THE CONTRIBUTION TO DISTRIBUTION NETWORK FAULT LEVELS FROM THE CONNECTION OF DISTRIBUTED GENERATION

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The Contribution to Distribution Network Fault Levels From the Connection of Distributed Generation

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URN

This work was commissioned and managed by the DTI's Distributed Generation Programme in support of the Technical Steering Group (TSG) of the Distributed Generation Co-ordinating Group (DGCG). The DGCG is jointly chaired by DTI and Ofgem, and further information can be found at www.distributed-generation.gov.uk

Contractor

KEMA Limited

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WS5 P01 Steering Group

The KEMA Consulting report for the Department of Trade and Industry's New & Renewable Energy Programme on *The Contribution to Distribution Network Fault Levels from the connection of Distributed Generation*

Introduction: In support of DGCG TSG WS5, the Department of Trade and Industry's New & Renewable Energy Programme commissioned KEMA Limited to undertake an investigation and report on '*The Contribution to Distribution Network Fault Levels from the connection of Distributed Generation*'.

The investigation was undertaken during 2004/5 and was subject to review and commentary by the TSG WS5 Project 01 Manager and other WS5 members while in progress. The final report was submitted to Future Energy Solutions (FES – acting for the DTI New & Renewable Energy Programme) in April 2005.

Objective: The aim of the study was to identify the likely impact that distributed generation (DG) will have on GB distribution network fault levels in the period to 2010, and addresses how these increased fault levels could be managed to ensure that they do not act as a barrier to the increased penetration of DG. The study also includes an overview of the likely longer term impact of new forms of generation.

The study focused on two areas in particular: the circumstances and scenarios that are most likely to give rise to fault level issues that require to be addressed; and the options and likely costs for addressing these fault level issues.

Methodology: Three main sources of information were used: KEMA's own experience in the Netherlands (where DG penetration exceeds current levels in GB); material already published; and analysis of DNOs' Long Term Development Statements. The study included some significant work to assess distribution network fault level headroom i.e. the extent to which fault levels can be raised before installation of replacement apparatus with higher fault level ratings becomes necessary.

Findings: KEMA have reported on their findings in the context of a range of levels of penetration of DG, providing a range of estimates of the costs attributable to resolving fault level increases. KEMA have reported their view that issues arising from increases in distribution network fault levels will not constrain achievement of current targets for DG penetration.

The KEMA report also includes commentary on international experience with HV (11 kV & 33 kV) connected DG, options for managing increased fault levels, the measurement and calculation of fault levels, and a summary of the characteristics of DG machines.

Next steps: TSG WS5 members have received the findings established in the KEMA report with interest. However, members are alert to the fact that changes in fault levels, arising from new DG connected to existing distribution networks, need to be considered in the context of other changes (e.g. voltage control, active management, etc). Caution should be exercised in the regard given to cost estimates attributable to fault level change, given that other changes will often be the trigger for additional expenditure incurred to enable connection.

Network Operators and generators are encouraged to read the KEMA report, and consider its findings in the context of generator connection charging proposals.

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Manager, TSG WS5 P01

May 2005

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Executive Summary

This document presents KEMA's view on the impact of distributed generation on fault levels in response to a request by the DGCG TSG Workstream 5.

The increasing demand on Great Britain's distribution networks imposed by new distributed generation (such as renewable, micro CHP or CHP) will impact on the operation of the network in a number of areas including voltage levels and fault levels. In general all new distributed generation contributes some increase to fault levels, and this would in some cases result in the fault level exceeding the design limit of the network equipment to which it is connected if no action is taken to address it.

This report focuses on two major areas: the circumstances and scenarios that are most likely to give rise to fault level issues that require to be addressed; and the options and likely costs for addressing these fault level issues.

In examining the circumstances and scenarios most likely to give rise to fault level issues, we examine the generic structure of the GB distribution networks and identify the areas where the type of distributed generation likely to require connection has the greatest contribution to fault level relative to the fault level headroom available at that point in the network. Our conclusion is that this is most likely to occur with the connection of distributed generation to urban 11 kV and 33 kV networks, and that the most likely form of distributed generation requiring connection to these networks is small, medium and large CHP, landfill gas and waste incineration. Whilst we conclude that the connection of distributed generation to urban 11 kV and 33 kV networks is most likely to result in fault level issues, there will also be instances of large-scale distributed generation connections to both rural and urban networks which provide sufficient contribution to fault levels to exceed the fault level headroom available at that particular location.

We also examine the likely impact of the fault level issue over time, particularly in the period to 2010 but also beyond that. In so doing, we consider the development of distributed generation to date in Great Britain, taking into account the factors that have influenced development to date but are in the process of changing, such as the change to the connection charging methodologies. The change from deep connection charging to shallower connection charging provides poorer locational signals than in the past, and may result in a significant increase in connection requests in areas with very low fault level headroom as the costs to the developer will now be lower than before.

We also consider the situation with regards to the levels of distributed generation currently in place in comparison to the Government's targets for 2010, and the potential paths towards the targets in relation to the fault level issue. In particular, we conclude that the targets in relation to CHP are unlikely to be met in the absence of a significant increase in small, medium and large CHP projects. An increase in CHP projects, which would be most likely to occur in urban areas, would lead to an increase in fault level issues as urban networks tend to have the lowest fault level headroom.

In examining the likely impact of the fault level issue over time we also consider historical experience in the Netherlands, where distributed generation penetration levels are higher than those in Great Britain. Our conclusion here is that distributed generation has been accommodated with little impact on the networks for a number of reasons which may not be readily applied to Great Britain. For example, the increase in distributed generation in the Netherlands has been over a much longer period of time (some 25 years), with the capacity of individual generators being very low to begin with, giving rise to a much more gradual decrease in fault level headroom. The longer timeframe for the introduction of distributed generation has also resulted in the potential for greater coincidence between substation refurbishment due to aging infrastructure and the need to increase fault level headroom due to the introduction of greater levels of distributed generation. In the Netherlands there would also appear to be a greater tendency towards proactive investment in network infrastructure which can accommodate higher levels of distributed generation, where it has been reasonably certain that such levels of distributed generation will materialise.

With regards to the options and costs for managing fault levels, we find that there is a small range of options utilised. The first option is connection to higher voltage levels or neighbouring substations with greater fault level headroom as a means of avoiding reinforcement costs at substations with inadequate fault level headroom. The remaining options, in increasing cost order, are typically splitting the network, increasing impedance, installing current limiting equipment, or reinforcing the network. Whilst network splitting is a valid option, it cannot be implemented in all circumstances, and reduces power quality, increases losses and reduces reliability. The introduction of increased impedance through current limiting reactors is the next option, but if permanently connected these have the disadvantage of introducing a permanent voltage drop and increasing losses. Transformers may also be used, but these are more commonly used for voltage regulation with standard designs providing only limited short circuit impedance. Other forms of current limiting devices such as Is limiters, superconducting fault current limiters and solid state fault current limiters are better technical solutions than simply increasing the impedance, but are either not permitted in Great Britain (Is limiter), or have not yet been developed successfully for operation in 11 kV and 33 kV networks (and are unlikely to be available by 2010). In general, the technically superior and most expensive option is to reinforce the network with higher rated equipment, which could include cables or overhead lines.

The options presented above are largely options to solve specific fault level issues as and when they arise, and with the exception of network reinforcement they do not increase capacity in the distribution networks to accommodate further distributed generation connections. This means that the more inexpensive options are best suited to slow growth in distributed generation and would be inappropriate to cope with a rapid acceleration which could occur in the period to 2010 if Government targets are to be met. In order to accommodate such a rapid acceleration, there are alternative options which may be required and which have been utilised in the Netherlands in cases where significant growth was predicted. These included building new networks capable of operating at 20 kV but operating them at 10 kV, such that they can be operated at 20 kV at a later date when required. The 20 kV rated equipment has a higher short circuit current capability. Refurbishment work to existing networks also resulted in similarly rated 20 kV rated equipment being installed but continuing to operate at 10 kV until such times as a change to 20 kV is required. Finally, networks specifically for distributed generation have also been built. Each of these options would require significant investment on the part of the DNOs.

In terms of the overall costs to DNOs of addressing fault level issues, there is a range of likely costs in the period to 2010 and probabilities of incurring such costs. Our analysis utilises the distribution of headroom in medium voltage urban networks and high voltage networks in Great Britain, the likely costs of addressing the fault level issue across this distribution specifically when connecting small, medium and large CHP, and the likely development scenarios for CHP in the period to 2010. This results in potential costs which are in the range £800k to £1.9 million per year across all DNOs (for a low CHP growth scenario) and £10 million to £18 million per year across all DNOs (for a high CHP growth scenario).

The figures provided above cover costs to address fault level issues for the connection of small, medium and large CHP to medium voltage urban networks and high voltage networks. This does not include provision for any costs for addressing fault level issues on connection of distributed generation to the low voltage networks, which will be small in comparison. Also, no costs are included for addressing fault level issues for large scale renewables (e.g., wind) projects, for which the costs could be of the order of £10 million per project, but not all of which can be apportioned to addressing fault level issues. Thus, overall cost estimates per year for medium voltage and high voltage networks can be built up as follows:

	Costs per year for Low CHP Growth	Costs per year for High CHP Growth
CHP connections (11 kV, 33 kV and 132 kV)	£800K to £1.9 million total	£10 million to £18 million total
Large scale distributed generation (non-CHP) connecting at 132 kV	Typically £10 million per project (a proportion of which will be to address fault level issues)	Typically £10 million per project (a proportion of which will be to address fault level issues)

In the longer term (to 2020-2030) it is not envisaged that fault levels will act as a "showstopper" for the further increase in penetration of distributed generation. This applies for penetration levels up to and beyond 50% of local generation in the low voltage network and to a lesser extent in the medium voltage network. However, in order to maintain an acceptable level of fault level headroom, investment will continue to be required in network reinforcement, and innovative solutions such as distributed generation networks may become more commonplace.

We also find that fault level measurement technology is not commercially available to allow on-line fault level monitoring; therefore fault level headroom calculations will continue to be based on IEC60909/G74 for the foreseeable period. These calculations must be reviewed regularly to account for the changing configuration of the network and loads over time in order to ensure that, amongst other things, adequate fault level headroom is maintained. Finally, DNOs are encouraged to consider reviewing cable short circuit ratings where particular issues exist, as original design ratings may be conservative and could potentially be increased in specific cases based on actual protection settings compared to those envisaged at the design stage.

1. Introduction

1.1 Background

The Department of Trade and Industry's New and Renewable Energy Programme, in support of the Distributed Generation Co-ordinating Group (DGCG) Technical Steering Group (TSG) Workstream 5, has commissioned KEMA Limited to undertake this Study to identify the likely impact that Distributed Generation (DG) will have on distribution network fault levels in the period to 2010. This is particularly important due to the increasing levels of new generation capacity from renewable and Combined Heat and Power (CHP) sources being embedded within electricity distribution networks and causing an increase in fault levels. A key finding of the DTI Renewables Advisory Board's (RAB) Grid Working Group, published in the 2003 RAB Annual Report, is that "grid constraints need to be addressed as the penetration of intermittent renewable capacity increases".

The Government has set targets (Ref. 1) for reducing greenhouse emissions and increasing the proportion of renewable forms of electricity generation. It is expected that 10% of electricity energy consumed in 2010 will be provided by renewable sources with 10 GWe capacity from CHP plants. As a consequence of meeting this target some 8 GW of renewable capacity (approximately 3000 installations) and 5 GW of CHP is needed (some 1000 CHP installations in addition to 1-3 million domestic CHP installations in the range of 1-5 kW (micro CHP)). The nature of these plants is such that the vast majority of them will be connected to the distribution networks. With the level of penetration of DG forecast for 2010, it is necessary to develop an understanding of the likely impact on fault levels now in order that the DGCG can recommend priorities for action required to assist the integration of small generation into the DNOs electrical networks.

In general all forms of DG contribute some increase to fault levels. The connection of DG to the distribution network could therefore result in fault levels exceeding the design limit of the network, particularly if it is already being operated close to its design limit (i.e., with low fault level headroom). When fault level design limits are exceeded, there is a risk of damage to and failure of the equipment with consequent risk of injury to personnel and interruption of supply under short circuit fault conditions.

The incidence of fault level issues is a function with three variables: the available headroom at any given point in the network; the fault level contribution from any DG type to be connected; and the number of DG projects which would result in the fault level design limit being exceeded if connected. This report examines all three variables and puts them in context of the likely impact on fault levels as a result of new DG connections in the period to 2010, and the likely costs of managing this.

There are a number of methods of managing the increase in fault levels introduced by increased penetration of DG. These methods fall into two groups: increasing the fault level design limit of the network, or reducing the fault level to below the design limit of the existing network. Potential solutions for both groups are discussed in the report.

As this report focuses on the fault level issue, the following issues related to the introduction of DG are noted, but are outwith the scope of this report:

- In addition to the potential increase to fault level magnitude the direction of the current could also change, affecting the operation of the protective devices. In this instance settings may need to be adjusted or protective devices may even need to be replaced by more sophisticated ones in order to ensure proper operation of power system protection schemes.

- The introduction of DG could result in a voltage rise on the network from the point of connection towards the substation, as opposed to a volt drop on the network away from the substation.

1.2 Aim of Study

The aim of this Study is to identify the likely impact that DG will have on GB distribution network fault levels in the period to 2010, and addresses how these increased fault levels could be managed to ensure that they do not act as a barrier to the increased penetration of DG. The Study also includes an overview of the likely longer term impact of new forms of generation.

1.3 Scope of Document

This document is KEMA Limited's report on the likely impact that DG will have on GB distribution network fault levels in the period to 2010, covering both the technical aspects of the issue and the financial aspects of dealing with the issue in order not to impede the increased penetration of DG.

The report draws on three main sources of information:

- KEMA's own experience of the issue in the Netherlands, where DG penetration is significantly higher than current levels in Great Britain.

