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APPLICATION OF FAULT CURRENT LIMITERS

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EXECUTIVE SUMMARY

The forecast growth in renewable and other forms of distributed generation (DG) on the UK's distribution networks may result in operational constraints due to the effects of increased (or reversed) loading on existing equipment, operating voltage exceedences and increased system fault levels. While the fault level increases are not expected to be widespread across the UK distribution networks, recent work has identified that the following areas may be affected:

- dense urban 11kV and 33kV distribution networks, where the existing equipment ratings are currently limited
- isolated 132kV substations where large-scale DG projects connect into rural networks
- isolated low voltage (LV) situations, where high levels of DG penetration are realised.

A review of the current state of fault current limiter (FCL) technology has been carried out and shows that there are currently no appropriate FCL solutions commercially available to be integrated into UK distribution networks. There is however significant research and development work progressing in the FCL active device field with a number of medium voltage (MV) FCLs being developed and tested around the world. The focus of these developments is moving to high voltage (HV) levels where the potential financial benefits that will be realised with the adoption of these devices are expected to be highest. The appropriate FCL limiting technologies currently being developed are as follows:

- Solid state breakers
- Superconducting FCLs (including superconducting transformers)
- Magnetic FCLs, and
- Active network controllers

Commercialisation of these products will only occur following further field tests and experience as well as material development in the case of high temperature superconducting (HTS) FCL technologies.

The installation of FCL devices has the benefit of allowing power networks to operate with high "normal operating" fault levels (ie with low source impedances), while limiting the actual fault current flowing at the fault location to levels that allow the safe operation of existing power system equipment. The implementation of FCL devices may also provide the opportunity to increase distribution and transmission equipment utilisation and reduce reinforcement requirements.

A tool that will allow an overall analysis of UK distribution networks is recommended to identify to the industry the application opportunities for FCL devices in the UK.

Manufacturers will only provide commercially available product solutions if a robust business case is identifiable. A high level “functional specification” for an analytical model is outlined in this report, which identifies the relevant inputs and outputs required to inform the user of the scale and scope of the fault level problems expected on UK distribution networks. It is intended that the model be built using a bottom-up approach, based on the typical networks that have been identified in an ongoing University of Strathclyde project. The simulation results could then be scaled upwards to provide a generalised picture for each UK Distribution Network Operator (DNO). Summation of the DNO’s results would be required to generate a representative picture of the locations and economic scale of the problems faced due to increasing system fault levels on the UK distribution networks.

A roadmap is presented that provides an “action agenda” highlighting the steps that should be followed to implement solutions to the expected fault level problems. The stages making up the roadmap include quantification of the scope and scale of the fault level problem on UK distribution networks, as well as identification of the optimal fault current limiting solution to address the problems. Recognition of the stakeholders who will be impacted by the implementation of FCL technology is also included in the roadmap with the final stages including commercialisation of the relevant FCL technologies, and the design and implementation of the solutions on the UK’s distribution networks.

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GLOSSARY

BERR	Department for Business, Enterprise and Regulatory Reform
CHP	Combined Heat and Power
DAPAS	Dream of Advanced Power Systems by Applied Superconductivity' Technology Program - Korea
DCHP	Domestic Combined Heat and Power
DFIG	Doubly Fed Induction Generator
DG	Distributed Generation
DGCG	Distributed Generation Coordinating Group
DNO	Distribution Network Operator
DTI	Department of Trade and Industry - was disbanded and renamed BERR in June 2007
DWG	Distributed Working Group
EPRI	Electric Power Research Institute
ESQCR	Electricity Safety, Quality and Continuity Regulations (2002)
FACTS	Flexible Alternating Current Transmission System
FCL	Fault Current Limiter
HSE	Health and Safety Executive
HTS	High Temperature Superconductor
HV	High Voltage (132kV)
IPC	Interphase Power Controller
LV	Low voltage (230V - 400V)
MFCL	Magnetic Fault Current Limiter
MV	Medium Voltage (11kV - 33kV)
MVAr	Mega Volt Amperes Reactive
MW	Megawatts
PV	Photo Voltaic
R&D	Research and Development
SCADA	Supervisory Control And Data Acquisition
SCFCL	Superconducting Fault Current Limiter
SCFCLT	Superconducting Fault Current Limiting Transformer
STACOM	Static Compensator
SSFCL	Solid State Fault Current Limiter
SVC	Static Var Compensator
TSG	Technical Steering group
Var	Volt Amperes Reactive
WP	Work Programme

1. BACKGROUND AND INTRODUCTION

1.1 Background

The Department for Business, Enterprise and Regulatory Reform's (BERR) Distributed Working Group (DWG) continues the work of the earlier Distributed Generation Coordinating Group's (DGCG) Technical Steering Group (TSG), examining the issues to enable the integration of generation onto the distribution network. The DWG manages four Work Programme areas, one of which is Work Programme Two (WP 2), "Network Design for a Low Carbon Economy".

The objectives of WP 2 are to look at the technology, tools, techniques, processes and standards that will be required to construct power systems that are compatible with the developing trends in low-carbon energy technology. Projects will generally cover heavy current matters, main plant equipment and overall network design standards and codes.

This work is intended to form the first stage of Project 9 (P 9) of the WP 2, titled "Application of Fault Current Limiters". This project will facilitate the development of a low carbon economy as it promises to lower the cost and speed-up the connection of renewable generation to distribution networks.

PB Power has been appointed by the BERR under DWG WP02-P09 to undertake a review of fault current technology and potential applications of the technology. It is intended that PB Power revisit a report prepared under WS3 in 2004 (PB Power, 2004) to determine if changes to FCL technology has altered the position presented in the original report. The second stage of this work is to devise a roadmap and methodology that may be employed as a following piece of work, to assess the materiality of the anticipated fault level issues.

This work considers power networks defined by the following voltage levels:

- LV networks which include distribution plant and equipment at 400V and 230V
- MV distribution reticulation voltage levels between 11kV and 33kV, and
- HV sub-transmission networks designed and operated at 132kV.

1.2 Introduction

The objectives of this project are to:

- investigate the current state of the technological solutions available for distribution level fault current limitation
- devise a suitable block diagram methodology which may be used as a basis for the development of a model to determine the likelihood, implications and optimal solutions of the fault level problems expected on sub-transmission voltage power systems
- develop an initial roadmap to be followed to identify future fault level issues and their solutions.

Section 2 and 3 describe the literature review that has been carried out to investigate the recent work already carried out to identify fault level issues, as well as the current state of applicable fault limiting technology.

The outline methodology is described in Section 4, with the roadmap that should be followed presented in Section 5.

2. TECHNOLOGY AND APPLICATION REVIEW

This review follows up an initial report prepared by PB Power in 2004 (PB Power, 2004). Where appropriate manufacturers and researchers have been approached to provide further information on the current status of their technology.

2.1 Fault current limiting techniques

There are active and passive methods of employing fault reduction and limitation on power systems.

Passive techniques such as the physical design of the power system components (eg high impedance transformers), network splitting, connecting generation at higher voltage levels and sequential tripping all are effective solutions that can be employed to increase the source impedance and reduce fault levels. However, each of the solutions listed above result in one of more of the following disadvantages;

- lower system reliability
- increased operational complexity
- increased cost
- reduction in power quality
- degradation of power system stability

Alternatively the power system can be designed to have a relatively high normal operating fault level which will result in increased power quality and higher overall equipment utilisation. The actual fault currents could be limited to levels that are within the rating of the associated electrical equipment, so as to allow safe operation, reliable protection operation and effective fault clearances on the power system.

There are so-called "active" devices that can be employed in power systems to reduce the actual current that flows during fault conditions. Some examples of active fault current limiting devices are listed below:

- Explosive I_s Limiters and fuses
- Solid state fault current limiting circuit breakers
- Superconducting fault current limiters
- Interphase power controllers
- Active fault level management

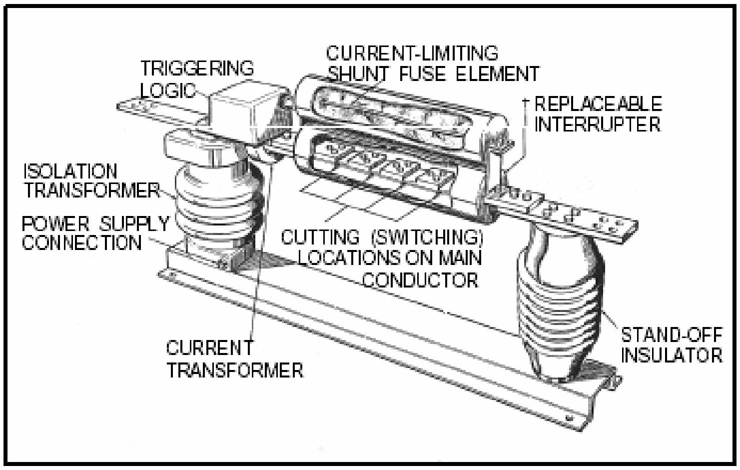
All of the devices listed above effectively provide small impedance under normal system operating conditions and an increased impedance during fault conditions. An investigation has been carried out to determine the current state of development of the various fault limiting technologies and the market readiness for the implementation of the devices. The results of this investigation are presented in Section 2.2.

2.2 Current state of fault current limiting technologies

2.2.1 Explosive I_s Limiters and fuses

Use of these devices has not been identified within the UK utility sector, but a previous report (PB Power, 2004) indicated limited industrial use of I_s Limiter technology. There are manufacturers with commercially available current limiting devices, for use at service voltages ranging from 450V to 38kV.

