INDUSTRY CONSULTATION ON GRID CONNECTION OF SMALL PV SYSTEMS

ETSU S/P2/00332/REP

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The work described in this report was carried out under contract as part of the New and Renewable Energy Programme, managed by ETSU on behalf of the Department of Trade and Industry. The views and judgements expressed in this report are those of the contractor and do not necessarily reflect those of ETSU or the Department of Trade and Industry..

First published 2000

EXECUTIVE SUMMARY

This report presents the results of consultation within the PV industry and the electricity supply industry concerning guidelines for the connection of small PV systems to the electricity network.

OBJECTIVES

The aim of this project was to contribute to the development of a final version of the draft Engineering Recommendation G77 that will be fully acceptable to the PV industry and the electricity supply industry.

The main objectives were:

- to enhance consultation between the PV industry and the electricity supply industry
- to improve the current information on the construction and performance of inverters now on the market, in relation to the requirements of the draft G77
- to estimate the cost of upgrading inverters to comply with G77
- to conduct a hazard assessment of inverters in grid connected mode in order to shed light on relative priorities for performance requirements
- to gather information on the outstanding technical issues, namely the injection of direct current into the grid and the necessity of using a mechanical break for isolation from the grid
- to review the information arising from the study with the intent to develop a redraft of G77 which will be fully acceptable to both industries

BACKGROUND

Although relatively few photovoltaic systems are connected to the electricity network in the UK it is expected that the number of requests for connection will increase rapidly in the near future. In the absence of an international standard for connection of photovoltaic generators it was necessary to produce guidelines for the industry.

Earlier work carried out by EA Technology and Halcrow Gilbert resulted in 'UK Technical Guidelines for Inverter-Connected Single- Phase Photovoltaic Generators up to 5 kVA'. This document was then adopted by the Electricity Association as Draft Engineering Recommendation G77 and circulated to its members in September 1998.

This document has been revised a number of times over the past couple of years. Its development was supported by experimental work carried out at the Southampton Photovoltaic Test and Reference facility at the University of Southampton.

At a meeting on 23rd June 1999 at which both the electricity supply industry and the PV industry were represented, it was agreed that the G77 document needed to be developed such that all parties could fully endorse its application. Differences of opinion remained on certain technical aspects. The electricity supply industry stood by their view that they needed a document that would be acceptable to all the DNOs and safeguard their interests and obligations. The PV industry felt that the G77 document was still unnecessarily restrictive and did not recognise modern safety technologies. At least in part, these differences arose from lack of access to the full information or from the non-availability of information.

It was decided to issue G77 at the earliest whilst recognising that it might be revised within a year or two with more experience of installations and more technical evidence available. In view of the imminent applications for the connection of many more PV systems to the network it was agreed that these differences should be resolved as quickly as possible in order to allow expansion of the PV market in a desirable way.

This situation led to the proposal to carry out this project, which polls together three topical areas of related work that the PV industry wished to undertake.

SUMMARY OF THE WORK

Three specific areas of work were undertaken to increase the current understanding of the technical issues and contribute towards the consultation process.

Firstly, a comprehensive market survey of inverters was undertaken in order to assess which inverters would be likely to be approved for connection in the UK. Eventually it is expected that inverter manufacturers wishing to sell their product in the UK market will send their inverter to be type tested according to the guidance given in G77. As an interim measure, technical information was obtained from all the major inverter manufacturers and analysed against the requirements of G77. Where inverters do not meet the requirements of G77 it is possible, in some cases, to add on components (disconnect relays and / or isolation transformers) such that they would be approved for connection. Prices were obtained for these components in order to assess the viability of 'upgrading' existing inverters.

Further information was collected on two key technical areas: the requirement in G77 for a mechanical disconnect and the limit for DC injection. Both recommendations have proved controversial. The electricity industry is anxious to maintain safety standards and quality of supply. The PV industry, while not wishing to compromise safety, are concerned that a high level of protection is achieved through an effective and appropriate technical solution. Electrical insulation testing was performed on an inverter design utilising a semiconductor switch, rather than a mechanical disconnect. No further experimental work was possible under the project with regards to DC injection. In the case of both technical areas, the available information was collated and summarised in order to present a comprehensive argument.