- Material already published concerning fault level issues and possible solutions.

- The Long-Term Development Statements (LTDS) published by each of the DNOs.

This study includes the LV (400V and 230V) and MV (11 kV and 33 kV) networks where the majority of DG will be connected. In addition, the study includes the HV (132 kV) distribution network in England and Wales where a small number of very large DG schemes will be connected.

Whilst this document refers to fault levels generically, it is recognised that there are two relevant fault level design limits: make current, and break current. These are referred to separately within the document where relevant, as are the differing contributions to make current and break current from differing types of DG.

1.4 Structure of Document

The structure of the remainder of this document is as follows:

- Section 2 assesses the current situation and provides a technical review of the likely impact on the network of all types of faults.
- Section 3 details the options for managing increased fault levels with an estimate of likely costs.
- Section 4 assesses the methods and techniques of calculating and measuring fault level values.
- Section 5 comments on the extent to which DG may be constrained as a consequence of network fault level limitations.
- Section 6 contains details of the characteristics of different forms of DG.
- Section 7 provides an overview of the longer term perspective (to 2020-2030).
- Appendix A provides an example of a specific DG integration project in the Netherlands.

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2. Technical Review

2.1 Introduction

This section of the document contains a technical review of the likely impact of DG on distribution network fault levels in the period to 2010. This review is based on several elements:

- The fault level headroom available across the distribution networks;
- The fault level contribution from all DG types;
- The current levels and growth trends of DG penetration;
- Potential scenarios for growth in DG penetration in the period to 2010 as a result of government targets, regulatory regimes and incentivisation;
- Experience in the Netherlands, which has a higher level of DG penetration than GB.

The technical review will demonstrate that there are particular types of distribution networks at particular voltage levels that are much more likely to suffer from fault level issues. These will be further analysed to develop an overview of the fault level headroom available in these network types at these particular voltage levels. The review will also identify the DG types most likely to be connected to these network types and voltage levels, and will examine a small number of scenarios for the growth in DG penetration in the period to 2010.

International experience will also be reviewed particularly in the Netherlands, where DG penetration levels are higher than those in GB. This will show that while DG has historically been accommodated with little impact on the networks, this cannot be readily applied to GB.

2.2 Relationship between DG and Fault Levels

Many of the effects caused by connecting generation to the distribution network are related to the planning and design of the network. Historically the distribution network has been designed as shown in Figure 2.1 to accommodate power flow from the grid supply points downward through tiers of networks operating at lower voltage to the electricity consumers. The network is designed to meet the needs of normal operation, fault conditions and abnormal operation (e.g., when the network has been re-configured for maintenance).

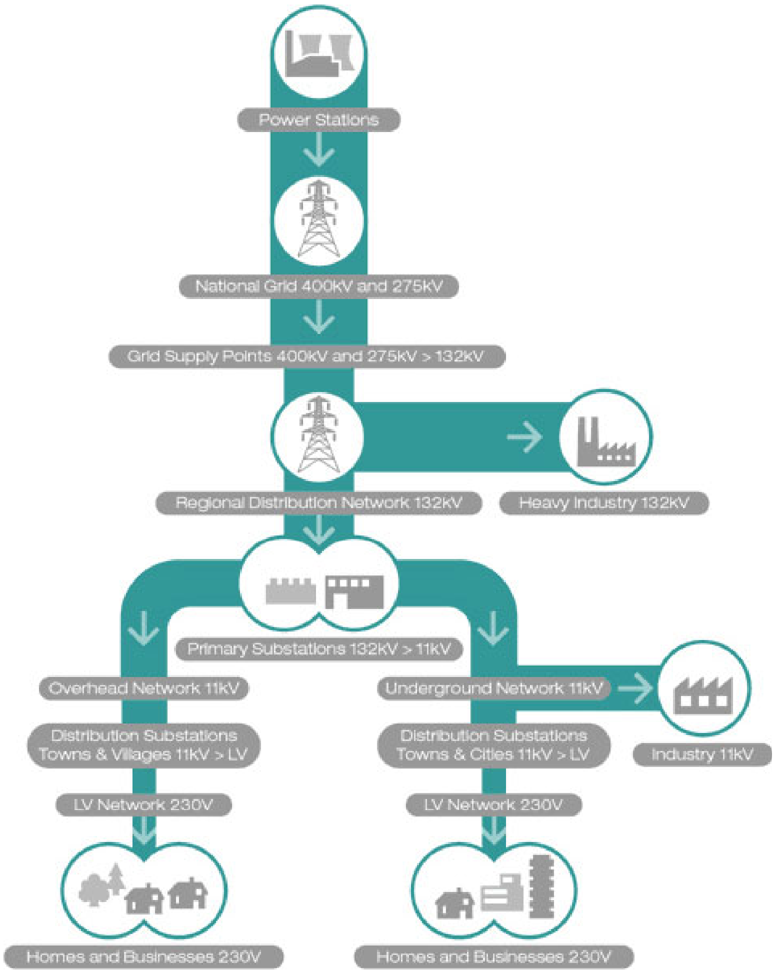


Figure 2.1 – Traditional Network schematic

When a short circuit fault occurs in the distribution network a fault current will flow to the fault location. The fault current comprises the current from connected generation and from rotating load such as motors at customer sites. This fault current is detected by the protection system and will be cleared by circuit breakers or fuses.

DNOs calculate fault levels, during network planning and also for operational networks, based on connected generation and known connected rotating equipment at customer sites, in order to ensure that they remain within the design limits of the network. Fault level can be an issue in all types of networks at all voltage levels, and if fault levels exceed the equipment, cable or overhead line ratings then there are two broad options to address it:

- The network configuration may be modified and/or additional equipment may be installed, in order to reduce the fault level at the specific parts of the network where the fault level exceeds design limits.

- The appropriate equipment, and potentially cables and lines, may be uprated to withstand the fault level (i.e., increase the design limits).

Traditionally, in an environment where the primary forms of generation are connected to the distribution networks via supply transformers from the transmission network, the main changes to fault levels over time were due to additional supply transformers and also due to changes in rotating load at customer sites.

In today's distribution networks, the presence of DG provides an additional contribution to the fault level, and the embedded nature of the DG makes the fault current calculations more complex as they should take into account the consequences of operational switching combinations to a degree not required when all generation was via the transmission network. The fault level contribution from DG is determined by a number of factors, including:

- The type of DG, as different types of DG contribute different fault currents.

- The distance of the DG from the fault, as the increased cable impedance over longer distances will reduce the fault current.

- Whether or not a transformer is present between the fault location and the contributing DG (which is often the case for voltage regulation purposes), as transformer short circuit impedance may assist in limiting the fault current.

- The configuration of the network between the DG and the fault, as different paths for the flow of the fault current will alter the magnitude of the fault current (due to cable impedances and other installed equipment).

- The method of coupling the DG to the network. Directly connected DG will contribute significantly higher fault current than DG connected via power electronics (PE) interfaces.

Apart from the contribution to the fault current, faults have other effects (including mechanical and thermal effects). For the purposes of this report we will focus only on the effect on fault levels, but the switch-off criteria of protection settings and the prevention of accidental "islanding" (i.e., the operation of a part of the network in complete isolation from the rest of the network) should also be noted. The prevention of accidental islanding is important to avoid the risk of DNO maintenance personnel working on a part of the system that is still energised. (Note: This has happened in the Netherlands in a large area fitted with roof photovoltaic (PV) systems (Ref. 2)).

It is likely that the rules for disconnecting DG plant when faults occur will have to be revised in the future. In Denmark and Ireland there are already specific guidelines for network support in place with respect to windfarms (Refs. 3, 39). As DNOs issue guidelines for network support of DG in case of faults, these new criteria and guidelines will lead to new criteria for protection settings, adjustments and modification of the technology used in DG plant.

2.3 Likely Impact in the Period to 2010

In this section the various types of DG have been grouped into three network levels as follows:

- Low voltage (LV), covering up to and including 460V.
- Medium voltage (MV), covering levels greater than LV up to and including 33 kV.
- High voltage (HV), covering levels greater than MV up to and including 132 kV.

The assessment in this section addresses the likelihood of fault level issues at each of these voltage levels, based on a number of development scenarios for DG in the period to 2010.

2.3.1 LV connected DG

It is generally anticipated that LV connected DG will be limited in the period to 2010 to consist mainly of domestic micro CHP, PV, and mini CHP used in buildings such as offices, swimming pools, and small shops. There may also be some small individual wind turbines in place.

The report on System Integration of Additional Micro-generation (SIAM) (Ref. 4) found that the maximum outcome (upper bound) of micro-generation is approximately 2.5 GW by 2010 (see Table 2.1 below).

	2010		2015		2020	
Scenario	**GW**	**TWh**	**GW**	**TWh**	**GW**	**TWh**
Low	0.37	0.96	1.19	3.07	2.23	5.65
Mid	1.23	3.22	4.06	10.36	7.92	19.41
High	2.48	6.48	8.26	21.15	15.78	39.22

Table 2.1 – Micro-generation Forecasts from SIAM Report (Ref. 4)

This table also summarises the capacity (GW) and energy (TWh) assumed in the scenarios for the penetration of micro-generation until 2020. To put the values of the high scenario in context, the 6.5 TWh figure in 2010 would represent some 1.5% of total energy demand, while the 2.5 GW of capacity in 2010 would represent 3% of peak load in Great Britain.

The SIAM report states that existing LV networks can accept up to 100% penetration of micro-generation, where the percentage refers to the numbers of properties installing a micro-generator of any type with a rating nominally of 1.0 – 1.1 kW, provided some steps are taken to reconfigure the network as penetration levels increase. The main problem was identified as voltage regulation, which can be solved by adjusting transformer tap changers or in some cases replacing a transformer.

TSG Workstream 1 project 6 (WS1P06) also produced scenarios for DG development specifically for workstream 5 (Ref. 24). These scenarios forecast that the capacity available from LV connected micro CHP, PV and mini CHP in 2010 will be around 1 GW if the government targets for CHP are to be met through pro-rata growth in existing CHP types at all voltage levels. An additional high figure of around 4.3 GW is also given should all domestic central heating boiler replacements in the period to 2010 be replaced with 1 kW CHP units. The WS1P06 scenarios also include a low forecast of 0.4 GW, based on low growth consistent with unfavourable market prices for gas and electricity.

In the SIAM report, the analysis of networks with micro-generation with a load density of 5 MW/km^2 (inner city) showed that even without micro-generation a minimum length of cable would be needed between a consumer and the 800 kVA distribution transformer to keep single phase faults below 16 kA. To some extent this cable impedance buffers the rise in fault level on the LV busbars caused by micro-generation on feeders.

The fault contribution from micro-generation to a single phase fault is further reduced by having a direct contribution from only one third of the generators on the affected feeder. The impact in this worst case situation in an area with 100% DG would add about 1 kA to the fault levels (this is 6-7% of the 16 kA commonly used). In the Dutch study (Ref. 5) for a similar case with larger plant (mini CHP) a maximum increase of

> The level of penetration of DG on the LV network will increase, but by 2010 will still only be an extremely small proportion of total energy demand. Even at 100% penetration the likely worst case increase in fault levels will be typically 6–7%. This means that it is likely that there will only be very few situations where network reconfiguration or uprating of equipment is required to address fault level issues.

25% was found. As stated before such conditions are likely to be extremely unusual in the period to 2010, but may occur occasionally in cities with meshed LV distribution.

In rural areas there are mainly problems with the voltage profile (voltage is low at the end of the feeder) rather than with fault levels. Furthermore the penetration of micro CHP or even PV is likely to be very gradual and is likely to be widely dispersed in the rural areas.

Therefore, in the period to 2010 no real problems are foreseen with fault levels specifically while the amount of DG plant in the LV network is still very limited. However, it is possible that in some isolated situations, DG penetration levels are sufficiently high to necessitate network reconfiguration or uprating of equipment. This may occur in areas where there is a high density of micro CHP, or PV demonstrator areas, which is likely to be in urban areas.

2.3.2 International experience with LV connected DG

Great Britain has been a relatively late adopter of large levels of DG and it worth considering the experience in international distribution networks that are further advanced. Much of this report looks at the Dutch distribution networks, where similar fault levels standards are applied. In the Netherlands the fault level for the LV network in urban areas is 16, 25 or 31.5 kA and is mainly determined by the 10/0.4 kV transformer short circuit impedance (400 to 1600 kVA transformers with impedances between 4 and 6%). This is similar to Great Britain where 11/0.4 kV transformers are in use. In the older parts of major Dutch cities a meshed LV network is present, as in British cities, and the radial distribution concept for the newer developed areas is also similar. Note there are also significant differences, mainly in the rural areas, where Great Britain uses overhead lines and the Netherlands uses cables.

Studies performed by KEMA for DNOs in the Netherlands have shown that the LV network is easily capable of accepting up to 100% of DG (Refs. 5, 6, 7, 8). In a study (Ref. 5) into the technical consequences of large amounts of micro and mini CHP in the LV network the conclusion is that voltage regulation is the biggest technical issue and “it is not expected that fault levels by micro and mini CHP (up to 100 kW) will have any influence on the low voltage network”. In other studies (Refs. 6 and 7) low (and medium) voltage networks with large amounts of DG (up to 100% PV or micro CHP) are investigated. The conclusion from these studies was that, once again, the voltage regulation profile is the main problem with increasing levels of DG and that existing fault levels are only slightly increased.

The possible large uptake of micro CHP in the LV network is a particular point of interest for Dutch DNOs. In The Netherlands nearly ever household has a gas fired central heating system and the national gas company Gasunie is planning a large micro CHP introduction scheme. However, studies by DNOs, universities and KEMA give similar results to GB-based studies (Refs. 4, 9) and indicate that a large amount of micro CHP, say up to 50% of the load, will not cause any problems and even up to 100% and beyond is possible. However, there will be specific locations where even 20% might give a problem with voltage regulation (e.g., in weak rural networks with a small feeder transformer).