Figure 2-1 Layout of a triggered I_s Limiter



(Sourced from PB Power report, 2004, p. 85)

These devices are not considered to be failsafe and require servicing after each operation. A DTI commissioned report issued in 2004 (PB Power, 2004) concluded that the installation of I_s Limiters would lead to:

- difficulties related to compliance with UK Health and Safety Executive (HSE) safety legislation
- duty holders bound by The Electricity Safety, Quality and Continuity Regulations 2002 (ESQCR) being in breach of their license conditions and therefore open to prosecution
- potentially being in breach of the absolute requirements of Regulations 5 and 11 of the Electricity at Work Regulations

Their suitability for higher voltage applications is also limited and, with the current legislative and regulatory environment in the UK unlikely to change in the near-term, it is unlikely that these devices will offer a practical solution to electrical networks with high fault level problems.

2.2.2 Solid state fault current limiting (SSFCL) circuit breakers

Solid state devices can be used to increase the source impedance and limit fault currents during fault conditions only. Electronic switches ensure that reactors or resistors are inserted in the path of the fault current within a few ms following fault inception, thereby increasing the series impedance and limiting the fault current. Wu et al maintain however that “the SSFCL is still not widely used in practice due to its high cost, low reliability, and complicated auxiliary system” (Wu et al, 2003, p. 11).

A DTI commissioned report published in 2006 indicated that ABB had developed an 11kV solid state circuit breaker which was installed at a substation in Switzerland. At that time, the product had not been commercialised due to high costs and cooling requirement issues (PB Power, 2006, p. 17).

Development is underway of a solid state device that will limit fault current by inserting a series resistor into the circuit through which the fault current flows. EPRI indicates that the objective of this project is to offer a commercial SSFCL at “six times the cost of conventional mechanical circuit breakers and relays” (ERPI, 2007).

EPRI reveals that a single phase MV (69kV) prototype has already been lab tested and a three-phase prototype has been constructed and is to be lab tested during 2007, with several MV SSFCLs being placed in the field for extended tests. As such EPRI consider this to be a low risk project, with the results being implementable in one to two years. They plan to begin field trials on a “transmission class” (115kV) device in 2008.

The EPRI source predicts; “In the near term, we see the use of the SSFCL in special cases where its application has enough value to justify a premium cost. In the future, the availability of the next generation of new solid-state switches […] offers the prospect of making solid-state power handling much more affordable and widespread” (ERPI, 2007).

2.2.3 Superconducting fault current limiters (SCFCLs)

A paper by Noe and Steurer (2007) describes the methods of operation and states of development of the various types of SCFCL. Brief descriptions of the various technologies presented in this paper are included in Section 2.2.3.1 to Section 2.2.3.6 of this report.

SCFCLs are not currently commercially available but successful field trials have recently been undertaken in Germany and the USA. The current development status of SCFCL technology is presented in 2.2.3.6.

2.2.3.1 Resistive

The operation of this type of SCFCL is based on the quench of the superconducting material, which describes its transition from the superconducting state to the normal conducting state. The quench occurs rapidly when the short circuit current flowing through the SCFCL exceeds the superconductor’s critical current (Noe and Steurer, 2007, p. 17).

This variation of the SCFCL utilises a resistor in parallel with the superconducting material that protects the superconductor from hotspots that may develop during the quench, as well as avoiding damaging overvoltages over the SCFCL.

These SCFCLs are considered fail safe and can be built to exhibit negligible impedance during normal system operation. A recovery time is however required following a quench, which can range from one second to under one minute, depending on the material employed. One current disadvantage is that there is energy loss caused by the current leads passing from room temperature to cryogenic temperature that will result in a loss of approximately 40-50 W/kA heat loss per current lead at cold temperature (Noe and Steurer, 2007, p. 17). This would equate to a maximum operating loss of approximately 80kW for a three phase SCFCL operating in series with a 10MW generator connected at 11kV.

2.2.3.2 Resistive Magnetic

Noe and Steurer (2007, p. 17) describe this variation of the SCFCL that utilises a parallel inductance with the superconducting material. Their paper describes how the increasing magnetic field, caused by the growing current flowing in the inductor under fault conditions, accelerates the quench and mitigates the hot spot phenomenon in the superconducting material.

2.2.3.3 Bridge Type SCFCL

This SCFCL employs solid state technology to control the flow of current through a superconducting inductance. Noe and Steurer (2007) describe the operation of this type of SCFCL, and explain how a non-superconducting material may, in principle, be used for the inductive impedance. The disadvantages of this Bridge Type SCFCL are that it is not considered to be fail-safe device, and it exhibits relatively high total energy losses.

2.2.3.4 DC biased Iron core SCFCLs

Noe and Steurer (2007) explain that these devices incorporate two iron-core coils that are driven into saturation by introducing a DC bias current under normal operating conditions. These two cores are placed in the series path of the potential fault current. While these two cores are in operating in saturation mode, their (and hence the SCFCL) inductances are low. When a fault current flows, these coils will be driven out of saturation resulting in an increase in the apparent coil inductance.

This concept has the advantage of requiring relatively less superconductor material, and a smaller cryogenic system is required to cool the device. The requirement for the iron cores does however make the device bulky when compared to other SCFCL devices (Noe and Steurer, 2007, p. 18).

2.2.3.5 Power Electronics

Power electronic components may be used to interrupt the fault current and direct it through a limiting superconducting impedance, thereby controlling the magnitude of the fault current along the particular path. Once again, these devices will not be considered fail-safe as the failure of one power electronic device can lead to maloperation of the fault current limiting device.

2.2.3.6 Current status of SCFCL technology

In 2001 ABB reported the successful test of an 8kV, 6.4 MVA ***resistive SCFCL*** (Chen et al, 2002). No new information regarding this development was available, with ABB concluding that the widespread application of such devices would only be achieved with the realisation of low cost superconductors and cost effective and reliable cooling.

Nexans Superconductors have developed a three-phase, 10MVA, 10kV ***resistive SCFCL*** that was field tested in Germany for one year from 2003. It was named CURL 10 and the test was deemed successful for MV applications. The device is currently undergoing further testing in Germany.

Following on from the Nexans CURL 10 resistive SCFCL development described in the paragraph above, the company have moved to develop a resistive type SCFCL with magnetic field assisted quench (ie ***resistive magnetic*** as described in Section 2.2.3.2). The aim of this project is to develop a 110kV, 1.8kA demonstrator which is planned for 2008. (Noe and Steurer, 2007, p. 25).

Following earlier successful research relating to the Matrix Fault Current Limiter Project, an American based project is developing a 138kV SCFCL using the pure ***resistive SCFCL*** concept and the latest second generation (2G) superconducting components (Superpower, 2006a). This project forms part of the US Department of Energy's Superconductivity Partnership Initiative program and the use of the 2G components promise to make this development more cost effective and commercially viable. The project aims to have a three-phase prototype by 2009 (Superpower, 2006b).

Noe and Steurer (2007, p. 25) report that a national project is currently underway in Japan to develop and demonstrate a 6.6kV, 600A ***resistive SCFCL*** application. In Korea, the ten-year "Dream of Advanced Power Systems by Applied Superconductivity (DAPAS) Technology Program" is aiming to commercialise superconducting power equipment. During the first phase of the program they have successfully built and tested a 6.6kV SCFCL. The second phase aims to have a 22.9kV 630A resistive SCFCL built and tested in 2007.

Past research and development of the ***bridge type SCFCL*** in America, Japan, China and Korea is detailed in Noe and Steurer (2007, p. 25, 26), but this reference indicates that there is no current activity underway to further develop this technology.

Innopower in China are developing a 35kV prototype ***DC biased iron core SCFCL*** that is due to be tested in 2007 (Noe and Steurer, 2007, p. 26).

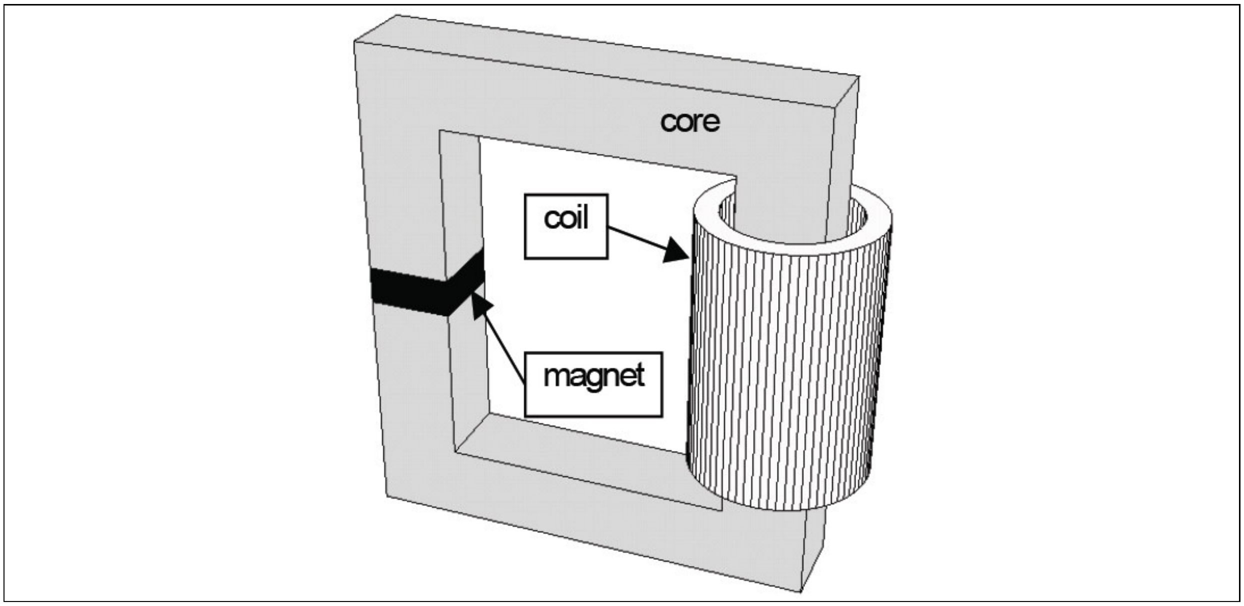
Noe and Steurer (2007, p. 26) claim that a demonstrator ***SCFCL*** using ***power electronics*** is to be developed and tested in early 2007. The feasibility of this development has been confirmed and manufacturability studies show that the cost and size for MV application seem attractive. No other information is readily available on this product development activity.

