction
Access	Very significant increase in access issues along line route.	Very significant increase in access issues along cable route.
Traffic Management	Very significant increase in access issues along line route.	Very significant increase in access issues along cable route.
Socio-economics	Increase opportunities for job creation during construction and to a lesser extent during maintenance periods	Increase opportunities for job creation during construction and to a lesser extent during maintenance periods
EMF	Potentially more opportunity for exposure along the line route. However exposure limits will be within guidance levels.	Cables are typically buried 1 m below ground. However, although an individual standing directly above the cable would be closer than to an OHL, the design of the cable and its screens limits EMF to acceptable levels.

From a planning perspective a new overhead line would also require additional planning consideration as an EIA would be required as well as a Section 37 Consent in Scotland or a Development Consent Order from the IPC in England and Wales. An underground cable would not require planning consent except potentially for joint bays that would be required approximately every 500 to 800 m. As good practice an environmental assessment should be made as part of the route determination process.

When considering each candidate technology the characteristic that appears to have the most influence on the potential for environmental impacts is the associated footprint. Another important consideration is that all but one of the options would be sited alongside an existing substation while a TCSC scheme located in the middle of a transmission line requires the development of an entirely new site. The environmental impacts associated with the conversion of an existing line will be considerably less than those associated with the installation of a completely new transmission line, and this should make gaining consent for such conversions commensurately easier.

Construction of any of the candidate technologies is unlikely to result in a significant socio-economic impact. Employment opportunities will be created during the construction phase and where possible these jobs could be filled locally to the site. However these positions will only be short term and, as the substations are unlikely to be manned, no permanent employment will be created. Some economic benefits would be felt by the local community due to construction personnel spending in local shops, petrol stations, restaurants etc and there would likely be opportunities for local hotels to benefit, however this would also be a minor short term gain.

Another aspect to consider is the effect of the area on recreational value. This will be highly site specific and dependant upon the existing use of the land to be developed and the surrounding area, although the presence of the existing substations will most likely already have influenced the surrounding land use.

It is not possible to directly equate any increase in transmission capacity that may arise from FACTS devices (or HVDC schemes) with any particular change in CO_2 emissions. Any such changes are determined by the change in generation mix, which is not of itself a function of the grid transmission infrastructure. The utilisation of FACTS or HVDC schemes would impact directly on CO_2 emissions as follows;

- The CO_2 that is emitted as a result of the manufacture and installation of the devices.
- Any changes to CO_2 emissions that arise as a result of different energy losses from the FACTS devices.

An indirect affect on CO_2 emissions from increasing the capacity of the grid to carry additional power flows is that the increase may facilitate the connection of additional generation capacity. This additional capacity could be provided by renewable sources.

As far as onshore HVDC schemes are concerned, the potential impacts are generally independent of whether the scheme is configured in a point-to-point link or a multi-terminal configuration, since a multi-terminal link is functionally simply an extension of a point-to-point link. The potential environmental impacts of back-to back HVDC schemes are less since no interconnecting transmission line is required. Table 8-3 and Table 8-4 show typical converter station footprints using LCC and VSC technologies respectively.

Table 8-3: Onshore HVDC (LCC) Converter Station Footprints

LCC Converter Station Rating	Length [m]	Width [m]	Height [m]
± 500 kV 3000 MW Bipole	400	400	21
± 600 kV 4000 MW Bipole	400	400	22

Table 8-4 Onshore HVDC (VSC) Converter Station Footprints

VSC Converter Station Rating	Length [m]	Width [m]	Height [m]
± 200 kV 350 MW	80	32	13
± 200 kV 700 MW	90	65	16
± 300 kV 1000 MW	110	75	24

9. Technical and Non-Technical Barriers

9.1 Summary of Work Carried Out

The work on identifying the technical and non-technical barriers relevant to FACTS devices was carried out under WP1 Task 4 and is reported in detail in Reference 4. This work took as its starting point the device ratings that had been determined as necessary by the system modelling studies discussed in Section 7. For each device, a review was then made covering:-

- Possible technical barriers (control and/or operational issues, transformer requirements, losses etc)
- Any potential supply chain issues including the ability of the industry to commercially deliver the technologies
- Potential solutions to any issues raised.

The work on identifying the supply chain issues and barriers to the application of multi-terminal HVDC transmission in the UK transmission grid was carried out under WP2 Task 4 and is reported in detail in Reference 8. The approach taken in this task was to research written papers, contact suppliers, review associated web sites, extract and review information from past conferences, and hold discussions with other HVDC experts. Additionally, potential barriers were considered as part of the WP2 Task 2 assessment of the feasibility of multi-terminal HVDC in the UK Grid reported in Reference 7 (discussed in Section 6 of this report) and the WP2 Task 4 assessment of the impacts of multi-terminal HVDC in the UK Grid reported in Reference 8 (also discussed in Section 6 of this report).