As stated above, the main technical problems are related to voltage regulation, voltage profile and the protection of (maintenance) personnel and equipment. The challenge is to use the micro CHP for network support, and deferral and avoidance of network investments for DNOs, rather than simply disconnecting them whenever there is a problem in the network (which is the case at the moment because of lack of suitable monitoring and control tools).

At the current time the Netherlands does not yet have any experience with large amounts of micro CHP in urban networks. There are a few newly developed residential areas where the equivalent of some 2MW peak solar (Ref. 10) is installed on some 500 rooftops. Fault levels have not been a problem because all the PV systems are equipped with PE interfaces. The only problems encountered were related to power quality (harmonic generation from inverters (Ref. 11)) and safety for DNO maintenance workers (a situation occurred where part of the network went into islanding operation without being detected).

International studies indicate that the increased penetration of micro CHP on the LV network up to say 50% of the load can be accommodated largely without any action required to address fault level issues specifically. However, action may be required to address voltage regulation issues. The increased penetration of PV on the LV network does not contribute to fault levels where the PV systems are equipped with a PE inverter.

2.3.3 MV and HV connected DG

The majority of the 8 GW of renewable capacity and 5 GW of new CHP required to meet the 2010 targets is expected to be connected to the MV networks. A small number of larger schemes will also be integrated into the HV networks. In general the number of plant will be limited as the average size of each installation may be quite high, with the Government targets set in 2003 predicting approximately 3000 new renewable generation installations, and 1000 new CHP installations (excluding LV connected domestic CHP installations) by 2010. The renewable installations will be mainly wind turbines, either as stand-alone applications or combined in (smaller) windfarms, and biomass plant. Smaller contributions will also be made from tidal stream and wave power, landfill gas and waste incineration. The CHPs are likely to be associated with industrial centres, large offices, shops and residential buildings, and agricultural greenhouses.

The scenarios of DG development (Ref. 24) also provides similar figures as an upper level scenario, with a lower level scenario of 3.7 GW new renewable and just under 1 GW new CHP (again excluding LV connected domestic CHP installations). Using the same approximations for each installation capacity as for the Government targets, this would result in just under 1400 new renewable generation installations, and 200 new CHP installations.

Current evidence shows that development of new renewable generation is moving towards the 2010 target. However, the current trend in the development of new CHP is that there has been very little increase in new CHP in recent times, and it is highly unlikely that the target will be met unless developers and/or consumers are incentivised to install CHP in the period to 2010. In combining these two scenarios it is also possible that the proportional contributions from renewable generation and CHP towards the target will be different to that originally predicted, and that renewable generation will make a more significant contribution to counter the lower contribution from CHP.

In considering the MV and HV networks that the renewable generation and CHP will be connected to, we can correlate the DG type to the network type (adapted from Ref. 24) as shown in Table 2.2 below.

DG Type	Network Voltage Level	Location	Typical Capacity [MW]	Added Capacity 2003 – 2010 [MW]
Onshore Wind	MV, HV	Rural, 66% to 75% Scotland	0.4 – 4 (per turbine)	2000 – 7000
Offshore Wind	MV, HV	Rural, predominantly England & Wales	150 – 500	1000 – 5000
Tidal Stream and Wave Power	MV	Rural, coastal	0.75 – 5	100 – 250
Biomass	MV	Rural	0.5 – 10	200 – 850
Landfill Gas	MV	Semi-urban	0.5 – 5	200
Waste Incineration	MV	Semi-urban	20 – 40	200
Small CHP	MV	Urban	0.5 – 5	70 – 400
Medium CHP	MV	Urban	5 – 50	500 – 1100
Large CHP (>50MWe)	MV, HV	Industrial centres	50 – 400	400 – 2400

Table 2.2 – DG Types, Typical Connections and Capacities

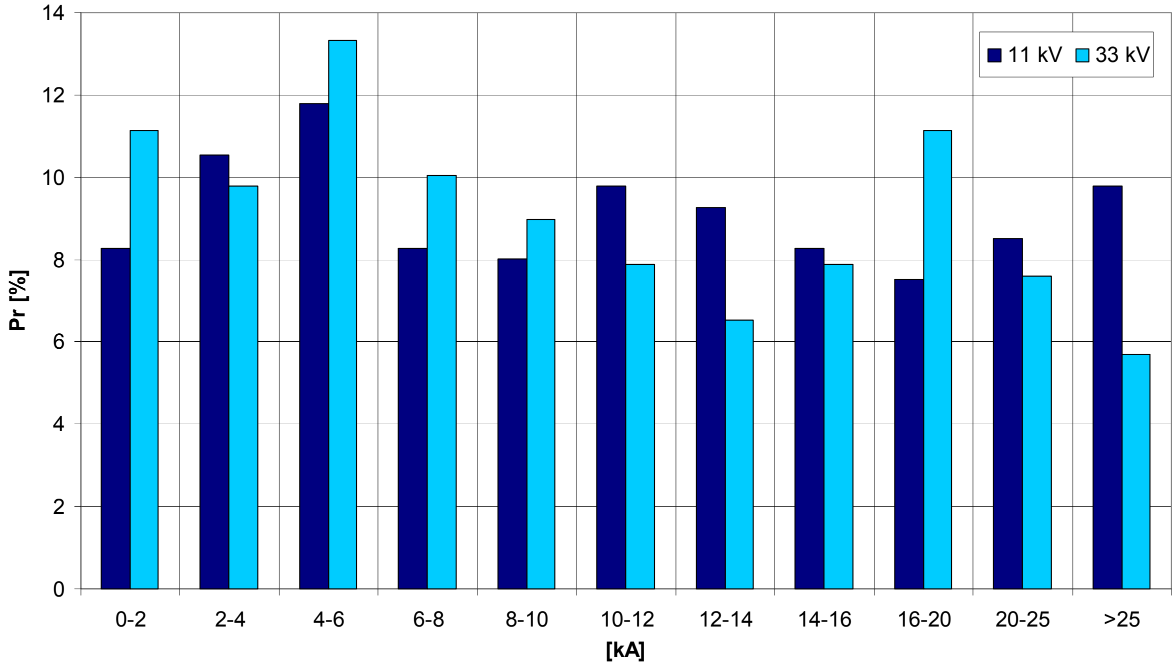
The density of urban MV networks in comparison to rural MV networks means that it is significantly more likely that urban MV networks have low fault level headroom availability, and better voltage control due to shorter circuit lengths, whereas rural MV networks have poorer voltage control due to longer circuit lengths, and higher fault level headroom availability. It is therefore expected that the majority of fault level issues will occur in urban, semi-urban and industrial MV networks, and will therefore be caused by the connection of CHP (which being synchronous generators will contribute to both make current and break current as detailed in Section 6 of this document), and to a lesser extent landfill gas and waste incineration schemes.

The DG types with the highest capacity per project and therefore the highest fault level contribution per project will be large scale onshore and offshore wind projects, which are most likely to be connected to rural HV networks (and which will contribute primarily to the make current as today's wind turbines make little or no contribution to the break current as detailed in Section 6 of this document). It is therefore expected that, even when connecting to rural HV networks which will typically have the highest fault level headroom availability, large scale onshore and offshore wind developments will occasionally require some action to be taken with regards to fault levels. The number of instances where this is required will be low primarily due to the low numbers of projects of this nature.

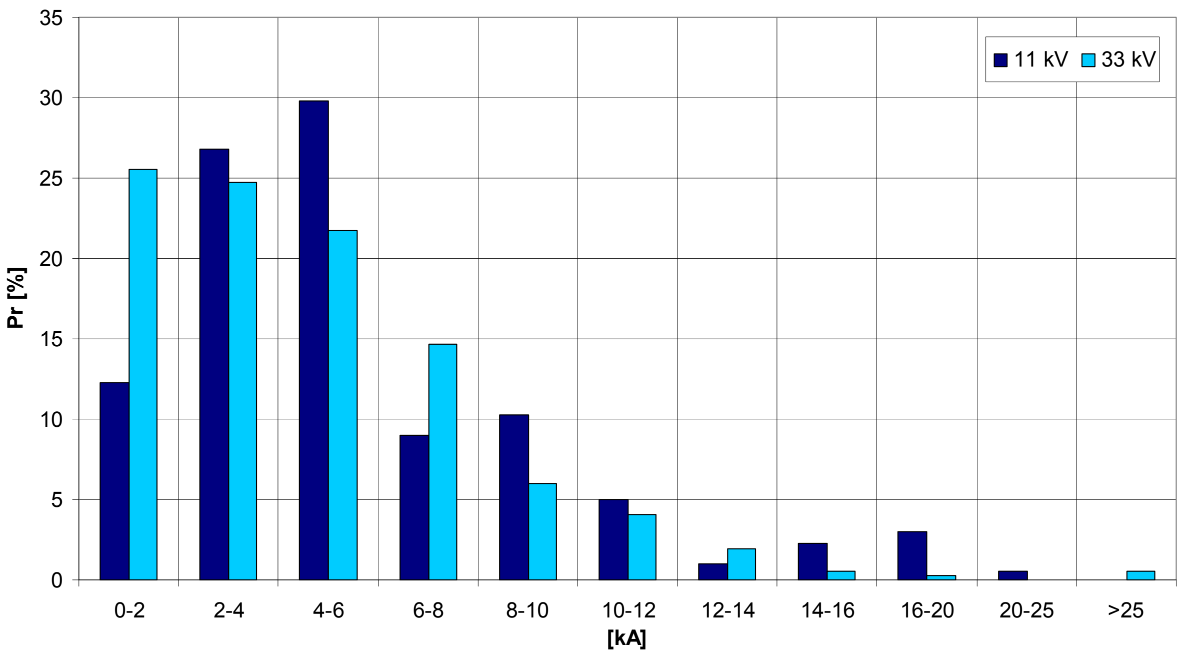
It is clear from the above that the majority of fault level issues are likely to occur in urban MV networks. However, there is currently no analysis available to provide an indication of the likely scale of the problem. This can be investigated by examining the fault level headroom availability in urban MV networks as provided by the DNOs in their long term development statements, in order to determine the capabilities of the existing urban MV networks to accommodate additional DG without the need for action to be taken to address the fault level issue.

The chart in Figure 2.2 shows the distribution of headroom availability, both in terms of make current and break current, in urban MV networks across a number of DNOs in GB. Urban networks were determined through a manual process of identifying substations located in built-up city areas. Data from five DNO areas was analysed, covering around 3,000 substations, and it is assumed that the results are representative of urban MV networks in GB as a whole.

Make Current (Peak)



Break Current (rms)



Note: The horizontal axis shows the (categorised) available headroom in kA. For each bar the vertical axis shows the percentage of substations that belong to this category. Example: of all 11 kV sub-stations, 8 % have a make current headroom of more than 8 kA but less than 10 kA. By summing the values for the two leftmost bars, it follows that the percentage of 11 kV substations with less than 4 kA make current headroom equals approximately 18 %.

Figure 2.2 – Distribution of Headroom Availability in Urban MV Networks

It can be seen from Figure 2.2 that there is a significant proportion of substations in urban MV networks that have less than 4 kA headroom availability, both in terms of make current and break current. As detailed in Section 6 of this document, different types of DG contribute differently to both make current and break current, some of which could be above 4 kA for a single DG project. Given this, there are many cases where no additional DG can be connected without addressing the fault level issue.

Analysis indicates that, in the period to 2010, the main area of concern with respect to fault levels is in urban MV networks, where there is a significant proportion of substations that do not have sufficient fault level headroom to accommodate additional DG of the type that would typically be connected to such substations. There will also be a small number of (rural) HV substations where the fault level contribution from large scale renewables (e.g., wind) projects would be sufficient to make them exceed their design limits, thus requiring major reinforcement works.

Both graphs in Figure 2.2 are shown with the same kA ranges on the horizontal axis, in order to provide a direct comparison between make current and break current headroom availability. However, as there is not a one to one relationship between make current and break current, this makes the shape of the graphs look very different. The typical ratio between make current and break current is 2.5, so plotting the make current headroom distribution in kA ranges which are 2.5 times the kA ranges of the break current headroom graph, as shown in Figure 2.3, provides a graph which shows a shape of make current headroom distribution more in line with the shape of the break current headroom distribution.

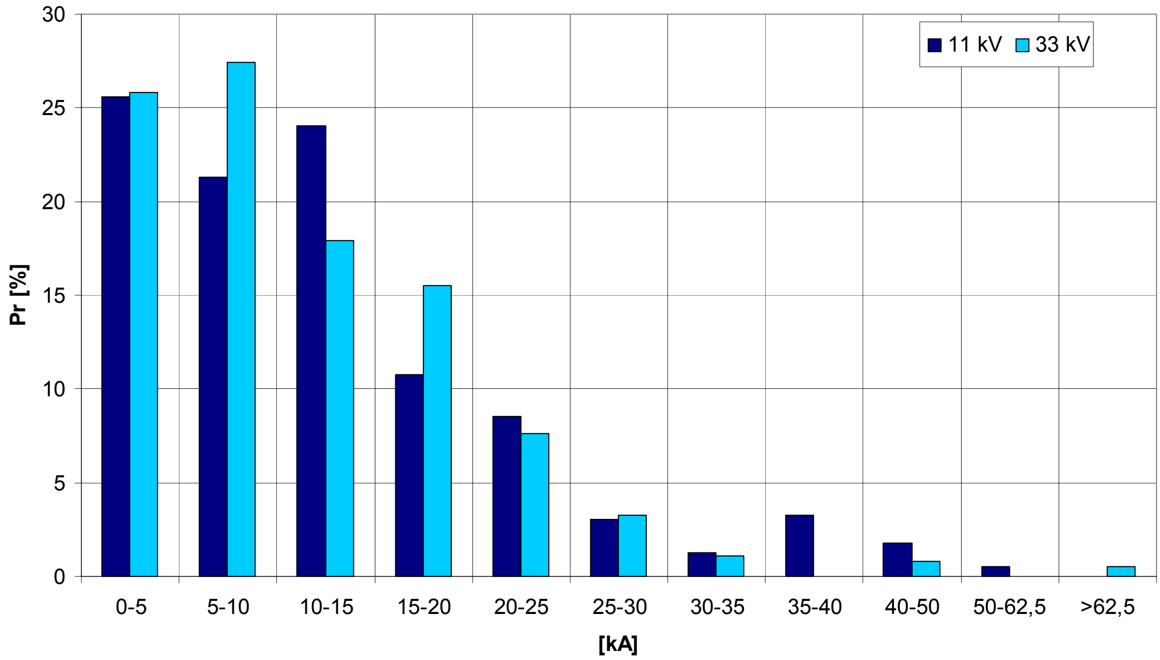


Figure 2.3 – Distribution of Make Current Headroom Availability in Urban MV Networks

We can also make an assessment of the change in this distribution in the period to 2010, given potential scenarios of the development of DG. In order to develop these scenarios we have made the following assumptions:

- All CHP plants contribute to the fault level due to the characteristics of the plant.
- We can divide the DG types into three main groups (small CHP, medium CHP and large CHP). Landfill gas is treated as belonging to the same group as small CHP, and waste incineration is treated as belonging to the medium CHP group.
- The distribution of projects amongst the three main groups, the voltage levels and the fault level contribution is represented in Table 2.3 below.