Many challenges lay ahead for developers and manufacturers of SCFCLs. As utility (substation) based solutions will be required to have a life in excess of 30 years, the ageing and long term behaviour of the superconducting material needs to be understood. As this is relatively new and unexploited technology, such information is not available at this stage. As a result of the relatively high cost of these superconducting devices, research and development is currently focused on the MV and HV applications where large technical and economic benefits are to be achieved.

2.2.4 Magnetic fault current limiter (MFCL)

Areva T&D Technology Centre is developing a MFCL, based on a laminated iron C-core with a demagnetised magnet in the air gap. Figure 2-2 shows a diagrammatic representation of the prototype model, showing the coil that would form part of the series fault limiting circuit, the iron core and the magnet. Areva state that the reactance of their MFCL automatically increases during a fault as the magnet is magnetised by the high fault current. A more complete description of the concept is provided in a paper written by Chong et al (2006).

Figure 2-2 Diagrammatic representation of Areva's model MFCL design



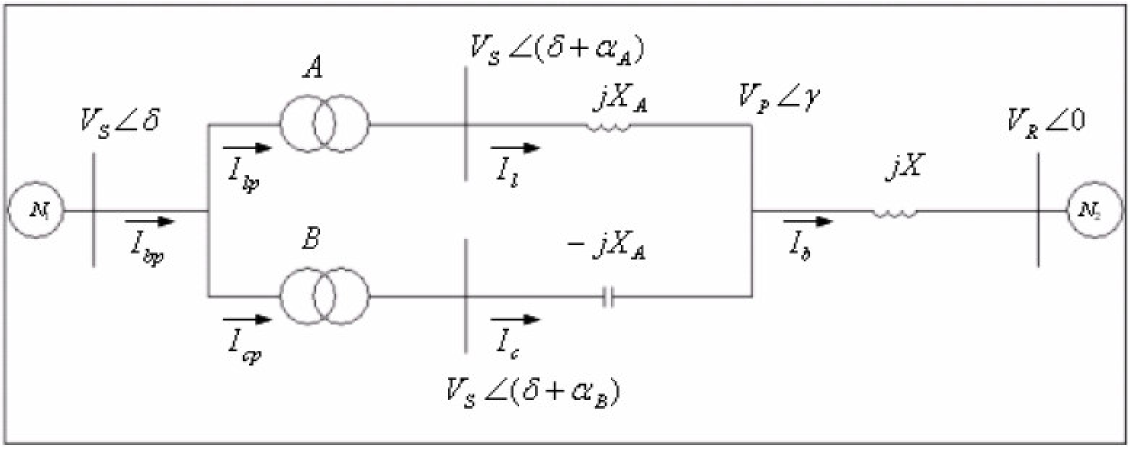
(Sourced from presentation by Sturgess et al, 2006)

The 400V (250A) prototype has been designed and built, its performance simulated and it was under test in 2006. No further information on this project was forthcoming from Areva.

2.2.5 Interphase power controllers (IPC)

IPCs are not a new technology, but its implementation is limited on power systems presumably because of the high capital investment required. IPCs utilise two parallel phase-shifting transformers with series reactors and capacitors included in each of the parallel branch, as shown in Figure 2-3.

Figure 2-3 IPC single line diagram, showing the IPC in series with a transmission line



(Sourced from paper by Farmad et al, 2006, p.1494)

The parallel impedances (jX_A and $-jX_A$ in Figure 2-3) form a parallel circuit tuned to the fundamental frequency of the network. These high-impedance IPCs have the unique properties of presenting high impedance to through-flowing fault currents and decoupling the voltages at their terminals. They are intended for implementing ties not otherwise possible because of high short-circuit levels.

2.2.6 Active fault level management

Active fault level management refers to a control scheme that regulates the power system's fault levels by monitoring the network topography and the levels of connected generation. Switching actions are implemented to increase the source impedance when the fault levels approach maximum limits, informed by the real time state of the power system.

A DTI commissioned report published in 2004 states "there are currently no systems in place to automatically control the network to ensure that design fault levels are not exceeded. The responsibility rests with the DNOs System Design to design a suitably robust network so that equipment operates within its limits" (Roberts, D, 2004, p. 3).

KEMA compiled a report for the DTI that cited Dutch research into intelligent networks and stated that active fault level management was at an early stage of development (in 2005), would be "very expensive" and it was not likely to become a reality within the following ten years (KEMA, 2005, p. 36).

In 2006 the University of Strathclyde prepared a register of active management pilots, trials, research and development and demonstration activities. Analysis of the register shows that only 10% of the projects in the register were associated with fault level management, and of this 10%, nearly all of them were at the R&D stage of development (Ault and Currie, 2006).

A UK based BERR part-funded project led by Econnect Ltd. that is working to develop an active network controller started in 2004. The project was set to run up to February 2007, and "involves preliminary research to develop a device which will address and solve anticipated problems associated with voltage rise, short circuit levels and reverse power flow in order to accommodate large numbers of small scale embedded generators (SSEGs) on LV distribution networks”. No further information on this project was made available by Econnect.

Whether the active networks concept is considered to be fail safe is yet to be determined. The system could fail, or communication links could be lost which would result in loss of control action. Operational procedures could be put in place for this eventuality which would ensure that the system was operated safely during periods when the active controller is not operational.

2.2.7 Superconducting fault current limiting transformers (SFCLT)

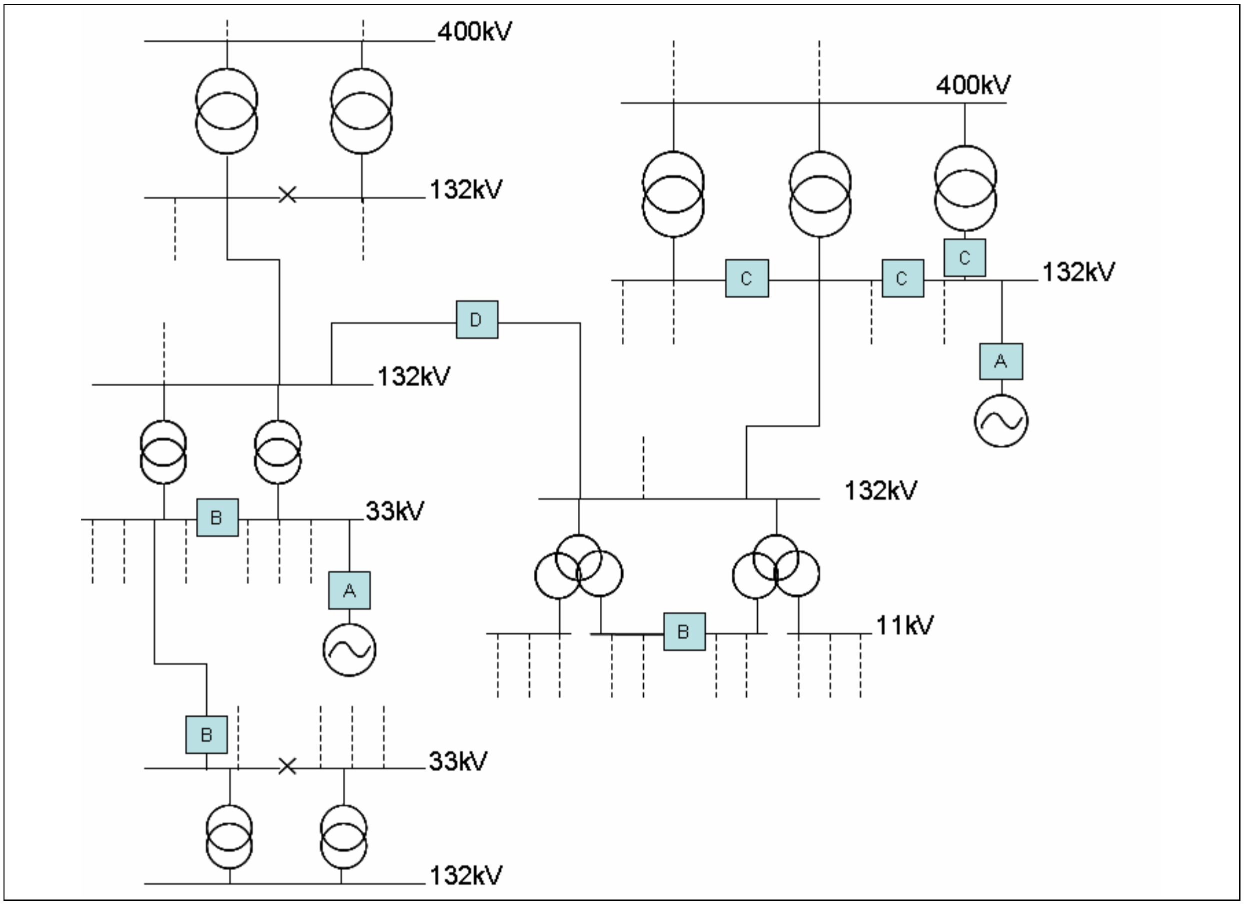
Transformers can be built to incorporate superconducting material into their secondary winding. A benefit of this type of transformer is the relatively low transformer leakage impedance under normal operating conditions. This promises lower operating losses and enhanced power system stability. The increased impedance brought about by the quench of the superconducting material during fault conditions reduces the fault current flow through the transformer, and hence the contribution to the LV fault level.