The findings on barriers are presented below followed by consideration of supply chain issues (since these are in general common for FACTS and HVDC).

9.2 Technical Issues - Findings for FACTS Devices

9.2.1 SVCs

9.2.1.1 Maturity

SVCs have been available since the 1970s and have been successfully applied on the UK transmission system for over 20 years providing an output range of up to 225 MVAr per unit. They are considered as conventional technology that has been proven practically.

9.2.1.2 Required Ratings

There should be no major technical barriers to increasing the size of SVCs to the required ratings (indicated by the system modelling studies discussed in Section 7 to be of the order of ±450 MVAr), This rating could be achieved by connecting smaller SVCs in parallel. Very large SVCs such as the 720 MVAr (+575/-145) unit at Black Oak in the USA have been installed outside the UK. To be utilised in the UK network, a large SVC would be required to connect to the 400 kV network. This is not a technical barrier as a transformer is used to step up the SVC voltage (typically 13 to 36 kV) to the system voltage.

9.2.1.3 Transformer Size

Single unit ratings in excess of around 500 MVA may lead to transport problems for three-phase transformers and necessitate the adoption of single phase designs.

9.2.1.4 Footprint

The footprint of SVCs is a particular problem with very large areas required (up to double that of a similarly rated STATCOM). This is likely to remain a major issue, particularly with the large rated SVCs envisaged for transmission applications. It is possible to adopt ‘compact’ design configurations (for example, the +150/-106 MVAr SVCs at St Johns Wood substation (London) that occupy a relatively smaller footprint). However this can be expected to increase costs and may not be appropriate to a rural environment.

9.2.2 STATCOMs

9.2.2.1 Maturity

The use of STATCOMs is starting to increase with a number units ordered for UK projects, such as the London Box wind farm. Nevertheless, with the exception of NG’s East Claydon installation, UK experience with these devices is quite limited.

9.2.2.2 Required Ratings

The system modelling studies discussed in Section 7 indicated that the required size of an STATCOM required for the UK network would be of the order of ±450 MVAr. STATCOMs are shunt devices and the required capacity can be achieved by connecting multiple systems in parallel.

Devices of this rating are not presently available and so further development will be required to achieve a proven ±450 MVAr STATCOM.

9.2.2.3 Losses

Current STATCOM devices incur higher losses than an equivalent SVC. It is anticipated that developments in IGBT devices and commutation schemes will bring down STATCOM losses over time. Despite this, IGBT devices (and therefore existing and near future STATCOMs) can be expected to have higher losses than an equivalent SVC in the short to medium future. This is because switching losses dominate the overall losses, and IGBT devices would always have higher rates of switching than thyristor devices such as SVC (as thyristor devices will only have a switch on operation once per cycle). There is slight counter balancing by the losses incurred in the capacitors and inductors of the SVC, but the overall relative situation is still expected to remain unchanged for the near future.

9.2.2.4 Costs

The cost of a STATCOM is understood to be between 120% and 150% of the cost of a similarly sized SVC device. In the past in the UK STATCOMs have generally only been installed where an SVC device is not practical, such as where the space available is limited. There are also technical reasons to prefer STATCOMs over SVC devices such as the lack of resonant effects, ability to aid fault ride through performance and the higher controllability of output; however, historically in the UK, the main motivation for the use of STATCOM has been the smaller footprint.

The cost of installing a STATCOM may be reduced by the development of higher powered IGBTs which would reduce the number of components and hence project cost. It is likely that the cost of STATCOMs would also be reduced by a more wide spread application of these devices worldwide as this will introduce more economies of scale and competition into the market.

Capitalisation of the losses associated with the operation of a STATCOM could be a significant negative factor in the commercial evaluation of their possible installation in some situations.

9.2.3 TCSCs

9.2.3.1 Maturity

The UK is a relatively small country with a dense population; this has resulted in power stations being located near to one another and relatively near to load centres. This has meant that, by international standards, the UK does not have very long transmission lines and as such there has been no requirement for TCSCs in the UK network.

Elsewhere, TCSCs have been applied commercially for 20 years, although the number of developments has been limited as such experience with these devices is also quite limited. The TALA transmission scheme in India has two 110 Mvar TCSC devices connected to a line rated for 400 kV, and for a current of 3200 A. It has not been determined if TCSC with larger current ratings are possible.

9.2.3.2 Required Rating

The 3200 A rated TALA transmission scheme is comparable with some high rated lines in the UK and as such there should be no technological barriers to installing similarly rated TCSC devices in the UK network. However, National Grid's 400kV 'L6' type lines can have post-fault continuous ratings of greater than 5000 A, so this may present a possible barrier.

