Programme Area: Energy Storage and Distribution

Project: Network Capacity

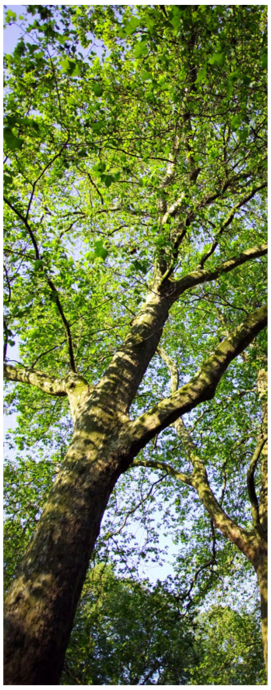
Title: Impact of Active Power Flow Management Solutions

Abstract:

This document reports the results of an initial literature review assessing the capabilities and impacts on the transmission and distribution systems of Active Network Management and related technologies. This includes discussion of the challenges and opportunities arising.

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 2 Final Report
Impact of Active Power Flow Management Solutions

July 2010
The Energy Technologies Institute (ETI)

Mott MacDonald

The ETI Energy Storage and Distribution Programme

WP 1 Task 2 Final Report
 - Impact of Active Power Flow Management Solutions

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Issue and revision record

Revision	Date	Originator	Checker	Approver	Description
01	8th April 2010	R. Ball	K. Smith	R Ball	Original Issue
02	30th July 2010	R Ball Ray Ball	M Scutariu	R Ball Ray Ball	Revised in line with ETI comments.

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Content

1. Summary

1.1 Background

Mott MacDonald has been commissioned by the Energy Technologies Institute (ETI) to carry out the ETI's Network Capacity Project. This project is aimed at supporting the ETI's overall goal of accelerating the deployment of technologies that will help reduce greenhouse gas emissions and thus help achieve climate change goals. Specifically the project will assess the feasibility of two potential areas of development to improve the operation and increase the capacity of the UK onshore T&D systems. The outcome will be a thorough, coherent and well presented analysis that will enable the ETI to make informed decisions as to where future work in the programme should be directed.

- The first area of the project is 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 concentrates 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 will provide guidance in respect of technology development opportunities. The work has been structured into two packages.

- Work Package 1 concentrates on the novel technologies applicable to the existing HVAC grid with the potential to release capacity in the UK T&D networks. The work in this package comprises:
  - Task 1 – A literature review of the relevant power electronic technologies.
  - Task 2 – An assessment of the impact of active power flow management solutions.
  - Task 3 – Transmission system and integration studies that involve modelling of the various technologies integrated into the UK grid.
  - Task 4 – An assessment of barriers to development of the novel technologies.
  - Task 5 – A review of the social and environmental aspects associated with the novel technologies.
  - Task 6 – A "Technology Options, Benefits and Barriers" Workshop.
  - Task 7 – A "Multi Criteria Assessment" of the novel technologies.
  - Task 8 – The preparation of a final report for Work Package 1.

- 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:
  - Task 1 – A feasibility assessment of onshore multi-terminal HVDC Schemes in the UK.
  - Task 2 – An assessment of the performance of multi terminal HVDC systems integrated into the UK grid carried out by modelling studies.
  - Task 3 – An assessment of the possible impacts of multi-terminal HVDC schemes on renewable energy deployment and security of supply.
  - Task 4 – A review of technical and non-technical barriers and supply chain issues that could impede possible application of multi terminal HVDC schemes in the UK.
  - Task 5 – The preparation of a final report for Work Package 2.

1.2 Work Package 1 Task 2 Final Report

Mott MacDonald commissioned Smarter Grid Solutions (SGS) to carry out an assessment of the impact of active power flow management solutions covered by the Work Package 1, Task 2 scope of work. The final report received from SGS is included as Appendix A. This report incorporates amendments to the report that have been made in response to ETI comments received on the draft report submitted in April 2010.

As agreed with ETI, this Work Package 1, Task 2 report has been published separately rather than being incorporated into a combined WP1 Task 2 & 3 report as originally envisaged.

Appendices

Appendix A - Smarter Grid Solutions
Impact of Active Power Flow Management Solutions

ETI Network Capacity Project

Work Package 1 Task 2

Impact of Active Power Flow Management Solutions

Issued to:	Mott MacDonald
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By:	Smarter Grid Solutions Ltd.
Date:	01/03/2010
Reference:	1008-01-01B

Document Issue Control

Project Start Date: **20/01/2010**

Project Reference: **1008-01**

Document Number: **01**

Version	Date	Prepared by	Checked by	Description
A	15/02/2010			Issued for comment
B	01/03/2010	Andrea Michiorri Colin Gault	Colin Foote	Revised and issued for final comment
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1 Introduction

The Energy Technologies Institute (ETI) 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.

The project is aimed at supporting the ETI's overall goal of accelerating the deployment of technologies that will help reduce greenhouse gas emissions and thus help achieve climate change goals. The outcome is to be a thorough, coherent and well presented analysis that will enable the ETI to make informed decisions as to where future work in the programme should be directed.

1.1 Project Structure

Work Package 1 concentrates on the novel technologies with the potential to release capacity in the UK T&D networks. The work comprises literature review and modelling of the various technologies integrated into the networks to determine their effectiveness and requirements for such integration. It also includes analysis of environmental and social impacts, and of the barriers to development and deployment.

Task 2 in Work Package 1 is to assess and quantify the impact of active power flow management on UK distribution networks and the impact on the transmission system of such technology changes applied to distribution networks. Active power flow management is defined in the broadest terms and to be consistent with the technical scope of the project includes power electronic based devices and converters, reactive compensation, phase shifting transformers and all types of active network management.

This report is the outcome of Task 2 and is concerned with a literature-based review of technologies and the potential impact of their deployment in UK distribution networks. Tasks 1 and 3 will deliver more detailed assessments of power electronic technologies and their integration into the transmission system. Tasks 4 and 5 will have a less technical emphasis by considering the barriers to development and environmental and social impacts. The outcomes of Tasks 1 to 5 will be collated and used in the Task 6 workshop, which will inform the multi-criteria assessment to be performed in Task 7. Task 8 will deliver a final report on Work Package 1 to consolidate the outputs from all tasks and provide clear recommendations to the ETI in respect of its Energy Networks Programme scope, technology development opportunities and research and development priorities.

1.2 Task Methodology

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 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 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

1.3 Report Contents

Section 2 presents a literature review covering material relevant to the application of new technologies in facilitating the connection of additional generation to distribution networks in the UK. Section 3 reviews the technologies of interest to the project. In section 4 there is analysis and discussion of the impact on distribution networks. In section 5 the impacts on the transmission network are discussed. Section 6 presents conclusions and recommendations.

2 Literature Review

A broad range of sources have 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. This section highlights the most interesting and relevant documents with a short summary of their content.

2.1 Investigative Industry Reports

The electricity supply industry in the UK has invested considerable effort in recent years in assessing new technologies and network changes necessary to support the connection of renewable and distributed generation. Government and other agencies have funded various pieces of work that have produced reports available to the industry as a whole. Recent reports of greatest relevance to this project are summarised below.

2.1.1 Electricity Networks Strategy Group

In a series of reports issued through the ENSG, presentations at various industry events and discussions with stakeholders, the UK transmission owners (TOs) – National Grid, Scottish Power and Scottish & Southern Energy – have indicated what they consider to be the network upgrades necessary to accommodate new generation, including a massive growth in renewables, over the coming decades.

Electricity Networks Strategy Group, "Our Electricity Transmission Network: A Vision for 2020", 4th March 2009, URN/09/752

Electricity Networks Strategy Group, "Demonstrating the Need for Electricity Infrastructure", June 2009, ENSGR 2009-22

Electricity Networks Strategy Group, "Our Electricity Transmission Network: A Vision for 2020. Full Report", July 2009, ENSGR 2009-026, URN: 09D/717

Electricity Networks Strategy Group, "Our Electricity Transmission Network: A Vision for 2020. Addendum Report. Further Analysis – 2030 Generation and Demand Scenarios", July 2009, ENSGR 2009-21, URN: 09D/715

A substantial body of work has been produced to assess the changes to the transmission network necessary to facilitate the new generation, including the significant expansion of renewables, required to meet the Government's 2020 goals. The analysis applies the existing standards and approaches to network security, as described in the Security and Quality of Supply Standard (SQSS). However, apart from traditional solutions like re-conductoring circuits, upgrading to a higher voltage and constructing new lines, the proposals include a number of new or previously unused technologies.

The TOs aim to maximise the use of existing assets before resorting to new or replacement assets. This is partly a recognition that traditional methods of enhancing system capacity, particularly those which involve new overhead line routes, are difficult to achieve due to planning constraints and environmental concerns. This can result in long delays in providing the required capacity and facilitating the connection new renewable generation, which is a primary driver for the work being undertaken in this project. The report describes the use of technologies not used before on the GB transmission system to either maximise the use of existing assets or provide new infrastructure with minimal environmental impact and an acceptable level of technological risk. These technologies include series compensation, HVDC and subsea cables.

The full Vision 2020 report includes descriptions of series compensation, HVDC and subsea cable technologies, and so is a useful reference for information on their application to the UK transmission network. Consideration was given to multi-terminal HVDC and it was concluded that in the timescales involved for the western HVDC link, this is not a viable technical solution. The eastern HVDC link has a longer lead time and the TOs remain open to the possibility of technical developments making multi-terminal HVDC a feasible option, which provides an opportunity for ETI development support to have an impact.

It also discusses costs and some of the programme issues that represent potential barriers to deployment. The typical estimated time for delivery of new transmission infrastructure is seven years. Supply chain risks include the availability of submarine cable installation vessels and overhead line design and installation resources. The outages necessary to perform work on the system are difficult to secure and it is important that work is co-ordinated to make best use of those outages. Further delays may result from environmental and local concerns that can only be identified as work proceeds.

The addendum report tests the proposed reinforcements against a range of generation scenarios up to 2030. The analysis concludes that the vision for the 2020 network is robust, although some of the proposed reinforcements may require some modifications or need to be developed in a way that accommodates future requirements.

Apart from delivering a technical assessment, the work is designed to build political will and prompt action. The TOs, and many others in the industry, argue that planning decisions must reflect the need for strategic, anticipatory investment in infrastructure to prepare for expected new generator connections. It is noted that many network developments occur in large increments and the most efficient, co-ordinated and flexible solution may need to be larger than the development for which immediate generator commitments have been received.

Distribution Networks

In terms of new and renewable generation connected to distribution networks, the scenarios that were studied assume significant growth. From 2020 to 2030 it is assumed that Combined Heat and Power (CHP) grows from 4.4 GW to 9 GW, although it is noted that the level of embedded CHP has not changed over the last five years. In the same time frame, renewable embedded generation is expected to grow from around 3.5 GW to 11 GW with contributions from a wide range of sources including wind, wave, tidal, biomass, hydro and biogas. Micro-generation is anticipated to expand at a rate matching the highest seen in Europe, which was the expansion of solar PV in Germany. Embedded generation is expected to make an important contribution to the overall energy mix and if these new sources do not appear then more renewable generation will have to be connected to the transmission network to meet the Government's targets. The ENSG analysis does not consider changes to the distribution networks or the application of new technologies to facilitate the connection of this embedded generation.

There is a strong defence of the need for a transmission network even if there is significant growth in generation at distribution level. It is argued that large quantities of decentralised renewable generation lead to uncertainty in energy supply and large variations in network flows at the distribution level. The transmission system will continue to play an essential role in balancing the system and securing supplies across the country.

Electricity Networks Strategy Group, "A Smart Grid Vision", November 2009

The Government and Ofgem asked the ENSG to produce a high-level vision of what a UK smart grid might look like and the challenges it would help address. The purpose was to promote debate, not to define a specific path. The context is the Government's policy on carbon targets and it is recommended that there is alignment with other policy development. It is acknowledged that there is significant uncertainty and further work is required. A definition for the Smart Grid is given as follows:

A Smart Grid as part of an electricity power system can intelligently integrate the actions of all users connected to it – generators, consumers and those that do both – in order to efficiently deliver sustainable, economic and secure electricity supplies.

A Smart Grid employs communications, innovative products and services together with intelligent monitoring and control technologies to:

1. Facilitate connection and operation of generators of all sizes and technologies
2. Enable the demand side to play a part in optimising the operation of the system
3. Extend system balancing into distribution and the home
4. Provide consumers with greater information and choice of supply
5. Significantly reduce the environmental impact of the total electricity supply system
6. Deliver required levels of reliability, flexibility, quality and security of supply

In many ways the smart grid is concerned with developments on distribution networks, whether to facilitate demand side participation in system operation or to allow the connection of additional small-scale generators. The technologies reviewed in this report have a role to play in this transition and thereby support the ETI's role in smart grid development.

2.1.2 Other Studies of Renewables Impact on the Grid

While the ENSG work represents the views of the transmission owners and so forms the most likely basis for development of the transmission network, a number of other studies have been commissioned in recent years to examine the impact of renewables on the UK network.

Xero Energy (Scott,N.C., Smeed,M.R., McLaren,A.C.), "Pentland Firth Tidal Energy Project Grid Options Study", 8 January 2009, Prepared for Highlands and Islands Enterprise, Reference Rep 1072/001/002C

The report presents a study of possible network reinforcements and alternative technologies that could be used to help connect marine energy resources in the Pentland Firth to the main transmission system. The focus is on the integration of large amounts of renewable generation in a peripheral area of the network so some of the analysis is relevant to other areas also. The following technologies and approaches are identified for facilitating the transition and reducing network reinforcement cost.

- Short term access – making available capacity that has been assigned to other generators but is not being used
- Connect and manage – allowing generators to connect before the necessary reinforcements and actively managing their connection
- Thermal loading dependent generator constraint

- Dynamic line rating
- Substation voltage control
- In-line voltage regulators
- Voltage dependent generator constraints

Sinclair Knight Merz (in association with AEA Energy & Environment), "Quantification of Constraints on the Growth of UK Renewable Generating Capacity", June 2008

This report considers a range of renewable generation technologies and attempts to quantify the constraints on their growth. The report discusses the issues and then presents "growth curves" for each technology that estimate the expected growth in capacity up to 2030 under three different scenarios. The low, medium and high growth scenarios assume constraints on growth are addressed to varying degrees. Some of the findings on constraints include:

- Supply chain
    - Manufacturers of wind turbines and sub-sea cables have order books full for the next five years
    - It is assumed that HVDC converters will not be required for at least five years and this should be long enough for existing manufacturers to increase capacity as necessary
    - Engineers with the appropriate skills are in extremely short supply in the UK
    - Biomass fuel faces a range of limitations
    - Specialist vessels required to install offshore wind farms are very limited
- Planning
    - Long delays and inconsistency in local planning authority decisions
    - Long delays in national planning authority decisions
- Grid
    - Bottlenecks in Scotland restrict the connection of onshore wind, although this should be addressed in large part by the Beauly-Denny line
    - Limits on grid entry capacity at coastal substations in England restrict the connection of offshore wind, although this might be eased by the retirement of existing generators
    - Conventional planning and operation methods do not take full account of the characteristics of renewable sources, e.g. intermittency, and can lead to excessive infrastructure specification

Sinclair Knight Merz (for the Department for Business Enterprise and Regulatory Reform), "Growth Scenarios for UK Renewables Generation and Implications for Future Developments and Operation of Electricity Networks", June 2008, BERR Publication URN 08/1021

This report considers the level of generation to be expected from each form of generation in 2020 and assesses how the growth of renewables will impact upon the electricity network. The report, at a high level, assesses the costs, benefits and issues to be addressed in adding high levels of renewable generation to the generation mix of the future. The report does this for three scenarios: Low, Medium and High renewables (35%, 40% and 50% of total electricity delivered). For these scenarios an assessment has been made with regards to conventional plant retirements as well as the likely addition of new coal plant and two new nuclear power stations. An assumption has been made that most of the increase in renewable energy will come from wind power and this has been split based on the maximum expected amount of onshore wind being 14 GW and the rest being made up from offshore wind generators. The impact of the new renewable generating capacity is assessed with the assumed 2020 network capability factoring in the completion of already commissioned and planned reinforcements.

The report describes different renewable generation technologies but goes into some detail on wind power, including an assessment of the wind resource around the British Isles and the output profiles that can be expected. It also describes the various means of connection to the grid, including HVDC, and assigns costs to the different options.

TNEI, "Assessment of the Grid Connection Options for the Scottish Islands", 27 March 2007, Prepared for Highlands and Islands Enterprise

This report was commissioned as a result of the existing network connection between the Scottish islands and the Scottish mainland being insufficient to transport the future projected levels of renewable power generation. The assessment was based on the following estimates for the renewable generation on the main Island Groups:

- 1000 MW on the Western Isles
- 600 MW on Shetland
- 200 MW on Orkney
- 1000 MW associated with the Beatrice offshore wind farm

In this report the pros and cons of both AC and DC technology are considered with a combination of both technologies being believed to provide the most effective solution. Included within the analysis are the estimated TNUoS charges incurred as a result of the connections.

High level connection analysis within the report uncovers that due to the increasing utilisation factor on the existing transmission network there are now few locations where reinforcements would not be triggered by the connection of significant levels of generation. A generator with a low capacity factor such as wind makes it more difficult to justify longer more expensive connections due to the low utilisation of the assets however two sources of generation with similar capacity factors and sufficiently low correlation could share the assets to increase the asset utilisation, but at the cost of generation curtailment at certain times.

Mott MacDonald, "The Carbon Trust & DTI Renewables Network Impact Study, Final Report", January 2004

Mott MacDonald (Forbes,I., Luby,S., Harrison,S.), "The Carbon Trust & DTI Renewables Network Impact Study, Annex 3: Distribution Network Topography Analysis", November 2003

This work assesses the costs of future scenarios relating to the increase in renewable generation, and more specifically wind farms. Through the use of a generic model set up to represent a typical rural network an assessment is made of how an increase in distributed generation will impact the network. Estimation is made as to the level of investment required for three different scenarios up to 2010 and then three more scenarios up to 2020. These scenarios are based on information about planned projects already underway and other projects in the pipeline. The main outcome of this report is that for the grid to be ready in time for the connection of these new renewable generation sources over £1 billion has to be invested before 2020 and the process of upgrading has to begin immediately to ensure the grid is capable of coping with the connection of renewable generators already at the planning stages.

The reports emphasise the need for network reinforcements and give an estimate of the likely costs. It is noted that the investment required is much greater than the allowed capital investment under Ofgem's price controls. It recommends alterations to the price controls to allow for the investment. It also recommends acceleration of the planning process, on a government level, to allow for the necessary infrastructure to be put in place in time for the increase in grid connections in rural areas where the network is not as robust. Grid code compliance is also identified as an issue with wind farms having difficulty with fault ride through and this report suggests a relaxation of the fault ride through requirements for new wind farms if a potential bottleneck is to be avoided.

These reports were written in 2003/4 and a significant amount has changed between then and now with regards to developers' plans for renewable generation and in wind turbine technology. The network companies and Ofgem are now reaching agreements on capital investment to address the problems mentioned in the report. Planning permission for new transmission lines, especially at the higher voltages, is still recognised as a significant barrier.

Technical specifics contained within section 2 of this report are of particular interest to the assessment of new generation capacity on distribution networks. Typical networks are illustrated with the level of generation that can connect to various points shown. Generators up to 5 MVA would be connected at 11 kV with the largest connection, 5 MVA, being connected to the 11 kV busbar or to the 33 kV busbar through a dedicated 33/11 kV transformer and the smaller connections being made to existing 11 kV feeders. Generators between 5 MVA and 20 MVA would connect onto the network at 33 kV, generators between 20 MVA and 200 MVA would connect to the network at 132 kV and generators larger than 200 MVA would connect to the network at 275 kV/400 kV.

2.1.3 Distributed Generation and Active Network Management

Generation connected at distribution level is referred to as distributed, embedded, dispersed or decentralised generation. The impact of distributed generation on distribution networks has been fertile ground for academic study over the last few years and industry working groups have been established to examine the issues. There has been steady growth in distributed generation over the last few years but not the explosion in capacity that some people expected. Active network management includes a range of methods used to enable the connection of distributed generation. Some of the most useful reports are summarised below.

Sinclair Knight Merz, "Current Technology Issues and Identification of Technical Opportunities for Active Network Management (ANM)", 2008, DTI(BERR)/Ofgem Distribution Working Group Programme 3: Enabling Active Network Management, Contract Number DG/CG/00104/00/00, URN Number 08/621

This project considered current technology issues and opportunities with regards to active network management (ANM) as a means of connecting more generation to distribution networks, and produced a practical set of recommendations aimed at enabling a near term increase in ANM. A literature review found that a large body of work exists on the subject of ANM technologies and that many new technologies are nearing the latter stages of development in the UK – this includes a description and assessment of the Orkney Registered Power Zone (RPZ) and recognition of the value of the ANM Register (see below).