The high relative cost of this type of transformer however stands in the way of its wide scale commercial exploitation. These devices are not currently commercially available. The Okubo Endo Laboratory (Japanese) website states that the laboratory has designed and manufactured a 6.6kV / 210V, 3-Phase, 100kVA SFCLT. The function of which has been verified by operational characteristic examinations.

2.3 Practical applications

Active fault current limiting devices could be built into existing and new-build power systems to reduce the actual fault currents and negate the need for equipment replacement. Figure 2-4 shows some of the possible applications for FCL technology on existing and new-build distribution power networks.

Figure 2-4 Possible practical applications for FCLs on HV and MV networks



2.3.1 Generation connections

The addition of new generation to existing power systems will increase the power system fault levels, most predominantly close to the generator connection point. It is for this reason that the installation of a FCL in series with a generator connection (as shown by the blocks labelled [A] in Figure 2-4) may negate the need for replacement of existing switchgear in a substation by minimising the fault infeed from the particular generator at the point of common coupling. FCLs in series with generators could be applied in industrial, distribution (distributed generation) and transmission systems, assuming that the technology is suited to operation at the associated voltage levels.

As existing system equipment fault ratings sometimes dictate that new generation connect at higher system voltage levels, the series connected FCL could ensure that a more cost-effective lower voltage connection design becomes practical.

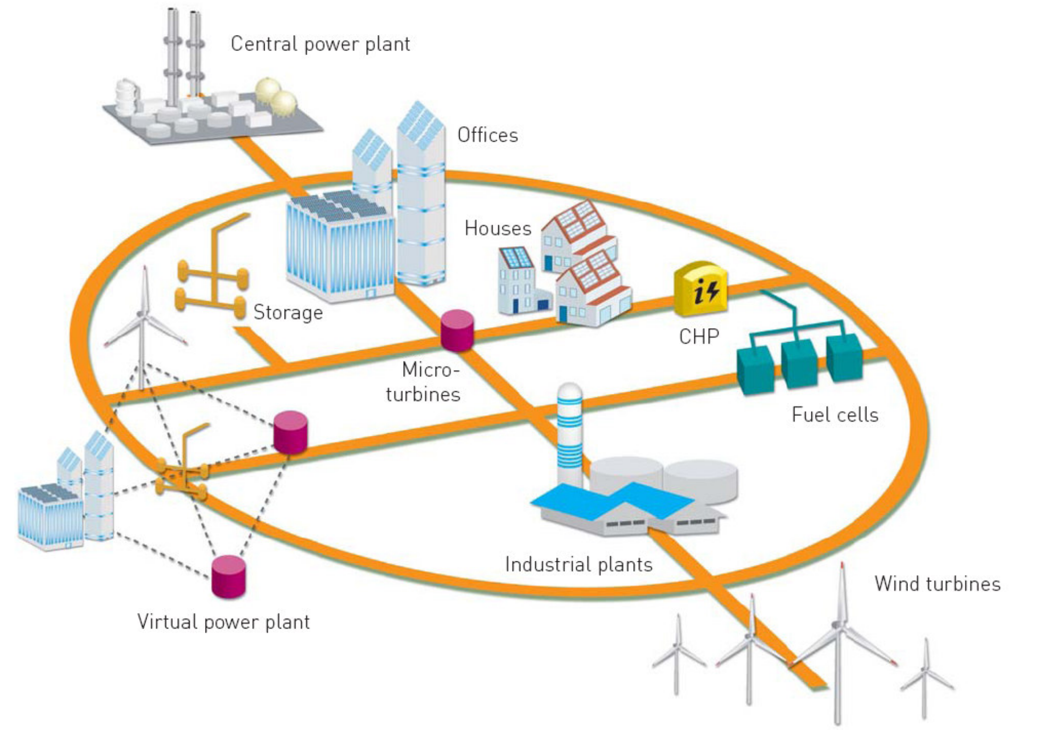
High normal-operating load ratings and low operating losses will however be required from such a device, as well as high levels of associated reliability.

2.3.2 Paralleling grids and bus sections

2.3.2.1 LV and MV grids

High concentration of installed micro generation at LV levels, as well as DG connected developments connecting into existing MV networks, may be able to utilise FCL technology to prevent expensive asset replacement that will be necessary to ensure safe operating conditions at substations/switchboards on the network. Figure 2-5 shows a depiction of a future MV and LV power networks in developed urban areas, with an interconnected mesh grid system being utilised to distribute the power generated from the variety of generation technologies and locations distributed throughout the vicinity.

Figure 2-5 Depiction of future MV and LV electrical distribution networks



Future: *Operation of system will be shared between* ***central and distributed generators****. Control of distributed generators could be aggregated to form microgrids or 'virtual' power plants to facilitate their integration both in the physical system and in the market.*

(Diagram sourced from a report published by the European Commission (2006), p. 18)

The blocks labelled [B] in Figure 2-4 indicate possible application locations for FCLs in MV networks, which could also be applied to isolated LV switchboards and substations. The resulting high "normal operating" fault level would benefit the end consumer by reducing the level of harmonics and flicker, as well as attenuating voltage dips brought about by network and equipment switching. Distribution system reliability would also be improved by coupling split busbars at the MV substations.

2.3.2.2 HV grids

Splitting 132kV busbars is a solution often used to work around high fault level problems. FCLs at this voltage level could be used to run the busbars solid, thereby providing more flexibility for system operation and lower source impedances. Significant savings brought about with the deferral of transformer replacement/upgrading is a potential benefit that may be achieved with the use of FCLs at HV levels (as shown by the blocks labelled [C] in Figure 2-4).

Increased 132kV system reliability and utilisation of existing transformers and circuits may be achieved with the use of HV FCLs. The coupling of adjacent 132kV systems (as shown by the blocks labelled [D] in Figure 2-4) will safely increase the normal operating fault levels which may realise the following benefits:

- increased power quality, with interference caused by system harmonics attenuated and flicker reduced
- smaller system voltage dips
- lower system losses as the paralleled transformers could possibly be operated at lower load levels

2.3.3 Power Plant Auxiliaries

Increasing the reliability of power plant auxiliary power supply systems and at the same time reducing or maintaining the actual fault currents to within the ratings of existing equipment would be an attractive proposition for power plant owners.

Power plant auxiliaries are usually supplied through auxiliary step down transformers from the power plant generators which results in the high fault levels on the auxiliary plant. For new developments, smaller conductors could be specified and significant cost savings achieved with the reduction of fault currents. The lowering of power system operating losses that could be achieved with the adoption of FCLs and the subsequent reduction of auxiliary transformer impedance would appeal to the owners and shareholders of power plant companies alike.

2.3.4 Ship propulsion systems

Electric propulsion in modern ships is replacing the more traditional mechanical drives. This electrification requires relatively large amounts of power with typical values of up to 150MW being required for a destroyer class ship (Noe and Steurer, 2007, p. 22). The relatively low voltages used in ships' power systems (between 5 and 15kV) make fault level design aspects of the associated power systems a critical factor. The use of FCLs can lead to significant savings when designed as an integral part of the power systems of modern ships.

Noe and Steurer (2007, p. 22) indicate that there is currently a national project in the UK aimed at developing a 6.6kV, 400A SCFCL demonstrator for application within ships' power systems.

2.4 Future outlook

Existing active commercial fault current limiting devices such as I_s Limiters and fuses have been developed for LV and MV applications up to approximately 36kV. Younger technologies such as steady state circuit breakers and superconducting fault current limiters offer superior performance over these existing devices. The most significant advantage is the automatic recovery property which allows continuous operation of the device on the power system and removes the need for servicing following each fault limiting operation.

The development of Superconducting FCL technology seems to be focusing on 110kV voltage levels and above, positioning the devices at the more capital intensive power networks where the potential financial benefits are more substantial than those on offer at LV and MV levels.

Active network controllers will offer a real time control solution for networks with fault level problems that manifest themselves for short periods of time on existing networks with relatively high levels of DG.

Table 2.1 shows a summary of the technologies presented and discussed within this section.