9.2.3.3 Control

TCSCs are used to control the power flow in a transmission line. In a complex transmission network, such as the UK, there are many parallel paths for current to travel; TCSCs can be used to control this. Where more than one TCSC is installed it will be necessary to co-ordinate the control to get the best balance of power flow. The manufacturers have developed control regimes to provide this but these have only been implemented in the case of two TCSCs connected to parallel lines. There is a lack of experience and willingness on the part of network operators to use more extensive automated co-ordinated control schemes for post fault (dynamic) conditions. The primary concern of the network operators is that the schemes will not be able to fully factor in all the complexities of the network. There are also concerns over the interaction with the control actions of control centre staff and their maintaining a clear understanding of how the network and all connected devices will behave.

These barriers could be overcome by initiating pilot schemes for co-ordinated control in the first TCSCs installed in the UK. This would give the network operator experience and confidence in the co-ordinated control schemes.

9.2.3.4 Cost

Where TCSCs would offer advantages, the lack of application in the UK to date has been due predominantly to the cost and the unacceptable size of the required footprint. These have generally forced the network operator to select an alternative solution; this could be another parallel line, upgrading a conductor or installing a quadrature booster. As with SVC schemes, the cost of these projects may eventually be reduced by the developments happening in power electronic devices discussed elsewhere in this report.

9.3 Technical and Non-Technical Issues - Findings for HVDC

9.3.1 Feasibility Considerations

The following findings relevant to technical barriers to the possible adoption of multi-terminal HVDC in the UK Grid arose from the feasibility review summarised in Section 6:

- Power quality issues such as harmonics do not present a barrier. The processes that lead to the production of harmonics are well understood as are the means of controlling them by harmonic filters. These sorts of issues would be addressed by detail design for the particular application concerned.

- A technical barrier to the conversion of an AC line to DC is that the line insulators have to be changed to ones designed for operation on a DC system. This is an expensive undertaking and the overhead line conversion cost is estimated to be approximately 75% of a new overhead line cost (See Section 6.2.3.4).

- XLPE cable is considerably cheaper than the alternative mass impregnated type but is only capable of 325 kV and 1500 A at present. This would limit XLPE cabled VSC schemes to +/- 325 kV, 1500 A, 975 MW.

- Presently the use of current source converter (LCC) technology in a multi-terminal HVDC system configuration is limited to three terminals due to technical difficulties such as increased control system complexity and DC current balancing between the converters.

- In principle, a multi-terminal VSC-HVDC transmission system can be extended to any number of terminals without increasing the converter power system complexity significantly. However, a highly co-ordinated control system is required between the converter stations and robust DC circuit breakers are required to improve the possibility of system recovery from DC faults or loss of converters. These both present significant technical challenges. The control scheme would require robust, reliable, high speed communication links between each of the terminals of the multi-terminal VSC-HVDC transmission system. However, these terminals would be separated by tens or even hundreds of miles. An indication of the scale of the challenge is that there are no such co-ordinated control schemes in existence or known to be planned. The challenges presented by the development of DC circuit breakers are discussed in Section 6.2.1.1.

9.3.2 Grid Impacts

The following findings relevant to technical barriers to the possible adoption of multi-terminal HVDC in the UK Grid arose from the review of possible impacts on the Grid summarised in Section 6:

- The change of an existing ac transmission line to an HVDC one would result in an increase in system losses.
- The reliability of an HVDC scheme would be expected to be lower than that of an equivalent ac scheme. Reliability can be improved at the design phase by incorporating redundancy in the critical components but this has cost and footprint penalties. (The reliability of a converted overhead line itself would be expected to remain the same after HVDC conversion since the conversion does not by itself introduce additional failure modes, but the converter stations would introduce additional sources of unreliability).
- Very high HVDC circuit ratings (of the order of 4 GW or more) would be required to achieve an improvement on the theoretical thermal transmission capacity of an existing 400 kV UK HVAC link. Such a rating is significantly in excess of present VSC scheme capabilities and would dictate the use of bi-polar LCC converters to replace each individual circuit of a double circuit HVAC link. This would have significant cost and footprint implications.
- The NG transmission system is often operated such that the post-fault loading on the overhead line circuits exceeds the long-term post-fault capability. In this case the short term overload capacity of the HVAC system is exploited after the fault has occurred to allow power transfers to be reduced (e.g. by automatic tripping of generating plant through an 'Operational Tripping' scheme or instructing reductions in generation output). This sort of capability is not possible with HVDC technologies in view of their limited overload capacity.
- In some circumstances, HVAC to HVDC conversion provides benefits such as enabling long distance power transmission, eliminating reactive power flows from long HVAC cable circuits and enabling asynchronous system connections. However, in view of the short transmission distances involved in the UK these would not be of benefit to the onshore UK transmission system.