CHP Type	Distribution of number of projects [%]	Connected to 11 kV [%]	33 kV [%]	132 kV [%]	Fault Level Contribution (make current) at 11 kV [kA]	33 kV [kA]	132 kV [kA]
Small	80	95	5	0	0.1 – 2	0.03 – 0.5	N/A

CHP Type	Distribution of number of projects [%]	Connected to			Fault Level Contribution (make current) at		
		11 kV [%]	33 kV [%]	132 kV [%]	11 kV [kA]	33 kV [kA]	132 kV [kA]
Medium	15	0	60	40	N/A	0.5 – 2.5	0.09 – 0.9
Large	5	0	10	90	N/A	1.5 - 3.5	0.4 – 8

Table 2.3 – Typical DG Projects Connecting to MV and HV Networks

Taking Table 2.3 and Figure 2.2, it can be seen that the fault level contribution from any single project will only result in a fault level issue at those substations with the insufficient headroom availability.

2.3.3.1 Scenario 1 – Organic CHP Growth

In this scenario we consider that CHP continues to grow at the levels predicted as the low growth scenario. This scenario is based on the following assumptions:

- The number of projects (GB-wide) is in the range of 10-30 a year up to 2010.
- Government targets are not met.
- Projects are randomly distributed amongst substations.
- The number of substations remains the same (no new ones are built).
- No load growth.

Due to the slow rate of CHP growth and therefore the limited number of projects, it is more likely that any given project can be integrated in the existing network, either at the local substation or a nearby substation. This will help keep costs low as the need for major substation upgrade is likely only to be required occasionally, but the longer term effect will be that the headroom distribution will not change for the better, as no additional headroom is being created and existing headroom is being consumed slowly.

It is worth noting that if scenario 1 comes to fruition, it is more likely that other forms of DG, such as large scale wind, are promoted in order to meet the overall targets. This would mean an increase in the number of occurrences of fault level issues in the rural HV networks to which these large scale wind projects would be connected.

2.3.3.2 Scenario 2 – CHP Growth to Meet Targets

In this scenario we consider that CHP growth accelerates in order to meet the 2010 targets. It is possible that such acceleration is triggered by a change to the regulatory regime or incentivisation of CHP. It is also possible that the change to the connection charging regime introduced in the Distribution Price Control from April 2005 will encourage new DG developments. As the connection charging regime is moving towards shallower reinforcement costs to the generator, it is possible that DG developments in areas where fault level headroom is an issue become financially more attractive to the generator.

This scenario is based on the following assumptions:

- The number of projects (GB-wide) is in the range of 100-200 a year up to 2010.
- The fault level headroom distribution will change.
- The number of substations will increase (in some cases, new substations will be built to address fault level issues).
- No load growth.

Due to the high rate of CHP growth, the potential to integrate such DG into the existing network, either at the local substation or a nearby substation at the same or higher voltage level, will reduce very quickly. As a consequence, projects will tend to have high costs associated with them, either because cables or overhead lines will be longer (substations with headroom availability are further away), major substation upgrade work is required, or new substations need to be built.

In this scenario it is likely that the cost-effectivity of continuing to integrate DG into the existing network will be questionable, as fault level issues will continue to get worse over time as the distribution of headroom availability gets poorer, especially in areas where there are concentrations of CHP projects. Where there are such concentrations of CHP projects the construction of a separate DG network might be advantageous.

When considering the possible scenarios for the development of DG in the period to 2010, two more likely scenarios emerge. One is that CHP continues to experience low growth, and this can be integrated using relatively simple technical solutions to avoid reinforcement costs in many cases. However, there will still be cases where substation upgrades will be required. Also, low CHP growth may be offset by greater numbers of larger scale projects such as wind projects, which may also require major substation upgrades or new build.

Alternatively, changes to the regulatory regime or incentivisation may trigger a large uptake in CHP. In terms of impact on fault levels, this will have the greatest impact as it will result in a greater number of fault level issues. This scenario may also necessitate greater levels of investment in longer terms solutions which increase fault level headroom and therefore build additional capability into the networks in terms of accommodating further DG.

2.3.4 International Experience with MV and HV connected DG

An interesting comparison can be made with the Netherlands where the amount of DG from CHP presently is around 30% of peak load. This is actually somewhat lower than the situation in the late 1980's and early 1990's, the decrease being due to increased imports, and less promotion (in the form of governmental subsidies) of CHP. The DG is mainly located in the MV (10 and 20 kV) network. The outcome of the high level Dutch VDEN-working group on DG found that additional network costs to incorporate CHP were predominantly related to voltage regulation (Ref. 12) and that this high DG percentage had been reached without significant problems in the distribution network.

The Netherlands arrived at this high level of DG with classical network design with expensive measures (e.g., replacement of switchgear) undertaken only occasionally to deal with the increased fault levels. However, there are significant differences between the way in which DG has developed in the Netherlands compared to that in GB which result in the experience in the Netherlands not being readily applicable in GB, as detailed below.

2.3.4.1 Timeframe

The increase in DG in the Netherlands has been over a long period of time (some 25 years). Therefore, when DG was first being introduced, the capacity of individual generators would have been very low, giving rise to a much more gradual decrease in fault level headroom. The low capacity generators included both wind turbines, because wind turbine technology was not capable of delivering larger generators at the time, and CHP, which was principally in the form of smaller generators associated with agricultural greenhouses rather than large industrial plants.

The longer timeframe for the introduction of DG also means that there has been the potential for greater coincidence between substation refurbishment due to aging infrastructure and the need to increase fault level headroom due to the introduction of greater levels of distributed generation. Equally well, DG introduction over a longer period of time has allowed load growth related network investment over time to be better aligned to cope with the impact of the introduction of the DG.

2.3.4.2 Alternative Options

There would also appear to be a greater use of alternative options to avoid reinforcement costs in the Netherlands compared to GB when the DNOs are faced with fault level issues. This can be seen from the priority order of solutions that are investigated in the Netherlands whenever fault level issues are to be addressed, where the two most likely solutions are:

- Connection to higher voltage levels. Where there is insufficient fault level headroom at a specific substation, the possibility of connection to the next voltage level is investigated, where there is a greater likelihood of there being sufficient fault level headroom available.

- Connection to a neighbouring substation. Where the nearest substation does not have sufficient fault level headroom, the possibility of connection to a neighbouring substation (with sufficient fault level headroom) is investigated.

For connections of up to 10 MVA, there is a standard connection charge according to the power rating, with additional charges according to the length of cable used. Above 10 MVA the generator pays all shallow costs associated with the connection.

Also, the use of Is Limiters is permitted in the Netherlands, and although these are only in limited use they have been used in specific cases, in conjunction with network splitting, to address fault level issues without having to undertake network reinforcement. This is most likely in unlicensed industrial networks.

2.3.4.3 Proactive Investment

In the Netherlands, there have been greater levels of proactive investment in the distribution networks to make them more capable of accommodating increasing levels of DG. This has been done in specific areas where significant growth in DG was predicted, and has included:

- Building new networks capable of operating at 20 kV but operating them at 10 kV, such that they can be operated at 20 kV at a later date when required. The 20 kV rated equipment has a higher short circuit current capability.

- Refurbishment work to existing networks involving installing 20 kV rated equipment (with a higher short circuit current capability) but continuing to operate it at 10 kV until such times as a change to 20 kV is required.

- Networks specifically for distributed generation have also been built.

Each of these options required significant proactive investment on the part of the DNOs. Also, note that the first two options do not remove the need for additional investment when a network is eventually switched from 10 kV to 20 kV, as investment is also required for the final modifications to the network prior to switching over to 20 kV operation. However, they do reduce the level of investment required at one time to convert a network from 10 kV to 20 kV. Generators are also required to make further investments as their transformers will require to be changed to supply at the new voltage level.

The historic development of integration of large amounts (up to 30%) of CHP in the Netherlands has been achieved over a significantly longer period of time than is forecast for GB. This has resulted in a much more gradual decrease in fault level headroom availability, due to the lower capacity of early DG and the potential for greater alignment between the introduction of DG and the upgrading of aging assets and also load growth related network investments. This has also been accompanied by specific proactive investment in building the capability for the networks to accommodate further DG. The way in which this situation has developed to date is therefore not particularly applicable to GB.

3. Options for Managing Increased Fault Levels

3.1 Introduction

This section provides an overview of fault level management methods available and in use and provides an estimated cost for the implementation of solutions to the fault level issue in general.

This section also presents our estimate of the likely costs for the implementation of solutions to the fault level issue, based on the types of solution available and the number of occasions that these solutions are likely to be employed.

3.2 Overview of Fault Level Management Methods

Possible solutions for addressing the increase in fault levels due to DG are provided in several studies (Refs. 13, 14). The following summary gives a brief overview and contains primarily permanent solutions for use in MV and HV networks.

3.2.1 Uprating and replacement of components

When fault levels go beyond the existing design limits due to the connection of DG, uprating the capability of existing equipment such as circuit breakers is an option to increase the fault level capabilities of the network. Most often the network equipment will be replaced with equipment having a higher design rating. This is a method that is widely used throughout the world as a traditional solution to the problem of increased fault levels. It is a familiar approach for DNO operations and maintenance personnel, requiring no new technology or design approaches. It is also possible that a large area of the network must be reworked from the point of connection, making this a relatively expensive solution if transformers and cables or overhead lines are also involved.

3.2.2 Increase impedance

It is possible to introduce higher impedances in the network to limit the fault level. The use of current limiting reactors is a relatively cost effective solution but needs additional effort to maintain the voltage profile, and increases the network losses. This solution is reasonably widespread in the Netherlands, but is used on a limited basis in Great Britain, where replacement of switchgear appears to be a more common solution. Also, one to one transformers can be used to connect the (larger) individual DG plant to the network. In the Netherlands transformers are often used for the connection of both CHP and windfarms. The techniques are well established but most cost-effective when applied at the design stage rather than as a retro-fit option when problems occur.

3.2.3 Is limiter

The Is limiter or fault current limiter senses the rapid rise of the fault current and fires a pyrotechnic charge to open the main current path. The current is commutated to the parallel path where a conventional fuse operates. The key advantage of using an Is limiter is that it retains the existing low network impedance under normal network conditions (no losses), combined with the effectiveness of operation of a fuse. A major disadvantage is the replacement of contacts and fuses after each operation and the requirement for careful adjustment of protective relay settings to maintain selectivity. This technique has been used in specific cases since the 1980's in the Netherlands with positive experience. Is limiters are relatively cost effective solutions but do require different or additional maintenance and health and safety measures (due to the explosive charge). This makes them expensive to implement and because they are currently not permitted for use in public networks in GB they are unlikely to become widely used in the period to 2010. TSG Workstream 3 project 4 (WS3P04) has undertaken some work on the potential of using Is limiters in GB.

3.2.4 Superconducting fault current limiter

A superconducting fault current limiter (SFCL) behaves like an Is limiter in that it has very low impedance at normal operation but when a fault occurs the impedance rises very quickly limiting the current. When the fault is cleared it returns to its normal state. Throughout the world, research has been undertaken by manufacturers (e.g.. ABB and Siemens) to develop an SFCL and the technology has been amply demonstrated. In Great Britain VA Tech is researching this technology (Ref. 15). It would be an ideal component technically, but it is an expensive solution. It is not expected that these devices will be commercially available within the next 10 years. Maintaining superconducting devices could also be an additional burden for the DNO.

3.2.5 Power Electronics

For various reasons, an increasing number of DG types have become available which use a PE converter interface. These provide a much lower fault current contribution than either synchronous or asynchronous machines, effectively providing no additional contribution to the fault level. PE is an area of rapid technological development (Ref. 16). The power ratings continue to increase while the costs are reducing, and it is becoming more and more commonplace for smaller DG plant to incorporate such an interface. Although these power electronic devices are generally not installed by the DNO they can provide additional controllability to improve sub-system performance and provide additional system functionality.

3.2.6 Solid state fault current limiter

Because of the rapid development of power electronics the idea of a solid state fault current limiter (SSFCL) emerged with similar functionality an Is limiter or SFCL. SSFCLs currently exist and are available from several manufacturers, and are in use for LV connected DG. For MV the application is still under development (Ref. 17) and the main problem is the losses during normal operation (which is less of a problem for LV). Because of the technical problems that remain to be solved it is not expected that MV SSFCLs will enter the market within the next 10 years. Note that if successful, this is a superior solution than the SFCL because no special cooling circuitry is needed.