Table 2.1 Summary of the status of fault current limiting technologies

Technology	Manufacturer/ Developer	Application voltage level	Status	Time to market
I_s Limiter	ABB and G&W Electric	450V - 38kV	Commercially Available	Available
Solid state breaker	ABB	11kV	Field Test	Unknown
	EPRI	69kV	2 years to test manufacture	Unknown
Superconducting Fault Current Limiters	ABB	8kV	Successful test 2001	On hold
	Nexans (CURL 10)	10kV (10MVA)	Field test in progress	Unknown
	Nexans	110kV (1.8kA)	Demonstrator planned for 2008	Unknown
	SuperPower (and others, USA)	138kV	R&D, Prototype expected 2009	Unknown
	Japan	6.6kV	Testing complete	Unknown
	Korea (DAPAS program)	6.6kV	Testing complete	Unknown
		22.9kV	R&D, Prototype expected 2007	Unknown
	Innopower (China)	35kV (100MVA)	Field testing 2007	Unknown
	Power Electronics SCFCL (unknown developer)	MV	Demonstrator due early 2007	Unknown
Magnetic Fault Current Limiter	Areva	400V (250A) prototype	Test	Unknown
Interphase power controllers	ABB	HV networks	Commercially available	
Active network controllers	Econnect University of Northumbria VA Tech T&D UK (now Siemens)	LV Distribution networks (11kV)	R&D	Unknown (R&D project set to complete Feb 2007)

3. DISTRIBUTION FAULT LEVEL ANALYSIS

3.1 Review of past work

Studies commissioned by the DTI and OfGEM have been carried out in the recent past to determine and quantify the impact of new generation technologies, DNO future plans and future networks. The various reports commissioned which contain reference to system fault levels are briefly described in the following text:

Powergen (2002) reviewed two sample networks in the East Midlands, to determine the network effects and constraints that would present themselves with the growth in embedded generation resulting from government policy and targets, up to 2010. The growth in renewables, as well as CHP was included in these analyses. This work reported that the growing system fault levels would constrain the connection of the target amounts of renewables and CHP, assuming that synchronous generators were employed. The fault level constraints would be the limiting factor (as opposed to load flow or transient stability issues that were also considered) primarily in their urban sample network (132kV, 33kV and 11kV) and at the 11kV primaries on their rural sample network.

Ilex Energy Consulting (2002) produced a report that quantified the costs associated with the planned levels of renewable generation on UK transmission and distribution networks between 2010 and 2020. This report confirmed that the distribution reinforcement costs generally increase with the addition of renewable generation. Ilex further indicated that significant increases in distribution costs would however be realised where high regional concentration of smaller scale generation were realised as well as where a large number of generators were concentrated at a particular voltage level.

A DTI commissioned report compiled by KEMA (2005) indicated that fault levels would not be problematic in the majority of LV networks, with even a 100% penetration of micro CHP increasing the LV fault levels by 6-7%. KEMA expect that fault level problems would manifest in the following areas in the period to 2010:

- MV urban networks. The increase in power generated from small, medium and large CHP as well as landfill gas and waste fuelled generation will lead to the increase in fault levels on already densely connected 11kV and 33kV networks which currently have the lowest fault level headroom[1]

- Rural HV substations. Large scale DG projects connecting into rural networks will lead to localised instances where equipment fault level ratings are exceeded which will require major reinforcement works

- Isolated LV situations. LV networks with high levels of DG penetration may require fault level related reinforcement where, for example, micro CHP is installed in high density urban areas. KEMA indicate that they do not have experience with networks where large amounts of micro CHP are installed in urban networks.

[1] Fault level headroom refers to the amount that fault levels can increase before installation of replacement equipment with higher fault level ratings becomes necessary.

3.2 Requirement for further work

The studies discussed in Section 3.1 indicate that there will be situations where the growth in distribution system fault levels will require substantial reinforcement of existing networks and substation equipment. The current state of research and development of appropriate fault level limiting technologies is presented in Section 2. From this review we conclude that there is currently no appropriate and commercially available technology that offers a fault limiting or fault level control solution for UK distribution networks. There are however a number of research and development trials that are underway and may offer solutions in the medium term.

Analysis should be carried out, focusing specifically on distribution fault level issues, that will inform the electricity supply industry which system voltage levels will be most affected by the rising fault level problems. This analysis may be used to identify the likely financial implications of the reinforcements made necessary by the rising distribution system fault levels so that research, development and commercialisation of the appropriate technology will be achieved.

As there is currently no practical fault level measurement technology commercially available, fault calculations will be required to estimate the fault level headroom at the nodes on the distribution networks. The following sections outline a methodology that could be used as a guide to build an analytical model. This model would be built and used to assess the approximate scale and identify the general network locations (eg voltage level) that would be affected by the rising distribution system fault levels.

4. OUTLINE METHODOLOGY FOR ASSESSING THE MATERIALITY OF THE FAULT LEVEL PROBLEM

An outline methodology is presented in this section, which may be used as a guide to set up a model to be used to assess the scale and severity of fault level problems that are expected on the UK distribution networks. The following discussion is presented in three sections:

- the relevant inputs that will be required for the analysis
- the high level functionality required within the model, and
- the outputs required from the model that will be used to inform the analysis.

The following sections are intended to be the "functional specification" for the model. A bottom up approach has been recommended for the model, assuming that the appropriate typical network types will be modelled and scaled upwards to provide a generalised picture per DNO. The results for the DNOs would then be summed to generate a general UK distribution network picture.

4.1 Power system model definition

The fault level calculation results will be influenced by the network topology, equipment impedance, demand that contributes short circuit fault current and the generation connected to the power system.

4.1.1 Network topology

The inputs relative to the model will begin with an identification of the type of networks that are present on the UK DNOs power systems. The work currently being undertaken by the University of Strathclyde has defined 6 "typical networks" (Foote et al, 2006) that apply to the UK distribution systems. We would propose the utilisation of these typical networks in the model, to further the good work already being conducted. Significant effort has already been expended on the identification and categorisation of these networks, based on information provided by the UK DNOs. The results of this work fit with the requirement for base generic networks that could be used for a fault level model for generic UK distribution systems. The typical networks however only represent distribution networks down to the 33kV voltage level, with 33/11kV transformers and 11kV busbars being included.

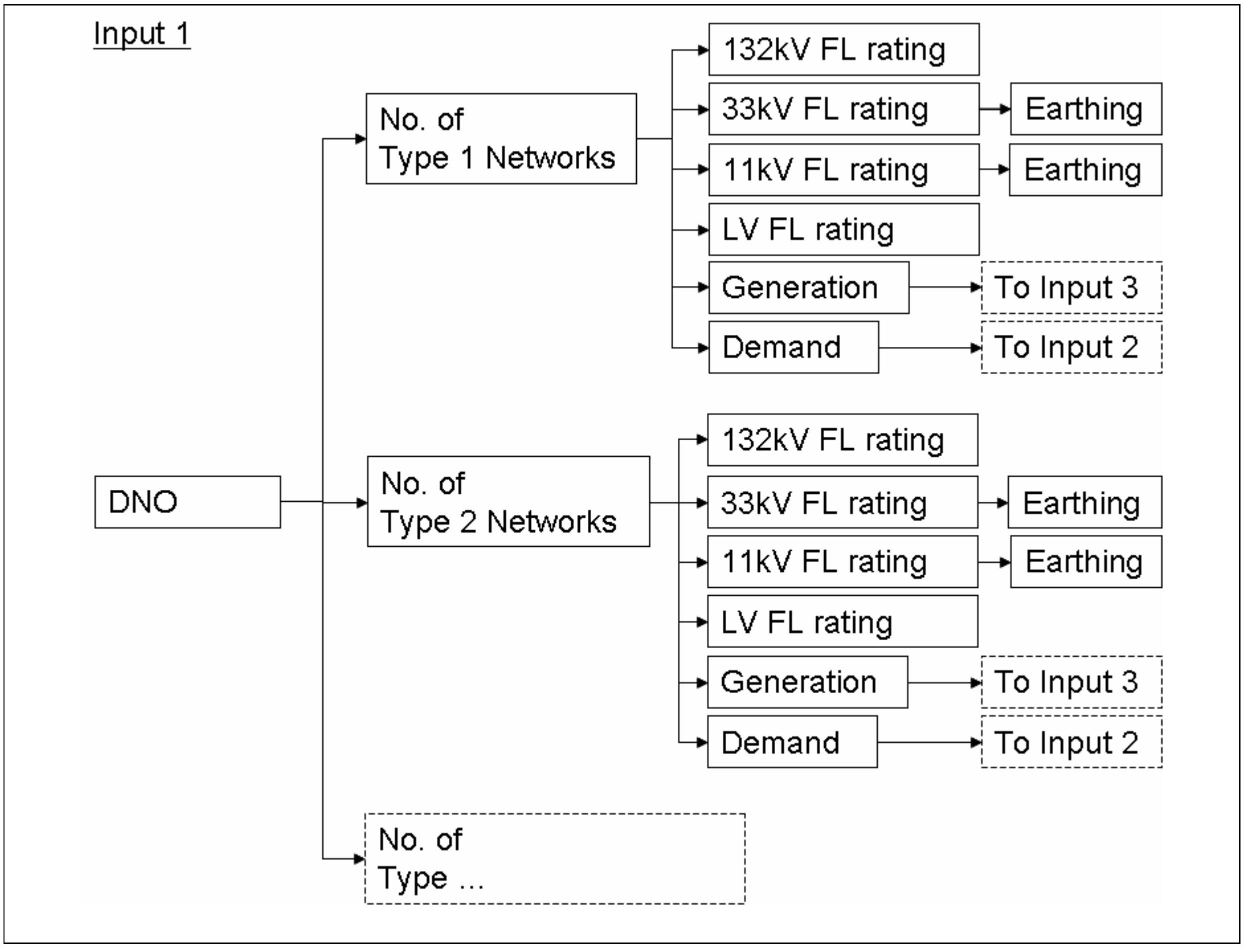
A study carried out by PB Power (PB Power, 2005) developed generic urban, rural and meshed distribution network models including 11kV and 400V voltage levels. The rural and urban networks were derived from information provided by the UK DNO's, standard distribution system configurations and manufacturers' data. The meshed network was based on a physical Scottish Power Manweb network. These 11kV and 400V networks could be "bolted on" to the appropriate Strathclyde typical network model to provide generic distribution networks that could be used to measure the impact of DG at voltage levels from LV to EHV.