9.3.3 Converter Issues

There are no technical barriers to the possible use of thyristor based LCC high-voltage DC transmission. It is a well-established technology with many installations in operation throughout the world and is available from a number of manufacturers including ABB, Areva and Siemens. The limits of this technology are well-known, namely high VAR consumption, large harmonic current emissions, and large installation size.

There are some technical barriers to the possible application of VSC based HVDC schemes:

- Higher losses.
- Limited voltages and powers at present.
- Unable to clear line faults. For a point to point system the AC side breakers must be tripped to clear the DC fault.

- For multi-terminal schemes a fast operating DC breaker must be developed..

9.3.4 Non-Technical Issues

Two non-technical barriers were identified by the review:

- The lack of a good concise reference source dealing with the major aspect of the various HVDC technologies with updated information on the capabilities and limitations of modern HVDC devices and schemes.

- Personal barriers to change. This can result in organisations preferring to continue to use old familiar design solutions rather than adopt new technologies.

9.4 ANM (Active Network Management)

Existing network management systems can be perceived as a barrier to the deployment of new technologies, particularly active network management. Studies of existing SCADA infrastructure indicate that there are fundamental limitations of existing systems associated with speed of operation, determinism in response times, reliability and resilience that would limit their applicability where the consequences associated with the failure of the system are large. Thus, it is not always possible to implement ANM on existing platforms and new measurement, communication and control systems may be required.

Conventional network reinforcements are typically designed for a lifetime of 40 years or more. ANM schemes are expected to have lifetimes similar to protection or SCADA and so may require replacement or upgrade earlier than a conventional reinforcement solution. This affects the calculation of overall costs but ANM offers additional flexibility and a way to achieve marginal increases in capacity at relatively low cost, providing a means of dealing with uncertainty in network planning.

9.4.1 Power Flow Management

As for other ANM technologies, the principle barriers to the deployment of active power management technologies are the lack of experience and confidence on the part of network operators and established approaches to generator connections, both commercially and technically, which are both tightly governed by regulations and industry-agreed frameworks. Depending on the circumstances there will be other more specific technical and operational barriers to deployment of power flow management.

9.4.2 Dynamic Thermal Ratings

A barrier to the application of dynamic thermal ratings is the disruption to existing assumptions and methods in planning and operation of the network. Dynamic ratings introduce variability to a parameter that was previously considered constant, although transmission and distribution network operators do already take account of time-dependent cyclic and emergency ratings. There can also be technical complications and additional cost due to the necessity of monitoring equipment and communications. Complications can arise in the identification of critical spans on overhead lines for variable meteorological conditions. Any system must also be robust to measurement and communication failure.

9.4.3 Voltage Management

Barriers to deployment of voltage management schemes include:

- The relatively tight range of acceptable voltages and the potentially large impact of distributed generation
- The complexity of the relationship between voltages at different parts of a network and the output of connected generation
- The rate of change of voltage and speed of response required

These barriers have not prevented some voltage management schemes being deployed but restrict the wider adoption of these methods. The barriers can be mitigated with improvements in technologies for measurement, computation and communications, and the deployment of faster and more flexible reactive compensation devices.

9.4.4 Demand Side Management

Barriers to the wider application of DSM are that it requires a contractual agreement between the network operator and the user defining the amount of load that can be removed or assigned to the user, and the modality of the control and tariffs and penalties applied. Other barriers include the need for a suitable communications and control infrastructure and the basic lack of availability of loads suitable for DSM.

9.5 Common Barriers

It was observed in the workshop that the current Grid Code and security of supply standards favour AC over DC, having been written with classical synchronous generators in mind. Thus the technical framework for the industry assumes the continuation of existing practice rather than encouraging greater use of FACTS or HVDC.

The cost of HVDC and FACTS schemes is a barrier given the existence of cheaper solutions that deliver the same capability.

A transmission system operator (TSO) may prefer to invest in new lines instead of FACTS or HVDC due to their limited experience in operating with FACTS and HVDC. There is very little accumulated knowledge regarding FACTS and HVDC within the sector.

There are difficulties and complexities in coordinating the control actions between the FACTS connected at different locations and between FACTS and HVDC.

The project has identified a range of barriers that restrict further use of the technologies. Within the multi criteria assessment activity of Task 7, by reviewing the barriers faced by each technology a single set of barriers was identified; some are specific to particular technologies but others are common to multiple technologies. The common barriers are listed below.