Several promising technologies were considered for detailed assessment:

- Inline voltage regulators
- SVCs and STATCOMs
- Active voltage controllers
- Dynamic line rating systems

They were assessed in terms of the following factors:

- Technical functionality and barriers
- Operational impact
- Planning impact
- Other issues, including eligibility for IFI/RPZ funding

The biggest concern expressed by DNOs regarding ANM and similar control schemes is that of creating niche pockets of non-standard technology around the network and causing legacy problems. In part, these concerns relate to the operational and long term maintenance issues associated with complex and non-standard logic sequences that might require regular reprogramming as the network changes or is reconfigured. It has been noted that off the shelf ANM systems are not available and that each system must be highly customised. In general, and in contrast to what is in prospect with widespread ANM deployment, the preference is for networks to become as uniform and non-complex as possible. It has also been noted that despite the many smart protection relays now being installed in substations, very little of the available functionality is being used. This indicates a strong tendency away from non-standard equipment, settings or logic.

These concerns highlight the need to find modular solutions that will allow DNO staff to plan, design, maintain and operate ANM systems across the network in a standard manner, preferably not dissimilar to current methods. Systems requiring DNOs to acquire completely new skills or to radically change staff roles, culture or business structures seem unlikely to be seen as appropriate solutions for implementation within a short time frame. However, it must be noted that DNOs are obliged under their licences to provide least cost solutions to connecting parties regardless of resource issues.

PB Power, Lower Watts Consulting, "Future Network Architectures", 2007, Distribution Working Group Horizon Scanning Project 01, BERR Contract Number DG/DTI/00102/00/00, URN Number 07/1654

The purpose of this work was to examine distribution network architectures and how they might be made compatible with 2020 scenarios with more distributed generation. The report is quite comprehensive covering technical issues and the impact on commercial and regulatory frameworks but does not go into depth on any one topic. The appendices include a review of equipment and systems describing current approaches and ongoing developments. There is also a summary of the literature survey including a review of EU Smart Grids project.

The report describes existing distribution network architectures and the challenges associated with the connection of generation. The integration of distributed generation is discussed in terms of traditional solutions, alternative topologies and enabling technologies. The discussion of network architectures suitable for 2020 identifies the need for active network management (ANM) solutions, among others, but does not specify in any detail how they would be delivered. The relationship between ANM and the SCADA/NMS is highlighted as an important issue to be resolved. There is a lot of discussion of Virtual Power Plants (VPP) with reference to the European FENIX project. An analysis is performed to calculate indicative costs for each of the three 2020 scenarios.

EA Technology, "A Technical Review and Assessment of Active Network Management Infrastructures and Practices", April 2006, DTI/Ofgem Distribution Working Group Programme 3: Enabling Active Network Management, Contract Number DG/CG/00068/00, URN Number 06/1196

This report explores approaches and infrastructures for active operational control of distribution networks. The report reviews the development of ANM, current network architectures, and various implementations of ANM. Regulatory and technical barriers that prevent the adoption of ANM are identified and actions to overcome these barriers recommended. The main technical issues are identified as:

- Monitoring and control of 11 kV and below
- Decision making levels and data collection strategy (which will influence the de-centralisation of control authority and autonomy)
- Standardisation of protocols (and ensuring flexibility in communications and interfaces)
- Co-ordination of generators
- Increased use of advanced control schemes
- Voltage control (requiring the combination and co-ordination of different equipment in different situations, including power electronic based devices)
- Development of "cell" networks (which means implementing local control to manage the interface with the transmission network or neighbouring cells)

There is a brief review of power electronic devices that might be used on distribution networks to facilitate generation connections, including:

- STATCOMs or DVars (as alternatives to conventional SVCs or capacitor banks)
- Superconducting magnetic energy storage
- HVDC and DC-DC links
- Solid state voltage regulators
- Solid state circuit breakers
- Solid state fault current limiters

PB Power, "New Technologies to Facilitate Increased Levels of Distributed Generation", 2006, Distributed Generation Co-ordinating Group Technical Steering Group Workstream 5: Long-Term Network Solutions, Contract Number DG/DTI/00039/05/00, URN Number 06/1829

This report commissioned by the DTI and compiled by PB Power presents the results of research on new or emerging technologies that would have the potential to allow increased levels of distributed generation to be connected to the network in the near term.

The review identified that the technologies likely to have the most impact on the connection of additional generation before 2010 were super-conducting fault current limiters, in-line voltage regulators, micro-grid controllers and reactive power compensators such as FACTS (Flexible AC

Transmission Systems), SVCs and STATCOMs. It was also highlighted that the successful connection and operation of large quantities of distributed generation would require a high speed reliable communications network to be established.

Based on consultation with leading manufacturers, ten years is estimated as the average time necessary to bring innovations in network technologies to the market. The lack of clear market direction is a cause of reduced innovation in the industry. It is also noted that the manufacturers operate globally and the UK is just one of many markets. Any requirement to comply with UK-specific standards (e.g. ENA Technical Specifications) as opposed to international IEC standards increases production costs and reduces the scope for product development. Any requirement for UK specific standards raises issues with regard to global product development.

2.2 Ofgem

As industry regulator, Ofgem publishes a wide range of documents covering all technical and economic aspects of the industry. For each initiative or project Ofgem will typically commission consultants to conduct analysis in support of whatever topic is under consideration. The most relevant work recently has been as part of the Transmission Access Review and the RPI-X@20 project. The recently finalised fifth Distribution Price Control Review (DPCR5) encourages distribution network operators to facilitate new generator connections.

2.2.1 Transmission Access Review

The Transmission Access Review (TAR) was announced in the Government's Energy White Paper 2007 and is being led by Ofgem and the Department for Energy and Climate Change (DECC). The review covers the present technical, commercial and regulatory framework for the delivery of new transmission infrastructure and the management of the existing grid capacity to ensure that they remain fit for purpose as the proportion of renewable generation on the system grows. In particular, the review hopes to address the large number of electricity generators waiting in a queue to gain access to the transmission network.

The TAR called for significant reform to the current grid access arrangements whilst stating that connections to the system must meet generator requirements and be delivered quickly and efficiently. The TAR defined the characteristics of an efficient access regime and then described three access models that could deliver the reforms.

- Model A – this adopts a connect and manage approach to transmission access
- Model B – this uses market based mechanisms to deliver access to the party that values it most at any one time
- Model C – is based on locational marginal pricing

Short term solutions were proposed such as access sharing between generators, derogations from the GB Security and Quality of Supply Standard (GBSQSS), better management of the generator queue and short term release of capacity if it became available. Improvements are sought in four main areas:

- Transmission system capability - the capability of the GB network could be increased by applying weather based ratings more widely as well as hot-wiring transmission lines (operating transmission lines at higher temperatures than their original design capabilities)

- Transmission system utilisation – measuring utilisation helps the transmission licensees identify areas that need reinforcing
- Limiting factors in current regulatory framework – the licensees suggested a review of the current GBSQSS with a view to exploring the possibility of removing regional differences, probabilistic approaches to security, lower standards of security and allowing the use of inter-trips in planning timescales
- Development – new monitoring and protection solutions allowing faster disconnections are being explored that if proven would allow the transmission system to operate closer to the limit of its capabilities

The outcome of the TAR will influence future opportunities for generation access to the GB transmission system. The industry was unable to reach agreement on the necessary amendments to the transmission regime and the decision on which approach to adopt now lies with DECC.

2.2.2 Survey of Innovation Projects

KEMA, "RPI-X@20: Technological change in electricity and gas networks. A sample of survey of international innovation projects. Final report", 9 October 2009, 10010757 Rev 1

This report was commissioned by Ofgem to review innovation on electricity and gas networks, to understand what has encouraged that innovation and how it will bring benefits to customers and wider stakeholders. Around 200 projects were identified in a global scan of innovation and filtered down to 20 case studies that are beyond the research stage and relevant to the Great Britain context. A higher degree of innovation activity is observed at distribution voltage levels compared with transmission, and this is attributed in part to the higher volumes of distributed generation connecting on these networks. The case study review includes an assessment of "regulatory fit" in the GB context, which is a measure of how easily the innovations could be deployed within the current regulatory framework. Three types of project are identified as not having a straightforward regulatory fit:

- Innovations that involve new energy transactions such as storage devices
- Innovations that involve new energy vectors such as hydrogen
- Innovations that potentially create new commercial interfaces and service interactions between market players, such as micro-grids and virtual power plants

2.2.3 Distribution Price Control Review

The distribution network operators (DNOs) are subject to price control regulation where every five years Ofgem sets the maximum revenues that each DNO can collect from customers. The regulatory settlement includes a range of obligations and incentives to encourage DNOs to innovate and find more efficient ways to provide an appropriate level of network capacity, security, reliability and quality of service.

The next price control period runs from 1 April 2010 to 31 March 2015. One objective for Ofgem is to ensure that DNOs give appropriate consideration to innovative solutions, including the use of new techniques to safely and efficiently defer conventional reinforcement and network extension. DPCR5 will also see the introduction of a £500m Low Carbon Networks (LCN) Fund to encourage the distribution network operators (DNOs) to try out new technology, operating and commercial arrangements. The objective of these trials and demonstration projects is to help all DNOs understand how they can provide security of supply at value for money as the country moves to a low carbon economy, and what role they could play in facilitating the low carbon and energy saving initiatives that are underway to tackle climate change. The LCN Fund is likely to prompt a wide range of innovative projects, many aligned with Smart Grid themes, and will provide opportunities for new technologies, including those supported by the ETI, to be tested on UK networks.

2.3 National Grid

In its role as Great Britain System Operator (GBSO), National Grid is required to produce a Seven Year Statement (SYS) on an annual basis, which is issued in May each year. In December 2009 it also published the first Offshore Development Information Statement (ODIS), which is also to be issued annually. The two Scottish transmission licensees are required to assist National Grid in preparing these documents.

National Grid also produce other documents as necessary to inform the industry and consult on proposed changes to the industry operating arrangements. All of these documents are available from the National Grid web site.

2.3.1 Seven Year Statement

The SYS presents a wide range of information relating to the transmission system in Great Britain including information on demand, generation, plant margins, the characteristics of the existing and planned GB transmission system, its expected performance and capability and other related information. This information is intended to assist existing and prospective users of the transmission system in assessing the opportunities available to them.

The SYS describes how technologies like quad boosters and reactive compensation are used to enhance the capacity of the network but does not go into any detail on the possibility of using other technologies.

Information on existing distributed generation, presented in section 4.2, was obtained from the SYS.

2.3.2 Offshore Development Information Statement

The purpose of the ODIS is to support the co-ordinated development of the offshore and onshore electricity grid in Great Britain. The report identifies a range of network solutions to form a vision of how the offshore and onshore reinforcements could be developed but it is highlighted that it will be the responsibility of individual onshore/offshore network owners to develop detailed designs.

The statement discusses the use of HVDC for offshore connections. It suggests that the general view is that for generation further than 60 km from shore HVDC transmission is technically superior to AC. It is acknowledged that multi-terminal HVDC may reduce the transmission works required to connect offshore capacity but notes that it is new technology and may pose unknown technical problems.

National Grid is monitoring the development of multi-terminal HVDC and related technologies and the results of a recent review are presented in the ODIS appendices. These appendices provide useful information on the present and anticipated future status of various technologies crucial to the development of offshore transmission networks. The review covers:

- HVDC:
    - Voltage Source Converters
    - Current Source Converters
    - GIS Switchgear
    - Extruded Subsea Cable

- Mass Impregnated Insulated Subsea Cable
- Onshore Cable
- Overhead Lines

- HVAC:
  - Three Core 132 kV and 220 kV AC Subsea Cable
  - Transformers
  - GIS Switchgear
  - Shunt Reactors
  - Shunt Capacitor Banks
  - Static VAR Compensators
  - STATCOMs
- Structures and Construction:
  - Offshore Platforms
  - Subsea Cable Installation
  - Subsea Cable Obstacle Crossing
  - Horizontal Directional Drilling and Onshore Cable Installation
  - Shoreline Transitions/Landfall

2.3.3 Operating the Networks in 2020

National Grid is undertaking a consultation to seek views on the technical challenges faced in operating the transmission networks in 2020. The location, type and size of generators connected to the transmission networks and patterns of consumer demand have started to change and the pace and magnitude of this change is expected to grow as emission and renewable energy targets are met. The consultation covers a range of issues with an emphasis on system balancing and security of supply.

It is anticipated that DNOs will face an increasing demand for network capacity, particularly from embedded generation and new loads like heat pumps and electric vehicles. The DNOs are expected to try and get the most from their networks by deploying new forms of active management, some of which will exploit the new smart metering infrastructure. This is expected to change the level and pattern of demand seen on the transmission network.

The "Gone Green" scenario, upon which the analysis and discussion are based, assumes an increase of 6 GW in embedded generation capacity between 2009/10 and 2020/21 to almost 15 GW. Some 45% of this capacity (7 GW) is assumed to be Combined Heat and Power (CHP) plant with the remaining proportion (8 GW) comprising generation from renewable sources: wind, solar, tidal, biomass and hydro-power.

The effect of embedded generation on transmission network operation is summarised in three main areas of impact:

- Demand forecasts are based on measureable parameters (e.g. temperature), time of day and historic demand; any variations not visible to the system operator (e.g. embedded generation output) increase the forecast error and require higher levels of reserve

- If embedded generation has low resilience to disturbances then increasing penetration will exacerbate disturbances like large frequency deviations
- Not fully understanding the local impact of embedded generation (in terms of power flows and fault level infeeds on distribution networks) can result in sub-optimal running arrangements at the boundary between transmission and distribution

In considering the impact of embedded generation on the transmission network, National Grid place greatest emphasis on system balancing and system security, including resilience to disturbances. There is concern over the potentially greater cost for generation reserve and response due to the lack of visibility, from National Grid's perspective, of embedded generation. The resilience to disturbances is of special concern in the UK where the compact and meshed transmission network means that voltage dips are seen over a very wide area. With respect to embedded generation there does not seem to be any particular concern over issues like voltage control, reactive power balance, sub-synchronous resonance or interacting oscillatory modes, and harmonic distortion. All of these issues can be addressed with the types of solutions already in use. Thus, to remove barriers to the further deployment of renewable embedded generation the most important areas to address are visibility, including accurate forecasting and real-time monitoring, and resilience to disturbances, or fault ride through performance.

2.4 Distribution Network Operators

The distribution network operators (DNOs) in Great Britain are required by a condition of their license to publish a Long Term Development Statement (LTDS) each year. A summary version of the LTDS is normally available on the web site of each company and the full statement is provided on request. The DNOs are also required to publish reports on their research and development activities under the Innovation Funding Incentive.

2.4.1 Long Term Development Statements

The LTDS describes each distribution network, including equipment parameters down to 33 kV, and discusses the opportunities for connecting new generation. Each DNO takes a slightly different approach to the LTDS and the level of commentary on generation connections varies widely. The most relevant and interesting information is highlighted below.

All the DNOs point out to prospective generators that the limitations and requirements on connection will depend on the exact location and the circumstances on the local network. Scottish Power Manweb is unusual in including a map showing the location of four areas identified in the Welsh Assembly Technical Advice Note 8 as requiring an upgrade to the electricity network infrastructure in that area to facilitate the connection of generation.

All identify fault levels, voltages and thermal limits as the principal barriers. Solutions to excessive fault levels include replacement of switchgear or using transformers with higher impedance. Excessive voltage rise can be addressed by an appropriate connection design, negotiating appropriate voltage limits with the generator, re-conductoring existing lines or installing voltage regulators.

EDF make the most interesting comments on the impact of additional generation and the use of new technologies to facilitate connections. As with other DNOs, there is recognition that distributed generation might allow them to defer network reinforcement but also that it may have adverse effects. Changes in system power factor and the ability to withstand disturbances are highlighted as issues of concern. There is a warning that distribution costs are likely to increase as networks are redesigned to be more actively managed and challenges are listed as:

- Managing system fault levels
- Ensuring adequate regulation of power factor and voltage
- Managing network capacity to varying and potentially unpredictable real-time permutations of generation and demand volumes
- Reducing, as far as practicable, the possibility of network constraints limiting generation export
- Managing losses
- Precluding the possibility of system overloads
- Ensuring that standards of power quality are maintained
- Co-ordinating protection systems to ensure that quality of supply is not compromised

EDF acknowledge that some of these challenges might be solved using new technologies like FACTS devices, including STATCOMs, SVCs or basic fixed shunts. EDF state that they see some of these technologies being deployed selectively until the capital costs of the equipment are reduced and the reliability is increased.

2.4.2 IFI and RPZ Activities

As part of the fourth Distribution Price Control Review (DPCR4) effective from 1 April 2005 until 31 March 2010, Ofgem introduced two new incentives: the Innovation Funding Incentive (IFI) and Registered Power Zones (RPZ). The primary aim of these two incentives was to encourage the distribution network operators (DNOs) to apply innovation in the way they pursue the technical development of their networks. A Good Practice Guide (Engineering Recommendation G85) was produced by the DNOs. IFI is to continue into the DPCR5 period, starting April 2010, but RPZ is being superseded by the Low Carbon Network (LCN) Fund, which will provide funding for the trialling of new technologies.

Open reporting (i.e. available in the public domain) of IFI and RPZ projects is required by Ofgem; this is intended to stimulate good management and promote sharing of innovation good practice. The latest reports (mostly for 2008-9 but 2007-8 for some DNOs) were reviewed to assess current activities relevant to this project.

<u>Registered Power Zones</u>

RPZs are focused specifically on the connection of generation to distribution systems. The estimates made by DNOs as part of the DPCR4 process indicated that some 10 GW of generation could be connected in the five year period. This generation was expected to connect at all distribution voltage levels bringing new system design and operating challenges. RPZs were therefore intended to encourage DNOs to develop and demonstrate new, more cost effective ways of connecting and operating generation that deliver specific benefits to new distributed generators (DG) and broader benefits to consumers generally.

The three RPZs currently registered in the UK are:

1. Orkney, SSE, where the SGi active power flow management system has been deployed
2. Martham, EDF, where the GenAVC active voltage management system has been deployed
3. Skegness, E.On, where thermal monitoring of overhead lines has been deployed

The RPZ in Orkney, Scotland uses a power flow management system developed by Smarter Grid Solutions to allow increased generation to be connected to the local network. The RPZ in Martham, Norfolk has the connection of a landfill gas generator to the local 11 kV network managed by the

GenAVC system developed by Senergy Econnect. The RPZ in the area of Skegness, Lincolnshire increases the potential connection of non firm wind generation capacity to the local 33 kV network by employing a dynamic rating system developed with Areva. Thus, the RPZs have implemented some forms of active management but have not been primarily concerned with demonstrating the use of power electronic based technologies to facilitate generation connections; the Orkney network does use a D-VAR to aid voltage management and there are already some wind farms employing STATCOMs to fulfil their connection obligations.

Innovation Funding Incentive

The IFI is intended to provide funding for research and development (R&D) projects focused on the technical development of distribution networks to deliver value (i.e. financial, supply quality, environmental, safety) to end consumers. IFI projects can embrace any aspect of distribution system asset management from design through to construction, commissioning, operation, maintenance and decommissioning. A DNO is allowed to spend up to 0.5% of its revenue on eligible IFI projects.

The IFI projects by all DNOs have been reviewed with particular attention given to the projects aimed at facilitating the connection of distributed generation. A number of projects involve several DNOs. Among active management projects, the greatest number are concerned with voltage control, followed by dynamic ratings and then integrated, multi-function ANM. Power electronic applications at the distribution level are studied in projects on the intelligent universal transformer (in collaboration with EPRI) and the multi-terminal micro grid. Furthermore, overcoming fault level limits on the connection of distributed generation is the subject of the MANTIS and superconducting fault current limiter projects.

2.5 Industry Documents

The electricity industry in the UK operates within a technical and commercial framework that is described in a collection of industry documents. These are updated from time to time as the needs of network users change. For distribution networks the most important document is the Distribution Code (DCode). This makes reference to a number of other documents that are either formally recognised as part of the DCode or are recognised only as providing useful support. These documents are available from the Energy Networks Association, which acts for the network operators that are its members.

The Distribution Code, www.dcode.org.uk

Licensed distribution businesses in the UK are obliged under Condition 9 of their licences to maintain a Distribution Code detailing the technical parameters and considerations relating to connection to and use of their systems. All DNOs currently operate the same version of the code, and the code is maintained by the Distribution Code Review Panel. All modifications to the Code have to be approved by Ofgem.

Engineering Technical Report 124, Energy Networks Association, 2004, Guidelines for actively managing power flows associated with the connection of a single distributed generation plant

Engineering Technical Report 124 provides guidance on how to employ ANM solutions to overcome power flow constraints associated with the connection of distributed generation. Solutions are offered for expanding network capacity for the connection of an individual DG unit. These include direct inter-trip, measured power flow, and demand following. Power electronic based solutions are not covered and the connection of multiple DG units is outside the scope of this report.

Engineering Technical Report 126, Energy Networks Association, August 2004, Guidelines for Actively Managing Voltage Levels Associated with the Connection of a Single Distributed Generation Plant

Engineering Technical Report 126 provides guidance on how to employ ANM solutions to overcome voltage control limitations associated with the connection of a single DG plant. ANM solutions are defined as optimising the utilisation of distribution networks in terms of their capability to accept the connection of DG but this report only considers the control of steady state voltage. The report is written for single DG installations but it is suggested that the principles may be extrapolated to cater for networks with multiple DG installations, although it is acknowledged that scheduling and other commercial arrangements are outside of its scope.