3.2.7 Network splitting and reconfiguration

Network splitting can significantly reduce the fault level at a busbar. However, network splitting reduces power quality in general due to the increased source impedance, and it increases system losses and the risk of supply failure (i.e., reduces reliability). Another possibility to reduce the fault level is to reconfigure and alter the existing connectivity of the distribution network. Distribution networks are designed to allow their connectivity to be altered, either in response to a fault or to allow a section of network to be isolated for maintenance purposes. Both solutions require new protective setting and switching sequences (Refs. 18, 19). Next to uprating and the use of current limiting reactors, these techniques have been widely used in the Dutch MV network (Ref. 20). Many of the disadvantages of network splitting can be avoided by the use of Is limiters such that the network is only split when the fault occurs. This has been used in specific cases in the Netherlands.

3.2.8 Sequential switching

Sequential switching is a method by which the multiple sources contributing to any fault current are separated prior to the clearance of the faulted section. This solution has some safety risks to people and equipment because there is the risk that a sequential switching scheme fails to prevent a circuit breaker opening before the fault current has been reduced sufficiently. Another issue is the increased complexity and dependency on information and communication technology, particularly if equipment at more than one site is involved, and the technical issues associated with the deliberate introduction of a protection operation time delay. The associated costs are low to medium but a careful assessment with other options should be made with respect to risk. It is likely that this is a solution for use in isolated cases only.

3.2.9 Active fault level management

The management of fault level could be carried out within operational as well as planning timescales by developing the evolution of the network from “fit and forget” to “actively managed” as part of the transition to “intelligent networks”. Active fault level management would consist of simple activities such as reconfiguring the network combined with more dynamic and active measures like temporarily introduced impedances, and actively shifted loads. The latter would require much more flexible networks. In practice this means that some active controllable components are introduced to the network and more monitoring and information about the status of the network is required. Internationally (Ref. 21) there is ongoing research concerning “intelligent” networks. In the Netherlands for example a large, Government funded 8 year programme on intelligence in networks, part of the IOP-EMVT (Ref. 22), is under way with the participation of universities, industry and the DNOs. However, active fault level management is at an early stage of development, will be very expensive and is not likely to become reality within the next 10 years.

3.3 Fault Level Management Costs

Costs associated solely attributed to fault levels are extremely difficult to estimate because of the fact that fault levels is only one of several technical problems associated with the integration of DG that may need to be resolved. For LV connected DG it is unlikely that any occasion exists where fault levels are the only problem to be solved, as fault levels play only a minor role as detailed in Section 2. For MV and HV connected DG the situation is somewhat more complicated, with DG such as CHP connecting to urban MV networks (and in some cases HV networks) most likely to result in fault level issues. There will also be occasional instances of large-scale DG connecting to rural HV networks resulting in fault level issues, for which the costs will be very high and will vary dramatically on a project by project basis, so it is not possible to undertake a substantial analysis. For these reasons the analysis and resultant costs presented in this section are based on dealing with the connection of DG such as CHP to HV and urban MV networks.

The costs directly associated with fault levels presented below for GB for the period to 2010 are best estimates based on the information currently available and the analysis undertaken for this report. These have been developed using a bottom up approach, which utilises estimates of the number and types of DG connections that will require technical solutions, and develops estimated costs based on the likely cost of each type of technical solution.

3.3.1 DG connected to MV and HV

DG connected to the MV or HV networks can have costs associated with fault levels in both the MV and HV network itself and the higher voltage network to which it is connected.

Again an order of magnitude estimate of the investment required by DNOs directly related to fault levels is difficult to give, as investments in networks will often solve a variety of technical problems. However, this section attempts to approximate how much investment will be required in the GB MV and HV distribution networks in the period to 2010, specifically to address the scenarios developed in Section 2.

In order to present an estimate of the overall costs, we have developed a model of up to four potential solutions for fault level issues at each voltage level (11 kV, 33 kV, 132 kV), which is presented in Table 3.1 below, along with typical costs. Actual solutions and costs may vary widely from this, and the typical costs presented in Table 3.1 are based on a combination of the examples given in the DNOs published connection charging methodologies, the Technical Guide to the Connection of Generation to the Distribution Network (Ref. 38), and experience. Note that all costs provided in this section do not take into account any change to costs over time.

Voltage level	Solution 1	Solution 2	Solution 3	Solution 4
11 kV	Current limiting reactor for the DG feeder. Typical cost £50k	New cable connection to an 11 kV substation with sufficient headroom. Typical cost 5km * £40k = £200k	New overhead line to the 33 kV level. Typical cost 15km * £40k = £600k	Uprate complete substation. Typical cost £1,500k
33 kV	Current limiting reactors in all other feeders (assuming the existing busbar has enough capacity). Typical cost 8 * £100k = £800k	New cable connection to a 33 kV substation with sufficient headroom. Typical cost 10km * £80k = £800k	New overhead line connection to the 132 kV level. Typical cost 15km * £200k = £3,000k	Uprate complete substation. Typical cost £5,000k

Voltage level	Solution 1	Solution 2	Solution 3	Solution 4
132 kV	Uprate complete substation. Typical cost £10,000k	Create a new 132 kV substation. Typical cost £20,000k		

Note: Uprating substations in general also means working on the surrounding network to remove local constraints. For this reason the costs are in general higher than just for uprating the substation alone (a factor of 1.5 - 2 times is assumed here).

Table 3.1 – Potential Solutions and Typical Costs

In Table 3.2 below a distribution is assumed for the application of the available solutions, for both CHP growth scenarios outlined in section 2 of this report.

Voltage level	Scenario	Solution 1 [%]	Solution 2 [%]	Solution 3 [%]	Solution 4 [%]
11 kV	Organic	20	50	20	10
	Meet Target	10	20	50	20
33 kV	Organic	5	70	20	5
	Meet Target	0	50	30	20
132 kV	Organic	50	50	N/A	N/A
	Meet Target	20	80	N/A	N/A

Table 3.2 – Distribution of Potential Solutions for Different DG Growth Scenarios

In the slow uptake scenario (Organic) more inexpensive solutions are possible than in the high growth scenario (Meet Target). Note that these are assumed likely distributions and do not necessarily reflect actual GB DNO behaviour.

3.3.1.1 Scenario 1 – Organic CHP Growth

Using the potential solutions shown in Table 3.1, the distribution of solutions as shown in Table 3.2, and the distribution of available headroom in Figure 2.2, the range of potential costs can be calculated using Monte-Carlo analysis. These costs are slightly higher when considering make current compared to break current. The results of the analysis for make current are shown in Figure 3.1 below.

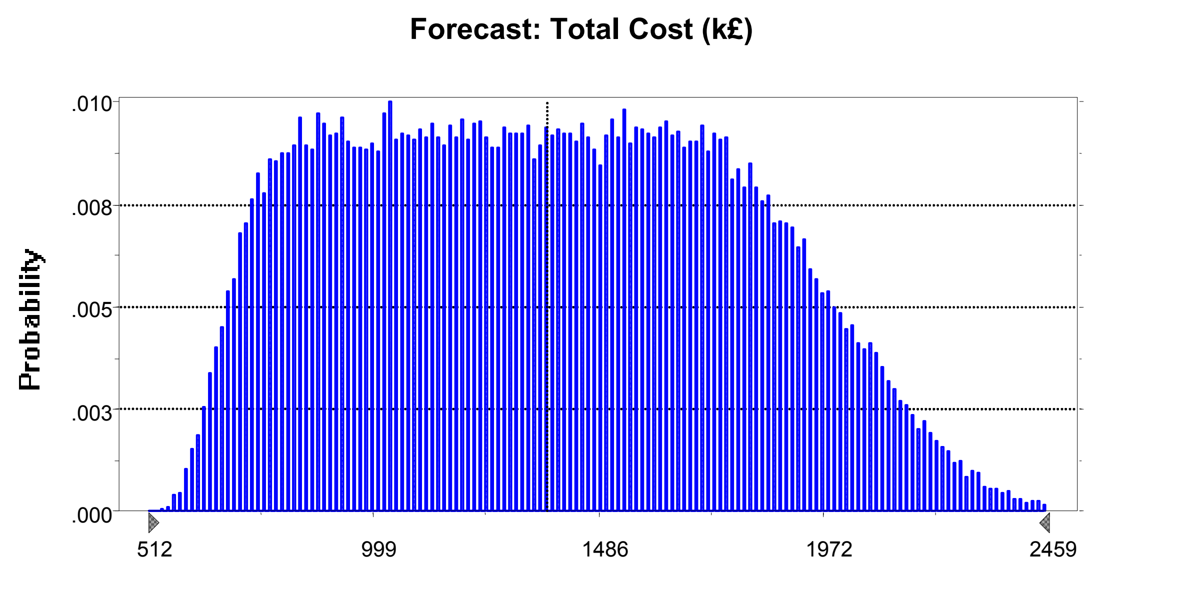


Figure 3.1 – Cost Distribution for Low CHP Growth Scenario

Using the 10% - 90% range of results from Figure 3.1, this indicates that organic CHP growth could result in costs of between £800k per year and £1.9 million per year across all DNOs in the period to 2010. Note that this figure does not include provision for costs for the connection of distributed generation to the LV networks, or for large scale wind projects, for which the costs could be of the order of £10 million per project. Figure 3.2 shows the distribution of costs per voltage level, showing the costs at the 132 kV level as the highest, but with the greatest uncertainty. Costs at the 11 kV level are the lowest and have the least uncertainty.

Figure 3.3 contains a sensitivity chart for the parameters used in the analysis. It shows that the most sensitive parameter is the assumed number of projects per year, followed by the fault level distributions for 132 kV and 33 kV (for which actual data was used in the analysis), and the assumed costs for the more expensive solutions at 132 kV and 33 kV respectively. Thus the most sensitive assumptions made are the number of projects per year and the assumed costs for the more expensive solutions at 132 kV and 33 kV. Should further accuracy of this analysis be required, we would recommend further refinement of these assumptions in particular.