- High costs

- Limited deployment experience in the UK
- Lack of necessary technical skills in the UK
- Maturity level of the technologies
- Restrictions in the supply chain
- Lack of manufacturing standards or compatibility
- Footprint and other environmental constraints
- Regulatory constraints
- Technical performance in terms of losses/efficiency
- Technical limitations and operational constraints
- Negative impacts on quality of supply

9.6 Supply Chain Issues

9.6.1 SVCs

The major European transmission equipment manufacturers (ABB, Areva and Siemens) offer SVCs for transmission applications and have previously all supplied to the UK. Other Suppliers outside Europe have produced SVCs but have a limited UK track record.

The non-active components of SVCs (e.g. capacitor banks, air cored reactors, switchgear, instrument transformers, surge arresters etc) are commonly found in conventional substations and are manufactured in significant volumes around the world. There do not appear to be any major technical barriers to increasing production to meet future demand for SVC technology.

Although the application of SVCs in transmission systems is still relatively uncommon, scaling up the production of thyristor switching modules is also not seen to be a significant issue. The modules are assembled using components supplied from the semiconductor industry, production of which could be readily scaled up. Assembly and testing is on a module basis and does not require significant capital investment in plant.

9.6.2 STATCOMs

ABB and Siemens have commercially available designs “SVC Light” and “SVC Plus” respectively. Areva (soon to be Alstom) are presently developing a STATCOM that is anticipated to be commercially available relatively soon. STATCOMs have gained some market share in North America where American Superconductor offers a modular STATCOM under the name: “D-VAR”. However, the limited rating of the D-VAR would currently preclude its use in high-power applications. Other supply chain issues are as for SVCs.

9.6.3 Power transformers

The European manufacturing facilities for large power transformers has been under pressure in recent years (following a long period of rationalisation to address overcapacity in the industry). This has resulted in lead times in excess of two years from order to delivery. We anticipate that this position will ease in the immediate future due to new capacity coming on stream in Europe and transfer of production to other facilities outside Europe. Consequently the availability of transformers is unlikely to be a barrier to adoption of SVCs. Power transformers for HVDC schemes have their own very special requirements and thus may be subject to more challenging supply restrictions.

9.6.4 Specialist Engineering Resources

In our view, the major supply chain barrier to widespread adoption of SVCs is the limited availability of specialist engineering resources to design, install and commission these equipments. Due to the relatively low order base, scaling up capacity will be challenging and may take some time to deliver results. Furthermore, many of the skills that are relevant to SVC design are liable to be reassigned to HVDC transmission projects to help meet the expected demand in this area.

In addition to increasing the level of specialist engineering resources, the lack of engineering skills could be partly addressed if the UK were to adopt a ‘standard’ SVC design that could be applied anywhere on the system without significant project-specific design. Such an approach has already been adopted by NG, albeit for different reasons, in the procurement of re-locatable SVCs. Rather than being customised to a specific application, these were designed to a worst-case specification allowing them to be relocated in future to other parts of the network without modification. Although equipment costs would be increased by a standardisation policy (since the design would not be optimised for the application), there would be a saving in engineering costs and procurement lead times could be reduced.

9.6.5 Increasing World Wide Demand

In the last 5 years, the benefits of HVDC have become more appreciated worldwide. World demand for electricity has increased with some countries seeing increases in the order of 8% per year. China for example built 90 000 MW of new generation in one year alone. This increasing demand from very large schemes has already placed a strain and is likely to continue placing a strain on HVDC Suppliers.

9.6.6 Limited number of suppliers

There are only three viable suppliers for current source converters at present, ABB, Siemens and AREVA. The same three suppliers are also actively pursuing Voltage Source Converters. These three suppliers also produce AC FACTs devices and much of the AC Transmission equipment so as demand increases their engineering resources and manufacturing facilities are under even more stress and pressure.

Also the number of suppliers (ABB, Prysmain, Nexans, Silec) of DC underground cables is also limited and their order books are full for many months. Thus the cable may have to ordered early or the in-service date delayed for the project.

9.6.7 Sub-supplier and Raw material Issues

There are a limited number of sub-suppliers and this has resulted in longer deliveries and increases in costs. These sub-suppliers also service the AC Transmission market which is also under the same pressures. The volatility of commodity prices for copper, steel, and other raw materials, makes it more difficult to do comparisons between HVDC and AC transmission and it is likely most published information on this topic is out dated.

9.6.8 Limited UK capabilities in HVDC Supply, Installation and Maintenance

There is general limited capability with a lack of knowledge, good information and experience in applying HVDC Transmission in the UK. Part of the problem is that the technology is advancing so rapidly it is hard to keep up even if you work in the HVDC industry. The other part is that staff may be very knowledgeable and experienced in the AC industry and HVDC is a new and relatively unknown area to them. There is a real lack of good complete information on HVDC Transmission and how to apply it properly. Thus planners and consultants are potentially hesitant to recommend something that is outside their area of expertise.

9.6.9 Development Drivers

IGBT development is driven by the industrial drive industry (e.g. for moving trains or ships) and not specialised for FACTS or HVDC deployment.