2.6 Academic Work

The expansion of renewable energy, distributed generation, active power flow management and all the technologies covered by this project have been subject to extensive academic research and many hundreds of papers have been published on these topics. Given the focus on application and implementation on UK networks, however, a lot of academic work is irrelevant or covers material too far from deployment. The review has, therefore, focused on the work done in industry working groups or that published by the network operators and regulator as that is more relevant.

Nevertheless, some academic work has been identified and reviewed to inform the quantification of the supposed benefits of the technologies. In particular, a variety of work has been done on calculating the additional generation capacity that might be connected as a result of applying active network management. Some of the most useful and relevant is highlighted below.

In addition, recent work at the University of Strathclyde on identifying examples of active network management has been highlighted as a useful source of information.

Morren,J., de Haan,S.W.H., "Maximum Penetration Level of Distributed Generation without Violating Voltage Limits", 20th International Conference on Electricity Distribution, CIRED 2009, Prague, 8-11 June 2009, Paper 0271

This paper investigates reactive power compensation (by the DG unit itself) combined with overrating of the DG converter and generation curtailment to mitigate local voltage increases and achieve an increase in allowable DG penetration. The DG units are assumed to absorb as much reactive power as possible to limit the voltage increase they cause. Case studies with typical networks show that reactive power control by the DG unit can increase the allowable DG by 15-50%, depending on the X/R ratio and the rating of the DG converter. DG curtailment can achieve a 100% increase in allowable penetration level. There is no discussion of how generation curtailment should or could be implemented.

L.F.Ochoa, C.J.Dent, G.P.Harrison, "Maximisation of Intermittent Distributed Generation in Active Networks", CIRED Seminar 2008

A multi-period steady-state analysis is proposed for maximising the connection of intermittent distributed generation (DG) through an optimal power flow (OPF)-based technique adapted for active network management. A scenario is envisaged where the tap changing capabilities at the substation and DG curtailment are used as means to allow maximum absorption of wind power while respecting voltage, thermal and fault level limits. A medium voltage distribution network is analysed considering different loading levels and discretised wind power outputs over a year.

In addition to network constraints traditionally used in OPF formulations, variables and constraints derived from ANM schemes and other technical-economic constraints are incorporated in the approach. This includes scope for co-ordinated voltage control, energy curtailment and limitation of energy losses. It is concluded that active network management allows generation capacity to be 2.6 times that possible with a conventional passive network.

The authors acknowledge that the location of new generation capacity is outside the control of DNOs but claim that the OPF technique can help DNOs understand the capabilities of the network to accommodate DG and provide guidelines for the definition of connection incentives.

Harrison, G.P., Wallace, A.R.; "Optimal Power Flow Evaluation of Distribution Network Capacity for the Connection of Distributed Generation"; IEE Proceedings, Generation, Transmission and Distribution, Vol. 152, No. 1, P115-122, January 2005

The authors identify that incorrectly sited or sized DG could potentially saturate available network capacity and have an impact on the rate and volume of renewable generator connections. They model fixed power factor generation as negative loads and then use an optimal power flow (OPF) to perform load shedding, identifying available headroom on the network within thermal and voltage constraints. This approach is termed "reverse load-ability" and would require a schedule of locations that were identified as being appropriate for DG connections. Such an approach may not be too far from reality for some countries, but in many markets no means exists yet for DNOs to identify and/or communicate preferred locations for DG units.

Harrison and others at the University of Edinburgh have done considerable work in this area and continue to publish the results of new analyses.

Celli, G., Ghiana, E., Mocci, S., Pilo, F.; "A Multiobjective Evolutionary Algorithm for the Sizing and Siting of Distributed Generation"; IEEE Transactions on Power Systems, Vol. 20, No. 2, May 2005

This paper tackles the location and sizing of DG with respect to accomplishing multiple objectives simultaneously (in terms of constraints in an optimisation problem). The methodology adopted is focused on providing a tool or approach that allows the power system planner to select the most appropriate compromise between the objectives. The objectives considered are cost of network reinforcement, cost of purchased energy, cost of energy losses and cost of energy not supplied. Again the potential for this planning approach to be applied in the UK context is limited due to network operators being unable to direct DG location.

Keane, A., O'Malley, M.; "Optimal Allocation of Embedded Generation on Distribution Networks"; IEEE Transactions on Power Systems, Vol. 20, No. 3, August 2005

Keane, A., O'Malley, M.; "Optimal Utilization of Distribution Networks for Energy Harvesting"; IEEE Transactions on Power Systems, Vol. 22, No. 1, February 2007

Keane and O'Malley present a technique for identifying the optimal location and size of DG units using a linear programming method. In the later work, they present a methodology to maximise the amount of energy that can be "harvested" from a particular distribution network. They study the possibility of extending capacity for DG connections beyond "firm" levels and define this as holding potential for increasing the collective energy generated by connected DG units.

Gómez,M., Cámara,M.,A., Jiménez,E., Martínez-Cámara,E., "Custom power equipment to facilitate the penetration of embedded generation in distribution networks", 11th Spanish Portuguese Conference on Electrical Engineering (11CHLIE), 2-4 July 2009, Zaragoza, Spain

This work examines the use of power electronic devices connected to medium and low voltage networks to mitigate or compensate the influence of disturbances, which may arise or be exacerbated by the presence of distributed generation. The concept of a custom power park is introduced, where power quality is maintained at high levels through the use of new technologies. Custom power technologies are split into network reconfiguration devices like the static current limiter, the static circuit breaker and static transfer switch, and compensation devices like distribution static synchronous compensator (D-STATCOM), dynamic voltage restorer (DVR) and unified power quality conditioner (UPQC).

University of Strathclyde (MacDonald,R., Currie,R., Ault,G.), "Active Networks Deployment Register", January 2008, http://cimphony.org/cimphony/anm (as at 10 February 2010)

The Active Network Management register lists and describes ANM activities as compiled by researchers at the University of Strathclyde. At the time of writing the register has 120 entries in total. The ANM register provides ready access to a wealth of material on relevant activities. Some of the projects that are most relevant to this report are described in Table 1.

Table 1: Active network management projects

Lead Organisation	Project Title	Summary of Technology/ Activity
Cooper Industries	In-line voltage regulators	Cooper Industries manufacture in-line voltage regulators for 2.4 kV to 34.5 kV systems. These provide a 32 step +/-10% tap range with ratings between 33 kVA and 1 MVA in both directions to provide voltage regulation of the downstream circuit.
Dynamic Ratings	Dynamic transformer rating equipment	Optical fibre temperature measurement is employed to determine transformer winding temperature and provide an input to dynamic rating and insulation ageing software. It can be fitted to new transformers or retrofitted to existing transformers.
Industrial and academic consortium	Improvement of the quality of supply in Distributed Generation networks through the integrated application of power electronic techniques (DGFACTS)	The EU-funded DGFACTS project introduced the use of FACTS devices in distribution systems to improve stability and quality of supply according to characteristics and requirements. This should allow a higher degree of renewable energy sources and distributed generation penetration in current and evolving distribution systems.
American Superconductors	D-VAR	The Dynamic VAR system is similar to a STATCOM and provides an instantaneous continuous source of reactive power. It can be used to resolve voltage stability issues, increase transfer capabilities, minimise voltage flicker, improve fault ride through or for steady state voltage regulation.
American Superconductors	SuperVAR	SuperVAR machines are rotating machines that utilise high temperature superconductor technology and serve as reactive power “shock absorbers” for the grid, dynamically generating or absorbing reactive power.
American Superconductors	D-SMES	D-SMES is a shunt connected FACTS device designed to increase grid stability, improve power transfer, and increase reliability. Unlike other FACTS devices, D-SMES injects real power as well as dynamic reactive power to more quickly compensate for disturbances. Fast response time prevents motor stalling, the principal cause of voltage collapse. The proprietary inverter design is based on the Power Electronic Building Block (PEBB) concept. Each trailer contains four quadrant IGBT inverters rated at 250 kW and stacked to handle the output demands of the system. The inverters provide up to 2.3 times nominal instantaneous over-current capability and can also be configured for continuous VAR support. Each 250 kW block operates independently, improving reliability.

2.7 Manufacturers

The manufacturers and suppliers of the technologies of interest provide a wealth of material in data sheets, case studies and other material on their web sites. By way of summarising the information available, major manufacturers and suppliers (to the UK market) are listed in Table 2 and identified with the technologies they offer.

Table 2: Technologies by manufacturer / supplier

Manufacturer / Supplier	HVDC	Other power electronic converters	Shunt compensation (fixed or controllable)	Series compensation (fixed or controllable)	Phase shifting transformers	Active Network Management solutions
GE			X	X		X
Siemens	X		X	X	X	X
ABB	X		X	X		x
Areva	X		X	X	X	x
American Superconductor		X	X			
Senergy Econnect						X
Smarter Grid Solutions						X
EA Technology						X

3 Technologies

A literature-based review of active power flow management technologies has been performed. For the purposes of this project, active power flow management is defined broadly to include a range of power electronic and reactive compensation technologies as well as the different methods based on enhanced measurement, communication and control that are described as active network management (ANM).

The review of technologies is split into five groups:

1. **Power electronic converters**

   The review covers the alternative ways of converting from AC to DC to enable HVDC transmission. HVDC is not expected to be deployed in UK distribution networks in the near term but similar converter technologies will be used to connect generators at distribution level. For example, converters are an important feature of variable speed wind turbines and are also used with some micro generation sources. Power electronics are also being used in new low voltage transformers to provide enhanced voltage control.

2. **Shunt compensation**

   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 emerging.

3. **Series compensation**

   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 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.

4. **Phase shifting transformers**

   Phase shifting transformers, also known as quadrature boosters, are used on transmission networks to alter the angle of 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 available capacity. This review considers the use of this technology at distribution level.

5. **Active Network Management**

   Active distribution network management covers a range of technologies built around additional monitoring of network conditions and the use of additional control methods, including generators or other distributed energy resources. Active network management is normally associated with the connection of distributed generation and offers a number of ways in which the maximum capacity of generation can be increased. Similar methods might also be used to satisfy other objectives such as reducing losses or improving quality of supply.

To support the assessment and quantification of the impact on UK distribution networks, each technology has been reviewed in terms of the following:

- Supposed benefits with respect to facilitating additional generation capacity and an increase in network utilisation, and also the potential to improve system operation, stability and security
- Barriers to deployment, including technical, commercial, regulatory, organisational and cultural/momentum barriers, especially those specific to the UK context
- Proposed solutions to the barriers, highlighting development gaps and challenges and opportunities for ETI technology development support
- Maturity and risk, including an assessment of the technology readiness level (TRL)
- Example products and case studies

3.1 Power Electronic Converters

Power electronic converters enable conversion between AC and DC, or between AC at different frequencies. This makes it possible to transmit power in DC form and also enables exploitation of variable frequency systems and close control of power injections into the network.

High Voltage Direct Current (HVDC) transmission 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. HVDC is the preferred option for connecting large offshore wind farms that are a significant distance from the shore. Planned HVDC links between parts of the main interconnected transmission system in the UK will provide additional capacity and relieve congestion. There are three principal technology options in HVDC.

3.1.1 Line Commutated Converter

A line commutated converter (LCC) uses thyristors and commutation is carried out 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 slow to react to a reverse in the direction of power flow. As this technology is line commutated it requires a strong AC grid to operate or the installation of extra devices such as a Synchronous Condenser. The problems of LCC are overcome with CCC and VSC, as described below. There are no apparent opportunities for technology development to enhance the use of LCC itself in connecting additional distributed generation.

LCC is a proven technology with many installations in operation throughout the world; TRL = 9. LCC based HVDC is available from a number of manufacturers including ABB, Areva and Siemens.

Example deployments of LCC include:

- ABB – NorNed (Norway-Netherlands)

  A 580 km (the longest in the world), 700 MW, 450 kV link connecting Norway to Netherlands

- 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

3.1.2 Capacitor Commutated Converter

A Capacitor Commutated Converter (CCC) can be used as an alternative to the traditional LCC in HVDC installations. The difference is that a CCC has a capacitor 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. This reduces the reactive power requirements eliminating the need for switched shunt capacitor banks. This reduction in reactive power also reduces the required rating of the converter transformer.

Other benefits include:

- Improved stability of long cable installations
- Improved stability when connected to weak AC systems
- Simplified switchyard
- Reduced area requirements

The main disadvantages are:

- Higher valve voltage stresses and higher valve switching losses
- Higher harmonics on both DC and AC sides
- Radio frequency noise
- Cannot provide extra reactive power at low power transfer

The problems of CCC are overcome with VSC, as described below. There are no apparent opportunities for technology development to enhance the use of CCC itself in connecting additional generation.

The technology is mature and available on the market, but with few implementations. Currently the major manufacturer for this technology is ABB; TRL = 8.

Example deployments of CCC include:

- ABB – Garabi (Brazil)

  An 1100 MW, 500 kV interconnection between the Brazilian and Argentinian networks

- ABB – Rapid City (USA)

  A 200 MW, 230 kV interconnection between the eastern and western USA networks

3.1.3 Voltage Source Converter

A Voltage Source Converter (VSC) uses bidirectional rectifiers/inverters to convert between AC and DC for HVDC transmission. VSC is an alternative to the traditional LCC and 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 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 and is therefore suited to the connection of offshore wind farms
- Smaller footprint and weight when compared to traditional HVDC

Barriers to deployment include:

- More expensive than conventional alternatives
- Lower ratings than traditional HVDC (limited by IGBT current rating)
- Higher losses

The barriers are expected to be overcome by advances in technology bringing about cheaper components with lower losses. The current limitation to the power capabilities is the rating of the IGBT but the current technology facilitates transfer of up to 1200 MW.

There are VSC projects at various stages from conception to completion; TRL = 9. The technology is available from a number of manufacturers.

Example deployments include:

- ABB – NordE.ON 1 offshore wind farm (Germany)

  A 75 km, 400 MW, 150 kV link between the NordE.ON 1 wind farm cluster and the German grid

- Siemens – Transbay Cable Project (USA)

  A 400 MW, 200 kV link in the San Francisco bay (under construction)

- ABB – Estlink (Finland-Estonia)

  A 105 km, 350 MW, 150 kV link between the Finnish and Estonian network; black start capability is implemented on the Estonian side to allow fast restoration of the grid following a blackout

3.2 Shunt Compensation

Shunt compensation is usually used in AC transmission as a form of voltage control, but can perform other functions like power oscillation damping and transmission capacity improvement. 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.

Mechanically Switched Capacitors (MSCs) provide switchable blocks of inductance and capacitance that are used to offset reactive requirements where they change slowly through the day or where a response is required following a disturbance. MSCs are reliable and may be operated either by remote control or by automatic control.

Technological advances in power electronics has led to devices that can provide the benefits of fixed or switched shunts but with closer and faster control of reactive power. This technology is more attractive than the traditional fixed shunt when developing a modern day grid. The two principal technologies are reviewed below.

3.2.1 Static Var Compensators

Static Var Compensators (SVCs) are parallel connected power electronic devices than can be used to generate or absorb reactive power. This is done using thyristor controlled reactors and capacitors.

Static Var Compensators (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. SVCs have high year-round availability and perform reliably. They operate under automatic control with remote adjustment of control parameters.

Benefits include:

- Dynamic reactive power compensation
- Steady state and transient stability enhancement
- Voltage regulation
- Increased power transfer capacity
- Three-phase voltage balancing
- Reduced transmission losses
- Flicker mitigation
- Oscillation damping

SVC technology has been shown to work effectively but is prevented from being deployed more widely by cost. Any initiative to reduce the cost of the technology, whether in materials, assembly or simply through competition would reduce the barriers to deployment.

The technology is proven and commercialised and is available from a number of manufacturers; TRL = 9. There are a large number of deployments around the world and several in the UK.

3.2.2 Static Synchronous Compensator

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 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.

Benefits include:

- Faster response time than fixed shunts or SVCs
- Can be connected to weak grids
- Can provide power factor correction
- Provides voltage control
- Active harmonics cancellation
- Flicker mitigation
- Unsymmetrical load balancing
- Enhanced ride through capability
- High reliability and availability

The barriers to deployment for STATCOMS are that, in comparison with SVCs, they have a limited track record and impose higher costs and losses. The proposed solutions to the barriers are the same as for SVC: reductions in cost through developments in materials, assembly or greater competition.

The technology is mature and commercialised and available from a number of manufacturers including ABB, Siemens, American Superconductor and Elspec; TRL = 9. There are a large number of deployments around the world, including several associated with the connection of wind farms in the UK.

3.3 Series Compensation

Series compensation is used to alter the reactance of a line by installing a capacitor or reactor in series with the line. Power electronics allows a controllable device, like thyristor controlled series compensation (TCSC), to do the same job as a fixed capacitor or reactor but with greater control over its reactance. A capacitor in series with an AC overhead line will reduce the overall reactance of the line and a reactor in series will increase the overall reactance. TCSC can provide both capacitive and inductive compensation.

The benefits of being able to alter the reactance of lines are:

- A reduction in short circuit fault current, which may allow additional generation to connect without exceeding the limits of existing switchgear
- A reduction in load dependant voltage drops, which may allow greater network utilisation
- A reduction of system transfer impedance and transmission angle, which can improve system stability
- An ability to influence load flow in parallel or alternative circuits, which may allow greater network utilisation

Some of these benefits conflict with one another so could not be delivered together.

The barriers to employing this technology in the UK include the extensive system modelling required to ensure consistent performance under varying conditions as well as the potential for series compensation to introduce sub-synchronous resonance into the network.

The need for extensive modelling can be met with improved analysis tools and an increase in the number of people with the skills to perform the necessary analysis. Outsourcing of analysis to other countries has limited scope because the tools and skills are not widely available elsewhere and network studies rely on detailed understanding of the networks concerned, which comes from being closely involved with their design and operation.

The potential problem of sub-synchronous resonance will be better understood by improved modelling and simulation, can be tested with gradual deployments, and can then be managed with appropriate monitoring equipment and protection.

Series compensation is a mature technology used quite extensively in other countries. While the technical risks associated with deployment in the UK remain a concern, the risks in procuring and installing this technology are well known and understood by network operators; TRL = 9. The technology is supplied by a number of manufacturers.

3.4 Phase Shifting Transformers

A phase shifting transformer is able to adjust the voltage phase angle and thereby provide control over power flow. The phase-shifting effect is realised by the particular connection of a series and a shunt transformer equipped with a tap changer. The two transformers produce voltages in quadrature and the resulting output is a combination of the two; a transformer of this type is sometimes called a quadrature (or quad) booster. The phase angle can be modified without a significant change in voltage magnitude, although the transformer will normally be able to modify voltage magnitude as well.

Phase-shifting transformers can help to reduce congestion on transmission and distribution networks by forcing power to flow into underutilised lines. There are no notable barriers to the deployment of this technology. Phase shifting transformers are already in use in the UK transmission network and have been considered for use in distribution networks. Their cost is higher than traditional transformers because of the more complex structure. The relatively higher costs might be partially reduced through bulk ordering or supply chain improvements, especially for standardised transformers.

The technology is tested and reliable and is on the market from a number of manufacturers; TRL = 9. 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.

3.5 Active Network 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 (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 DSO may also have the possibility to manage electricity flows using a flexible network topology."

In this review a number of active network management (ANM) technologies are discussed in terms of the scope for them to enhance the capacity of UK distribution networks to accommodate new generation.

3.5.1 Power Flow Management

Power flow management is concerned with addressing thermal limits on 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, which may be based on either a pre-fault or post-fault network limit.

Special Protection Schemes (SPSs) are emerging that are being used to 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.

More refined approaches will control the power output of generation based on power flow measurements. This represents a much more dynamic solution that requires real-time monitoring and control. Such a scheme could make use of short-term power ratings of circuits. Generation is given time to reduce power output in a controlled manner; short term thermal limits can be exploited for a sudden change in available network capacity that might result from an outage on the system. An inter-tripping scheme can provide back-up to a scheme of this nature.

Where thermal limits place a restriction on the capacity of generation that could be connected, power flow management can allow greater capacity to be connected. The output of the new generators will be curtailed at certain times according to conditions on the network and this must be taken into account when assessing the financial viability of connection. For intermittent renewable sources like wind, this type of connection is appropriate because a wind farm will rarely ever need the full export capacity that would be provided by a conventional approach.

Power flow management can be implemented with off-the-shelf components for measurement, communications and control. As for other ANM technologies, the principle barriers to deployment are lack of experience on the part of network operators and inflexibility in their 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.

These barriers can be overcome with:

- 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

Power flow management technology has been fully developed and tested and is currently available on the market; TRL = 8. Example deployments include:

- Scottish and Southern Energy with Senergy Econnect – Deucheran Hill Wind Farm (UK)

  The scheme manages access to the transmission system for a wind farm. Measurements of load and circuit breaker positions allow decisions to be made through logic control to restrict the output of or trip the wind farm.

- EDF Energy Networks – Scroby Sands Offshore Wind Farm (UK)

  An intelligent control system utilises additional capacity during intact network conditions, while sending curtailment signals to the wind farm during fault conditions when there is insufficient circuit capacity.

- Scottish and Southern Energy with Smarter Grid Solutions – Orkney RPZ (UK)

  The “SGi” system installed as part of the Orkney Registered Power Zone (RPZ) manages multiple non-firm generators against multiple power flow constraints. This has allowed additional generators to connect where otherwise an expensive reinforcement of the network would have been required.