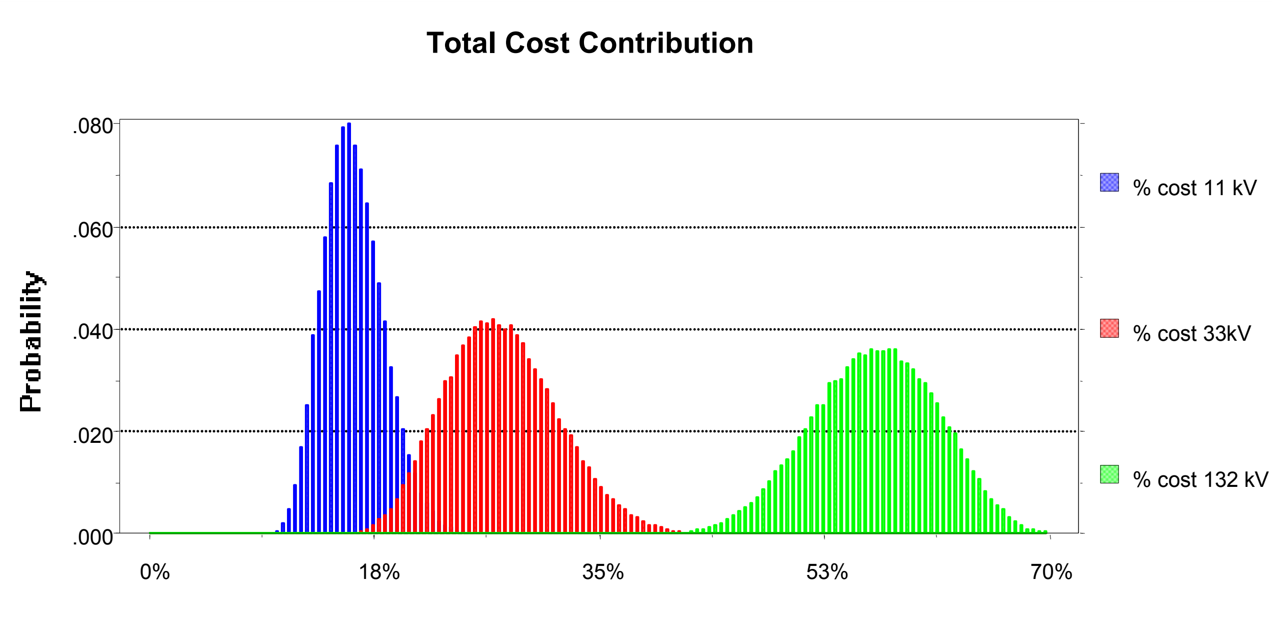


Figure 3.2 – Cost Distribution per Voltage Level for Low CHP Growth Scenario

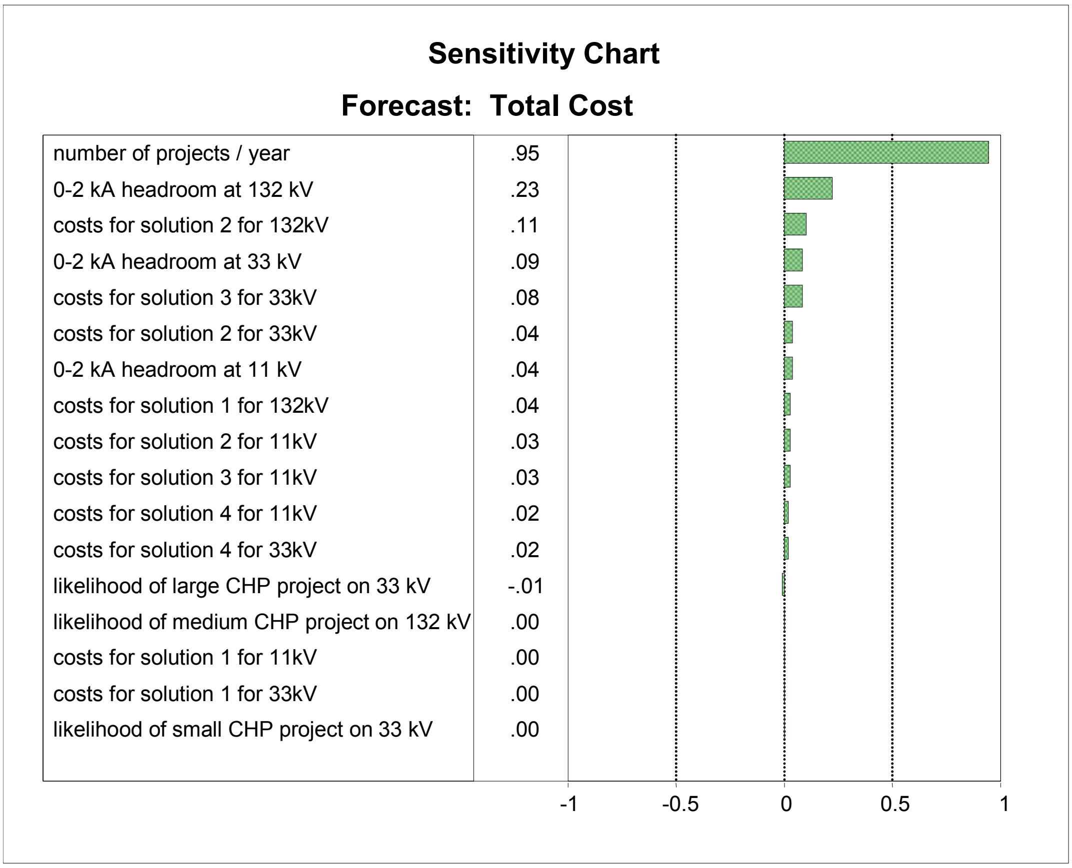


Figure 3.3 – Sensitivity Chart for Low CHP Growth Scenario

3.3.1.2 Scenario 2 – CHP Growth to Meet Targets

Using the potential solutions shown in Table 3.1, the distribution of solutions as shown in Table 3.2, and the distribution of available headroom in Figure 2.2, the range of potential costs can be calculated using Monte-Carlo analysis. As with scenario 1, these costs are slightly higher when considering make current compared to break current. The results of this analysis for make current are shown in Figure 3.4 below.

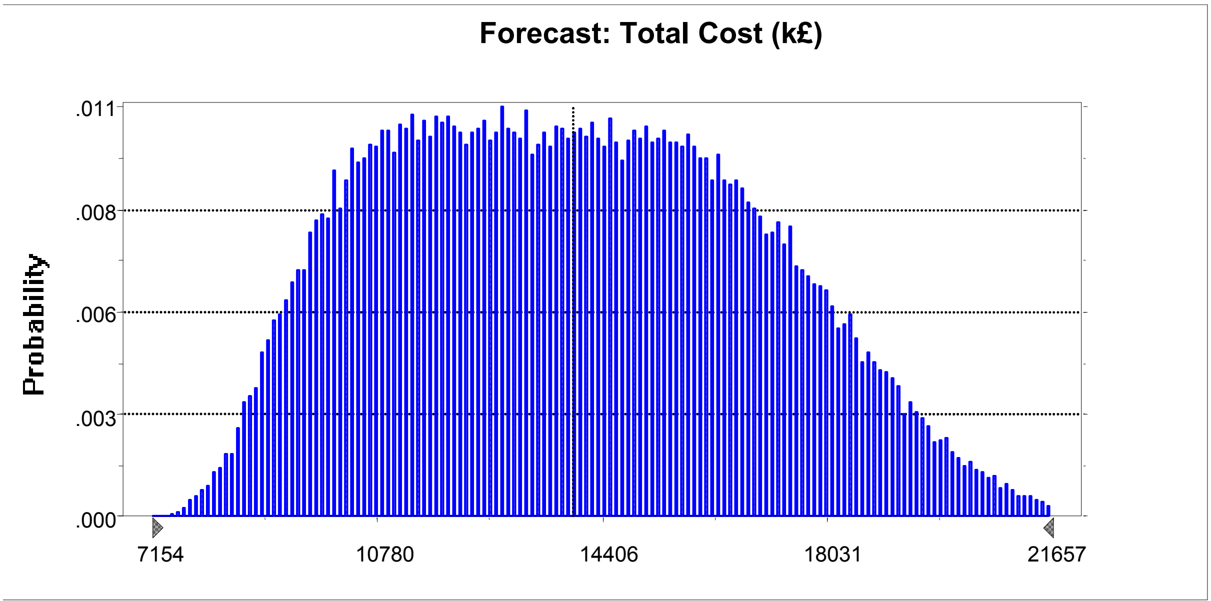


Figure 3.4 – Cost Distribution for High CHP Growth Scenario

Using the 10% - 90% range of results from Figure 3.4, this indicates that CHP growth to meet targets could result in costs of between £10 million per year and £18 million per year across all DNOs in the period to 2010. Note that this figure does not include provision for costs for the connection of distributed generation to the LV networks, or for large scale wind projects, for which the costs could be of the order of £10 million per project. Figure 3.5 shows the costs per voltage level, showing the costs at the 132 kV level as likely to be the highest, but with the greatest uncertainty. Costs at the 11 kV level are the lowest and have the least uncertainty.

Figure 3.6 contains a sensitivity chart for the parameters used in the analysis. As with the low growth scenario, it shows that the most sensitive assumptions made are the number of projects per year and the assumed costs for the more expensive solutions at 132 kV and 33 kV. Should further accuracy of this analysis be required, we would recommend further refinement of these assumptions in particular.

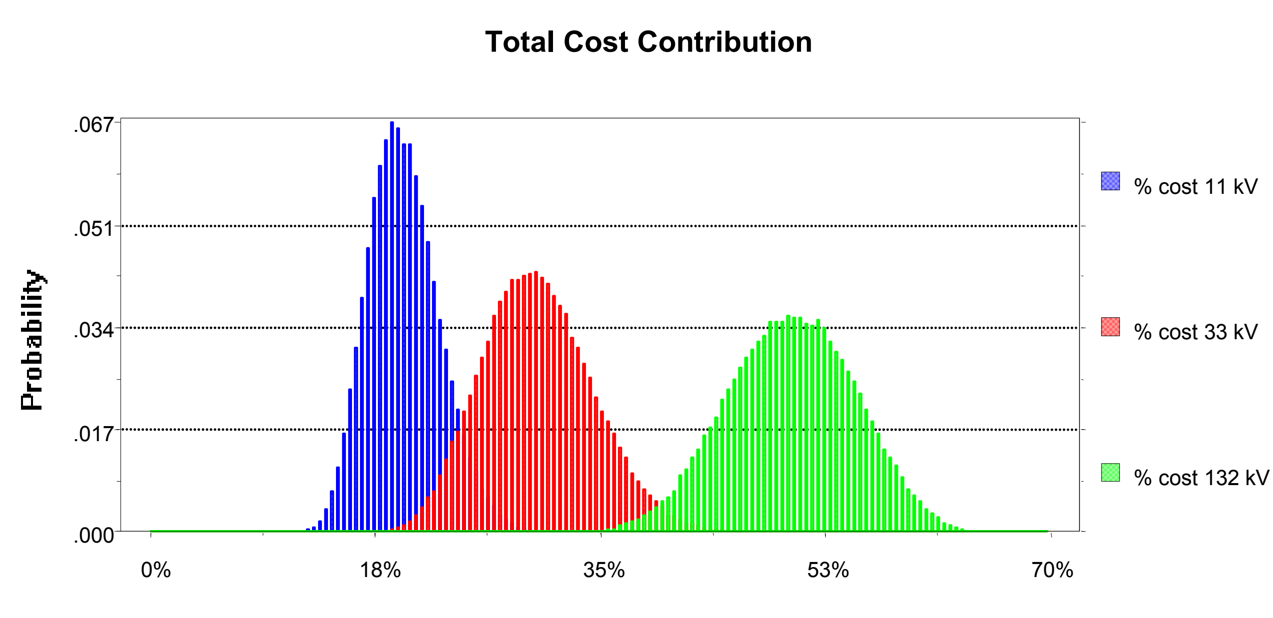


Figure 3.5 – Cost Distribution per Voltage Level for High CHP Growth Scenario

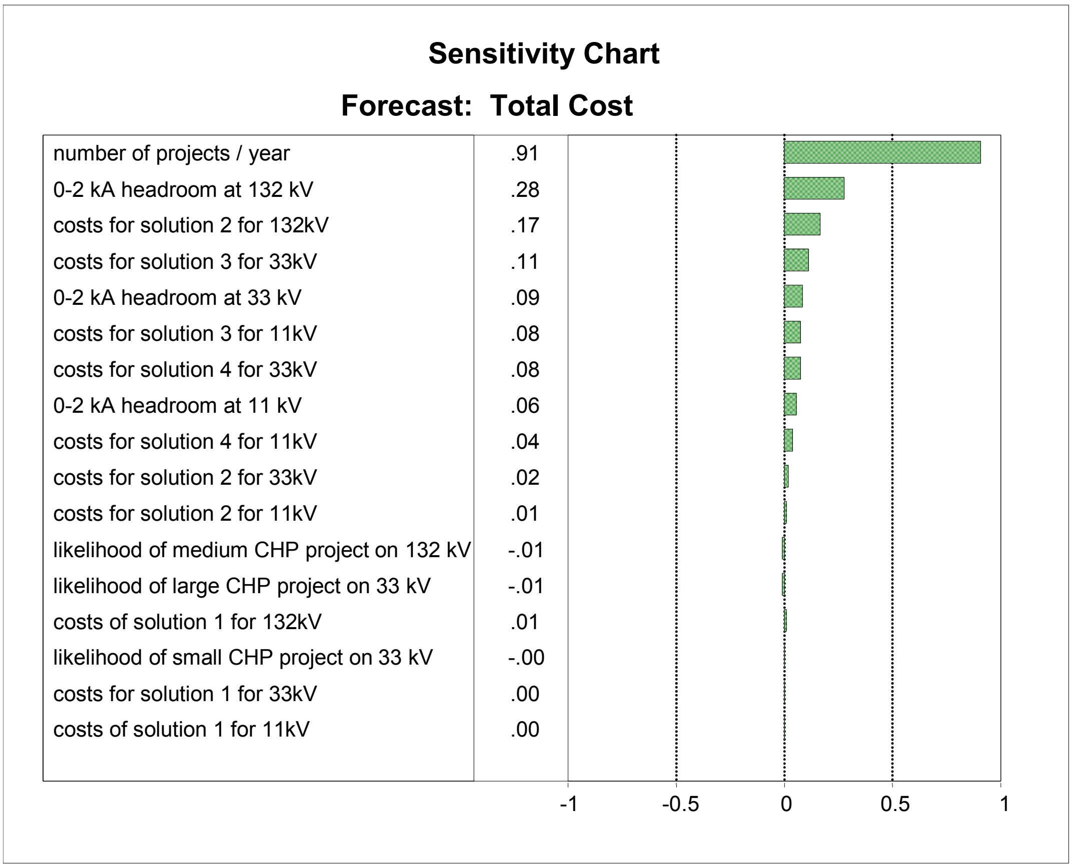


Figure 3.6 – Sensitivity Chart for High CHP Growth Scenario

Costs to address fault level issues for the integration of DG into the GB distribution networks in the period to 2010 are very difficult to estimate. Any costs developed are based on several assumptions, and there is more than one scenario of DG growth possible in the period. However, we have developed cost estimates based on a low CHP growth scenario and a high CHP growth scenario. Costs are estimated to be in the range £800k to £1.9 million per year across all DNOs (for a low CHP growth scenario) and £10 million to £18 million per year across all DNOs (for a high CHP growth scenario). Note that these figures do not include provision for any costs for addressing fault level issues on connection of distributed generation to the low voltage networks, or addressing fault level issues for large scale renewables (e.g., wind) projects, for which the costs could be of the order of £10 million per project

3.4 Case Study Example

An example of a particular project in the Netherlands to accommodate a large amount of DG is provided in Appendix A, illustrating where investment has been made to develop the capability to accommodate current and future DG projects.

4. Measurement and Calculation of Fault Level Values

4.1 Introduction

The connection of DG can raise the fault levels on existing equipment, due to the fault contributions from the DG itself, to values beyond the capacity of existing switchgear. At the planning stage, fault levels are calculated in order to determine whether or not they exceed the design limit of existing equipment, and to determine the design limit required of new equipment. Fault levels tend not to be measured in operational networks.

DNOs must continue to be prudent in ensuring that they continue to operate within the available fault level headroom.

This section describes and comments on the methods of calculation currently in use and potential measurement methods.

4.2 Fault Level Calculation

The method of calculation of fault levels as used by the DNOs is described in IEC60909 – "short-circuit current calculation in three-phase ac systems". This calculation method gives rise to conservative results that could lead either to over-investment in network reinforcement or to the refusal of DG connections (Ref. 26). An alternative to the method presented in IEC60909 was adopted and issued in 1992, known as Engineering Recommendation G74 "Procedure to meet the requirements of IEC60909 for the calculation of short-circuit currents in three phase ac power systems". This procedure incorporates the contribution of rotating equipment at the customer site.

In the Report of CIRED Working Group No 4 on Dispersed Generation (Ref. 27), the results of a survey involving 16 countries are given. On the issue of short circuit calculations there was consensus that the fault level calculations were based on IEC60909, and that no particular attention was paid to unusual switching conditions caused by DG. In most cases the DNO planning department performs the system studies using either no data or at best estimated data for customer machines. Sometimes, for complex cases with large industrial customers, the DNO itself will perform systems studies with actual customer machine data themselves or will outsource this to a consulting firm. This can result in DG being sometimes refused based on the calculated fault levels being too high, which would necessitate major network reinforcement to resolve.

There have also been a small number of cases in the Netherlands where cable short circuit ratings have been increased as a result of a critical review. In these cases, the review typically focuses on comparing actual protection settings with the original design protection settings. In some cases the actual protection settings means that the cable is subject to short circuit conditions for a shorter period of time than originally anticipated, and therefore the short circuit rating of the cable can be increased.