Slow adoption of STATCOM devices is an issue. It has been estimated that SVC enquiries outnumber STATCOM enquiries by a ratio of 10:1.

9.6.10 Industry Standards

There is an absence of an industry wide standard across many of the separate FACTS and HVDC technologies and this should be addressed so that the risks incurred by TSOs when buying FACTs and HVDC are reduced. For example, there are many different types of static synchronous compensator (STATCOM). Similarly, different manufacturers produce other FACTS technologies according to different standards.

10. Multi-Criteria Technology Assessment

10.1 Summary of Work Carried Out

The work reviewed by this section was carried out under WP1 Tasks 6 and 7 and is reported in detail in References 5 and **Error! Reference source not found.**. The work consisted of the conducting of a multi-criteria assessment of the technology options; the assessment was based partly on the outcome of a workshop.

10.1.1 Workshop

A workshop was held to discuss the project activities and collect input from a wide range of stakeholders including researchers, manufacturers, network operators and the regulator. The main objectives of the workshop were to:

- Ensure all participants are informed about project activities and expected outcomes
- Consider the relative merits of the technologies under review
- Identify all issues that translate into benefits or barriers for the technologies under review
- Identify and prioritise assessment criteria
- Assess the range of opinions on uncertain, controversial and subjective issues
- Identify and assess technology development opportunities.

In particular, the workshop produced a list of development options and assessment criteria. These were subsequently revised for use in the multi criteria assessment:

The opportunities / options identified and used in the assessment were:

A. Support reviews of security and planning standards

B. Prompt changes in regulatory framework to change business drivers

C. Help to establish common standards and models

D. Support R&D in new switching devices for greater capability/performance, e.g. Silicon Carbide / Diamond

E. Commission work on new HVDC systems/topologies

F. Develop effective DC Breaker / Blocking Capability

G. R&D on coordination of HVDC in the UK

H. Support trials or demonstrations

I. Investigate use of energy storage to help solve ANM constraints

J. Develop condition monitoring and asset management tools for a network with increased power flows

K. Training and education, e.g. courses, conferences (HVDC, FACTS, ANM)

L. Replace or increase generator inertia or otherwise improve system dynamic response.

The assessment criteria developed in the workshop were drawn from the benefits and impacts ideas but were influenced by the project team to ensure certain issues were addressed. The assessment criteria were revised and refined following discussion with the ETI and further consideration of the development options and assessment method. The assessment criteria used in the assessment were:

1. Potential to enhance UK industrial capability and knowledge
2. Potential to reduce through-life costs of technology use
3. Potential to reduce the cost of electricity for consumers
4. Has a clear business case for all stakeholders
5. Potential to overcome or bypass problems with consents
6. Potential to enhance or accelerate Technologies Readiness Levels
7. Potential to reduce CO_2 emissions
8. More options and flexibility in network design and operation.
9. Impact on system security and reliability
10. Potential to enhance capacity of the existing network
11. Links with other developments or technologies.

10.1.2 Multi- Criteria Assessment

Following completion of the Workshop the multi-criteria assessment was carried out. This assessment:

- Used the outcomes of the workshop and the other tasks to perform an objective assessment of the technologies identified and examined
- Combined the results of quantitative and qualitative analysis with opinions gathered in the workshop

- Identified what was subjective and what reflected the range of opinions expressed at the workshop
- Provided a systematic, clear and consistent appraisal of the multiplicity of benefits and risks that supported recommendations on further work
- Identified the technology development options that address the most restrictive barriers and offer the optimal mix of benefits

The multi-criteria assessment was conducted using two spreadsheets, for development options and for technologies. Scores were assigned against each of the criteria and then these were combined with criteria weightings to produce overall scores. The spreadsheets allow for the easy modification of scores and weightings. The scores were based on the findings of the project and the workshop discussions. The criteria weightings were based on the preferences expressed by the workshop participants and then adjusted to reflect the sensitivity of the overall score to the weighting of different criteria.

The project covers a range of technologies, which fit into different categories and are related to one another in different ways. The technologies used in the multi-criteria assessment are listed below.

- HVDC: LCC
- HVDC: CCC
- HVDC: VSC
- DC breakers
- Series compensation: TCSC
- Shunt compensation: SVC
- Shunt compensation: STATCOM
- Phase shifting transformers / quadrature boosters
- Active power flow management
- Dynamic thermal ratings
- Active voltage management
- Demand side management
- Energy storage

The list of technologies includes all those within the scope of the project and those additionally considered through the work in other Tasks. The technologies are all explained in detail in the relevant Task reports. The list also includes DC breakers as they were identified as an important facilitating technology, and energy storage as it was identified as being complementary to active power flow management and of high potential value in a system with a large penetration of intermittent renewable sources.