3.5.2 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.

Studies carried out at EPRI suggest that dynamic thermal rating could increase component current carrying capacity by an average of 10-15%. Research at Durham University suggests that in the case of wind farm connections the correlation between the wind powering the wind farm and the wind cooling overhead conductors can increase a line connection capacity by up to 50%.

The main barrier to the application of dynamic thermal rating 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. There can also be technical complications and additional cost due to the necessity of monitoring equipment and communications.

Proposed solutions to the barriers are:

- 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)

The sensors, communications and computational technology required for dynamic thermal ratings are available commercially. Two UK distribution network operators, E.On Central Networks and Northern Ireland Electricity, have developed their own line temperature monitoring systems; TRL = 8.

Example deployments include:

- E.On Central Networks – Skegness (UK)

  Overhead line thermal monitoring for increasing non-firm distributed generation capacity on a 132 kV line

- Kema, Nuon – Amsterdam (Netherlands)

  Thermal monitoring through fibre optics on a 132 kV line with overhead and underground conductors and a power transformer

- Red Electrica de Espana, Iberdrola – Madrid (Spain)

  Meteorological monitoring based thermal rating of the transmission network of the Madrid area

- Dynamic Ratings – Kansas City (US)

  Optical fibre temperature measurement is employed to determine transformer winding temperature and provide an input to dynamic rating and insulation ageing software. This provides the ability to load transformers 10-20% higher than the static thermal rating.

3.5.3 Voltage Management

There are a number of ways in which voltage management can be improved to facilitate additional generator connections. The methods differ in the way voltages are measured and the way control actions are determined but all depend on modifying one of the following:

- The real power output of the generator, which overlaps with power flow management
- The reactive power to/from the generator or ancillary equipment, such as reactive compensation
- The tap position of transformers or voltage regulators

Different methods require local and remote voltage measurements to varying degrees, with local measurements preferred by network operators because it reduces the reliance on communications. 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. This means that methods relying on state estimation or other non-deterministic calculation methods are not favoured.

The maximum 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.

Barriers to deployment include:

- The relatively tight range of acceptable voltages and the potentially large impact of 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.

The level of maturity and market risk depends on the method. Simpler methods based on local measurement and control of a single piece of equipment are technically mature and readily available; TRL = 9. More complex methods based on remote measurements and co-ordinating multiple resources are only at the trial and demonstration stage; TRL = 7.

On-load tap changing transformers, in-line voltage regulators and reactive compensation are available from a large number of manufacturers. The capability of generators to alter their reactive power and contribute to voltage control depends on the specific technology but most modern wind turbines, for example, now offer voltage control capabilities. In the UK, two companies have trialled novel methods for controlling transformer tap position to enhance generator connection capacity, as identified below.

Example deployments include:

- Samotraki (Greece)

  In line voltage regulation for maximising wind farm output in the Samotraki-mainland connection

- Fundamentals – UK

  Field trials in four locations of the SuperTAPP n+ transformer tap changer relay, in collaboration with EDF Energy, Central Networks, CE Electric UK, ScottishPower, EA Technology

- Senergy Econnect – Martham (UK)

  A Registered Power Zone was registered by EDF Energy Networks using Senergy's GenAVC device for controlling transformer tap position in a network with embedded generation

3.5.4 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.

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 and controlling load in correspondence to available renewable energy could contribute to maximising renewable energy contribution.

DSM 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, 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.

Solutions to the barriers include economic incentives such as tariffs that provide an incentive for customers to accept partially flexible consumption. There is also a need for the development of appliances and industrial processes allowing a degree of flexibility in energy consumption. Some of the changes anticipated over the coming decades may open new opportunities for DSM. The roll-out of smart meters is expected to deliver new capabilities in DSM, although this will rely upon the installation of suitably controllable loads. The increased use of electrical heating and cooling offers scope for exploiting thermal inertias and energy storage. The anticipated expansion in electric vehicles will present new challenges with potentially significant increases in demand in certain areas but it is anticipated that it will be possible to shift and control that demand to some degree. Future electric vehicles might provide wide-scale distributed energy storage offering opportunities for control of demand and supply. Meanwhile, continuing developments in information and communication technologies is an enabler for DSM making it cheaper and easier to implement the necessary control systems.

DSM is technically and commercially mature for applications in small island systems, such as some of the deployments listed below; TRL = 9. There are a number of DSM participants in system balancing in Great Britain contributing to frequency control and system reserve; TRL = 9. DSM as part of the operation of a distribution network and to facilitate the connection of additional generation remains a proposed method and has not been deployed; TRL = 6.

Deployments of DSM include:

- Senergy Econnect – Various locations

  A frequency-based load management system has been deployed with resistive loads such as water heaters to enable the connection and use of greater levels of renewable generation in Fair Isle (UK), Eigg (UK) and Kynthos (Greece)

- Flexitricity – UK

  Flexitricity operates a “virtual power station” composed of small generators and electricity loads located on industrial and commercial sites. Internet communications are used to turn down electricity consumption and run generation for short periods when the national electricity system is under stress.

4 Impact on Distribution Networks

While it is anticipated that the majority of new renewable generation installed in the UK over the coming years will be in large, transmission-connected wind farms, there is still expected to be growth in the capacity of generation connected at distribution level. The distribution networks were not designed to accommodate large amounts of generation and there are considerable constraints on what can be connected. The technologies reviewed in this report offer some solutions to these constraints. This section presents an assessment of the impact of applying these technologies to facilitate additional generation at distribution level. The assessment attempts to compare quantitatively the additional generating capacity made possible with the technologies and discusses other issues relating to the use of the technologies.

4.1 Distribution Network Planning and Operation

The basic purpose of electricity distribution networks as designed and built in the UK is to deliver electrical power from the energy source, which normally means the transmission network, to consumers. This must be achieved within acceptable standards of safety and quality and at an acceptable cost. The requirements that must be met by distribution network operators (DNOs) are defined in legislation, regulations, standards and other formal documents. These objectives are augmented further by the goals and ambitions of the DNO itself. Electricity distribution networks are constrained by what is technically possible, what society and communities permit, and the cost of implementation. Thus, as with other complex engineering tasks, the basic electricity distribution network planning and operation “problem” is to meet, or get as close as possible to, all the objectives while meeting all the constraints.

In electricity distribution, objectives and constraints are concerned mainly with safety, quality, reliability and cost. Most issues may be viewed as both objectives and constraints. For example, most DNOs will claim to strive for ever-improving safety while also having to meet statutory safety standards. As with most complex problems, many of the objectives will be conflicting; for example, trying to minimise costs while making technical improvements.

The detailed requirements vary from one area to another but in the simplest terms, distribution networks are very similar all over the world. There are transformers, switches and ancillary equipment in substations, which are connected to sources, consumers and other substations by overhead lines and underground cables. In developed countries like the UK, electricity supply systems have been in operation for more than a century and now reach almost the entire population. Thus, there is a substantial installed base of assets to build upon. Furthermore, many items of equipment have a service life running into decades so may have to operate through widely varying circumstances. Network planners must tackle the problem of extending and renewing the system to meet all the demands put upon it, now and in the future.

DNOs in the UK act as network operators, which is distinct from the system operator role played by National Grid. The DNOs do not closely manage the generation and demand on their network; the network is designed and built to accommodate all expected conditions without active intervention. The level of monitoring on the network depends on the voltage level. Typically, the network management system (NMS), or Supervisory Control and Data Acquisition (SCADA) system, will allow an operator to see the current and voltage at all locations on the 132 kV and 33 kV network but this reduces until there is practically no monitoring at low voltage.

4.1.1 Distributed Generation

Distributed generation (DG) refers to generators connected directly to distribution networks. Typically, DG installations are smaller than conventional power stations, which are connected at transmission level, and may utilise unconventional energy sources or electrical technologies, such as renewable sources or power electronics. DG is also sometimes called embedded generation because it is embedded in distribution networks, or dispersed generation because small generators can be seen as dispersed around the system rather than being centralised like large, conventional power plants.

4.1.2 Network Constraints

The DNOs in the UK all identify three primary constraints on new DG connections:

- **Thermal capacity**, where the calculated ratings of existing cables, lines and transformers, and the approach taken with respect to security, means there is limited capacity to absorb and carry the power injected from new generators
- **Fault levels**, where the additional short circuit current contribution from new generators may mean that the rating of existing switchgear is exceeded
- **Voltage**, where the power flows caused by new generators might mean that voltages on parts of the network move outside the allowed limits at certain times or the step change in voltage that will occur for certain disturbances will be too great

The relative importance of each constraint varies depending on location, although fault levels are cited as the primary concern by many DNOs.

4.2 Existing Generation

The National Grid Seven Year Statement includes information on the amount of generation connected to UK distribution networks, which is collated from information submitted by all the DNOs. Information is provided on the type of generation and its capacity.

A summary of existing capacity is shown in Table 3. The generation types listed in the SYS have been interpreted to fit into a smaller set of categories as shown. The capacity of each type is split according to generator size. These sizes are used to estimate the capacity of generation connected at different voltage levels. It is assumed that:

- Generators smaller than 0.2 MW could be connected to the low voltage distribution network
- Generators between 0.2 and 5 MW are most likely to be connected at 11 kV
- Generators between 5 and 30 MW are most likely to be connected at 33 kV
- Generators greater than 30 MW are most likely to be connected at 132 kV

This assignment is only meant to provide a rough indication of how the existing generation capacity is split across the voltage levels.

Table 3: Summary of existing generation on UK distribution networks

Category	Less than 0.2 MW	Between 0.2 and 5 MW	Between 5 and 30 MW	Greater than 30 MW	Total	Percentage of Total
	LV	11 kV	33 kV	132 kV		
Biodiesel	0.1	0	0	0	0.1	0.0%
Biogas	0	0	57.6	0	57.6	0.8%
Biomass	0	2.9	22.5	69.3	94.7	1.3%
CHP	0	8.9	333.4	808.7	1151	15.4%
Coal	0	0	17	30	47	0.6%
Diesel	0	12.8	223.2	0	236	3.2%
Dual Fuel	0	0	22	33	55	0.7%
Gas	0.1	19.7	424.1	605	1048.9	14.1%
Gas CHP	0	0	230.9	666.7	897.6	12.0%
Geothermal	0	0	7	0	7	0.1%
Hydro	1.5	114.1	159.4	123	398	5.3%
Landfill	0	42.6	135.9	0	178.5	2.4%
Offshore Wind	0	4	9.9	912.8	926.7	12.4%
Oil	0	0	171.2	38	209.2	2.8%
Onshore Wind	0.1	64	682.7	422.1	1168.9	15.7%
Other	0	54.1	152.2	346	552.3	7.4%
PV	0	0	0	0	0	0.0%
Waste	0	63.6	282.7	66	412.3	5.5%
Wave	0	4.2	7	0	11.2	0.2%
Total	1.8	390.9	2938.7	4120.6	7451.9	100.0%
Percentage of Total	0.0%	5.2%	39.4%	55.3%	100.0%	

The information in the SYS indicates that the majority of generation capacity connected to distribution networks in the UK is formed of larger generators that are most likely to be connected at 132 kV. The capacity of low voltage connected generation is near zero, although it should be noted that the information compiled by National Grid, which is based on information provided by the DNOs, probably underestimates LV-connected generation as the DNOs are not always aware of generators being connected at this level.

The generator types that make the greatest contribution are onshore and offshore wind, gas-powered thermal plants and different types of combined heat and power (CHP).

The 7.4 GW of installed capacity at distribution level compares with a total capacity on the entire system of 83.6 GW. As discussed in the literature review, the total installed capacity is expected to grow up to and beyond 2020 and it is expected that DG will remain a small but significant fraction of the total.

4.3 Quantifying Potential Connection Capacity

The approach taken to quantifying how the different technologies might facilitate additional generation capacity is based on simplified analysis of connections at each of the main distribution voltage levels: 132 kV, 33 kV, 11 kV and low voltage (LV). The analysis produces a measure of the maximum generation capacity that could be accommodated in a single network area for each voltage level, which means:

- under a single Grid Supply Point (GSP) at 132 kV
- under a single Bulk Supply Point (BSP) at 33 kV

- under a single Primary Substation at 11 kV
- under a single Distribution Substation at LV

Each voltage level or network area and potential connecting generation is characterised in the simplest terms possible to assess thermal, fault level and voltage limits. Calculations are performed with average characteristics based on a review of the data in the LTDSs and other sources. Sensitivity analyses are performed to demonstrate how the characteristics influence limits on connection capacity and thereby give an indication of how circumstances vary depending on location.

The analyses of single network areas are translated to national estimates by multiplying by the number of similar network areas. This takes account of the cumulative effect of generation being installed in multiple network areas that are supplied from, or end up exporting into, a higher voltage network area. In considering this type of estimate it must be recognised that circumstances vary greatly and many networks have characteristics that are very different from what is typical or average.

In section 4.4 the technologies under review are assessed in terms of their possible impact on the network and generator characteristics or the scope for overcoming limits.

4.3.1 Network and Generator Characteristics

For thermal, fault level and voltage limits some simple characteristics are defined and explained to enable an analysis of maximum generation connection capacity. The characteristics are explained below and summarised in Table 4. The characteristics of typical distribution networks are based on data from the LTDS published by CE Electric for the Yorkshire distribution license area because of its composition of both urban and rural areas. The sensitivity analysis shows how variations in the average values affect the outcome.

4.3.1.1 Thermal Limits

The assessment of thermal limits is based on transformer ratings and demand. Line ratings are neglected in the analysis but the potential for dynamic line ratings to enhance capacity is discussed below.

A conservative assessment would limit generation capacity to the minimum demand in a network area to ensure there was no chance of power flow being reversed through the transformers and exported to a higher voltage level. This is a genuine limit in many UK distribution networks because the existing transformer tap changers, which are essential to voltage control, do not operate properly when power flow is reversed.

If the transformers can handle reverse power flow then power can be exported to a higher voltage level, which at a GSP will mean injecting power into the transmission network. Generation capacity might be limited to minimum demand plus the rating of the transformers. Transformer ratings are in MVA; it is assumed in the basic analysis that the maximum real power flow through a transformer is 0.9 times its MVA rating to take account of the necessary reactive power flows.

At the higher voltage levels, multiple transformers will be installed to ensure security of supply. Generation capacity might be limited to the secure or firm rating, which is based on one transformer being out of service, or a non-secure or non-firm rating, which is based on all equipment being in service.

If some form of active power flow management is implemented then generators can produce power according to variations in local demand. The maximum output will be equivalent to the maximum export through the transformers plus the maximum local demand.

If the generation output at any time depends on local demand then total energy production from the generator will depend on the local load factor or average demand. For most generation developers, energy production is more important than capacity because that is the basis for their income.

Average values for transformer ratings and demand at each voltage level are shown in Table 4.

Thermal limits will be assessed in terms of the MW capacity of transformers and MW demand, which translates directly to the possible MW capacity of generation. Generator power factor is neglected in the basic analysis of thermal limits but is otherwise assumed to be 0.95 leading or lagging.

4.3.1.2 Fault Level Limits

The assessment of fault level limits is based on existing fault levels and switchgear ratings. The difference between them gives fault level headroom, which sets the limit on additional generation capacity. It is common practice amongst the DNOs to try and keep fault levels below 95% of switchgear rating.

As with the other limits, the importance of fault level to generation capacity varies greatly depending on the location. Broadly speaking, fault levels are higher and likely to be closer to switchgear limits in urban areas. In rural areas fault levels are likely to be much lower but the switchgear may have correspondingly low ratings.

Average values for fault levels and switchgear ratings at each voltage level are shown in Table 4.

To assess fault level limits the basic assumption is that generators will deliver fault current equivalent to five times their rated current. The actual fault current contribution will depend on the particular generator technology and the details of its construction and operation, including its distance from the substation. For the purpose of the studies, fault level headroom of 100 MVA means that additional generator capacity would typically be limited to 20 MVA. With an assumed power factor of 0.95, this would mean a generator capacity of 19 MW.

4.3.1.3 Voltage Limits

The assessment of voltage limits is based on existing fault levels and X/R ratios. The fault level is an indication of the system impedance at a potential connection point. The impedance can be split into resistance, R, and reactance, X, according to the X/R ratio, for which typical values are assumed. Additional generation will have an impact on voltage that can be approximated by the equation

$$\Delta V \approx RP + XQ$$

where P is the real power and Q is the reactive power output from the generator (with all values in per unit). The change in voltage that is acceptable to the DNO will depend on the circumstances but the analysis assumes a basic limit of 0.05 per unit.

Average values for fault levels and X/R ratios at each voltage level are shown in Table 4.

A conservative assessment would assume that a generator is producing reactive power as well as real power, resulting in a more pronounced impact on voltage. With a power factor of 0.95 this means a generator producing 50 MW would also be producing 16.4 MVAr.

A more optimistic assessment assumes that the generator operates at unity power factor so only real power is produced and only the resistive component of the voltage change is counted. For example, if the fault level and X/R ratio translate into a resistance of 0.02 per unit (on a 100 MVA base) then the maximum generator capacity would be 0.05/0.02*100 = 250 MW.

An even more optimistic assessment assumes that the generator controls the absorption of reactive power to mitigate the voltage rise caused by its real power export. With a power factor of 0.95 this means a generator producing 50 MW could absorb up to 16.4 MVAr. If this is sufficient to fully compensate for the voltage rise caused by real power export then voltage is assumed to present no limit on capacity.

Another possibility is that the generator must absorb reactive power as part of its normal operation. So with a power factor of 0.95 a generator producing 50 MW will absorb 16.4 MVAr. Depending on the balance of resistance and reactance in the system impedance the voltage rise caused by real power export may be smaller than the voltage drop caused by reactive power import. The net voltage drop will set a limit on maximum generator capacity.

Table 4: Average network characteristics used for assessing generation connection capacity

		132 kV GSP	33 kV BSP	11 kV Primary	LV Distribution
Thermal Limits					
Transformer Ratings (MVA)	Firm (one transformer out of service)	240	77	22.5	0.25
	Non-firm (all equipment in service)	480	154	45	0.25
Demand (MW)	Minimum	80	5	1	0.01
	Average	120	27	7	0.04
	Maximum	200	50	13	0.2
Fault Level Limits					
Fault Level (MVA)		2671	636	166	9
Switchgear Rating (MVA)		4452	1060	277	15
Voltage Limits					
Fault Level (MVA)		2671	636	166	9
X/R Ratio		20	10	10	3

4.3.1.4 Limits Used in the Analysis

The simple analysis based on the network characteristics described above identifies ten possible thermal, fault level and voltage limits that can be used to quantify the amount of generation that can be connected a network area. The ten limits are listed in Table 5. In any given circumstance each of these limits will apply to a greater or lesser extent. Thermal, fault level or voltage limits will take precedence according to the particular characteristics of each network location. This simple analysis using average values is merely indicative of how maximum generator capacity is affected by different limits and is used only to illustrate the potential impact of the different technologies under review.

Table 5: Limits on distributed generation capacity

Identifier	Description
Limit 1	Thermal Limit - Minimum demand
Limit 2	Thermal Limit - Minimum demand + Transformer (firm)
Limit 3	Thermal Limit - Minimum demand + Transformer (non-firm)
Limit 4	Thermal Limit - Maximum demand + Transformer (firm)
Limit 5	Thermal Limit - Maximum demand + Transformer (non-firm)
Limit 6	Fault Level Limit
Limit 7	Voltage Limit - Generator produces MVArs
Limit 8	Voltage Limit - Generator at unity power factor
Limit 9	Voltage Limit - Generator absorbs MVArs (controllable)
Limit 10	Voltage Limit - Generator absorbs MVArs (fixed)

Limits 1-5 are thermal limits that could be applied under different circumstances. Limit 1 is the most conservative and restricts generation to the same level as minimum demand; this would ensure that there would be no reverse power flow through the transformers onto the higher voltage networks. Limit 5 is the most generous and would only be possible if some form of active management was installed to control the generation to avoid breaching thermal limits at times when demand is below maximum.

Limit 6 ensures that the rating of the switchgear installed on the network is not exceeded. The maximum acceptable fault level as a percentage of the rating may vary from location to location.

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. This limit is intended to cover both steady state and step change voltage effects with a simple assessment. The different voltage limits depend on the operation of the generator with regards to reactive power. The generator technology being installed will determine what limits the DNO would apply as some generator technologies operate with fixed power factors and some can provide full control of their reactive power.

The different limits can be mitigated using different technologies and the maximum capacity of distributed generation can thereby be enhanced.

4.3.2 Calculations with Average Values

Analysis was performed using the average values for the network characteristics shown in Table 4. The analysis produces lists of the limits in order of their priority when determining the maximum connectable generation. The limit that results in the lowest MW value for total generation capacity available is deemed to be the highest priority. The resulting priority lists for each voltage level are shown in Table 6 to Table 9. This analysis only allows for comparison of the different limits based on the average values and enables a rough approximation to be made of how much additional generation capacity is possible if certain limits are overcome or deemed irrelevant.