A 'hazard identification and assessment (HAZID)' exercise was conducted for photovoltaic embedded generators, based on the Hazard Management system developed for the oil and gas industry. The risk of islanded operation has already received considerable attention; the aim of this study was to present a more holistic exercise in order to identify and consider a much wider range of hazards such as component failure, grid supply failure and other events that might constitute a hazard.

The results of these studies were presented at two formal meetings in December 1999 and March 2000. The purpose of these meetings was twofold: firstly, to disseminate the information and ensure that it reached a wider audience, secondly to obtain the views of the industry on matters relating to grid connection of PV. In addition consultation has been ongoing informally, through e-mail, fax and phone in order to ensure that the information presented here is representative of the industry's views.

SUMMARY OF RESULTS

A number of documents have been produced as a result of this programme of research:

(i) a table summarising the technical performance of inverters (below 5 kVA) available on the market
(ii) a list of contact details for the inverter manufacturers
(iii) a list of contact details for suppliers of disconnect relays and isolation transformers
(iv) quotes for disconnect relays and isolation transformers
(v) a pro forma for applying for connection and then for commissioning of a PV installation
(vi) a list of contact details for the DNOs

These will be valuable tools for installers of PV systems enabling an easier and more standardised route for connecting PV systems to the electricity network. It is recommended that they are published on the PV-UK website to ensure a wider audience.

Two technical papers have been prepared on the issues of mechanical disconnect and DC injection. Additionally, a draft test schedule, and laboratory data, for testing an entire inverter to the same requirements specified for a mechanical relay in G77, was prepared. This was presented at a meeting of the G77 Consultative Group on 2 May 2000. It was agreed that the test schedule, laboratory data and other supporting data would be pulled together into a formal report for submission to the Electricity Association by the end of June. The Electricity Association will then distribute this report to its member companies for consideration. While it has not been possible to incorporate changes to the text of G77 prior to its publication it may be possible to enclose an addendum if a consensus is reached.

The HAZID exercise was successful in providing a wider perspective on the hazards associated with photovoltaic embedded generators. G77 or the IEE wiring regulations addresses many of the hazards identified. However, a number of specific areas were highlighted which need to be addressed to ensure safe installation and this work will be picked up by a further call for tenders from ETSU.

CONCLUSIONS AND RECOMMENDATIONS

The consultation process has led to a better understanding of the issues by the electricity and PV industry and this is reflected in the issue of G77 with a 'bedding in' period. There is a general consensus on the final document although its treatment of AC modules is not yet resolved.

It is expected that G77 will be published in May. The Electricity Association proposes to monitor its implementation over a period of 18 – 24 months and to then revise, if necessary, before it is formally referred to in the Distribution Code. There is therefore an opportunity to resolve the few remaining technical issues and learn from the benefit of experience.

In the interim a number of 'tools' have been produced that will make it easier for installers when designing and commissioning a PV system. This will help to remove some of the uncertainty concerning this 'new' technology and speed-up and standardise the procedure for applying for connection.

The consultation process and the HAZID exercise have resulted in a more comprehensive view of photovoltaic embedded generation and identified a number of areas where further work is needed, namely:

(i) Monitor the implementation of G77 during the 18-24 month 'bedding in' period
(ii) Conduct research to measure or model the impact of DC on the network and compare with other systems
(iii) Support input to the IEC Technical Committee 82 on Solar Photovoltaic Energy Systems
(iv) Underpinning research to the IEE Wiring Regulations work
(v) Develop guidelines and training programme for installers
(vi) Provide information for the Fire and Emergency services