At the Power Systems Engineering Research Center (PSERC) (Ref. 28) work is ongoing to develop a method to enhance the method of fault level calculation. It proposes the use of an index known as the average change of fault current (ACF) and the method of approximating the ACF for a given system. The ACF can be used to indicate the severity of the change of fault current due to installing new DG. Based on our experience in providing advice on European and American networks we believe that practical application of this method may be some years away. We are not aware that other methods are being developed specifically to address fault level calculation.

4.3 Fault Level Measurement

The current situation is that fault levels in the network are generally not measured. Event recording is done, and under fault conditions in higher voltage networks fault recording is done, but the actual fault level during normal operation is not measured.

Historically, there was no need for the DNOs to obtain accurate measurements of fault levels. This was because any network enhancement required took place on the basis of the DNO system studies, which included the (conservative) fault level calculations, thus ensuring that actual fault levels would be likely to be well below the design limit of the network. Now, with the expected uptake of DG and the erosion of fault level headroom if network enhancements are to be avoided or deferred, the need to measure actual fault levels to ensure that they are within design limits becomes greater.

At EA Technology, the Fault Level Monitor (FLM) has been developed to estimate network fault levels including the contribution from induction motor loads without requiring detailed information about the load or the network itself.

The principle of the FLM is that responses of the power system to naturally occurring disturbances are recorded and an estimation technique (Refs. 29, 30) is used to calculate the network fault level at the time of recording. Note that this is a “single point” estimate as fault levels can change over time depending on how much DG and customers’ rotating plant is actually connected. Following extensive tests carried out at two industrial substations and a wind farm, it was confirmed that the results obtained showed good agreement with standard calculation methods (Ref. 31).

The main advantages of the FLM include:

- Providing a check on the accuracy of the fault level calculations.
- Since the measured values will vary throughout the day, the FLM will be useful for fault level management. For example, a DNO could allow generators to connect if the measured fault level is say 90% of the computed value.

Although there are no other fault level measuring devices available on the market, and there is an industry project to develop the FLM commercially, there are a number of uncertainties in terms of the prospects for such a product:

- Expected sales, as the number of places in the network where the DNO wants to measure is limited.
- The equipment must be easy to connect and compatible with the DNO operational practices and data collecting systems (which differ widely throughout the world).
- The measuring period should cover a substantial period of time to build up a database of reliable values. It the measuring period is only a short period of time there will be less disturbances recorded and therefore a less accurate measure of fault levels.
- The DNO system planning department would require training on how to assess the value of the measurements and to use this in the system studies whilst still not having machine data from the customer site.

4.4 Conclusion

For the moment we have to accept that fault level calculations according to IEC60909 will inevitably be conservative. There is little activity in the international community to change this situation. If the DNOs seek to have a better understanding of the fault levels to better estimate the headroom there are two routes: either better modelling, or development of an FLM.

The problems associated with the first route is that the DNOs need to have a better understanding of what is happening in their network and must have data available from both the new DG plant and from machines at the customer site. However, it is unlikely that DNOs will be able to obtain customer site data.

DNOs are also encouraged to consider reviewing cable short circuit ratings where particular issues exist, as original design ratings may be conservative and could potentially be increased in specific cases based on actual protection settings compared to those envisaged at the design stage.

The route of developing a commercial FLM poses the problems that it will take quite some time to assess a single location (this has to be repeated over time). Furthermore the DNO has to develop criteria based on these measurements without actually knowing what is happening at the customer site. However, the route to an FLM fits well with a long term strategy to have more access to measured data in the network and as such could facilitate the realisation of active fault level management systems within the concept of "intelligent networks".

In the short term the most obvious solution for DNOs seeking to improve fault level calculations is to try to obtain more machine data at the client site and perform more detailed calculations. From a longer term perspective, stimulation of the development of a commercial FLM will be advantageous and having access to more detailed machine data during the development period creates a better overall understanding and gives more options for control of the network.

5. Constraints to DG Penetration due to Fault Level Limitations

5.1 Introduction

This section discusses the constraints to increased penetration of DG due to fault level limitations, at both the low and medium voltage network levels in the period to 2010.

5.2 LV Network

In order to assess the constraints due to fault level limitations on the LV network, we must consider what room there is for increases in the fault level at this network level. Typical fault ratings for LV equipment are 25 MVA or 35 kA (Note: reference impedance is used and this can differ widely in practice). The LV feeders with connected loads and DG are normally connected to an 11 kV transformer. When a fault in the LV network occurs the fault level current is determined predominantly by LV feeder transformer short circuit impedance. Due to the introduction of large amounts of small scale DG the present fault levels in the range of 1 to 1.5 MVA will rise some 20%, even if each household is equipped with generating capabilities up to 3 times the load as is shown in Ref. 9.

In a US study (Ref. 32) on the effort to integrate DG into the network it was found that with a penetration level of up to 25% of generation the impact on the network is very limited (sometimes affecting voltage profile and to a lesser extent system operation and control). Even with greater amounts of DG, fault levels do not appear as one of the concerns of network operators.

In the Boxum et al study (Ref. 8) a methodology is described to make a first estimate of the amount of decentralised power that can be integrated in the existing low voltage distribution network. The method is suitable for both urban and rural areas. The study was performed for different Dutch DNO LV networks and focused on power integration (preventing overload of components), voltage levels (regulation) and fault levels. It was found that in 80% of the cases the feeder transformer was the limiting factor constraining the amount of DG power to be integrated (the maximum power to be fed back in the MV network is determined by the transformer size). In the remaining 20% of cases the limiting factor was voltage regulation. When replaced

The low impact of DG on fault levels indicates that it is unlikely to be a constraint at the low voltage connection levels before 2010, provided that the appropriate investments are made when determined as being necessary.

with a bigger transformer, in 75% of the cases the maximum loading of the cable was the limiting factor and in 25% of the cases the voltage level. In none of the cases studied the fault level was a limiting factor.

5.3 MV/HV Network

The MV network has to cope with fault level contribution from the DG connected to the LV and the DG connected directly to the MV network. In the PB Power study (Ref. 9) fault levels increase was calculated for the 33 and 11 kV busbars when generation at LV was raised from 0 to 200% and the transformer rating of the 33/11 kV and 11/04 kV networks were doubled. The findings are that the fault level rise on 11 kV was approx 1 MVA, similar to that of the LV fault level rise due to the additional generation. This does not cause problems related to fault levels in the period to 2010 even with the fact that in some MV networks the remaining (calculated) fault level headroom is very limited (less than 10%). In general this limited headroom is caused by the fact that a lot of equipment installed is quite old and was designed for 13 kA (now the minimum recommended rating is 25kA). Some replacement programmes are already under way for this older equipment.

At the MV/HV level the main source for growth in fault levels is the connection of individual wind turbines, windfarms and CHP. In general the power rating of these generators is large enough to justify connection to the MV network. When a request for connection comes in, the planning department of the DNO treats them on an individual basis. When a larger CHP or a windfarm (> 5 MW) is to be connected, or where there is low fault level headroom availability, fault levels are an issue and are responsible for a large portion of the integration costs. The solutions are as described in Section 3.

There does not appear to be a significant constraint to scenario 1 (low CHP growth) as described in Section 2, as the solutions will be required largely to solve specific problems and the headroom availability is only gradually being consumed. However, there may be significant constraints to scenario 2 (high CHP growth) as described in Section 2, in that:

- A large number of projects require to be completed on an annual basis.
- Solving fault level issues on a project by project basis is likely to result in a rapid consumption of the remaining available headroom in areas of high growth (i.e., urban networks).
- A point will be reached where certain networks will not be able to accommodate further DG in the absence of investment in solutions which

increase the capability of the network to accommodate further DG (i.e., increase the headroom).

The most significant constraint to the development of DG in the period to 2010, in terms of fault levels, is the constraint on the MV networks in accommodating the levels of CHP required to meet Government targets. This constraint cannot be solved by addressing fault level issues on a project by project basis, without investment in increasing the overall headroom available in the networks.

6. Characteristics of DG Machines

6.1 Introduction

As mentioned in earlier sections of this report, the magnitude of the contribution to the fault level from DG depends on the type of generator and the type of network coupling. Really this information only allows statement of a typical range for the fault current contribution. Electrical parameters of a particular type of equipment (e.g. the short-circuit impedance of a transformer coupling the generator to the network) can assume different values making it impossible to make a general statement on the contribution of a particular scheme.

In the following section current and envisaged DG types have been listed with an indication of the typical range of fault current contribution. The characteristics of fault current over time is also described, providing detailed definitions of make current and break current, as well as typical values for different types of DG.

6.2 DG types and their Contributions

To assist with planning and indicative studies by DNOs, the following table provides a listing of types of existing and future DG and their approximate contribution to the fault current. The given value is the initial symmetrical short-circuit current (I_k", IEC60909-0 Clause 1.3.5) for a three-phase fault at the network terminals of the DG plant, expressed as multiple of the plant's rated current (I_r).

Type of equipment	Network [kV]	Network Coupling			Comment
		Direct	Trans-former	Power Electronics	
Induction generator	0.4 - 33	5 - 8	3 - 7	NA	Power rating 0.01 - 1 MW
Synchronous generator					
• small	0.4 - 33	5 - 8	3 - 7	NA	Power rating 0.5 - 5 MW
• medium	11 - 132	5 - 6	3 - 5	NA	Power rating 5 - 25 MW
• large	132	NA	2.5 - 4.5	NA	Power rating over 25 MW
Battery Energy Storage System	0.4 - 132	NA	NA	1 - 1.2	
Biomass system	0.4 - 33	Dependent on generator type.			

Type of equipment	Network [kV]	Network Coupling			Comment
		Direct	Trans-former	Power Electronics	
CHP system	0.4 - 132	Dependent on generator type.			
Fuel Cell system	0.4 - 33	NA	NA	1 - 1.2	
Landfill gas system	0.4 - 11	Dependent on generator type.			
Micro CHP generator	0.4	5 - 8	NA	1 - 1.2	Power rating 1-3 kW. Domestic application. Typically (single-phase) induction generator.
Mini CHP turbine	0.4 - 11	5 - 8	3 - 7	NA	Up to 500 kW. For blocks of houses, offices and shops. Typically induction generator.
PV system	0.4	NA	NA	1 - 1.2	
Tidal stream system	11	5 - 8	3 - 7	NA	
Waste incineration	0.4 - 132	Dependent on generator type.			
Wave power system	0.4 - 33	5 - 8	3 - 7	NA	Typically induction generator. See note 1.
Wind turbine					See note 1.
• squirrel-cage induction generator	0.4 - 11	5 - 8	3.5 - 6.5	NA	
• DFIG, type I	11 - 132	1 - 2	1 - 1.5	NA	See note 2.
• DFIG, type II	11 - 132	4 - 6	3 - 5	NA	See note 2.
• direct-drive synchronous	11 - 132	NA	NA	1 - 2	

NA = Not applicable

NOTES

1. Values apply to a single generating unit. Many units can be combined to a park and connected to a higher voltage network.

2. For type I the generator's rotor winding looks in to the converter's DC interlink when the IGBT switches open. For type II the generator's rotor winding is shorted and effectively the generator becomes an induction generator (Refs. 36, 37, 40).

Table 6.1 - DG contribution I_k''/I_r

6.3 Impact on make and break currents

Fault currents decrease over time. This is reflected in most LTDS reports by the fact that they distinguish between make and break fault levels.

The make fault level relates to the ability to withstand the mechanical forces caused by the flow of current. The relevant value is the peak short-circuit current (i_p) which is defined as the maximum possible instantaneous value of the prospective (available) short-circuit current (IEC60909-0 Clause 1.3.8).

The break fault level relates to the ability of circuit breakers to interrupt the fault current. The relevant value is the symmetrical short-circuit break current (I_b) which is defined as the r.m.s. value of an integral cycle of the symmetrical a.c. component of the prospective short-circuit current at the instant of contact separation of the first pole to open of a switching device (IEC60909-0 Clause 1.3.9).

For calculation of these values, refer to IEC60909-0 and G74. The currents in Table 6.1 can be used as make current contributions. For the contribution of DG to the break current, the following categories can be distinguished:

- DG types with an induction generator.
- DG types with a synchronous generator.
- DG types with a power electronic coupling.
- DFIG wind turbines.

The characteristics of each of these categories in terms of break current are detailed below.

6.3.1.1 Induction Generators

Induction generators get their magnetic excitation from the power system they are connected to. Shorting the machine at its terminals causes a collapse of the excitation, in turn resulting in a collapse of the fault current contribution. Typically currents decrease to a negligible value after 100 to 300 ms and so induction generators hardly increase the break current. As a first approximation the break current contribution can be assumed as zero.

6.3.1.2 Synchronous Generators

The contribution of a synchronous generator decreases from the so-called subtransient value (0-50 ms after fault initiation), via the transient value (50 ms - 1 s) to the steady-state short-circuit current (beyond 1 s). While the subtransient current is determined by the subtransient reactance, an electrical property of the machine, the transient and steady-state short-circuit currents depend strongly on the design of the excitation system. For the break current one can use a value for the generator current of about 1 to 3 times rated current.

6.3.1.3 DG with power electronics coupling

Power electronic devices cannot carry large currents for a long time. A sudden increase of the current is detected by protective circuits (typical setting 1.2 times rated current) causing the control electronics to stop the firing of the semiconductor valves. While thyristors will block only when there is a zero crossing of the current (worst case after 10 ms), forced-commutated devices such as IGBTs and MOSFETs block the current within milliseconds. In either case the contribution to the break current is zero.