Table 6: Priority list for generation capacity limits on the average 132 kV network

Priority	Identifier	Description	MW Limit
1	Limit 1	Thermal Limit - Minimum demand	80
2	Limit 2	Thermal Limit - Minimum demand + Transformer (firm)	296
3	Limit 6	Fault Level Limit	296.06
4	Limit 7	Voltage Limit - Generator produces MVArs	353.14
5	Limit 4	Thermal Limit - Maximum demand + Transformer (firm)	416
6	Limit 10	Voltage Limit - Generator absorbs MVArs (fixed)	479.85
7	Limit 3	Thermal Limit - Minimum demand + Transformer (non-firm)	512
8	Limit 5	Thermal Limit - Maximum demand + Transformer (non-firm)	632
9	Limit 8	Voltage Limit - Generator at unity power factor	2674.54
10	Limit 9	Voltage Limit - Generator absorbs MVArs (controllable)	unlimited

Table 7: Priority list for generation capacity limits on the average 33 kV network

Priority	Identifier	Description	MW Limit
1	Limit 1	Thermal Limit - Minimum demand	4.98
2	Limit 6	Fault Level Limit	70.49
3	Limit 2	Thermal Limit - Minimum demand + Transformer (firm)	74.28
4	Limit 7	Voltage Limit - Generator produces MVArs	74.55
5	Limit 4	Thermal Limit - Maximum demand + Transformer (firm)	119.12
6	Limit 10	Voltage Limit - Generator absorbs MVArs (fixed)	139.75
7	Limit 3	Thermal Limit - Minimum demand + Transformer (non-firm)	143.58
8	Limit 5	Thermal Limit - Maximum demand + Transformer (non-firm)	188.42
9	Limit 8	Voltage Limit - Generator at unity power factor	319.58
10	Limit 9	Voltage Limit - Generator absorbs MVArs (controllable)	unlimited

Table 8: Priority list for generation capacity limits on the average 11 kV network

Priority	Identifier	Description	MW Limit
1	Limit 1	Thermal Limit - Minimum demand	1.31
2	Limit 6	Fault Level Limit	18.42
3	Limit 7	Voltage Limit - Generator produces MVArs	19.48
4	Limit 2	Thermal Limit - Minimum demand + Transformer (firm)	21.57
5	Limit 4	Thermal Limit - Maximum demand + Transformer (firm)	33.41
6	Limit 10	Voltage Limit - Generator absorbs MVArs (fixed)	36.52
7	Limit 3	Thermal Limit - Minimum demand + Transformer (non-firm)	41.82
8	Limit 5	Thermal Limit - Maximum demand + Transformer (non-firm)	53.66
9	Limit 8	Voltage Limit - Generator at unity power factor	83.51
10	Limit 9	Voltage Limit - Generator absorbs MVArs (controllable)	unlimited

Table 9: Priority list for generation capacity limits on the average LV network

Priority	Identifier	Description	MW Limit
1	Limit 1	Thermal Limit - Minimum demand	0.01
2	Limit 2	Thermal Limit - Minimum demand + Transformer (firm)	0.235
3	Limit 3	Thermal Limit - Minimum demand + Transformer (non-firm)	0.235
4	Limit 4	Thermal Limit - Maximum demand + Transformer (firm)	0.425
5	Limit 5	Thermal Limit - Maximum demand + Transformer (non-firm)	0.425
6	Limit 7	Voltage Limit - Generator produces MVArs	0.717
7	Limit 6	Fault Level Limit	0.998
8	Limit 8	Voltage Limit - Generator at unity power factor	1.423
9	Limit 9	Voltage Limit - Generator absorbs MVArs (controllable)	102.026
10	Limit 10	Voltage Limit - Generator absorbs MVArs (fixed)	102.026

It can be seen from these tables that the highest priority limit at all voltage levels is the thermal limit based on minimum demand, limit 1. This is applied if it is unacceptable to have any export of power from the lower voltage onto the higher voltage through the transformers. This could be because the transformer is not adaptable to bi-directional power flow or because of constraints on the higher voltage network. The results for all four network areas indicate that if this limit can be overcome then substantially more DG can be connected. This demonstrates the potential value of overcoming this limit where it applies.

Limit 2, for which the minimum demand and the rating of a single transformer are used to determine available generation capacity, is also a high priority at all voltage levels. Where power export back up through the transformers is possible, limit 2 is the conventional limit used by DNOs to assess the feasibility of offering generators a firm connection. Generation added within this limit should be able to generate freely without breaching plant ratings on the network during normal conditions, or during N-1 network operating conditions at higher voltages.

The fault level limit 6 is highlighted by a number of DNOs within their LTDS. It is therefore not surprising that limit 6 is assigned a high priority at all voltage levels. The analysis shows how fault level limits compare to the other limits under these average circumstances but illustrates how overcoming thermal or voltage limits can still leave fault level as a limit on generation capacity.

The other limit that receives a high priority ranking at all voltage levels is limit 7, which is the most onerous of the voltage limits as it has the most pessimistic assumption regarding DG reactive power. This mode of operation, with the generator producing MVArs, results in a lower limit compared to the other modes of operation because there is voltage rise resulting from both real and reactive power. This limit is reached when the voltage change resulting from the connection of generation breaches 5%.

The limit that consistently has the lowest priority is limit 9, which assumes that generators try to absorb reactive power to compensate for the voltage change associated with real power export. The effectiveness depends on the X/R ratio in each network area. At higher voltages the higher X/R ratio means that absorbing reactive power can fully compensate for voltage changes caused by real power and this limit is effectively removed. This demonstrates the value of effective reactive power control, in that it has the potential in some circumstances to overcome all voltage limits, but also illustrates that no matter the flexibility and scope of reactive power control, thermal and fault level limits will remain.

On LV networks limits 2-3 and limits 4-5 are the same because it is assumed that there is only one transformer supplying the network area so firm and non-firm capacity is the same. Limits 9 and 10 are also the same on LV networks. This is because the X/R ratio is low and even with the maximum import of reactive power it is not possible to fully compensate for the voltage change due to real power export. The differences between the voltage levels serve to demonstrate how different technologies will deliver benefits to varying degrees.

Table 10 shows the maximum energy production (in MWh) each year associated with the thermal capacity limits 1-5. For limits 1-3 it is assumed that the generation can produce power at its maximum capacity for all 8760 hours in a year. For limits 4-5 it is assumed that generation output is actively managed to follow local demand so total energy production will correspond to average demand.

Table 10: Maximum energy production p.a. for different thermal limits

Identifier	Description	132 kV GSP	33 kV BSP	11 kV Primary	LV Dist.
Energy Limit 1	Limited to Minimum demand	700800	43645.7	11524.6	87.6
Energy Limit 2	Minimum Demand + Transformer (firm)	2592960	650713.7	188914.6	2058.6
Energy Limit 3	Minimum Demand + Transformer (non-firm)	4485120	1257781.7	366304.6	2058.6
Energy Limit 4	Average Demand + Transformer (firm)	2943360	847119.1	240775.0	2321.4
Energy Limit 5	Average Demand + Transformer (non-firm)	4835520	1454187.1	418165.0	2321.4

These values demonstrate that while active management may allow significantly higher capacity of DG, the increase in energy output that is enabled will be smaller. For any deployment of active power flow management it is necessary to estimate the expected energy output as part of the overall cost-benefit analysis.

4.3.2.1 National Estimates

The results of the analysis for each voltage level are translated to a national level based on the following estimates for Great Britain:

- There are approximately 200 132 kV GSPs or equivalent network areas
- There are approximately 1,000 33 kV BSPs or equivalent network areas
- There are approximately 4,000 11 kV primary substations or equivalent network areas
- There are approximately 700,000 LV distribution substations or equivalent network areas

It has already been noted that this analysis neglects the great diversity in distribution networks and the maximum generator capacities calculated for the average network characteristics are merely indicative and serve only to illustrate the impact of the different limits and different technologies under review. Based on the calculated maximum generator capacities in each network area and estimates of the number of equivalent areas, the ten limits suggest total maximum distributed generator capacities (in GW) as shown in Table 11.

The maximum capacity is not the same as maximum power output; in extreme conditions average DG load factor will be very low as it will depend on local energy requirements. At LV the multiplication of capacity limits in one area by the approximate number of areas produces some very high values that are totally unrealistic and so marked as “>1000”. The values for limit 9, which was assessed as imposing no limit at 132, 33 and 11 kV, is similarly marked.

Table 11: Estimate of national maximum distributed generation capacity (GW)

Identifier	Description	132 kV GSP	33 kV BSP	11 kV Primary	LV Dist.
Limit 1	Thermal Limit - Minimum demand	16	5	5	70
Limit 2	Thermal Limit - Minimum demand + Transformer (firm)	59	74	86	>1000
Limit 3	Thermal Limit - Minimum demand + Transformer (non-firm)	102	144	167	>1000
Limit 4	Thermal Limit - Maximum demand + Transformer (firm)	83	119	134	>1000
Limit 5	Thermal Limit - Maximum demand + Transformer (non-firm)	126	188	215	>1000
Limit 6	Fault Level Limit	59	70	74	>1000
Limit 7	Voltage Limit - Generator produces MVArs	71	75	78	>1000
Limit 8	Voltage Limit - Generator at unity power factor	535	320	334	>1000
Limit 9	Voltage Limit - Generator absorbs MVArs (controllable)	>1000	>1000	>1000	>1000
Limit 10	Voltage Limit - Generator absorbs MVArs (fixed)	96	140	146	>1000

Other limits not forming part of this analysis would restrict the maximum feasible capacity of DG – issues like system stability and balancing are discussed further below. The different voltage levels will affect one another so limits at higher voltages will be reflected at lower voltages. For example, the analysis suggests a very high potential capacity of LV connected DG but in any one area the capacity at LV will be restricted by limits at all higher voltages as well as those applying at each distribution transformer.

The interactions between voltage levels will be complex and will depend on each specific set of circumstances but it is reasonable to assume that the limits imposed at 132 kV will be reflected at lower voltage levels and therefore impose an overall limit on generation capacity at distribution level. The most onerous is thermal limit 1 based on minimum demand but this can be neglected at 132 kV because GSP transformers are normally able to accommodate reverse power flow. The overall limit on DG capacity is therefore estimated to be 59 GW, set jointly by the conventional thermal limit 2 and fault level limit 6. Connecting this amount of generation to the distribution networks would require a radical overhaul of the way the distribution and transmission systems are operated.

4.3.3 Sensitivity Analysis

A sensitivity analysis was carried out to assess how the priority assigned to 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. The variability range for the parameters was based on the typical range of values in UK distribution networks.

The graphs show the change in priority for each limit as the parameter is varied. The graphs for the 132 kV network area are shown below in Figure 1 to Figure 3. The graphs for lower voltages can be found in the Appendix in Figure 4 to Figure 12.

In the graphs the limits are colour coded to aid interpretation:

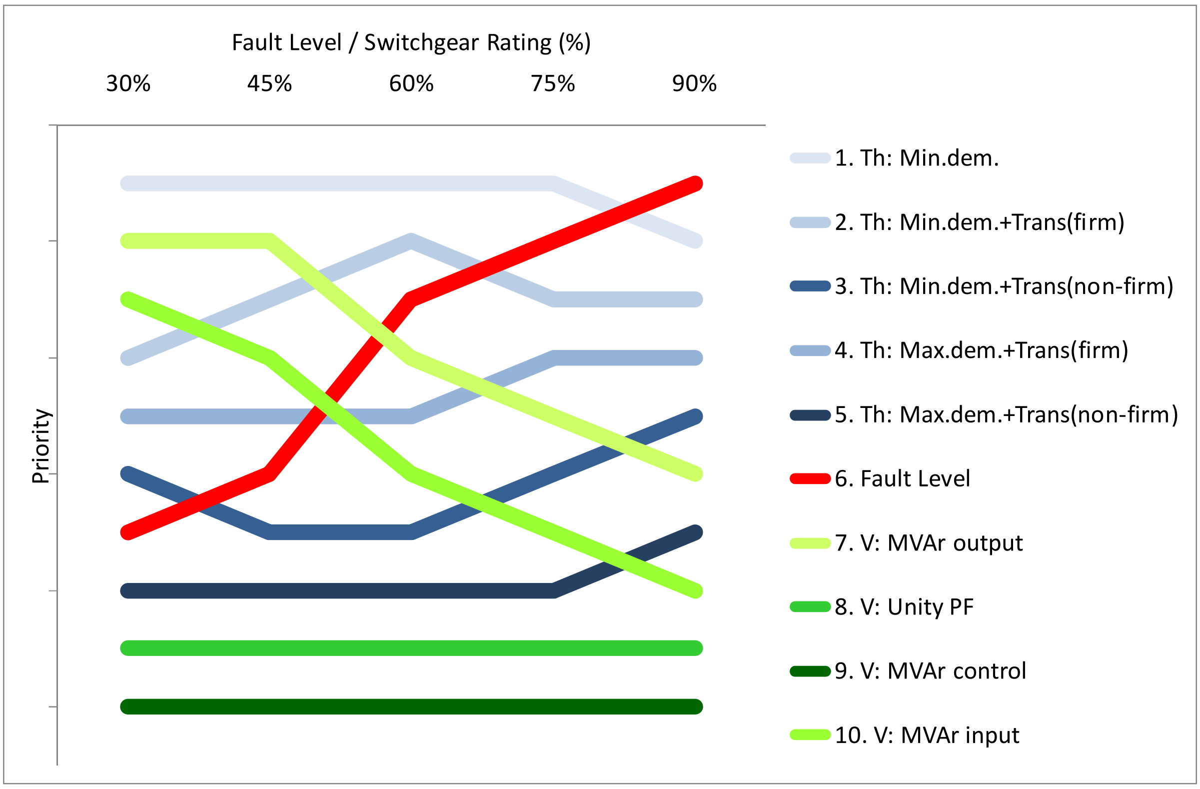
- The five thermal limits are in shades of blue
- The single fault level limit is in red
- The four voltage limits are in shades of green

The colour shades are such that the generally less onerous limits are darker. While some of the thermal or voltage limits may be irrelevant or overcome by some means, other limits will remain. The different shades of colour show how the different thermal or voltage limits relate to one another. The darkest blue, red and darkest green lines provide a comparison of thermal, fault level and voltage limits assuming the more onerous limits have been overcome and only the most extreme limits remain.

4.3.3.1 Fault Level

The 132 kV results for variation of fault level are shown in Figure 1. The fault level values were varied from 30% to 90% of the switchgear rating. The results show that when the fault level is increased the priority of voltage limits (green) falls as the higher fault level indicates lower system impedance and a stronger network. With lower system impedance it takes higher levels of generation to produce the same voltage changes. As expected the increase in fault level results in the fault level limit (red) increasing in priority. The thermal limits (blue) maintain a relatively steady priority level throughout the variation of fault level.

Figure 1: Sensitivity of limit priorities at 132 kV to changes in fault level

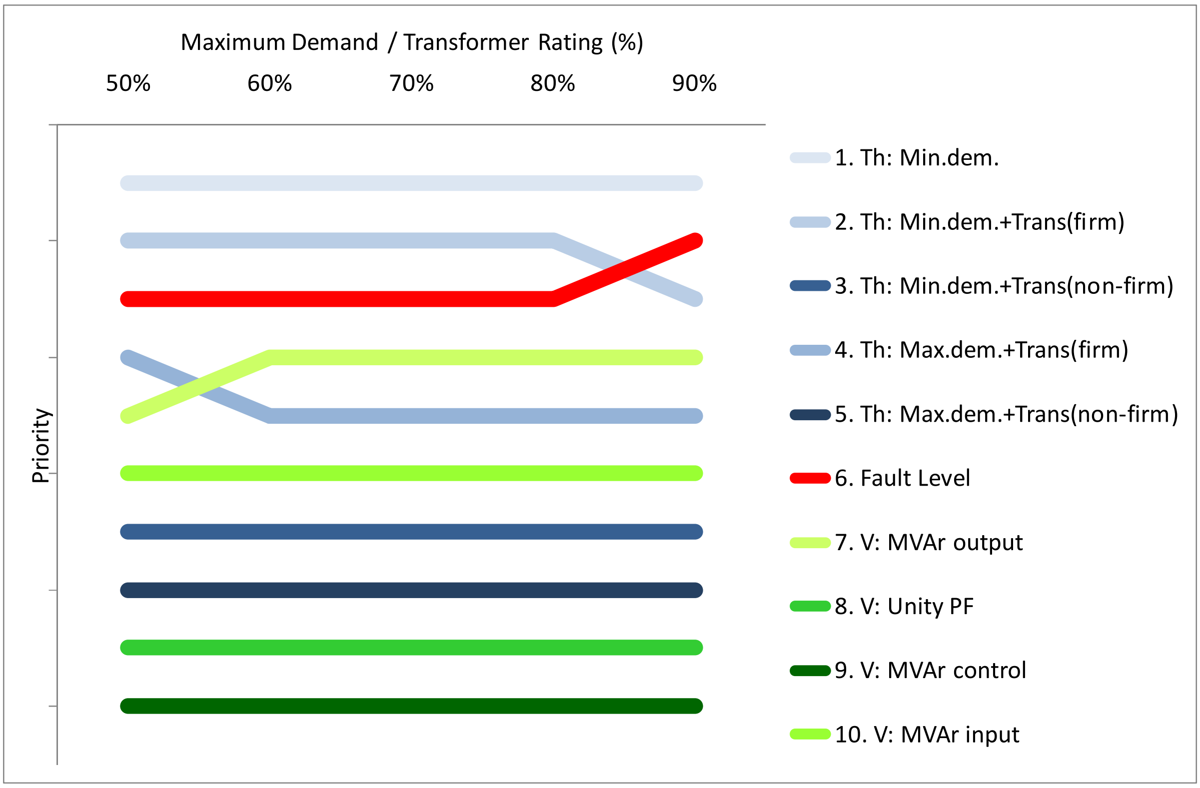


The fact that limit priorities change as fault level changes is indicative of the fact that fault level is very important in determining the potential generator capacity in any particular circumstance. Across distribution networks in the UK the fault level as a percentage of switchgear rating will vary widely and, as illustrated in the chart, the limit priorities will vary. The inverse relationship between fault level and voltage limits is an important feature of the chart as it illustrates the conflict around the “strength” of the network.

4.3.3.2 Demand

The results for varying the maximum demand on the network from 50% to 90% of the transformer rating are shown in Figure 2. The analysis assumes that minimum demand remains the same fraction of maximum demand and so also rises. The thermal limits (blue) remain in the upper part of the chart while the voltage limits (green) remain in the lower part. The fault level limit (red) stays near the top as third or second highest priority.

Figure 2: Sensitivity of limit priorities at 132 kV to changes in demand

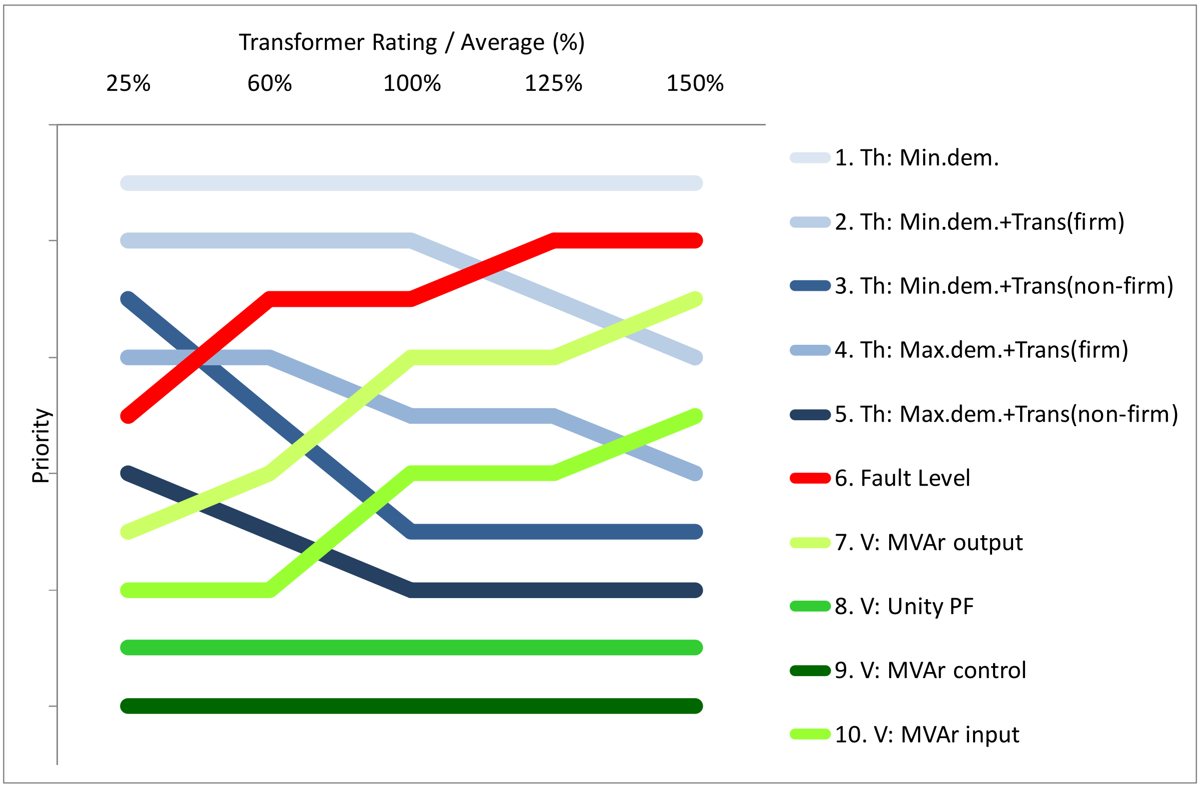


The sensitivity analysis indicates that variations in demand will not alter the basic order of limit priorities very much. Based on the average network characteristics, the different limits remain mostly in the same relative positions, except for minor changes resulting from an increase in minimum demand. In any given network the limit priorities and the maximum potential generator capacity will depend on the specific circumstances but changes in demand will not have a significant impact. Increases in demand will allow greater generation capacity as long as thermal limits remain the highest priority.