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Appendices

GLOSSARY OF TERMS

AC	Alternating current
BIPV	Building integrated photovoltaics
BS	British Standard
BSRIA	Building Services Research and Information Association
CDM	Construction, Design and Management
CE mark	Mark indicating compliance of electric & electronic products with European directives
CHP	Combined Heat and Power
DC	Direct current
DIY	Do-it-yourself
DNO	Distribution Network Operator
DTI	Department of Trade and Industry
EA	Electricity Association
EMC	Electromagnetic Compatibility
EPSRC	Engineering and Physical Sciences Research Council
ESI	Electricity Supply Industry
HAZID	Hazard Assessment and Identification
IEA	International Energy Agency
IEC	International Electrotechnical Commission (standards)
IEE	Institution of Electrical Engineers
KVA	kilo Volt Amps
LV	Low Voltage (up to 11 kV)
MOSFET	Metal Oxide Silicon Field Effect Transistor
MV	Medium Voltage (up to 132 kV)
PES	Public Electricity Supplier
PME	Protective Multiple Earthing
PV	Photovoltaic
PVPS	Photovoltaic Power Systems Programme
PV-UK	British Photovoltaic Association
QRA	Quantitative Risk Assessment
R&D	Research and Development
RCD	Residual Current Device (protection)
REC	Regional Electricity Company
RMS	Root mean square (current)
ROCOF	Rate of change of frequency
STaR	Southampton photovoltaic Test and Reference facility
UL	Underwriters Laboratories (USA)
UPS	Uninterruptible Power Supply
V/F	Voltage/Frequency

1 INTRODUCTION

1.1 PREFACE

This report has been prepared as a part of the Department of Trade and Industry's New and Renewable Energy Programme, under Agreement No. S/P2/00332/00/00 with ETSU for the DTI. It constitutes the final report for the project "Industry Consultation on Grid Connection of Small PV Systems". The project was managed by Halcrow Gilbert with contributions from SunDog, Shell Renewables and Solar Century. The work was carried out between September 1999 and May 2000.

1.2 CONTENT

The report presents the results of consultation within the electricity supply industry and the PV industry concerning guidelines for the connection of small PV systems to the electricity network. In particular, consultation on the content of Engineering Recommendation G77 contributing to the final draft which is now being circulated for approval by the Electricity Association to its members.

Three specific areas of work were undertaken to increase the current understanding of the technical issues and support the consultation process. Chapter 3 presents the results of a survey of the present market for inverters; to be used as a reference until inverters have been type approved. Chapter 4 contains a comprehensive summary of the available information and current understanding of two key technical issues, namely the requirement for a mechanical disconnect and the proposed limit for DC injection, specified in G77. Chapter 5 presents the results of a hazard identification exercise for embedded photovoltaic systems.

The conclusions are listed in chapter 6, together with recommendations for further work in specific areas where there is deemed to be insufficient data or consensus at the present time.

1.3 BACKGROUND

A feasibility study several years ago [1] showed that there are no fundamental reasons why PV systems with DC/AC inverters cannot be connected to the electricity network [1]. However, there are regulatory requirements to be met and the electricity companies responsible for the local networks (Distribution

[1] In the UK the 'grid' refers exclusively to the high-voltage transmission system. Photovoltaic generators will not be connected to the grid but to the distribution network. However, in other countries the term 'grid' is often used to cover both transmission and distribution and hence the phrase grid-connected is frequently maintained in the literature.

Network Operators [2], DNOs) have concerns over safety and effects upon the quality of supply.

The connection of photovoltaic generators to the distribution network is covered, in principle, by Engineering Recommendation G59/1 [2]. However, whilst this document does consider single-phase LV connected generators such as PV systems, it was written mainly to cater for larger generators, which would typically be connected to the MV network (11 kV and above). The procedures laid down in G59/1 place a significant burden in terms of time on the technical engineering departments of electricity companies to ensure safe, competent installation of embedded generators. This is acceptable when dealing with a handful of larger (> 1 MW) schemes but is not appropriate for a larger number of small schemes.

At present there are few PV systems connected to the electricity network in the UK. However, programmes (such as the DTI's 100 roofs domestic field trial, Scolar, BP Solarex's 'Sunflower' project and Solar Century's Home Power) indicate that the DNOs can expect to receive a rapidly increasing number of requests for connection in the near future.

It was with these reasons in mind that, in 1995, a project [3] was started, with the objective of drafting a new industry standard specifically for small photovoltaic embedded generators. The work was carried out by EA Technology and Halcrow Gilbert and funded by the DTI. A major feature of the project was the establishment of a Consultation Group with representatives from the electricity supply industry. This raised awareness of the issues and helped in developing solutions. The work was supported by the Co-ordinated Experimental Research programme [4] (funded by the DTI and EPSRC) and links with the International Energy Agency's Photovoltaic Power Systems programme (Task V).