4.1.2 Network and substation characteristics

The DNO networks should be identified relating to one of the 6 typical networks. Each of these typical networks should be modelled with a corresponding generic generation portfolio and demand characteristics. Figure 4-1 shows the first level of inputs that will be required to be included in the model.

The substation and power system equipment which are the cause of the lowest and limiting fault level ratings should be identified at all locations. Traditionally switchgear fault current ratings are used in fault level studies and analysis work, but as the networks develop around existing plant and equipment, it is becoming more likely that the fault level limits imposed at a particular substation or network location could be non-switchgear related (eg the fault withstand rating of cables).

Figure 4-1 Network inputs required for the model

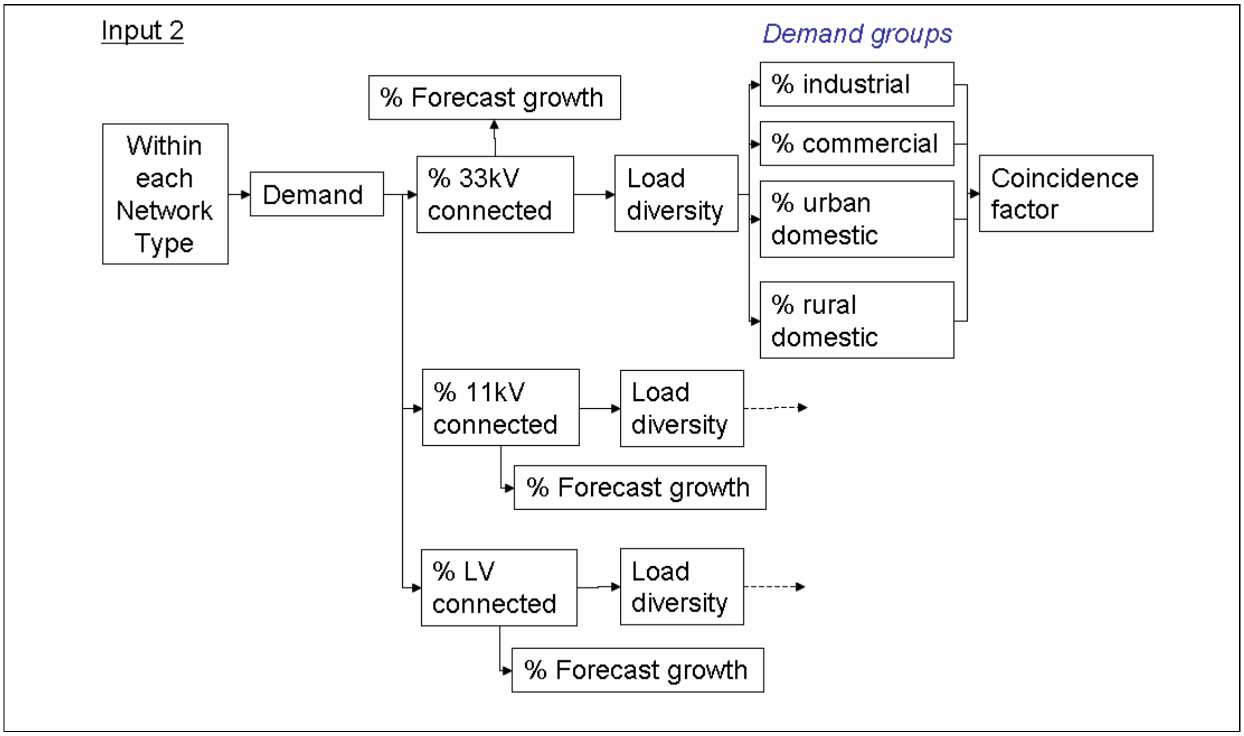


Most DNOs in the UK use earthing transformers or resistors to limit the single phase to earth fault currents on their MV networks. The model should however be adaptable enough to calculate these single phase to earth fault currents for those DNOs that do not use earthing resistors. The "earthing" input shown in Figure 4-1 will ensure that the zero sequence component of fault current is considered when assessing the system fault levels.

4.1.3 Demand

The type of load will be a factor to be considered in the model. The fault level contribution of various demand groups varies with the load types associated with each demand group. Some industrial, air conditioning and refrigeration load (employing directly connected compressor motors) for example, will provide short circuit fault current that will increase distribution system fault levels. The types of load (eg lighting, heating, resistive, motor, air conditioning, PWM supplied) assumed to make up each of the demand groups will be set for the different demand groups which are shown in Figure 4-2.

Figure 4-2 Demand characteristic inputs required for each typical network



Engineering Recommendation G74 provides guidance on how to include the fault current contribution from rotating plant on power systems. Historically DNOs have utilised the recommendations within ER G74 to calculate the make and break duty on the UK distribution networks. Industry impressions relating to G74 are that it is based on an isolated demand group and that that the overall characteristics of electrical demand have changed since compilation of the recommendation. With this in mind, a detailed consideration of the types of loads and their associated fault current contributions is recommended for implementation within the model.

For each demand group, the following should be specified as base assumptions to be applied within the model;

- Demand density
- demand load factor
- power factor
- average forecast growth rate for the demand group

The coincidence factor input shown in Figure 4-2 could define the coincidence of the demand category, relative to the network peak demand.

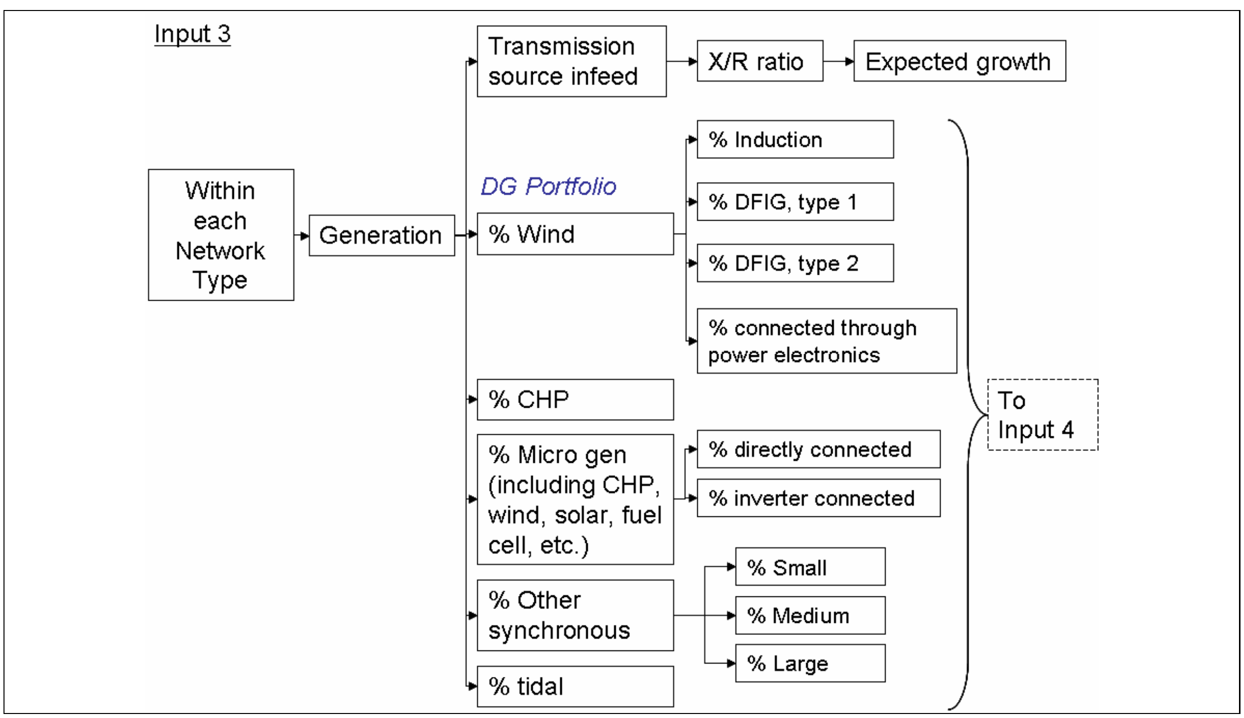
The forecast growth figure would be used to when considering the network in the specified future years.

Where there is uncertainty related to the inputs assigned to the demand groups, a probability distribution function should be assigned to these inputs. The Stage Two model development will incorporate a randomly generated mix (based on the probability distribution functions defined) of the input values into the simulations carried out as part of the simulation routine, as described in Sections 4.2.1 and 4.2.2.

4.1.4 Generation

The types of generation that are currently present on each of the typical networks shall be entered in to the model, so that the fault infeed from each of the different generation technologies can be accounted for and included in the analysis. Figure 4-3 shows the inputs that will be required to develop a typical generation portfolio. It should be noted that DG such as bio fuel, waste to power and incineration generation has all been included under the "other synchronous" generation block in Figure 4-3.