4.3.3.3 Transformer Rating

The transformer ratings were adjusted through a range of 25% to 150% of the average transformer rating at each voltage level. The results in Figure 3 show that there is some changing of limit priority as transformer rating changes. Thermal limits (blue) gradually reduce in priority, crossing over some of the voltage limits (green) that increase in priority as transformer rating increase. Fault level limit (red) increases in priority as the thermal limits become less onerous.

Figure 3: Sensitivity of limit priorities at 132 kV to changes in transformer rating



The chart illustrates that transformer rating has a large impact on the priority of thermal limits. The larger the transformer rating the less likely this is to be the limiting factor on generator connections. As thermal limits are relaxed the fault level and voltage limits become more important.

4.4 Enhancing Connection Capacity

There are conventional solutions available to enhance the ability of a network to accommodate additional generation capacity, as described below. The new technologies being considered in this project are then discussed as alternative ways of enhancing connection capacity.

4.4.1 Conventional Solutions

Conventional solutions to tackling limits on generation involve reinforcement or replacement of the existing network using similar methods and equipment. The conventional solutions are well understood and widely applied.

- Thermal limits are overcome by reinforcing or replacing existing lines or transformers. This may involve replacing conductors or insulation on overhead lines. In some circumstances it will be possible to increase thermal capacity with other modifications to existing equipment. Otherwise, increasing thermal capacity will involve replacement of existing assets, which is expensive and may face restrictions such as planning permission.
- Fault level limits are normally overcome by replacing switchgear with equipment of higher rating. In some circumstances it is possible to reduce fault levels by reconfiguring the network or applying certain operating restrictions. This can, however, result in degradation of supply quality as it may expose customers to a greater chance of interruption.
- Voltage limits might be overcome in similar ways to thermal limits because equipment with higher rating typically has lower impedance. Voltage problems might also be addressed with network reconfiguration or refinement of voltage control methods. The most common solution will normally be the construction of a dedicated line for a new generator to prevent existing customers being exposed to voltage fluctuations, but new lines face a range of restrictions.

Solutions to address thermal and voltage limits can exacerbate fault level problems. Network reinforcement to increase capacity and reduce system impedance will result in higher fault levels, which may then threaten switchgear ratings.

4.4.2 New Technologies

The new technologies have the potential to increase the capacity of new generation at distribution level in different ways and with varying impacts on the network. The impact of each technology on the potential capacity of generation connected at distribution level in the UK is discussed below and then summarised quantitatively in Table 12.

4.4.2.1 Power Electronic Converters

The power electronic converters have been reviewed primarily in the context of their use in HVDC transmission. This technology is applicable at distribution level although the costs may be prohibitive. Similar benefits can be derived from the use of the technologies in generator interfaces.

If used to connect new generators, HVDC would remove the additional fault level contribution and, if VSC technology were used, provide an additional means of controlling reactive power and voltage. A new line might be built to operate at DC but the large number of existing customers connected to distribution networks effectively prohibits the conversion of an existing line from AC to DC. Transformers are AC devices although a new HVDC link might be constructed to bypass an overloaded transformer or provide an interconnection to a less heavily loaded network area.

Thus, the power electronic converter technologies have the technical potential to remove the fault level limit 6 and voltage level limits 7, 8 and 10, to leave only the least restrictive voltage limit 9 on existing distribution networks. Reactive power capabilities might mean that thermal limits 2 to 5 could be relaxed slightly by enabling the full transformer MVA capacity to be used to export real power. Power electronic converter technologies could be applied at all distribution voltages, from HVDC-style schemes at 132 kV to micro-generation interfaces at LV.

4.4.2.2 Shunt Compensation

Shunt compensation technologies provide a means of controlling reactive power on distribution networks and thereby mitigating voltage limits. Power flow limits might be addressed to some degree by reducing the need for reactive power flows on the network but fault level limits would be unaffected.

The impact of shunt compensation can therefore be assessed as removing limits 7 and 10, and possibly also limit 8, to leave only the least restrictive voltage limit 9. Thermal limits 2 to 5 might be relaxed slightly by enabling the full transformer MVA capacity to be used to export real power. Fixed shunt compensation is already used at all voltage levels and, subject to costs and practical installation limitations, more advanced controlled shunts could be used at all voltage levels.

4.4.2.3 Series Compensation

Series compensation technologies provide a means of forcing power to flow in certain circuits and thereby maximise network capacity utilisation. At lower voltages distribution networks typically have a radial topology so there are few opportunities for directing power along alternative routes. In modifying network impedance they might also be used to reduce fault levels or voltage drops, although these impacts are not seen as primary drivers for the technology and only one of these effects could be achieved in any given situation.

Series compensation would not increase the thermal rating of the transformers supplying a given network area but might be used to share power export more evenly between neighbouring network areas. This is likely to be applicable only at 132 kV and, to a lesser extent, 33 kV.

4.4.2.4 Phase Shifting Transformers

Phase shifting transformers are similar to series compensation in that they provide a means of forcing power to flow in certain circuits. They face the same restrictions on applicability as series compensation where the benefits only really arise in an interconnected network with multiple paths for power to flow. Phase shifting transformers offer no special advantages in terms of fault level or voltage limits.

The installation of a phase shifting transformer at distribution level would probably mean replacing an existing transformer so this would provide an opportunity to address thermal limits in a network area. If the replacement transformer has a higher rating it might also be expected to have lower impedance, which might help relax voltage limits but might mean tighter fault level limits. It can be assumed that a replacement phase shifting transformer would have only a partial impact on thermal limits. Phase shifting transformers are likely to be deployed only at 33 kV or at 132 kV, where there are alternative paths for power flow or where there is an opportunity to force power off the distribution network and on to the transmission network.

4.4.2.5 Active Network Management

The different ANM methods will each have a different impact on generator capacity limits.

Power Flow Management

Power flow management is necessary to remove limits 2 and 3 and facilitate the greater generator capacity assumed with limits 4 and 5. If reverse power flow through the transformers is not possible and limit 1 applies, then power flow management could still enable generator capacity equivalent to maximum demand rather than minimum demand in the network area.

Power flow management might also be used to address voltage limits by curtailing generator output according to variations in demand and the available voltage headroom. It will not, however, have any impact on fault level limits.

Dynamic Thermal Ratings

It is estimated that dynamic thermal ratings can enhance the capacity of transformers by around 5%. Dynamic thermal ratings can have a greater impact on overhead lines, with an estimated increase in average rating of 10-20%. This means generator connections can be achieved much more cheaply than otherwise. Dynamic thermal ratings do not address fault level or voltage limits.

In this analysis it is assumed that dynamic thermal ratings would mean a small relaxation of limits 2 to 5. The methods are applicable at all voltage levels, subject to the cost implications.

Voltage Management

The ANM methods for voltage management can help address voltage limits and thermal limits to a small degree but will not have an impact on fault level limits.

The impact of active voltage management can be assessed as removing limits 7 and 10, and possibly also limit 8, to leave only the least restrictive voltage limit 9. Thermal limits 2 to 5 might be relaxed slightly by enabling the full transformer MVA capacity to be used to export real power. The methods are applicable at all voltage levels.

Demand Side Management

DSM has the potential to flatten the daily load curve and thereby increase the minimum and average load and reduce the maximum load. In the analysis with average values, 33 kV, 11 kV and LV minimum loads are assumed to be 10% of the maximum load; at 132 kV the minimum is assumed to be 40% of the maximum. DSM will not have an impact on fault level limits but, as with power flow management, might contribute to mitigating voltage limits.

The use of DSM could have an impact on thermal limits, which is interpreted as increasing thermal limits 2 and 3 to reflect an increase in minimum demand. DSM is applicable at all voltage levels although it will become more complex as the number of controlled loads increases at the lower voltages.

4.4.2.6 Summary of Impacts

The impacts of the different technologies are summarised quantitatively in Table 12. The analysis uses the estimates of national maximum DG capacity under all GSPs. Thermal limit 1 is neglected as being irrelevant at 132 kV and so removed for all technologies. Voltage limit 9 does not impose any practical limit at 132 kV and so is also removed. The impact of each technology in overcoming limits, as described above, results in some limits being removed and others changes as shown in Table 12.

Table 12: Impact on DG capacity limits of different technologies

Limit	Description	Base	Power Electronic Converters	Shunt Compensation	Series Compensation	Phase Shifting Transformers	Power Flow Management	Dynamic Thermal Ratings	Voltage Management	Demand Side Management
Thermal Limits										
1	Thermal Limit - Minimum demand	16	-	-	-	-	-	-	-	-
2	Thermal Limit - Minimum demand + Transformer (firm)	59	64	64	59	59	-	61	64	64
3	Thermal Limit - Minimum demand + Transformer (non-firm)	102	112	112	102	102	-	107	112	112
4	Thermal Limit - Maximum demand + Transformer (firm)	83	88	88	83	83	83	85	88	83
5	Thermal Limit - Maximum demand + Transformer (non-firm)	126	136	136	126	126	126	131	136	126
Fault Level Limit										
6	Fault Level Limit	59	-	59	59	59	59	59	59	59
Voltage Limits										
7	Voltage Limit - Generator produces MVArs	71	-	-	71	71	71	71	-	71
8	Voltage Limit - Generator at unity power factor	535	-	-	535	535	535	535	-	535
9	Voltage Limit - Generator absorbs MVArs (controllable)	>1000	-	-	-	-	-	-	-	-
10	Voltage Limit - Generator absorbs MVArs (fixed)	96	-	-	96	96	96	96	-	96

This simple quantitative assessment of DG capacity limits shows that while some limits may be overcome others will remain and continue to impose a limit. The values are derived from the analysis method described above and are only intended to allow comparison of the different technology options and illustrate the limitations of potential benefits.

While most of the technologies offer some improvement in thermal limits, power flow management is necessary to overcome limits 2 and 3 based on minimum demand.

Fault level limits persist with most of the technologies. Of the technologies under review, only power electronic converters offer a solution to fault level limits.

Voltage limits can be addressed with power electronic converters, shunt compensation and voltage management but will persist with other technologies.

The actual value of different technologies will depend on the specific circumstances and the nature of the limits on DG capacity in each network area. Where different limits take priority different technologies will come to the fore.

4.5 Other Impacts

Conventional distribution networks are described as passive because there is very limited on-line control of the network and almost all connections are for consumers. The expansion of distributed generation introduces energy sources into distribution networks, which in turn will require more active control of those networks, especially when it is only made possible through the use of novel technologies. Thus, there will be a transition to active distribution networks. Active distribution networks require monitoring and control akin to that currently used in transmission networks. Distribution network operators will have to manage generator-network interaction and a range of system issues like constraints, outage co-ordination, stability and security, and system recovery and restoration. This will require a new set of capabilities, in direct network control issues like voltage and power flow, and in network simulation and analysis like state estimation and real-time studies. All of these new requirements highlight the need for DNOs to adapt to new challenges.

4.5.1 Transition to Active Networks

In most cases, the transition to active distribution networks is likely to be gradual. Over time, more capabilities will be introduced as and when they are needed. This is necessary because of the massive installed asset base and need to maintain service at a level expected by existing users of the network. Technologies like those described above will gradually be introduced along with greater monitoring of the network. Implementing changes like this will also require an expansion in the number of people working in DNOs as well as improvements in their productivity through the use of new methods for planning and management of information.

In previous industry working groups, the transition to active networks was described in four levels:

1. In a “Passive” network the system operator only reacts to the network during unplanned outages. The infrastructure required to support this level of control involves the monitoring and control of particularly critical system components or sections.
2. A “Basic” active network is one where the system operator can react to planned abnormalities, such as circuit outages for maintenance. This requires some extension of the existing monitoring and control infrastructure, involving remote control over circuit breakers and the coordinated deployment of field staff to perform manual switching.
3. The “Intermediate” active network encompasses real-time monitoring of system conditions in addition to some control of connected generation and demand. The interaction between the system operator and DG is performed automatically to satisfy network performance, security or constraints. The infrastructure required for the “Basic” active network has been extended including the installation of communications links for coordinated control between network devices or components and DG.
4. The “Fully” active network is characterised by on-line real-time control of DG and load demand. Extensive monitoring and control functionality has been added to the network. In addition, the system operator is able to perform real-time modelling to assist in either the automatic or manual operation of the network.

The transition from “Passive” to “Basic” is already occurring in many DNOs in the UK. The transitions give an indication of the anticipated gradual and incremental nature of ANM deployment. In reality, the transition will not be as precise and as structured.

With the prospect of hundreds or even thousands of distributed generators added to a distribution network, to help keep additional costs to an acceptable level it will be necessary to utilise automated controllers that can maintain satisfactory network conditions without the need for human intervention. These devices will monitor the conditions on networks and instruct local generators to act in certain ways. For example, some generators might be instructed to mitigate harmonic effects on the network, or generator outputs may have to be adjusted to operate within network constraints.

4.5.2 Network Management Systems

Existing network management systems are perceived as a barrier to the deployment of new technologies, particularly active network management. This was explored in an industry report:

SP Power Systems (Roberts,D.A.), "Network Management Systems for Active Distribution Networks – A Feasibility Study", 2004, Contract Number: K/EL/00310/REP, URN Number 04/1361

Roberts presents a feasibility study regarding the deployment of ANM on the existing SCADA infrastructure. One of the key conclusions is that there are fundamental limitations of existing SCADA systems associated with speed of operation, reliability and resilience that would limit their applicability where the consequences associated with the failure of the system are large. Roberts also argues for simple, modular ANM schemes to be developed, that provide a route through the complexity associated with implementing ANM solutions for many individual DG units. This suggests that emerging ANM systems will be required to operate in parallel with existing SCADA systems and their accompanying communications links, likely requiring independent communications links to be established for ANM.

The findings are confirmed by other sources where it is shown that existing SCADA systems possess some of the functionality expected to be required by ANM systems. DNOs seem reluctant to utilise this existing capability, however, and there is a general lack of trust in deploying ANM technologies, whether through SCADA or not. Gaining the trust of DNOs through testing and trial of ANM systems that are deployed on trusted hardware platforms will be crucial, as will ensuring that simple measures are adopted first that can be easily understood, monitored and verified.

A range of structures and systems have been proposed for the active management of distribution networks with distributed generation. Each has their advantages and disadvantages or is designed for a particular set of circumstances on the network or in the regulatory and commercial framework in which the network is operated. The different structures can be broadly split between those with a strongly hierarchical structure and those with more distributed intelligence.

Existing control systems in distribution networks already exhibit some aspects of both hierarchical and distributed structures. For example, a traditional SCADA system with a control engineer at a central location is a hierarchical structure. However, examples can be found already of automation or control that acts independently of central control based on measurements taken in its own area. Furthermore, protection systems are designed to operate autonomously for reasons of safety and reliability. The question of distributed intelligence versus a control hierarchy (with a human at the top) will influence where new active management functionality will reside.

Some SCADA/DMS systems have the capability to specify logic functions that can trigger automatic control responses but this integration of automatic control is often neglected in favour of separate systems, which have the benefit of being distinct with a limited sphere of influence. The degree of automation will depend on a combination of factors including safety, cost, the type of analysis necessary and the overall impact of each decision.

Advances in tools for automatic information processing and analysis are likely to be of benefit. Fast, on-line simulation tools currently used by transmission network operators must be adapted to the distribution environment by taking account of the different topology and uncertainties that arise from having a high number of customer connection points, both load and generation.

It is possible to develop active network applications with communications systems that are inherently "unreliable". The expectation of communications failure must be built into the design of the application. Moving away from an absolute requirement for up to date information allows more flexibility and possibilities for active network operation.

4.5.3 Protection and Control

Safety is of primary importance in electricity distribution, and protection systems must be proven and reliable. Protection is technically complex and can be commercially controversial when it is concerned with the interface between a network and a generator or customer. This can place constraints on new developments and changes in the way things are done. However, there is scope for developments in many areas of DG protection. The possibility of exploiting improved communications is one of the main avenues being explored. To make a significant impact, there must be a standardisation of approaches and solutions in DG protection.

The connection of dynamic devices, like generators or some of the reviewed technologies, to distribution networks present a number of challenges but also offer opportunities to enhance network performance. Modern control design methodologies mean the numerous and distributed resources in electricity networks can be effectively controlled to meet local or global objectives. In addition, there are opportunities with smaller DG installations for protection and control systems to be integrated in combined interface units that provide cost-effective control without sacrificing the safety provided by protection.

Larger DG installations have a larger impact on the network and, apart from their own protection and control, will necessitate changes to the DNO's protection and control systems. This presents a number of challenges to network operators, including wider variations in power flows and conditions on the network, which may require the introduction of more adaptive protection and control. These new technologies can only be implemented if the DNO has a clear understanding of them and is confident that they will operate as intended. This results in the need for more analysis and new modelling tools.

4.5.4 Analysis and Modelling Tools

One of the primary challenges facing DNOs in using new technologies and connecting more DG is the modelling, simulation and analysis of network performance and behaviour. New technologies, such as DG and power electronics, require the development and validation of new models. With different incentives for stakeholders in the network and new ways of operating, new types of analysis will have to be performed. DNOs need not be the ones who develop new models and analysis methods – this task can be undertaken by academia or other external service providers – but they must have the capacity to absorb the outcomes and understand the results of new analyses. In line with changes in the industry and regulation, DNOs must also conduct more comprehensive economic and financial evaluation. This includes the proper consideration of externalities like environmental factors. Thus, the analysis that must be conducted by DNOs is both more extensive and more complex.

In the past, distribution networks have been over-designed and their components over-sized. This was due to a number of reasons. The additional capacity and security provided cover for the uncertainties of demand predictions. The acceptance of generous margins also made it possible to apply rules of thumb and use prepared tables and charts in design. However, the excess capacity built into the networks of the past has been taken up by load growth, and reduced expenditure in recent years means the excess capacity has not been replaced. Pressures on DNOs now mean that networks must be designed more precisely with less, potentially useless, spare capacity. This requires new rigour in the analysis of requirements and design of solutions.

Power system simulation and analysis is an important activity in the design and management of modern electricity supply systems. Simulation is used to ensure that the required standards of security and stability are met and that system design is optimised. Power system simulation can be a difficult and expensive task, requiring considerable knowledge and experience to perform detailed analyses. There are a wide variety of simulation tools and huge libraries of models and data available; and there are many approaches that may be taken to achieve a specific goal. Modern electricity systems are undergoing considerable change with the introduction of new technologies like distributed and renewable generation, and this is imposing an ever-greater simulation burden on the industry.

4.5.5 Adopting New Technologies and Methods

As a mature industry, electricity distribution is characterised by a relatively slow rate of change of technology. While great improvements have been made over the years in overhead lines, underground cables, transformers, switches and circuit breakers, the fundamental design principles of electricity networks have remained the same. The need for low costs, high reliability and unquestionable safety has limited the scope for experimentation. Thus, the conventional approach to planning and operation assumes that conventional technology will be used.

A special effort is required to consider, let alone incorporate, novel technologies. Typically, DNOs will select from a limited number of technically acceptable designs based on what has been done before. New technologies present more risk and may be more expensive initially. DNOs may lack the incentives necessary for a realistic business case to adopt new technologies to be made. Also, new methods are required to examine the impact of new technologies and exploit their use.

This issue will be of particular importance in the near future because in the developed world, many distribution companies have an ageing asset base that will largely be replaced over the next few decades. Cutbacks in investment have exacerbated the problem of ageing assets that will require wholesale replacement. New technologies will offer some opportunities to extend asset life but in replacing assets full account must be taken of the new demands that will be made of distribution networks, such as the integration of DG.

There are considerable barriers to be overcome. DNOs are slow to adopt new technologies for a range of reasons. Principal among these is cost effectiveness. Many new technologies offer slight improvements in performance or flexibility but, until they are widely adopted, remain too expensive. The use of new technologies will only occur where DNOs feel that they fully understand the technology. This provides justification for new modelling and analysis and enhancement of DNOs' abilities to absorb the outcomes of research and development. The use of radically different approaches also has to overcome the inertia of familiarity and corporate procedures as well as a culture built around the conventional approach to network planning.

4.5.6 Economic Issues

DG and changes to the way networks are operated can influence both the capital and operational expenditure of distribution companies. They must be confident that any investment in their network to accommodate DG will be fully recovered, either from the DG operator directly or through future payments from users of the system. The opportunity exists for distribution companies to make investment in the connection of DG to reduce operational expenditure and reduce the need for investment in areas such as load related reinforcement, asset replacement and performance improvement. As monopolies, distribution companies in the UK are subject to price control regulation. If the price control mechanism does not make allowance for funding contracts with DG as an alternative to investment in network assets then DG may not be financially attractive to distribution companies.