The work resulted in a draft document "UK Technical Guidelines for Inverter Connected Single Phase Photovoltaic (PV) Generators up to 5kVA". This was adopted by the Electricity Association as draft Engineering Recommendation G77 and circulated to its members in September 1998. Before agreeing the final draft, the G77 Working Group waited for the results of further work carried out under Phase II of the Co-ordinated Experimental Research programme by Southampton University. The aim of this work was to develop a type test procedure to enable manufacturers to check and ultimately to qualify their products to the requirements laid out in G77.

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[2] In the UK, a distinction is now drawn between Distribution and Supply. Therefore the term Distribution Network Operator is used to distinguish this from the other functions performed by the electricity companies

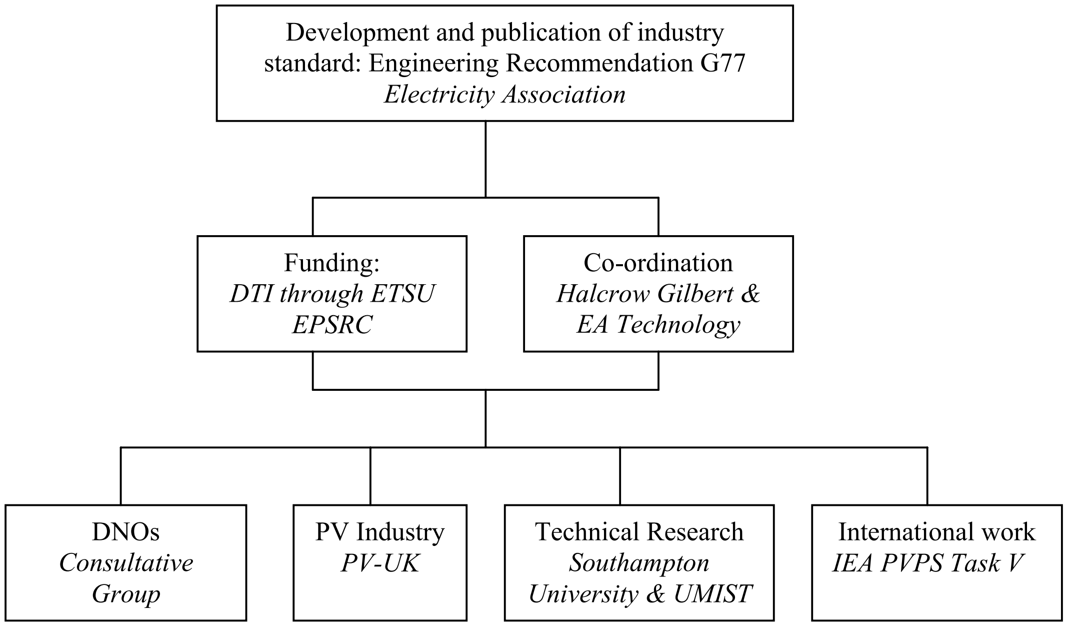

Figure 1: Consultation in the development of Engineering Recommendation G77

Throughout the development of G77 a delicate balance has had to be struck between the requirements of the DNOs and the needs of the PV industry. The DNOs are concerned primarily with power quality, reliability and the safety of the general public and personnel; the PV industry want open access to domestic electricity users with cost-effective products. The technical requirements being proposed by the DNOs are of particular concern to suppliers of PV systems with the integrated AC Module inverters. These are very compact, encapsulated and low cost units which, in the main, do not currently comply. The manufacturers state that compliance is either practically impossible or economically unacceptable. There is thought to be a huge market potential for these systems, including a DIY market, which leads to the prospect of illegal connections of equipment, which is unacceptable to the DNO. Tight regulations in the USA have led to a so-called 'guerrilla solar' movement, which connects systems without consulting with the DNOs. It is imperative that this situation is not replicated in the UK.