The outcomes from the workshop and multi-criteria assessment exercise are discussed below.

10.2 Outcomes

The assessment proved quite difficult because of the multitude of options of different types. It was often not possible to directly compare one option with another because their purpose and characteristics were quite different. Nevertheless, an assessment has been performed and the results do reveal something of the priorities of the workshop participants, the impacts and difficulties associated with different technologies, and the courses of action that are seen as most likely to meet the objectives relating to network capacity, the connection of renewables and the reduction in carbon emissions.

For the technologies of interest a common set of barriers was identified and the development options considered in terms of the barriers they might help to overcome. This revealed that the suggested development options will together have the greatest impact on HVDC technologies, which is consistent with the emphasis on HVDC in the overall project. It must be recognised that development options like “support trials or demonstrations” will only influence the specific technologies that are involved in the trial or demonstration. However, the analysis reveals that the development options expected to have the widest ranging impact, and so perhaps offering lower risk paths for investment, are:

- Support trials or demonstrations
- Help to establish common standards and models
- Support R&D in new devices for greater capability/performance
- Training and education, e.g. courses, conferences

The assessment results indicated that the assessment criteria would be fulfilled most effectively by pursuing the following development options:

- Investigate use of energy storage to help solve ANM constraints
- Prompt changes in regulatory framework to change business drivers
- Commission work on new HVDC systems/topologies
- Develop effective DC breaker of blocking capability

Notably, these top four best-performing options are all different from the top four identified as tackling common barriers. This shows that trying to satisfy the general objective of tackling barriers will not necessarily meet specific objectives, as reflected in the assessment criteria.

The assessment results indicated that the assessment criteria are best satisfied by the following technologies:

- Active power flow management

- DC breakers
- Energy storage
- HVDC: VSC

The high score for the development option of investigating energy storage and for energy storage as a technology reflects the discussions at the workshop, where energy storage was highlighted as being of particular interest and very relevant to the challenges faced in connecting more renewables to the existing system. It is an important outcome of this work that energy storage did not feature amongst the technologies identified for consideration but when industry stakeholders discussed the objectives and context for the assessment energy storage was highlighted as being of value.

The regulatory framework is under constant review but the multitude of stakeholders in the electricity sector means it is difficult for everyone to be satisfied. The high score for this option reflects the sense of frustration, perhaps most notably amongst engineers, that network companies are unable to be bold and take risks with new technologies and methods that might address some of the problems faced. Few think that network companies should be given free rein to try whatever they want, and incur large costs in so doing, but arguments persist about the balance of regulatory incentives and the need for constant fine-tuning according to the prevailing priorities.

Active power flow management is a prime example of where the technology is mature but the barriers to its use lie mainly in the regulatory and commercial framework, and what this means for the business drivers of different stakeholders. The problems associated with constraint payments and the principles to be applied in sharing network access are mainly commercial. It is perceived that the technology could be effective in meeting the assessment criteria, including enhancing network capacity and allowing more renewables to connect, but some changes to the regulatory environment may be necessary for this solution to be used widely.

For HVDC the development options that scored most highly were those concerned with new systems/topologies and the development of an effective DC breaker. DC breakers were one of the highest scoring technologies and the assessment results suggest that VSC is favoured over the older HVDC technologies. This reflects the view that the fundamental power electronic building blocks are available that can be used in series and parallel as necessary to achieve the desired ratings and so there is little pressing need for new devices from that point of view. New devices might help to improve efficiency or reduce manufacturing costs but are not expected to directly affect overall ratings. VSC promises to deliver much in terms of flexibility, control and the potential to operate multi-terminal systems. The challenge is at the systems level where all components must be made to work together and operate effectively within the existing AC network. DC breakers are seen as crucial for the deployment of multi-terminal HVDC and an essential element of the new systems/topologies that must be defined.

11. Opportunities

This section lists the research, development and possible investment opportunities that have been identified during the conduct of the study including the workshop. As agreed with the ETI no attempt has been made to judge whether or not particular opportunities may be of interest to the ETI. This judgement has been left for the ETI to make.

Devices/Materials

1. Increase the present current handling capability of IGBTs beyond 1500 A. This requires better packaging techniques such as the development of improved, multi-wafer packaging. Advances in this technology need to be targeted towards the power systems industry instead of focussing towards smaller, lower power electronic applications.
2. Develop designs of composite circuits that do not force all the current through IGBTs but shares some of the power flow burden with thyristor schemes (which can have a higher current rating) and forcing switching, or other intelligent operations such as harmonic compensation, to occur within the IGBT branches. This hybrid approach would allow better harmonics compensation and fast switching at the same time.
3. Improve the present voltage operating limits for IGBTs and thyristors of 6.5 kV and 8 kV respectively. This would potentially reduce the need to stack devices in series to achieve higher voltage operation.
4. Improve the ability of power electronics to deal with transient overloads.
5. Research into new semiconductor materials may achieve significant advances in voltage rating, operating temperature, and reduced switching losses. Silicon Carbide and diamond substrates are envisaged for the future as they can tolerate much higher temperatures and faster switching speeds.
6. Develop devices which are optimised for multi-level converter applications. In these devices, switching loss is no longer critical because of the reduced switching frequency and so optimisation between switching and conduction losses will differ from conventional applications.
7. Collect the appropriate statistical data needed to allow a substantiated reliability assessment of voltage source converters (VSC) to be carried out.