5 Impact on Transmission Networks

An expansion in generation capacity at distribution level and the use of new technologies to facilitate that expansion will have an impact on planning and operation of the transmission network. This section discusses some of that impact to help identify barriers to deployment.

The boundary between transmission and distribution is the Grid Supply Point (GSP) and this is where the greatest impact will be felt. Localised impacts at lower voltages within distribution networks will only have an impact on the transmission system in aggregate.

The transmission network is planned to meet the maximum demand required by the distribution network through the GSP and operated to ensure security of supply for the demand being met through the GSP. The connection and operation of DG units in distribution networks will impact on the boundary power flows and other aspects of transmission. The transmission operator requires an understanding of the generators and loads in each distribution network to be able to effectively manage and plan transmission infrastructure.

5.1 New Technologies

The use of new technologies in enhancing transmission network capacity will be dealt with in other Tasks. National Grid already uses phase shifting transformers (quadrature boosters) and Static Var Compensators (SVCs) and is planning to install more. Plans are also advancing for the deployment of series compensation and HVDC within Great Britain, as outline in the ENSG Vision for 2020.

The impact of DG on transmission networks has been explored and considered over a number of years but the potential impacts of new technologies being applied at distribution is less understood. Each of the technologies under consideration will have different impacts on the transmission network.

5.1.1 Power Electronic Converters

If electrically close to the transmission interface power electronic converters will have impacts similar to those of HVDC at transmission level. If deployed more deeply within distribution networks the impacts will be diluted and absorbed into the overall behaviour of a distribution network at a GSP.

5.1.2 Shunt Compensation

Shunt compensation has the potential to alter the exchange of reactive power between transmission and distribution. A reduction in reactive power demand will be to the benefit of the transmission network, which can be stressed by having to supply too much reactive power to distribution networks.

5.1.3 Series Compensation

Series compensation might be used to push more power on to the transmission network to relieve congested lines at distribution level. This will obviously have an impact on power flows. If deployed more deeply within distribution networks the impact of series compensation will not be observed at transmission level except where it results in a change in the overall power exchange.

5.1.4 Phase Shifting Transformers

Phase shifting transformers could be used at the interface with the transmission network to push more power on to the higher voltage lines and relieve congestion at distribution, which will have an impact on transmission power flows. If used more deeply within distribution networks then phase shifting transformers should not have any impact on the transmission system except in changes to the exchange of power resulting from any additional distributed generation that is enabled by their use.

5.1.5 Active Network Management

Where power flow management allows additional generation capacity to connect it will influence the exchange of power with the transmission network. If power flows are permitted to exceed the conventional secure limits then this will have to be taken into account in planning and operation. By controlling generation to “fill” the available capacity for export from an area, power flow management might help to reduce variability and thereby make the task of system balancing easier.

Dynamic thermal ratings applied at distribution level will allow greater power flows at certain locations and may therefore enable greater distributed generation, but will not have any particular impact on the transmission network. The technology could also be applied to the transmission network.

Voltage management is essentially a local control problem but deployment of an ANM scheme may affect exchange of reactive power with higher voltages. As with shunt compensation, any reduction in reactive power import from the transmission network would be a positive impact.

Demand side management has the potential to alter the demand profile and so affect transmission network operation. If anything it should make demand more predictable and so make system balancing easier. The transmission system operator already uses DSM services and is likely to use them more in the future.

5.2 General

The impact on the transmission network of additional distributed generation enabled by the deployment of new technologies can be assessed in terms of issues that the system operator has responsibility for.

5.2.1 Power Flows

From a transmission perspective, generation connected at distribution level is generally treated as negative demand. National Grid recognises that there is likely to be continuing growth in distributed generation and that it is important to facilitate this by addressing any transmission issues that arise. The SYS states that no insurmountable transmission problems are foreseen associated with accommodating new distributed generation. If distributed generation increased to a level where there were exports from a distribution network to the transmission system then, provided such transfers are within the capacity of the super grid transformers, this is not expected to lead to major technical difficulties. Depending on the location of new generation, however, there is the potential need for reinforcements to the transmission system.

Increasing levels of distributed generation will reduce the flows across the interfaces between the transmission and distribution networks at Grid Supply Points (GSPs). This may delay the need for reinforcement of parts of the transmission network but the impact will only be significant if the growth in distributed generation is enough to alter plans for transmission connected generation. A general reduction in the power flow from the transmission to distribution networks does not necessarily lead to a similar reduction in the bulk power transfer across the transmission system.

The requirements placed on the transmission system depend on the size and location of generation and demand but generation has the greater influence. Transmission constraints are well understood and widely discussed. Most of the major transmission reinforcement projects planned for the near future are primarily concerned with increasing power transfers from new generation. Any additional distributed generation in areas that already have an excess of generation, particularly the north, will exacerbate the problem of transmission network constraints. Conversely, any new distributed generation in areas that have a shortage of generation, principally London and the south, will help ease transmission constraints, although this would depend on that new generation displacing the operation of plant in the north.

5.2.2 System Balancing

Some visions of future electricity networks have demand satisfied entirely by local generation connected to the distribution. This would reduce substantially the need for an integrated transmission network. However, this is not a practical or realistic outcome on any significant scale so the combination of transmission and distribution will continue to be required to balance the fluctuations between generation and demand across the whole system from minute to minute.

National Grid expects that the predicted expansion in wind power, which is expected to be largely composed of large transmission-connected wind farms, will make the task of balancing generation and demand and resolving transmission constraints more onerous but that the task should remain manageable. Provided that the necessary flexible generation and other balancing services remain available, there is no technical ceiling on the amount of wind generation that may be accommodated and adequately managed. It is anticipated that balancing volumes and costs will increase as the wind portfolio increases so, as is often the case in electricity networks, economic limits are likely to be reached before technical limits. Similar issues arise with a more general expansion of distributed generation, which may or may not be wind but will present similar problems in system balancing.

5.2.3 Protection

The implications of approaches to protecting DG or associated equipment must be put in the context of the wider system. If the settings on DG protection relays are too sensitive then this could result in the loss of significant generating capacity during a system disturbance. The loss of this generation could in turn worsen the impact of the system disturbance. The performance of DG and the distribution network in terms of dynamic and transient stability must be considered.

Some of the technologies used in renewable and small generators are sensitive to voltage depressions, even when they last for very short periods of time. On the GB transmission system it typically takes 140 milliseconds for protective equipment to remove a line fault caused by lightning. Faults can result in voltage depressions over an extensive area and this may cause large amounts of distributed generation to trip. The requirements for connecting to the system, as specified in the Grid Code and Distribution Code, are constantly reviewed and revised to ensure minimum acceptable technical characteristics for different generation technologies connected to different parts of the system.

If new technologies, such as those reviewed in this report, are deployed to allow additional generation to connect then that generation will be reliant on those new technologies and their protection may be linked. If the new technologies are lost as a result of a disturbance then the associated DG may also be lost, either as a result of direct inter-tripping or due to the resulting impact on a system no longer able to accommodate the DG output.

The system operator is always concerned that protection or other corrective measures do not perform as they are supposed to or do not deliver the response that is expected of them and is necessary. This results in the operator tending to be cautious and scheduling more corrective action then is probably necessary.

5.2.4 Stability

As the volume of distributed generation grows the system operator will have to take due account of its impact on system stability.

If distributed generation displaces conventional transmission connected generators then there is likely to be a reduction in overall system inertia. This will depend on the generating technologies used but in general terms, lots of small generators can be expected to have a lower overall inertia then fewer large machines. A smaller inertia will mean frequency changes more rapidly, which will place additional requirements on generation reserve and response.

The system operator is concerned with the largest possible single loss of supply. Distribution connected generation will be much smaller than the largest transmission connected generators so will pose a much lesser threat to system stability. Even if all generation under a GSP were to be lost suddenly, this is likely to be a smaller amount than the loss of a large generating set or the loss of an HVDC link to a new offshore wind farm.

Where the new technologies can reduce the need for reactive power from the transmission network this should improve the voltage profile and reduce the risk of voltage instability. The system operator would have to be wary of sudden changes in reactive power flows caused by a disturbance or loss of equipment but distribution level technologies should all be small enough that their impact is limited.

The potential for power electronic converters and series compensation on the transmission network to result in oscillatory instability is being investigated in this project and elsewhere. Similar technologies deployed at distribution level should not impose any additional problems on the transmission network.

5.2.5 Complexity

The expansion of distributed generation and widespread use of active management technologies threatens to introduce greater complexity in an already complex system. The system operator must manage this complexity and deal with all its implications.

An ability to understand prevalent and expected conditions on the network is important in managing its operation and preparing for possible disturbances. As renewable sources depend greatly on the weather the system operator will have to develop techniques for understanding weather conditions and how they are about to change. Likewise, other influences on the output of distributed generation will have to be studied.

A more complex network with new technologies will require new software to perform the necessary simulation and analysis. The creation and maintenance of suitable models and obtaining all the necessary data from multiple parties will present challenges. While off-line analysis means some time can be spent in preparing studies, transmission system operation requires on-line analysis that must be quick, easy to run and robust.

Substantial changes at distribution level and at the interface with the transmission network will introduce new aspects to the relationship between the system operator and DNOs. Industry codes and standards will have to be devised and new contractual agreements reached. The system operator will be concerned about the possibility for lack of clarity and scope for variation in interpretation as these can result in failures and shortcomings in operation.

6 Conclusions and Recommendations

To be revised and reformatted...

Highlight barriers to deployment, development gaps and challenges, and opportunities for ETI development support

- The principle barriers to deployment of power electronic converters at distribution level are cost and losses. These are expected to be overcome by advances in technology bringing about cheaper components with lower losses.
- SVC technology has been shown to work effectively but is prevented from being deployed more widely by cost. Any initiative to reduce the cost of the technology, whether in materials, assembly or simply through competition would reduce the barriers to deployment.
- The barriers to deployment for STATCOMS are that, in comparison with SVCs, they have a limited track record and impose higher costs and losses. The proposed solutions to the barriers are the same as for SVC: reductions in cost through developments in materials, assembly or greater competition.
- The barriers to employing series compensation in the UK include the extensive system modelling required to ensure consistent performance under varying conditions as well as the potential for series compensation to introduce sub-synchronous resonance into the network. The need for extensive modelling can be met with improved analysis tools and an increase in the number of people with the skills to perform the necessary analysis. The potential problem of sub-synchronous resonance will be better understood by improved modelling and simulation, can be tested with gradual deployments, and can then be managed with appropriate monitoring equipment and protection.
- There are no notable barriers to the deployment of phase shifting transformers. Phase shifting transformers are already in use in the UK transmission network and have been considered for use in distribution networks.
- The principle barriers to deployment of power flow management are lack of experience on the part of network operators and inflexibility in their 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. These barriers can be overcome with pilot projects for providing experience and confidence, development and adoption of flexible industry standards and frameworks, and development of tools for facilitating planning and associated studies.
- The main barrier to the application of dynamic thermal rating is the disruption to existing assumptions and methods in planning and operation of the network. There can also be technical complications and additional cost due to the necessity of monitoring equipment and communications. Proposed solutions to the barriers are the development of a broadly accepted standard for operating the network with a non-firm transmission capacity and the commercial development of dynamic thermal rating solutions integrated with current network technologies (e.g. SCADA, substation relays).

- Barriers to deployment of active voltage management include the relatively tight range of acceptable voltages and the potentially large impact of generation, the complexity of the relationship between voltages at different parts of a network and the output of connected generation, and 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.
- Demand side management 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, 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. Solutions to the barriers include economic incentives such as tariffs that provide an incentive for customers to accept partially flexible consumption. There is also a need for the development of appliances and industrial processes allowing a degree of flexibility in energy consumption.

Comment on “regulatory fit” of the technology options in the GB context:

> No obvious problems with using any of these technologies in the GB regulatory context except for the new types of commercial agreements required for power flow management, voltage management and demand side management

Comment on the barriers due to the lack of manufacturing of the products required to substantially increase renewable generators in the UK, and other shortages like specialist plant and skills – this will be covered in Task 4

UK distribution network operators should engage with potential suppliers and in global efforts in standards development to ensure their particular requirements are catered for

> Try to identify some of those particular requirements, which make UK DNOs different from others elsewhere in the world

The transition from passive to active networks will be a multi-stage development with some expansion and integration of existing protection, SCADA/DMS and automation schemes. As far as possible, the possibility of future upgrading and extension should be considered in the design of the network and in the specification of both primary and secondary equipment.

Commentary on the quantitative analysis:

- Each voltage level or network area and potential connecting generation is characterised in the simplest terms possible to assess thermal, fault level and voltage limits. Calculations are performed with average characteristics based on a review of the data in the LTDSs and other sources. Sensitivity analyses are performed to demonstrate how the characteristics influence limits on connection capacity and thereby give an indication of how circumstances vary depending on location.

- The renewable sources of energy are not spread evenly across a distribution network area with the possibility that large amounts of these potential sites will not be located in areas where the network exhibits the average parameters as calculated for the analysis and so it is more than likely that a lot of new generation will require connection into weak areas of the network.
- The technology that provides the most benefit will vary from location to location
- The fact that limit priorities change as fault level changes is indicative of the fact that fault level is very important in determining the potential generator capacity in any particular circumstance. Across distribution networks in the UK the fault level as a percentage of switchgear rating will vary widely and, as illustrated in the chart, the limit priorities will vary. The inverse relationship between fault level and voltage limits is an important feature of the chart as it illustrates the conflict around the "strength" of the network.
- The sensitivity analysis indicates that variations in demand will not alter the basic order of limit priorities very much. Based on the average network characteristics, the different limits remain mostly in the same relative positions, except for minor changes resulting from an increase in minimum demand. In any given network the limit priorities and the maximum potential generator capacity will depend on the specific circumstances but changes in demand will not have a significant impact. Increases in demand will allow greater generation capacity as long as thermal limits remain the highest priority.
- The analysis illustrates that transformer rating has a large impact on the priority of thermal limits. The larger the transformer rating the less likely this is to be the limiting factor on generator connections. As thermal limits are relaxed the fault level and voltage limits become more important.

Enhancing connection capacity:

- The simple quantitative assessment of DG capacity limits shows that while some limits may be overcome others will remain and continue to impose a limit. The analysis is only intended to allow comparison of the different technology options and illustrate the limitations of potential benefits.
- While most of the technologies offer some improvement in thermal limits, power flow management is necessary to overcome limits 2 and 3 based on minimum demand.
- Fault level limits persist with most of the technologies. Of the technologies under review, only power electronic converters offer a solution to fault level limits.
- Voltage limits can be addressed with power electronic converters, shunt compensation and voltage management but will persist with other technologies.
- The actual value of different technologies will depend on the specific circumstances and the nature of the limits on DG capacity in each network area. Where different limits take priority different technologies will come to the fore.

Other impacts on DNOs:

- The more complicated technology added to the network the more complicated the network, making DNOs nervous and possibly unwilling to add power electronics or active network management systems to too many locations
- Staff will have to be trained to operate new technology

- New technologies take time to be adopted as the automatic response to limitations until they have been tried and tested and can be fully trusted by the DNO
- New technologies are expensive and the DNOs have strictly controlled budgets. Network reinforcement may be seen as an easier solution and offering better value for money as after it is installed it has a very long life cycle. Have to convince DNOs that network reinforcement is not the only or necessarily the best solution.

Impact on transmission:

- If electrically close to the transmission interface power electronic converters will have impacts similar to those of HVDC at transmission level. If deployed more deeply within distribution networks the impacts will be diluted and absorbed into the overall behaviour of a distribution network at a GSP.
- Shunt compensation has the potential to alter the exchange of reactive power between transmission and distribution. A reduction in reactive power demand will be to the benefit of the transmission network, which can be stressed by having to supply too much reactive power to distribution networks.
- Series compensation might be used to push more power on to the transmission network to relieve congested lines at distribution level. This will obviously have an impact on power flows. If deployed more deeply within distribution networks the impact of series compensation will not be observed at transmission level except where it results in a change in the overall power exchange.
- Phase shifting transformers could be used at the interface with the transmission network to push more power on to the higher voltage lines and relieve congestion at distribution, which will have an impact on transmission power flows. If used more deeply within distribution networks then phase shifting transformers should not have any impact on the transmission system except in changes to the exchange of power resulting from any additional distributed generation that is enabled by their use.
- Where power flow management allows additional generation capacity to connect it will influence the exchange of power with the transmission network. If power flows are permitted to exceed the conventional secure limits then this will have to be taken into account in planning and operation. By controlling generation to “fill” the available capacity for export from an area, power flow management might help to reduce variability and thereby make the task of system balancing easier.
- Dynamic thermal ratings applied at distribution level will allow greater power flows at certain locations and may therefore enable greater distributed generation, but will not have any particular impact on the transmission network. The technology could also be applied to the transmission network.
- Voltage management is essentially a local control problem but deployment of an ANM scheme may affect exchange of reactive power with higher voltages. As with shunt compensation, any reduction in reactive power import from the transmission network would be a positive impact.
- Demand side management has the potential to alter the demand profile and so affect transmission network operation. If anything it should make demand more predictable and so make system balancing easier. The transmission system operator already uses DSM services and is likely to use them more in the future.

7 Appendices

For the sensitivity analysis described in section 4.3.3 the plots for the 33 kV, 11 kV and LV level are presented here. Where necessary, the limits 8 and 9 have been removed from the generation capacity charts because they are much larger than the other values and distort the chart image if shown.