At a meeting on 23rd June 1999 at which both the electricity supply industry and the PV industry were represented, it was agreed that the G77 document needs to be developed such that all parties can fully endorse its application. Differences of opinion remained on certain technical aspects. The electricity supply industry stood by their view that they needed a document that would be acceptable to all the DNOs and safeguard their interests and obligations. The PV industry felt that the G77 document was unnecessarily restrictive and did not recognise modern safety technologies. At least in part, these differences arise from lack of access to the full information or from the non-availability of information. The electricity supply industry proposed to issue G77 at the earliest, whilst recognising that it might be revised within a year or two with more experience of installations and more technical evidence available. In view of the imminent applications for the connection of many more PV systems to the network it was agreed that these differences should be resolved as quickly as possible in order to allow expansion of the PV market in a desirable way.

The final resolution of these issues will have a profound effect on the future of domestic grid-connected PV systems in the UK and on the market opportunities for the UK PV industry. At present the non-uniformity of connection procedures across the country is a major barrier in the proliferation of the PV market.

Market development in the UK must be seen in the context of the increasing application of international standards and common products for European or international markets. The development of international standards for inverters is starting. A common understanding and uniform approach in the UK will greatly assist UK influence on international standards so that they become appropriate to UK conditions and acceptable here.

1.4 AIMS AND OBJECTIVES

The aim of this project was to contribute to the development of a final version of the draft Engineering Recommendation G77 that will be fully acceptable to the PV industry and the electricity supply industry. It draws together the items of work identified at the meeting of 23rd June.

The main objectives were:

- to enhance consultation between the PV industry and the electricity supply industry
- to improve the current information on the construction and performance of inverters now on the market, in relation to the requirements of the draft G77
- to estimate the cost of upgrading inverters to comply with G77
- to conduct a hazard assessment of inverters in grid connected mode in order to shed light on relative priorities for performance requirements
- to gather information on the outstanding technical issues, namely the injection of direct current into the grid and the necessity of using a mechanical break for isolation from the grid
- to review the information arising from the study with the intent to develop a redraft of G77 which will be fully acceptable to both industries

2 COMPLIANCE WITH G77

2.1 Key requirements of G77

Engineering Recommendation G77 [5] provides guidelines for the connection of inverter-connected single-phase photovoltaic (PV) generators up to 5 kVA to public distribution networks. G77 covers four main areas:

(i) Protection
(ii) Power Quality
(iii) Operation & Safety
(iv) Commissioning / Acceptance testing

These requirements form the basis for a type test for inverters, which is included as an appendix to G77. An inverter that passes the type test would then be regarded as acceptable for connection by the DNOs. The concept of a type test is widely used in industry: a type approval scheme requires that one or more samples of a product are tested and confirmed to meet the agreed requirements and further production is self certified to meet the same standards. The testing is usually carried out by an independent party.

An experimental procedure for type testing of inverters has recently been developed by Southampton University and is published by ETSU [6]**.** This does not limit the type testing of inverters to Southampton University; it is a procedure developed for the industry. It is not prescriptive (there may be more than one way of setting up a test circuit to check compliance with the type testing specifications in G77) but is an example that the industry may chose to make use of. The type test procedure at Southampton University has also been viewed by representatives from some of the DNOs and is deemed an acceptable test for inverters connected to their networks.

However, it is important to note that the use of a type-approved inverter is only part of G77 compliance. For example, the type test does not check whether a mechanical (as opposed to a solid state) relay is used or the location of the transformer. It is the responsibility of the installer to certify compliance with G77 when commissioning an installation.

The requirements of G77 are recognised to be more stringent than some standards that are currently in place in other countries, although other countries are still in the process of setting an industry standard. Therefore inverters manufactured for the German or Dutch market will not necessarily be acceptable in the UK. At present there is in fact only one UK inverter manufacturer and so it is inevitable that imported inverters will be widely used. In the absence of an international standard it was decided to conduct a preliminary survey of the inverters available on the world market to see which meet the requirements of G77 and, for those that don't, to estimate the cost of upgrading the inverter in order to comply with G77.

2.2 Market survey of inverters

The results of the market survey are presented in Table 1, together with a key of the symbols used, Table 2.

The inverter data table contains information on all the inverters that could be identified that would be applicable to the UK network. While every effort was made to find all suitable models, it cannot be guaranteed that every manufacturer is represented.