FACTS

8. Perform detailed studies into the potential opportunities for series compensation to be applied on the interconnected, 132 kV “sub-transmission” network in England and Wales, extending the type of analysis that has been performed for the transmission network and building on the ANM-focused assessment of distribution constraints performed in this project.

HVDC Breakers and Protection

9. The control of DC faults will require the development of DC circuit breakers at converter stations that can block DC line faults. This hardware must have sufficiently fast operation to prevent secondary failure of converter power electronics.
10. Protection systems need to be developed that can identify and isolate faulted sections of multi-terminal HVDC networks. These protection schemes must be integrated with hardware that can achieve rapid re-energisation of the DC network.

Active Network Management (ANM)

11. There are opportunities for specific ANM technologies to be fully tested and then developed into products that can more easily be rolled out more widely.
12. There is a potential to integrate power electronics devices into ANM to perform more advanced functions.
13. Different access right rules need to be developed, offering the opportunity to change the priority scheme for generation curtailment to rules based on the environmental impact of generators.
14. The potential for the adoption of Power Flow Management techniques would benefit from:
    - Pilot projects for providing experience and confidence
    - Development and adoption of flexible industry standards and frameworks
    - Development of tools for facilitating planning and associated studies.
15. The potential for the adoption of dynamic thermal rating techniques would benefit from:
    - The development of a broadly accepted standard for operating the network with a non-firm transmission capacity
    - The commercial development of dynamic thermal rating solutions integrated with current network technologies (e.g. SCADA, substation relays)
16. The potential for the adoption of voltage management techniques would benefit from:
    - Improvements in technologies for measurement, computation and communications.
    - The deployment of faster and more flexible reactive compensation devices.
17. The potential for the adoption of Demand Side Management techniques would benefit from:
    - Economic incentives such as tariffs that provide an incentive for customers to accept partially flexible consumption.
    - The development of appliances and industrial processes allowing a degree of flexibility in energy consumption.
    - The roll-out of smart meters and the installation of suitably controllable loads.
    - The increased use of electrical heating and cooling, which offers scope for exploiting thermal inertias and energy storage.
    - The anticipated expansion in the use of electric transport.
    - Developments in information and communication technologies making it cheaper and easier to implement the necessary control systems.
18. The potential for the connection of additional Distributed Generation would benefit from:
    - Protection and control systems to be integrated in combined interface units that provide cost-effective control without sacrificing the safety provided by protection.
    - Active distribution networks, which will in turn require monitoring and control akin to that currently used in transmission networks.

- Network simulation and analysis tools to allow DNOs to manage generator-network interactions and a range of system issues like constraints, outage co-ordination, stability and security, and system recovery and restoration.
- Further development of DNO's capabilities in direct network control issues like voltage and power flow.

Demonstrator Projects

19. Each of the technology areas would benefit from demonstrator projects. These would provide much needed practical experience in all aspects of the technology and allow them to be resolved before implementing the schemes more widely.

Future Networks

20. Research into the facilitation of trans-national pooling of generation. Such systems provide significant research and development opportunities. (This is the subject of a number of on-going state funded research programs (including EPSRC Supergen FLEXNET and the EU 'Twenties' consortium).

Energy Storage

21. The development of highly efficient energy storage technologies would complement the connection of greater levels of intermittent renewable energy to the UK Grid network and would help minimise the amount of generation curtailed with ANM.

Regulations

22. Carry out a review of existing regulations such as the NET SQSS to ensure that requirements written for previous generation technologies and transmission and distribution system supply models do not prevent the implementation of the FACTS, HVDC and ANM technologies.

Supply Chain

23. There should be development of standardised products in each technology area. This would reduce both manufacturing and design cost.

Education/Training

24. Promotion of conferences and seminars on HVDC Transmission technologies. These would help bring an awareness of the various changes and advantages of HVDC.
25. The publication of an up to date application guide and reference book on the FACTS and HVDC technologies.
26. Promotion of the introduction of HVDC Transmission at the undergraduate level in the university. This would provide a supply of graduates with a basic understanding of HVDC and prepare them for a possible career in HVDC.

12. References

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