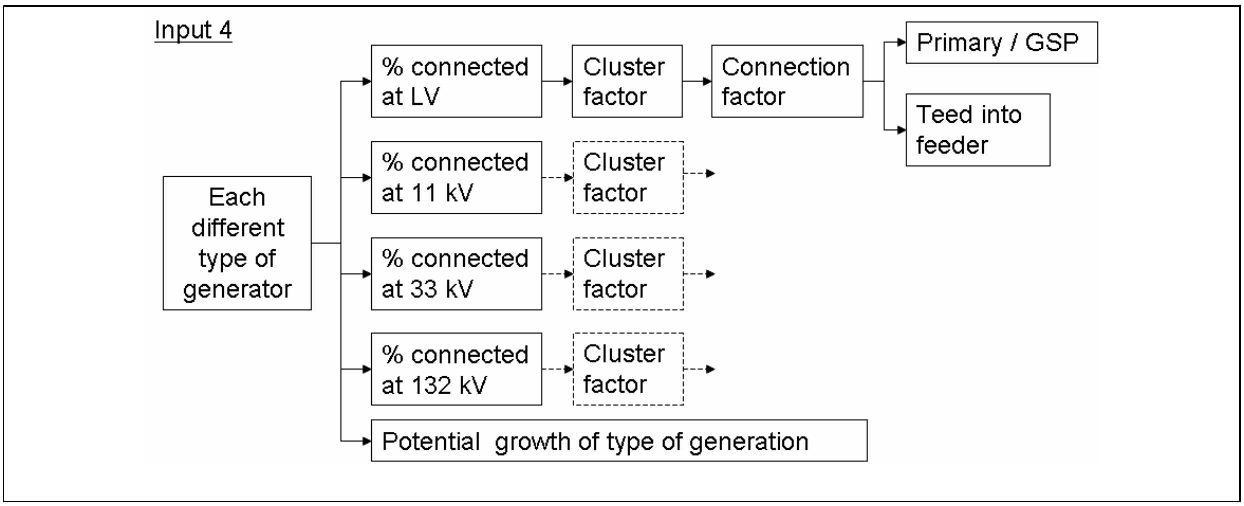
Figure 4-3 Generation portfolio inputs required for each typical network



Some embedded generation is connected through inverters (photovoltaic), and converters (some wind turbine driven generators), and as such will not result in significant increases in system fault levels. Synchronous generators, induction machines and induction generators will however contribute the network fault current and should be considered for fault calculations and analyses. Typical values for subtransient, transient and steady state impedances should be applied for each of the generation types, based on typical information supplied by manufacturers.

The generation on each of the typical networks should be defined by each of the descriptors shown in Figure 4-4. The voltage level of connection and the "cluster factor" will be used to generate the consolidated generation unit models that could be applied at the network nodes in the model. The cluster factor describes the way in which the specific type of generation is dispersed around the network, at a particular voltage level. For one large wind farm, for example, the cluster factor could be set to 1. On the contrary, for evenly distributed urban micro CHP could be defined as having a cluster factor of 0 on the urban distribution LV network.

Figure 4-4 Characteristics that should be included for each generation type



The location of the generation connection is an important fact to be considered for fault level analysis. Whether the fault current source is connected along a feeder or directly into a primary substation will have an effect on the increase in substation fault levels. The connection factor could be utilised to differentiate generation plant connected directly into a primary (eg a large power plant), as opposed to generation teed into a feeder remote from a distribution substation (eg a rural connected wind farm).

The forecast growth figure would be associated with the expected growth of the different generation technologies that are being entered in to the model. These could be based on government targets and policies, and also used to carry out sensitivity analysis for various generation forecasts.

Where there is uncertainty related to the inputs assigned to the generation inputs, a probability function should be assigned to these values. The model development will incorporate the range of expected values into the simulations carried out as part of the simulation routine, as described in Sections 4.2.1 and 4.2.2.

4.1.5 Fault current limiter device specification

The model will consider the application of FCL devices to different parts of the network, and as such the possible points of application should be defined, as well as the effect of the FCL technologies on the fault calculations. Figure 2-4 show the possible locations for the FCL devices that could be modelled as either an open circuit, series resistance or reactance for the purpose of fault level calculations. Appropriate costs should be assigned to the different FCL solutions, based on their application voltage level and required power ratings. These costs could then be used in the optimisation routine described in Section 4.2.2.

4.2 Model functionality

Two development phases will be required to realise the intended functionality of the model. Phase One will involve development of the network model, with Phase Two applying the model to determine the materiality of the fault level problem and the optimal FCL solution (if any is required).

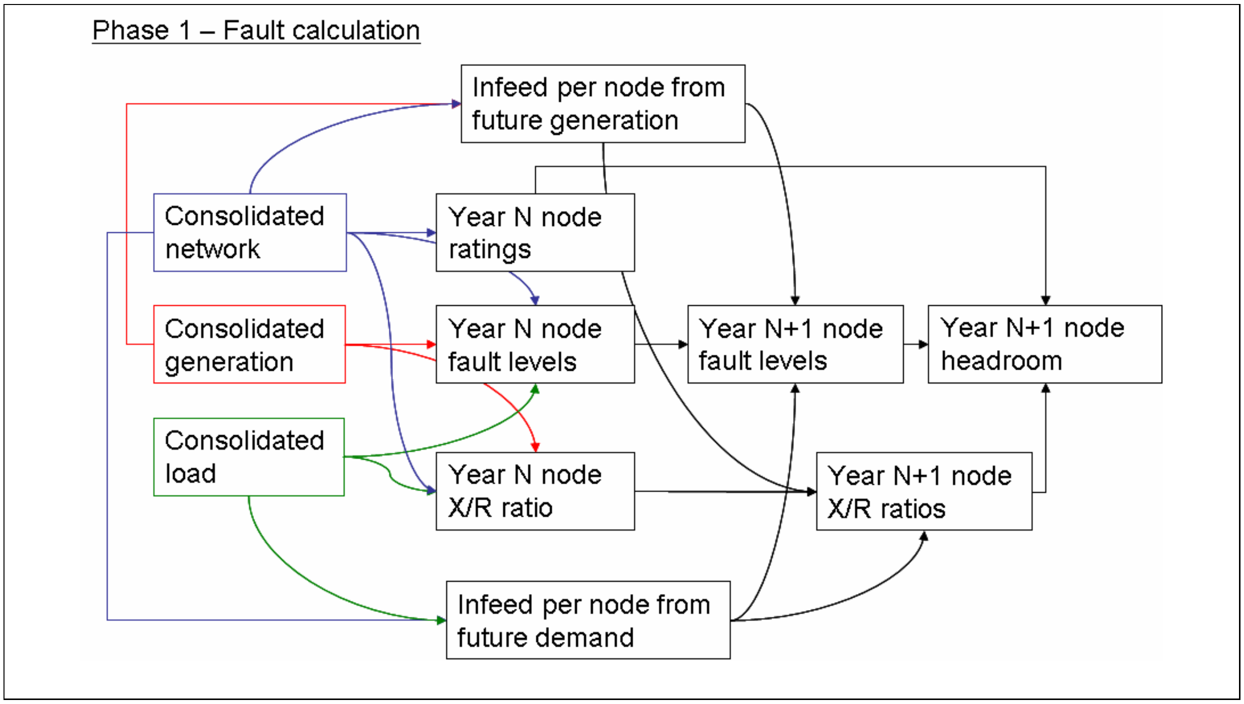
4.2.1 Phase One – model setup

All of the inputs discussed in Section 4.1 should be consolidated to allow for average demand and generator infeed to be modelled for each node of the typical network type. The properties of the generation and demand portfolios should include the following:

- Demand
    - Demand per typical network
    - Overall load factor
    - Overall load power factor
- Generation
    - Average generator/power station at each of the nodes at the voltage levels specified. This can be calculated by amalgamating all of the generation types specified in the generation input process, including the influence of the cluster factor
    - Overall generator infeed

Figure 4-5 shows the flow of the calculations within the model that will be required to estimate the future fault level.

Figure 4-5 Phase One model fault level calculation functionality



The model will be capable of analysing each of the typical network types, which will need to be scaled upwards in a portfolio to fit with the networks owned and operated by each particular DNO. To be able to scale the results upwards for all the distribution networks in the UK, the DNO specific results would be grouped and summed together. It should be remembered that this is a general assessment rather than a detailed fault level analysis and as such, a level of accuracy relating to the specific networks will be omitted. The challenge, involving input from each of the DNOs, will be to specify the typical network types that generally make up a DNO relative to the physical network topography. It is expected that in reality, each DNO network will be subtly different with factors such as voltage levels, equipment ratings, load diversity and generation (existing and potential) differing between networks.

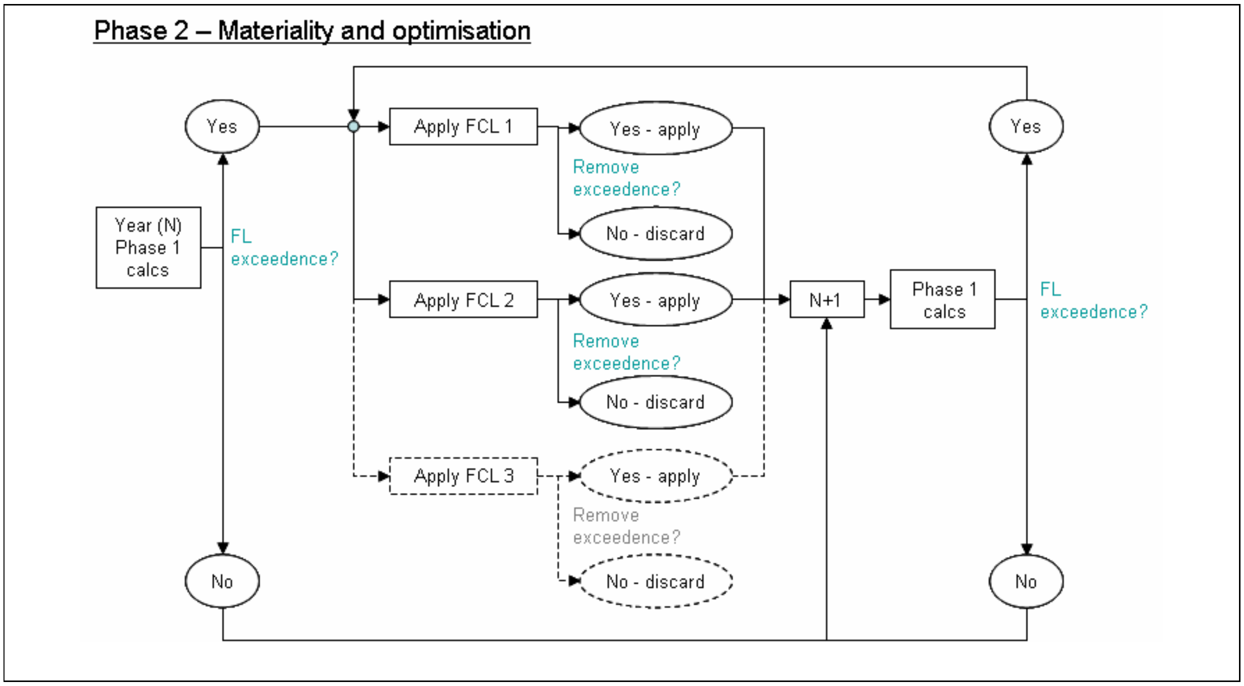
It may be possible to link certain characteristics of the typical networks, to simplify the model and generalise its analysis. Generation portfolios could be linked with (for example) network type and voltage level, or with demand diversity. The overall generation and demand levels could then be made scalable to adjust the typical network types to the actual networks. This practice will however result in a further loss of accuracy and increased generalisation of the model output which should be discouraged if at all possible.