Also, every effort has been made to ensure the accuracy of the information in the table and information on the inverters was obtained directly from the manufacturers themselves. Where information was not available or provided by the manufacturers, the relevant cell has been left blank. A contact list for the manufacturers is provided in Appendix B so that the manufacturer can be contacted directly for further information.

Ultimately, it is intended to keep a constantly updated version of the table published on the PV-UK web site.

Table 1: Survey of inverters rated at 5kW or below

manufacturer	model	Power range (W)	Type tested	CE	Power quality	Power factor	V/F band	loss of mains	mech. Relay	DC inj.	man.	notes
Aixcon	PU	1k,1k5, 2k5		✓	✓	1	h	fs	✓	t	DEU	7
Aixcon	SUNstring	1.3k, 2.6k		✓	✓	1	h	fs	✓	t	DEU	7
ASP	Top Class Grid	1k4, 2k3, 3k5	w	✓	✓	1	✗	fs			CHE	6
Bahrmann	BWR	2k3		✓	✓	1					DEU	
Dorfmuller	DMI	150 – 550		✓	✓	1	s	fs	✗	t	DEU	4,7
Fronius	Sunrise	750, 1k, 1k5, 2k	w	✓	✓	1	s/h	fs	✓	t	AUT	
Futronics	Grid Con	800 - 5k0 (modular)	w		✓				✓	m	GBR	1
Hardmeier	Solcolino	200, 3k4		✓	✓		h	fs	✗	m	CHE	4
KACO	PVI	2k6		✓	✓	1	h	fs	✓	✗	DEU	5
Karschny Elektronik	Solwex	1k, 1k5, 2k, 3k, 3k5, 5k		✓	✓		✗	fs/r	✓	t	DEU	6
Mastervolt	Sunmaster	150, 300, 400, 600, 2k5		✓	✓	~1	s/h	fs	✓	t	NLD	7
NADA (Microtech)	PG	700, 1k5, 4k	✓	✓	✓	1	h	fs	✓	t	GBR	
NKF	OK4E	100		✓	✓	1	s	fs	✗	m	NLD	
SMA	Sunny Boy	700,850, 1k1, 2k5	w	✓	✓	1	s	r	✓	t	DEU	
SMA	Sunny Boy (TL)	1k5, 2k		✓	✓	1	s	r	✓	✗	DEU	
Solar Fabrik	Convert	1k, 2k, 4k		✓	✓	>0.98	✗	fs/r		t,m	DEU	2,7
Solar Konzept	SKN	1k,1k7,2k2,2k4		✓	✓	>0.9	s	fs/r	✓	m	DEU	3
Sollatek	TGIS	150	w	✓	✓	~1	s	fs	✓	m	GBR	1
Solon AG	NEG	1k6		✓	✓		s	fs/r	✓	t	DEU	7
Sun Power	SunProfi	1k2,1k7, 2k5		✓	✓	1	h	fs/r	✓	t	DEU	
Sunways	Sunways	2k2, 3k3, 5k		✓	✓		h	r	✓	✗	DEU	2
Trace Engineering	SW	2k5, 3k3, 4k5	w	✓	✓		s/h	ad		t	USA	
UfE	NEG	3k8		✓	✓		s	fs	✓	t	DEU	
Wurth Solar	WE	650, 4k8		✓	✓	1	✗	fs	✗	t,m	DEU	4,6,8