6.3.1.4 DFIG Wind Turbines

The short-circuit behaviour of DFIG wind turbines is highly-dependent on the design of the generator and its electronics. Worst case is when the rotor winding is shorted when the converter blocks. The fault current contribution will reach peak values of four to six times rated current before decreasing to zero in about 100 to 200 ms. On most types, however, the blocking of the rotor converter will cause the unit to disconnect from the network within 25 to 100 ms. In either case the break current contribution is zero.

7. Longer term perspective (to 2020-2030)

7.1 Introduction

There is no doubt that our present day network, with its historically defined structure, will have to change to cope with the new demands of the future. A paradigm shift in network planning and network development is needed because DNOs are faced with increased uncertainty with respect to location and the amount of demand and generation. The generation is operating in a more intermittent manner whilst the diversity and numbers of generators increases quickly. As a consequence new rules are needed alongside ideas of how this transition to an electricity network of the future has to take shape and emerge from the present system. A few things are sure about the network of the future (see Figure 7.1):

- The assets will be utilised as much as technically possible.
- Many small scale generators (of fluctuating nature) are connected.
- Power flows will be in all directions (not only top-down).
- Information and communication technology (measure and control) will be widely used.

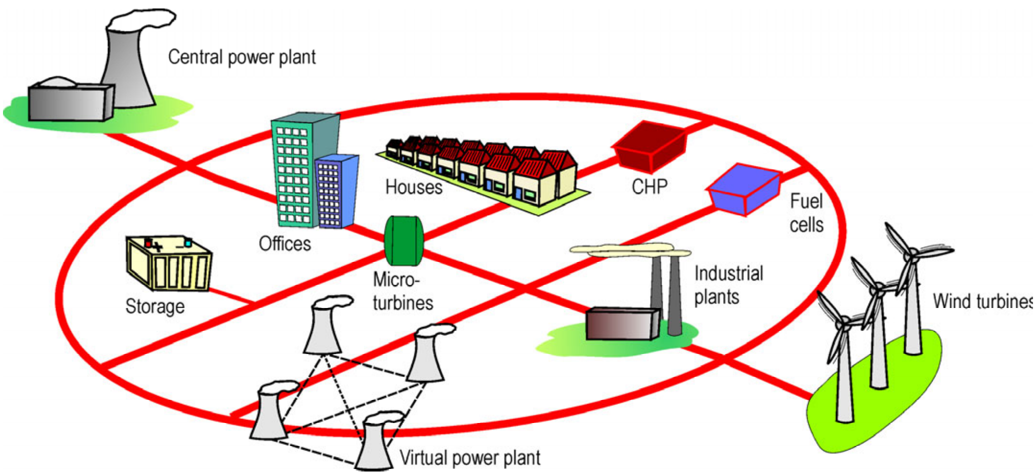


Figure 7.1 Vision of the future network (source KEMA)

When discussing the longer term perspective (to 2020-2030) of the distribution network fault levels and assessing the potential cost involved to remove this technical barrier, we have to take a look at some possible visions (scenarios) that might become reality. We have broken this down into two sections: the impact of new network design on coping with fault levels, and how new generation will impact on fault levels.

7.2 Network Design in 2020-2030

A key question to consider for the future is what will the power exchange layer look like in the future. Two models that can be examined are the camel or the dromedary model, which are illustrated in Figure 7.2. The Camel model envisages large power plants connected to one another via a high-voltage network, while a low-voltage network interconnects the micro networks. Power would then be exchanged between the high and low voltage networks over a relatively lightweight medium-voltage network. Alternatively, the dromedary model assumes that both the large-scale plants and the micro networks are connected to each other via a well-developed medium-voltage network.

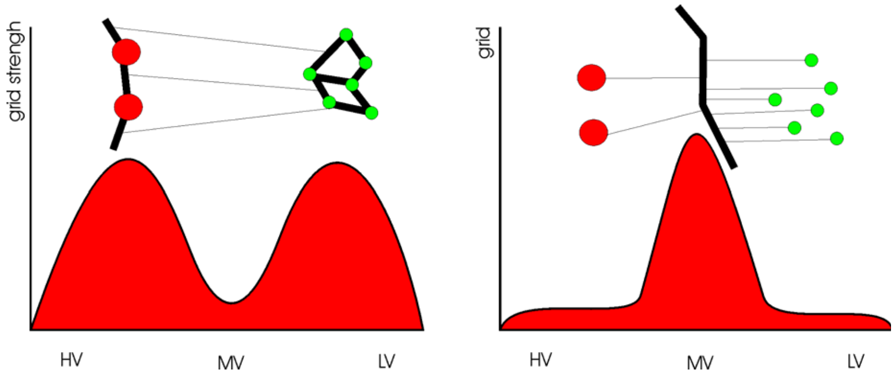


Figure 7.2 Camel and dromedary model for the exchange of power between large and small-scale generation during the transition to a future network system.

If the camel model is adopted, with a relatively weak MV interconnection layer, the investments are done mainly in the HV and LV network (MV network investments are avoided when possible). When looking at the LV network substantial investments are done locally (probably at the customers site) to maintain voltage levels within tolerances and as a consequence also limit the possible fault level increases in the LV network. Because maintaining the voltage levels is a difficult task in the LV network with a weak MV coupling there will probably be a large emphasis on information technology and control. The small generators will therefore be equipped with intelligence (power electronics interface) that will also limit the fault level contribution.

When the dromedary model is adopted, the MV network will be reinforced (transformers and controls) and serves as a primary means for keeping the voltage within limits (this resembles most closely the present network situation). As a consequence no special measures need to be taken at the local LV generators to reduce the fault level contribution. The DNO installs advanced measuring and control tools at the feeders and the MV substation transformers and switchgear is upgraded to make a "strong network". As a consequence of this reinforcement the fault level capabilities of the MV network are greatly enhanced. In this case to the main problem will be the maintenance of the voltage profiles within the tolerance. Remaining within tolerance will become increasingly difficult with only direct control functionality at the entrance point of the feeders, so it is therefore likely that there will again be a demand for intelligence (power electronics) being introduced at the individual connected generators.

Recent studies (Refs. 21, 33, 34, 35) suggest that ultimately the camel model will be adopted, in which case fault levels are only of concern in specific cases. It is not likely that a DNO will encounter high investments associated to cope with high fault levels because fault levels are limited by the use of power electronics at DG plant. If the transition is more gradual and first goes through a stage of dromedary development and then switches to the camel model, the remaining problems with fault levels will still tend to be specific cases. In this process the MV network will be reinforced and therefore capable of coping with the increase in fault levels.

7.3 New generation technologies

It is possible that in the period to 2020-2030, entirely new generation technologies might become commercially available, employing for example tidal wave energy, thermo- and piezoelectric energy or osmosis. Also micro turbines (gas-fired, wind), energy storage systems and fuel cell systems (mobile in cars and stationary) hopefully reach the point of becoming commercially viable. Of course there will be developments to increase the efficiency and ratings of all kind of existing equipment (e.g., gas turbines), but most promising is the rapid development of power electronics. Components will become cheaper over time and the power ratings are steadily increasing. As a consequence of these developments it is possible that new micro, mini and small CHP as well as small wind turbines will be equipped with power electronic inverters. Small and large fuel cell systems and storage systems (battery and /or flywheel), as well as large wind turbines (direct drives) will be developed (Ref. 36). None of these systems will contribute to the fault levels. All other generators not equipped with power electronics will continue to contribute to fault levels. Note that on the customer site the motors will be almost exclusively be equipped with VSDs (for superior controllability) and as such will not contribute to fault levels either.

A higher proportion of the connected DG in the LV and MV networks will have power electronics interfaces in 2020-2030 than is currently the case. These power electronics interfaces slow down the growth in fault levels. However, there will continue to be large DG connected which continue to contribute to the fault level. If the uptake of DG is very large, the fault level contribution will grow significantly.

7.4 Conclusion

As already concluded in earlier sections increasing fault levels are not a "show stopper" for the uptake of small scale DG in the period to 2010 assuming that the appropriate investments in the networks are made. In the longer term until 2020-2030 the expected network development, the uptake of new generation technologies and the appropriately rated power electronics interfaces could prevent further increases in fault levels from smaller scale DG, but will not assist in addressing the significant fault level contribution from large scale DG.

Appendix A: Example Netherlands DG Project

By 2000, some 25 wind turbines with a total installed power of 3.3 MW were connected to a rural 10 kV network. Most of these turbines were stand-alone units installed by farmers with power ratings typically ranging from 75 to 250 kW.

However, since the late 1990's turbine power ratings have increased significantly, and Government policy changed to favour wind parks and discourage stand-alone turbines. With new stand-alone sites becoming more difficult to develop, turbine owners started replacing their existing small turbines with larger ones. Within a matter of two years the DNO was faced with requests to increase the connection capacity from 3.3 MW to about 20 MW.

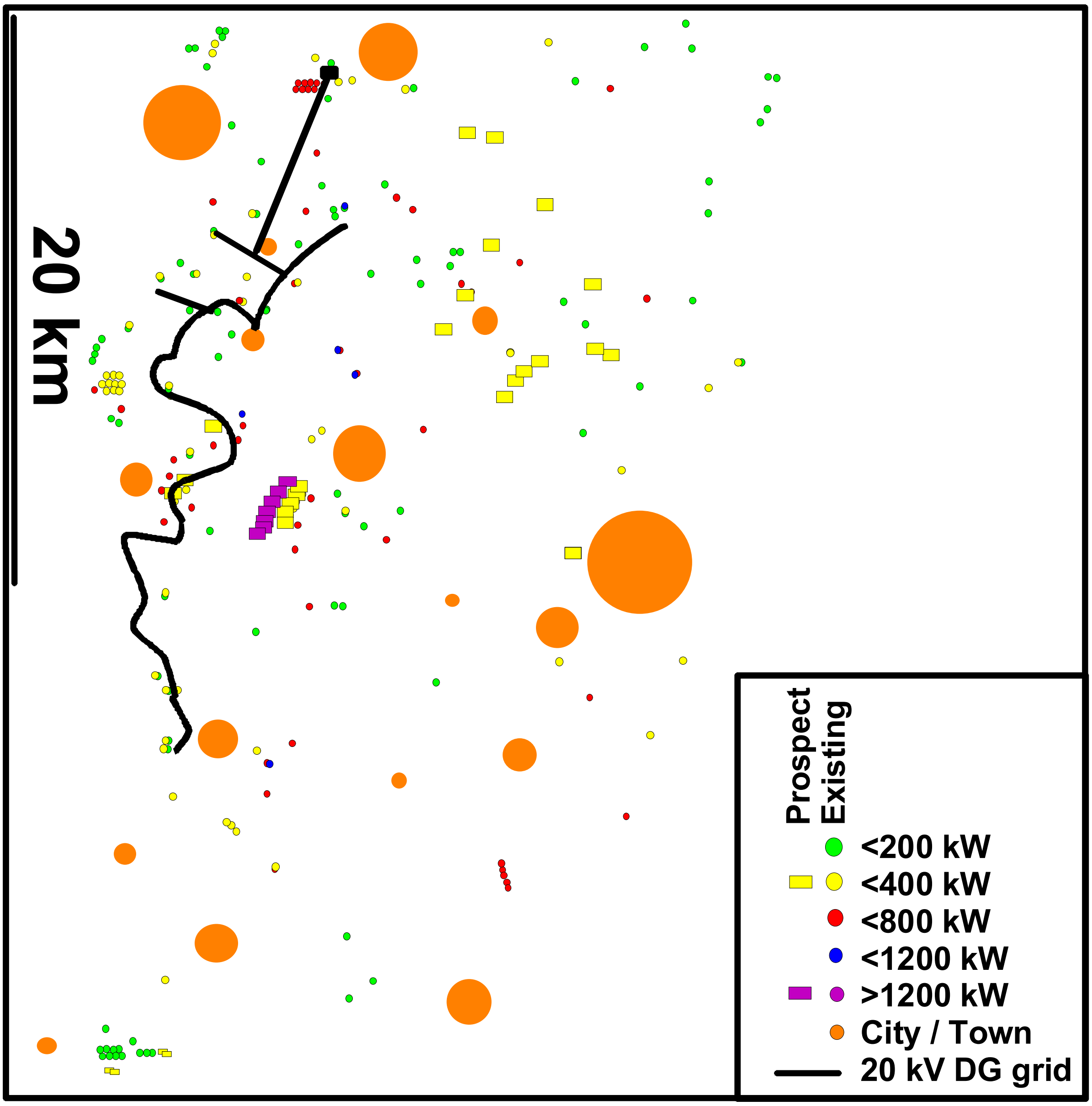
Besides the turbines already connected, the DNO had a portfolio of other prospective connections. Originally consisting of 10 sites with total power of 5.5 MW, the portfolio grew to about 20 sites with a total of 35 MW.

The massive increase in capacity required as a result of these connection requests was far beyond the capacity of the rural infrastructure, and the DNO was faced with three choices as follows:

- Increase the tolerance of the supply voltage.
- Reinforce the existing 10 kV network.
- Build a new and separate network infrastructure specifically for DG.

The DNO chose to build an entirely new and separate 20 kV network with adequate capacity for the potential DG growth. The network has its own 110/20 kV supply transformer. Some parts of the new network are still connected to the existing 10 kV network, but can in future be reconnected / switched over to the 20 kV network. The new network offers the DG initially no redundancy, reducing construction cost by 50 %. Instead the DNO compensates turbine owners for loss of energy due to non-availability of the network. If the amount of wind turbines keeps growing over time, partial redundancy will be introduced. Although use of 10 kV was technically possible and more economical, the transport capacity would be low and the existing infrastructure would reach its limits faster. The 20 kV voltage was therefore adopted as an investment for the future.

The investment cost for the new network was qualified as "deep cost" and was born by the DNO. The DG network was built at a cost of approximately €210 Euro per kW. The annual OPEX is about €1 per kW connected. Figure A.1 below shows a schematic of the new network and DG locations.



Note: Upgrades to existing wind turbines are shown by partially overlapping dots.

Figure A.1 – Dutch DG Network Schematic