The Phase One network model will assume the inputs as specified by the user, with the assigned probability distribution functions being used to provide a range of inputs for the sensitivity analyses described in Section 0.

4.2.2 Phase Two – materiality and FCL optimisation analysis

The Phase Two model development would involve utilising the models developed from Phase One to determine the materiality of the fault level problem on the typical distribution networks, under the conditions associated with the inputs as described in Section 4.1.

Figure 4-6 Phase Two model functionality



The network model would be initialised in the start year of the simulation with demand and generation portfolios and forecast growth based on the inputs specified by the user – a fault level calculation would be carried out for "Year N".

If there are no fault level exceedences detected, the model would loop to the following year and apply the forecast growth levels of demand and generation to the model. If no fault level exceedences are detected the model will continue to run through the simulation for the intended number of years.

When a fault level exceedence is detected, different FCLs are then applied to the model to reduce the fault level to below equipment ratings. The individual FCLs that reduce the problem fault levels sufficiently will be applied to the model and carried forward to the following simulation year. The simulation would effectively split into a number of scenarios at this stage with each effective FCL solution being carried forward individually to the following year of study. The simulation would loop through the years as described above (and in Figure 4-6) until the end of the study horizon, whereupon the results would be logged and the next simulation would begin with a different set of inputs.

This "multi-scenario" approach will allow identification of the optimal solution to specific fault level problems. The splitting of the simulation into a number of scenarios (as described in the paragraph above) will allow multiple potential solutions to be simulated for each problem.

An optimisation task at the end of Phase Two will select the optimal solution from all the scenarios within the Phase Two simulation, taking account of the cost and number of FCL solutions adopted over the study period for each scenario.

4.2.3 Phase Three – Sensitivity analysis

Sensitivity analyses will be required to assess the impact of the variable inputs associated with the future generation and demand scenarios. The Phase Three model development will generate and analyse a large number of randomly generated network scenarios, based on the variable inputs defined during Phase One. A Monte Carlo algorithm could, for example, be adopted for this task, applying a range of the different inputs based on the probability distribution functions defined for each. The model functionality described in Section 4.2.2 (ie Phase Two of the model development) will be used to process each individual scenario.

4.3 Required outputs

The model is intended to provide an indication of the network locations and scale of the anticipated fault level exceedences as well as the optimal (ie most appropriate) FCL solution to be applied on distribution networks in the UK. As such the outputs should provide an indication of the following:

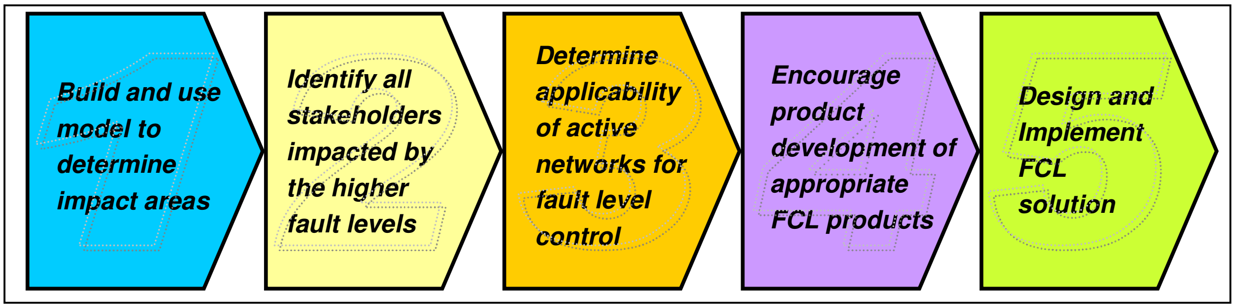
- Is there a likely fault level problem on the network?
- At which voltage level(s) are there fault level problems?
- What type of fault level problem is it likely to be? This output would indicate the severity of the fault level problem, if any. The output would include whether the fault level exceedences is associated with the make duty, the break duty or both the make and break duties of the equipment ratings
- The duration of the fault level problem. Does the fault level occur all the time or only during system peak demand periods, for example?
- The optimal FCL location(s) to rectify the fault level problem.

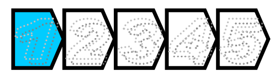
These outputs should allow judgement to be made regarding the scope and scale of the fault level problems expected on UK distribution networks. Working from bottom to top, the results from each of the typical networks can be scaled according to their prevalence within the UK.

5. ROADMAP

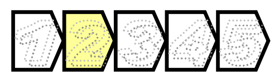
The roadmap presented in this section is the outline action agenda for moving forward that should provide a framework for those impacted by increasing system fault levels. The stages shown in Figure 5-1 indicate the path that could be followed in order to realise an appropriate and efficient solution for the future fault level problems.

Figure 5-1 Roadmap to be followed for realising appropriate fault level solution



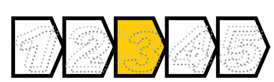


Stage one is expected to follow on from this piece of work. The model outlined in Section 4 (Phase One, Two and Three) should be built and utilised to better understand the future impact of the increased system fault levels on UK distribution networks.

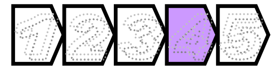


Stage two allows for the identification of the stakeholders that will be affected by the increased system fault levels, to ensure that the implementation of the FCL technology does not have negative impacts upon electricity users, producers or authorities. The stakeholders identified at this stage include the following:

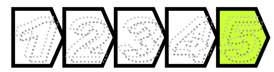
- UK DNOs
- Industrial electricity users
- Domestic electricity users
- Generation owners
- H&S E
- Government (eg BERR) and Regulators (OfGEM)
- Substation equipment manufacturers



Stage three is intended to address an issue already presented in Section 2.2.6. With the considerable funding and R&D effort that is currently being invested on the development of active grid controllers, the suitability of the active controller for safety critical applications should be investigated.



Stage four seeks to commercialise the appropriate technology that may be used for fault current limitation on power networks in the future. With the amount of R&D activity currently underway relating to the solid state, HTS and magnetic FCL technology, it is likely that some of these products will provide cost effective solutions in the future. The commercialisation of these products will require a solid business case, which will be provided by the stages preceding stage four.



Stage five is the implementation stage for the fault current limiting solutions, with the appropriate technology being deployed and commissioned on the UK power networks. It is expected that the re-setting and re-coordinating of some existing protection systems will be required as part of this stage, with other similar issues likely to be identified before this implementation stage. The identification of these issues must form part of the design stage of the solution, to ensure smooth transition between the different modes of operation.

6. CONCLUSIONS AND RECOMMENDATIONS

A review of the current state of FCL technology has been carried out and shows that there are currently no appropriate FCL solutions commercially available for use on UK distribution networks.

There is however significant research and development work progressing in the FCL active device field with a number of MV FCLs being developed and tested around the world. The focus of these developments is moving to HV levels where the potential financial benefits that will be realised with the adoption of these devices are expected to be highest. As the FCL technology develops and experience regarding the ageing of materials employed in HTS FCL devices is gained, the widespread commercialisation of these products may occur. This is however not expected at MV network level in the short term.

A review of the analyses already carried out on UK networks shows that fault level problems are likely to manifest in the following network locations:

- dense urban MV networks, where the existing fault level headroom is currently limited
- isolated HV substations where large-scale DG projects connect into rural networks
- isolated LV situations, where high levels of DG penetration are realised.

The outline methodology that could be adopted as a follow-on piece of work is presented. This simulation model could be used to determine the scope and scale of any fault level problems, as well as the optimal FCL solution to address these problems. The model could adopt the six typical UK networks developed by the University of Strathclyde, adding on the appropriate 11kV and LV networks developed as part of a PB Power study on Network Voltage Change and Reverse Power flow with DG (PB Power, 2005).

A roadmap listing actions required to progress the development of a solution to the expected fault level problems is presented. The roadmap includes steps required to:

- identify and quantify the scale of the fault level problem on UK distribution networks
- identify all the potential users and stakeholders that will be impacted with the implementation of FCL devices on UK distribution networks
- realise the FCL solutions appropriate to the expected fault level issues

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