Table 2: Key for inverter survey

Type tested		based upon the G77 type test developed at Southampton University
	✓	indicates inverter has a type test certificate
	w	indicates manufacturers are actively working on G77 / type test approval
CE mark	✓	indicates inverter is CE marked
Power Quality[3]	✓	indicates that the inverter meets the harmonics, voltage flicker and electromagnetic compatibility standards defined within G77
Power factor		displays the inverter power factor (G77 requires a power factor > 0.95)
V/F band		indicates whether the inverter can be set to meet the voltage and frequency limits prescribed in G77
	s	indicates that this can be set through software
	h	indicates that this is available only via a hardware alteration
Loss of mains		describes any method that the inverter uses to detect a loss of mains (G77 requires loss of mains protection in addition to the V/F band).
	fs	indicates the inverter performs a frequency shift
	r	indicates that the inverter monitors rate of change of frequency (ROCOF)
	a	indicates the inverter uses an accelerated drift method (USA)
		Note: many inverters can utilise the German ENS MSD method - however as this is deemed unacceptable under G77, this is not indicated in the table.
Mech. relay	✓	indicates that the inverter incorporates a mechanical relay to IEC 255 to perform automatic disconnection as required in G77
DC injection	**t**	indicates that the inverter has a transformer output stage (inherently no DC problems)
	m	indicates that constant ongoing monitoring occurs to ensure that DC injection is kept at or below a set value that is less than or equal to 5mA, as required in G77
Man.		indicates country of manufacture
Notes	1	Inverter under development
	2	Fmin can not be set as low as 47Hz
	3	DC output is monitored for within the inverter but level not disclosed
	4	Inverters use a relay with unknown status re. IEC255
	5	No transformer or monitoring for DC output. However, manufacturer claims DC injection not possible due to design of inverter.
	6	Frequency band currently outside G77 limits
	7	Available with this configuration as a special order
	8	Voltage band can not be set as wide as G77 limits

Further explanation of the above terms is provided in Appendix A

[3] Note: In the absence of type approved inverters, compliance with standards for harmonics, voltage flicker and electromagnetic compatibility is inferred from the EMC Directive, which is covered by the CE mark. This is an assumption, but a reasonable one considering that the CE mark transfers liability to the manufacturer.

2.3 Cost of components

Some inverters do not at present comply with G77. In the long term it is likely that inverter manufacturers will decide whether or not it is worth their while adapting their product in order to enter the UK market and there will be a number of products to choose from that comply with G77. In the interim, non-compliant inverters could be used provided that other components are added on, namely mechanical relays to IEC 255 and isolation transformers to prevent DC injection. These would, however, add significantly to the total cost of the inverter.

2.3.1 Disconnect relays

Disconnect relays can be split into four separate groups:

(i) Under/over voltage relay - These relays will operate when the grid voltage falls above or below set limits. Limits are typically adjustable via potentiometers on the relay.

Prices vary considerably, but start from ~ £120

(ii) Under/over frequency relay - These relays will operate when the grid frequency falls above or below set limits. Limits are typically adjustable via potentiometers on the relay.

Prices vary considerably, but start from ~ £160

(iii) Loss of mains relay - The function of these relays is to detect islanding operation of the connected generator. Commonly available as one or a combination of two types: rate of change of frequency (ROCOF) relays, or Vector shift relays.

ROCOF relays operate by monitoring the rate of change of mains frequency with respect to time (∗f/∗t). The relay will operate if ∗f/∗t exceeds a preset limit. The limit is measured in Hz/s and can typically be set via a potentiometer on the relay.

Vector shift relays monitor the length of each mains cycle. Operation of the relay occurs if there is a step change in the length of a cycle(s). The step change is measured in degrees and can be typically set via a potentiometer on the relay.

Prices vary considerably, but start from ~ £320

(iv) Combined or "G59" relay package - Most companies offer packages of a combination of the above relays. A package that includes all three categories of relay would provide full protection under G77. A complete set of such relays is commonly packaged under "G59".

Prices vary considerably, but start from ~ £530 for a full G59 package

Notes:

- Most relays are supplied as control relays only - they are designed to supply a control signal to operate a main contactor / circuit breaker. This main contactor would be situated between the inverter and point of connection to the grid.
- As standard, most relays require a manual reset after operation. Auto reset types are available as a special from some manufacturers. Other types can be reset by the addition of extra control circuitry.

Contact details for suppliers of disconnect relays are provided in Appendix C.

2.3.2 Isolation Transformers

The cost of a 240/240 50 Hz transformer obviously depends on the power rating. Prices depend on:
(i) whether the power rating is a standard size or has to be custom made
(ii) whether the transformers are bought in bulk

Prices start at:
£ 30 - 150 VA
£ 100 - 1 kVA
£ 270 - 5 kVA

These prices are inclusive of VAT.

Contact details for suppliers are provided in appendix D.