Figure 4: Sensitivity of limit priorities at 33 kV to changes in fault level

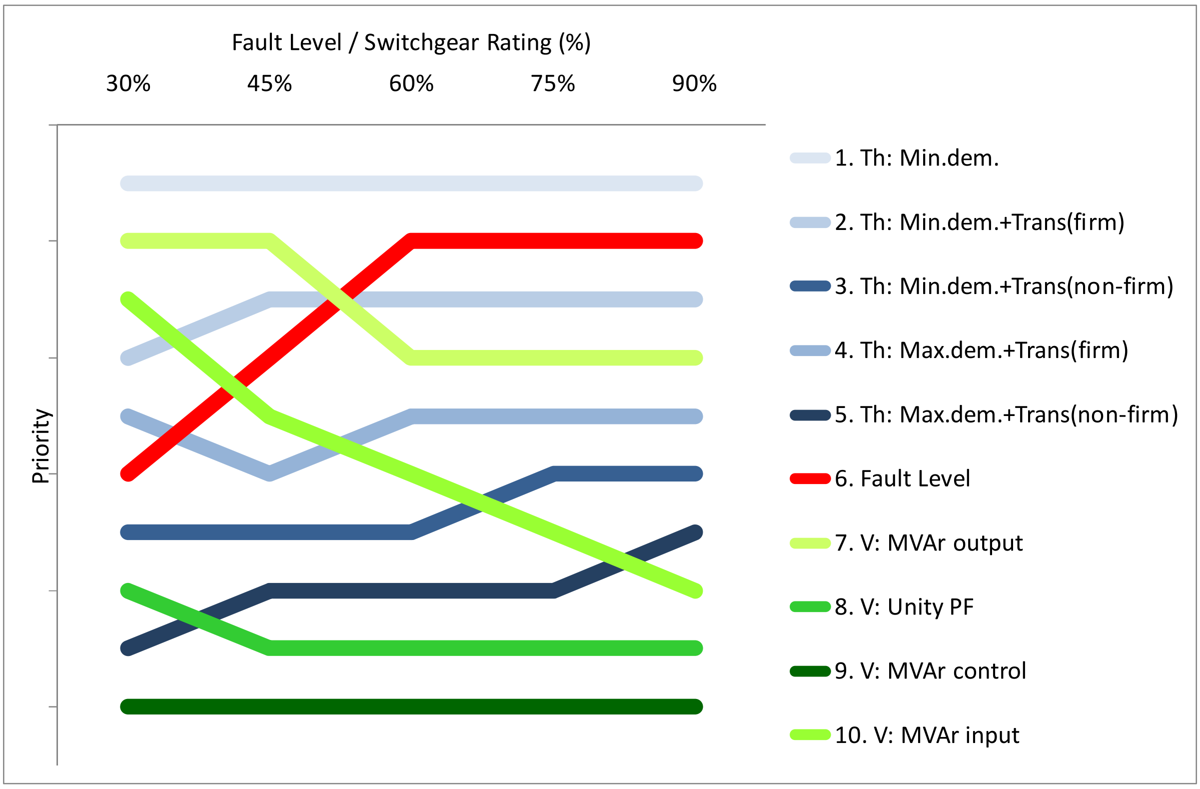


Figure 5: Sensitivity of limit priorities at 11 kV to changes in fault level

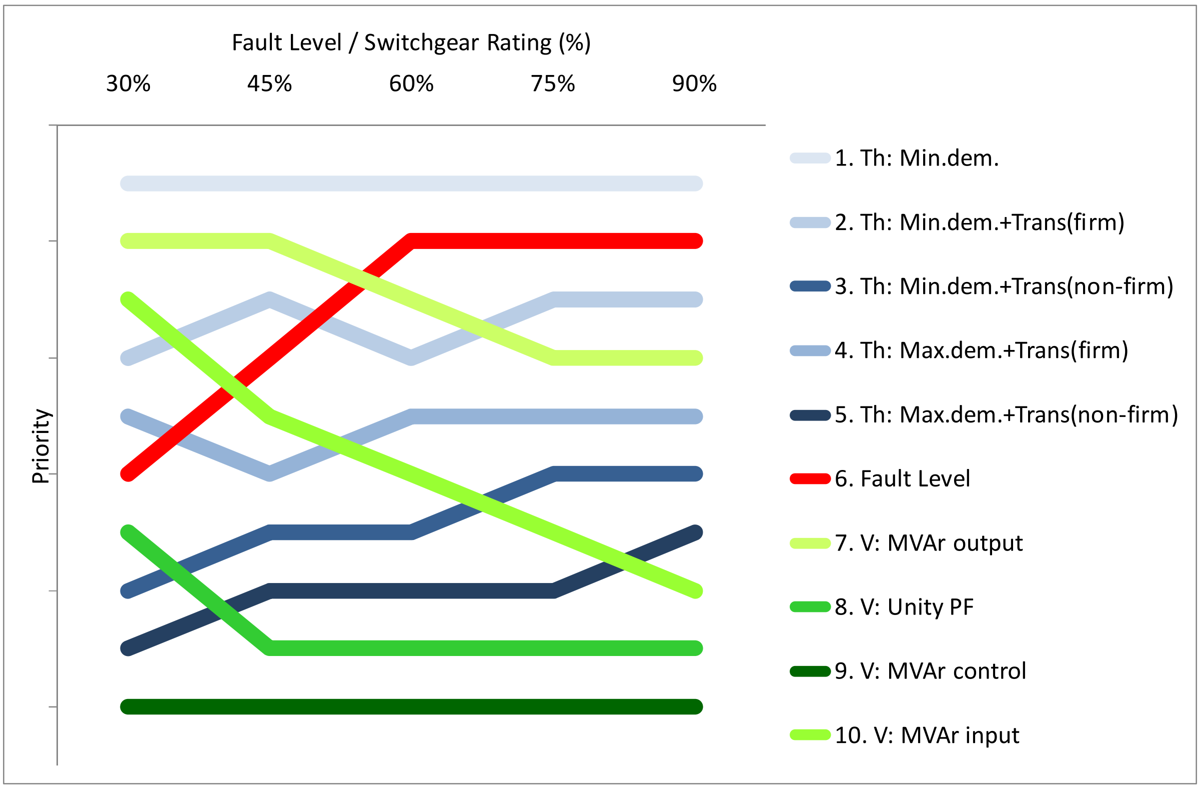


Figure 6: Sensitivity of limit priorities at LV to changes in fault level

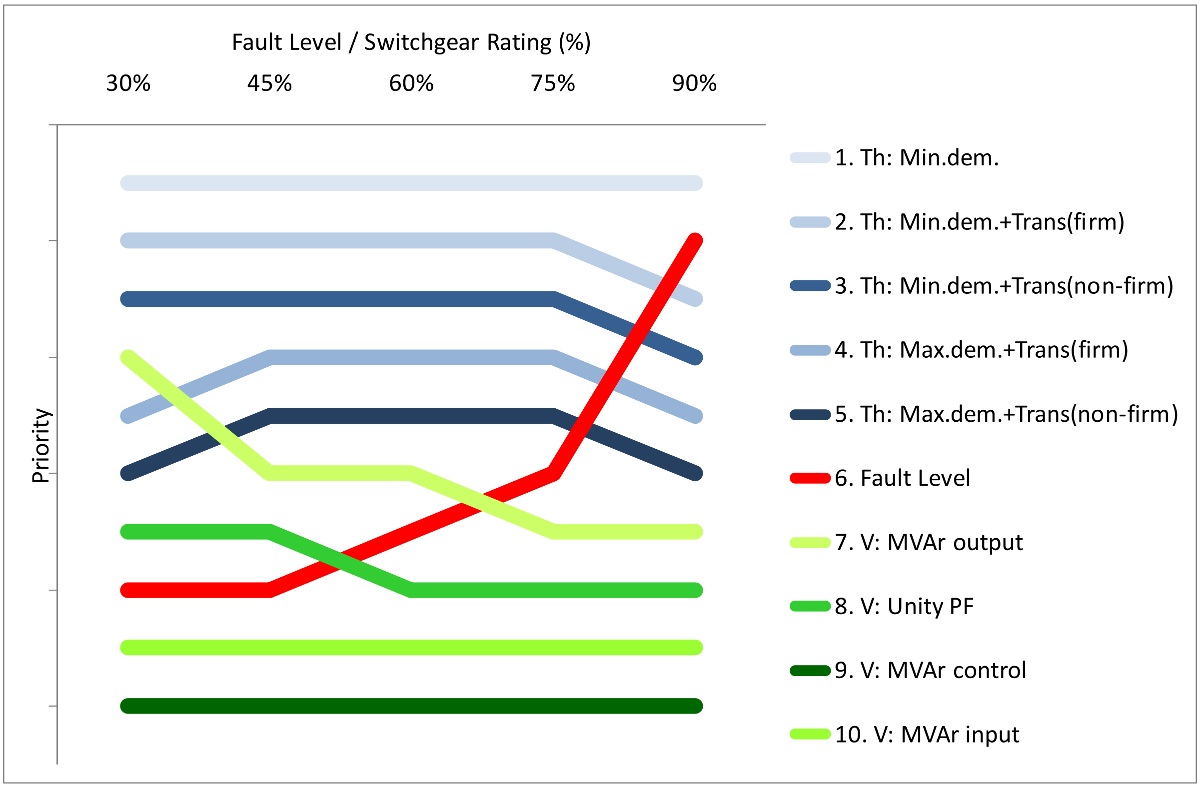


Figure 7: Sensitivity of limit priorities at 33 kV to changes in demand

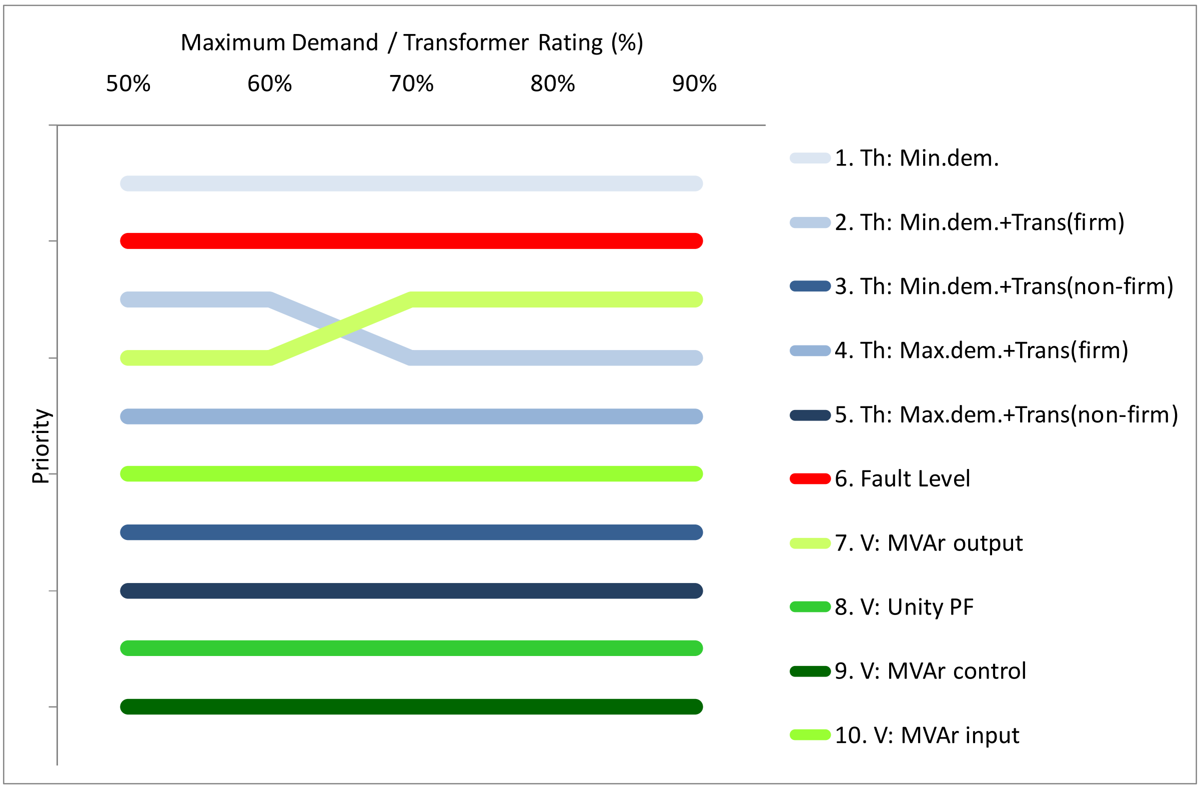


Figure 8: Sensitivity of limit priorities at 11 kV to changes in demand

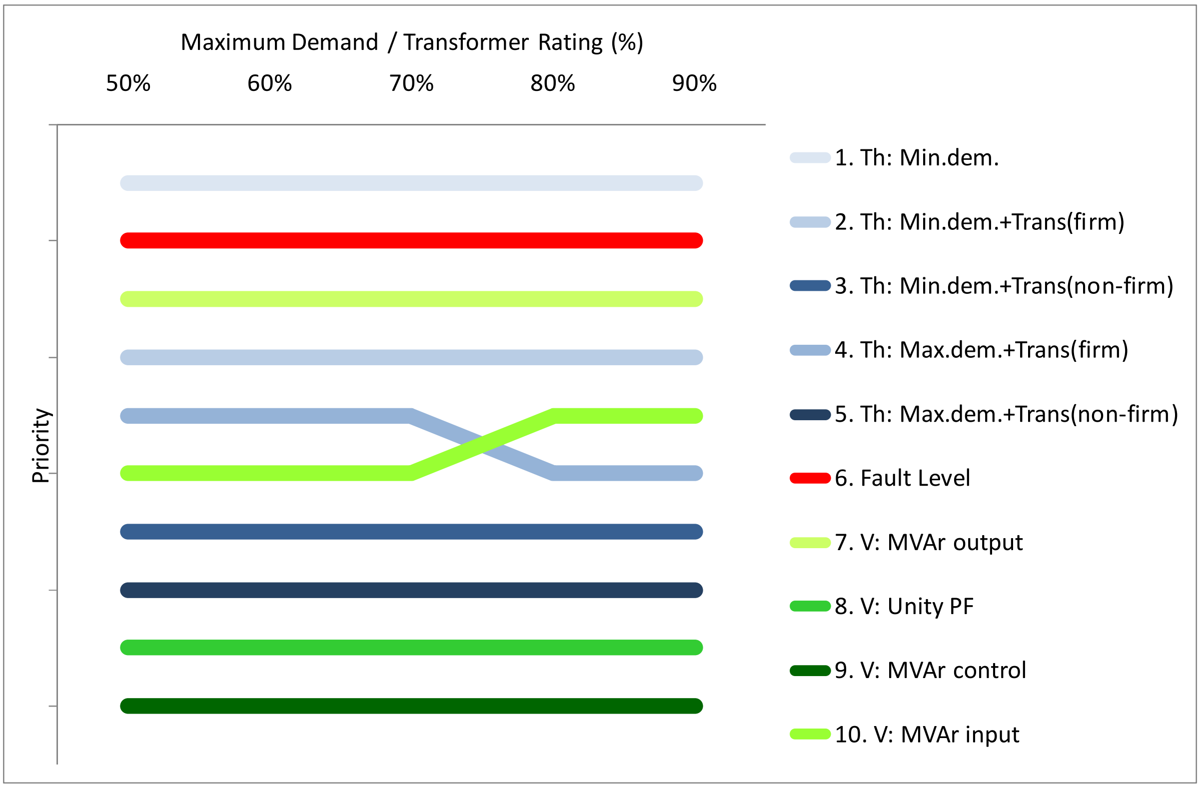


Figure 9: Sensitivity of limit priorities at LV to changes in demand

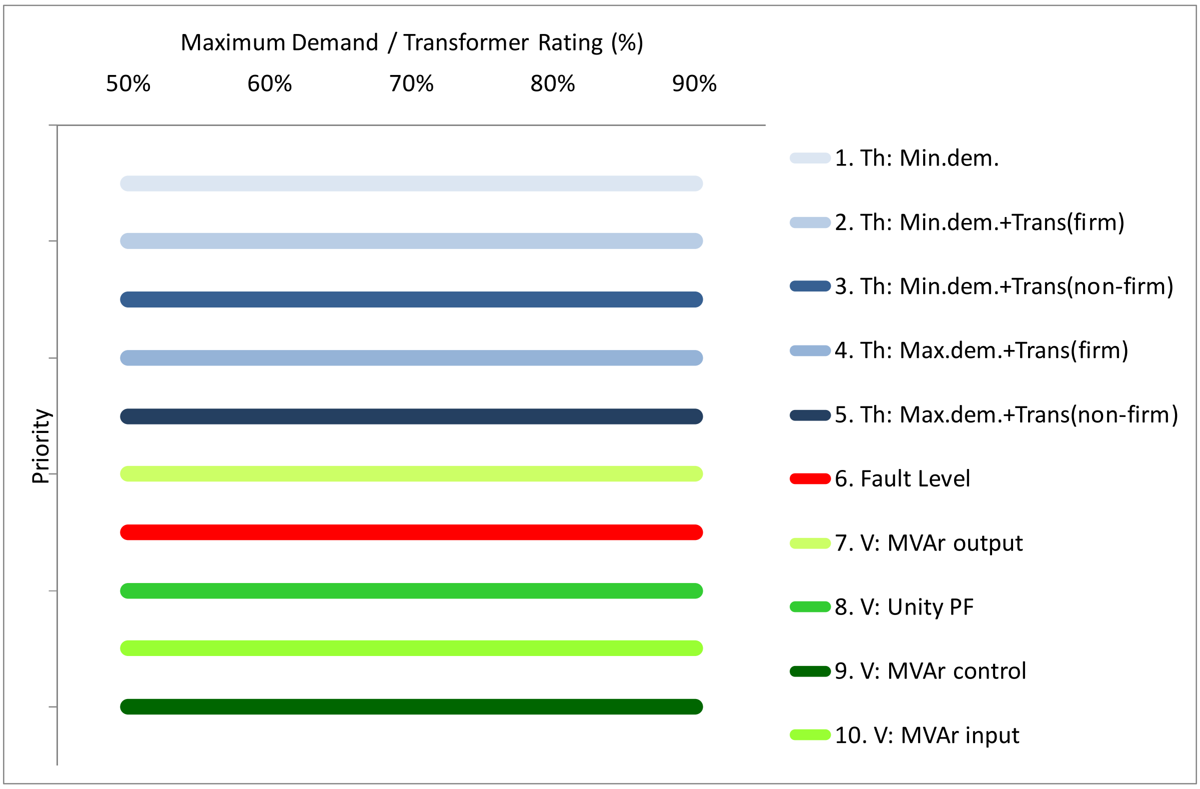


Figure 10: Sensitivity of limit priorities at 33 kV to changes in transformer rating

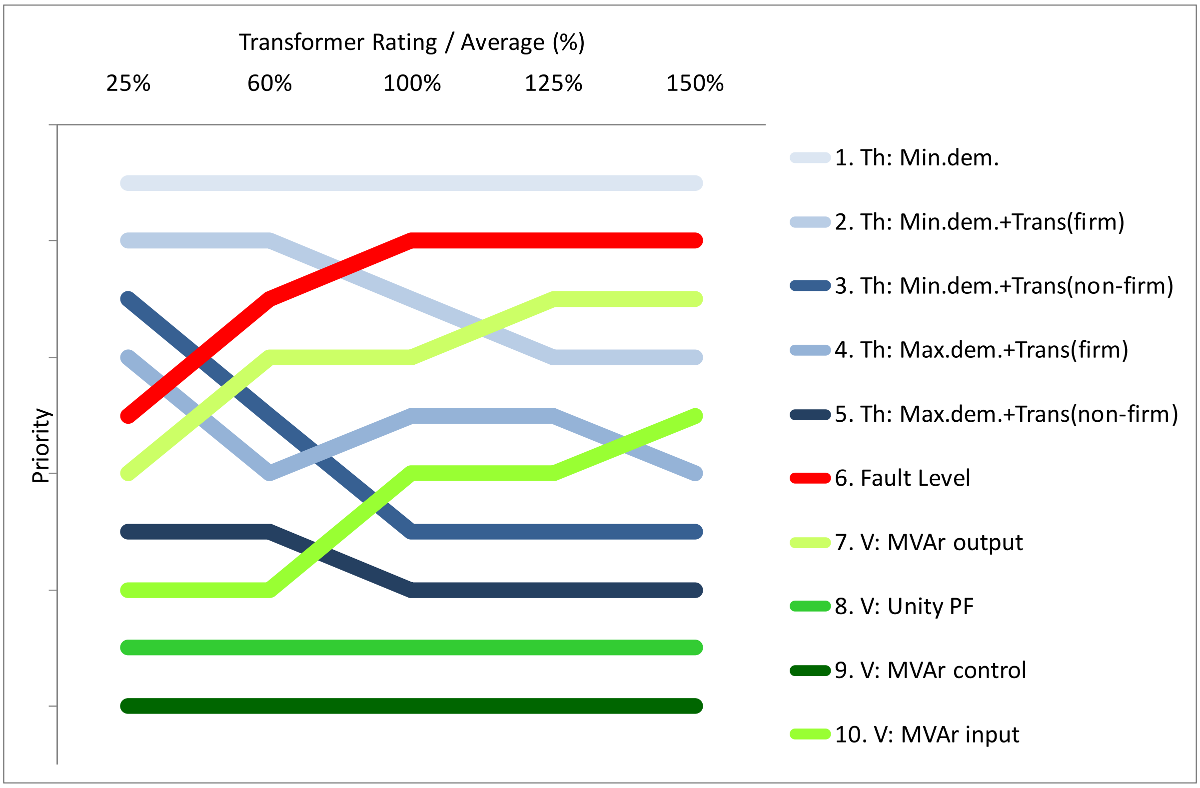


Figure 11: Sensitivity of limit priorities at 11 kV to changes in transformer rating

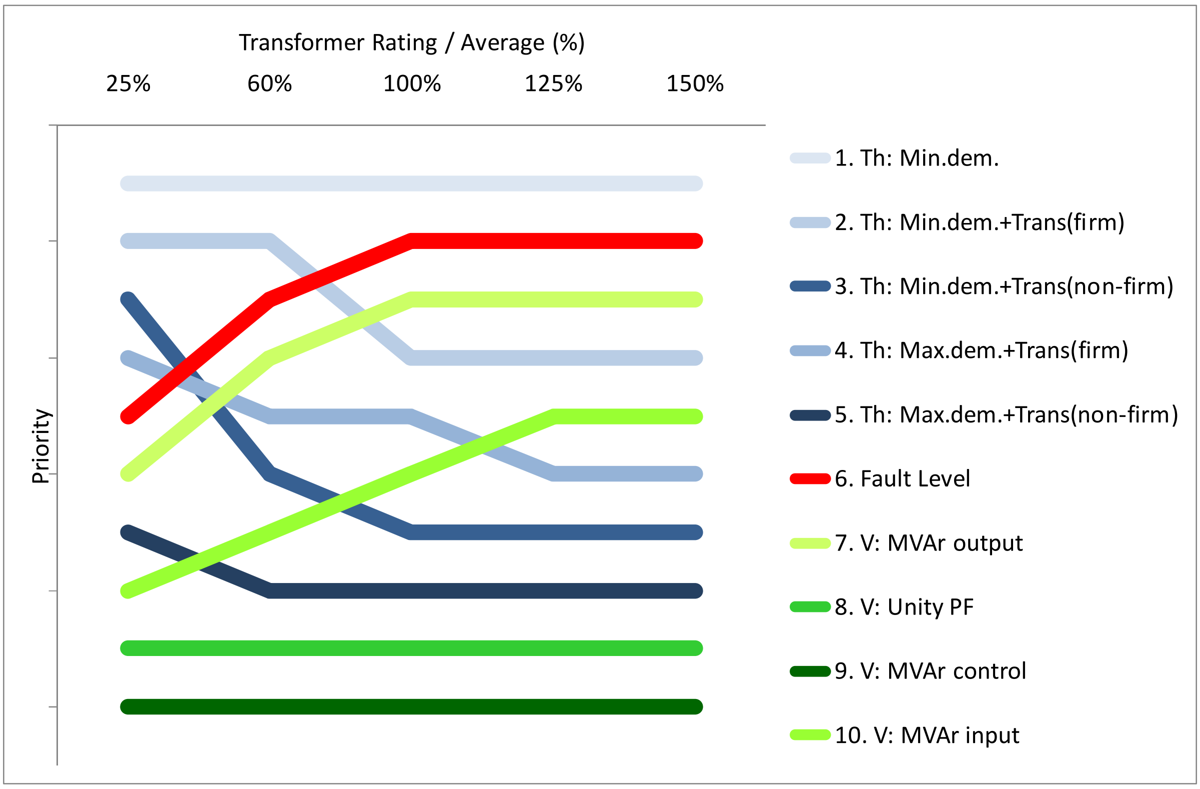


Figure 12: Sensitivity of limit priorities at LV to changes in transformer rating