3 DISCUSSION OF TECHNICAL ISSUES IN G77

3.1 Introduction

The final version of Engineering Recommendations G77 has been accepted by the DNOs and, largely, by the PV industry. However, there are three key areas where the basis for the recommendations given in G77 is unclear:

(i) loss of main protection
(ii) mechanical contacts for automatic disconnection
(iii) DC injection

In each case discussion is based around two central themes - safety and cost. While no one in the PV industry would wish to compromise safety, the industry is concerned that a high level of protection is achieved through a cost effective and appropriate technical solution.

Loss of mains protection is being analysed in more detail under another project to assess the risk of islanded operation [ETSU Project No: S/P2/0310/00/00 Strategic Photovoltaic Network Study]. Additional data has been collected, and is presented below, on the issues of mechanical disconnect and DC injection.

3.2 Mechanical disconnect

3.2.1 Background

G77 presently requires that the automatic disconnection function be performed by the use of a *mechanical relay* to IEC 255-5[7] (G77 section 3.2). The use of electronic disconnection, i.e. the use of *semiconductor switching*, is precluded.

The automatic disconnection function within an inverter is typically achieved by microprocessor monitoring and control circuits operating an internal relay. While it is relatively common for larger inverters to use a mechanical relay, some inverters use semiconductor switching.

3.2.2 Potential for failure

A relay may fail in either the open or closed position. An inverter relay failing in the open position presents no safety implications. However, a relay failing in the closed position presents serious safety implications as the inverter may continue to operate during a mains failure or out of bounds condition.

A mechanical relay may fail in the closed position due to the contacts welding together. Manufacturing defects, inductive surges, long term use or overloading can cause such failure.

A semiconductor relay may also fail in the closed position. This can be caused by similar events to those affecting a mechanical relay.

In addition, the circuits controlling any relay (mechanical or semiconductor), must be considered. In order to function, an inverter must have sense circuits connected downstream (grid side) of any control relay. These sense circuits are in turn connected to control circuits that operate the relay. These sense and control circuits must be able to withstand the same network disturbances as specified for the relay. Failure of these circuits could also lead to an inverter failing to disconnect during a mains failure or out of bounds condition.

3.2.3 Why consider semiconductor designs?

A significant category of inverters, AC module inverters, are currently only available with a semiconductor relay. While ultimately AC module inverters may become available with a mechanical relay, presently G77 effectively outlaws the use of AC modules.

Such units are becoming popular, are available at a relatively low price and are easy to install. They are readily available on the European market and from the World Wide Web. By outlawing their use there is the potential for "Guerrilla Solar" - systems installed without the knowledge or consent of the DNO.

Manufacturers with products utilising a semiconductor relay are also concerned by this clause in G77. With a strong case being available for the safety and reliability of semiconductor switches, they see this clause as restrictive to fair trade.

3.2.4 The case for semiconductor switching

It is important to stress that manufacturers of inverters featuring semiconductor switching are not asking for a relaxation of the safety protection measures contained within G77. What is being requested is that semiconductor switching can be considered providing it meets the safety standard.

For example, the manufacturer of a leading AC inverter (NKF) outlines a strong case for the use of a semiconductor switch. They claim that their design is as safe or better to that utilising a mechanical relay. With a mechanical relay there is the potential for welded contacts. While the use of high quality and appropriate relays may minimise this hazard it cannot be entirely avoided. They claim that their design is better as it meets the same standards and, in addition, has a backup failsafe protection.

The output of this inverter is formed of four MOSFETS operating as an "unfolding bridge". Each of these MOSFETS are switched on and off 50 times a second. Failure of any one of these MOSFETS to switch off causes very high currents to flow resulting in the blowing of an internal fuse. Failure of a mechanical relay is only apparent when the inverter fails to switch off following a fault. In this design a fault is instantly detected as the switch is "checked" 50 times a second.

This inverter has been tested and approved in many countries, including the US where it has the appropriate UL listing. During tests for the UL listing, MOSFET failures were simulated and in each case the internal fuse blew.

3.2.5 An alternative approach

Engineering Recommendation G77 specifies that an inverter must utilise a mechanical disconnect to IEC255-5. It has been noted however, that this requirement does not take into account the circuit operating the relay and may not provide the degree of protection required. An inverter containing a relay rated itself to IEC255-5 may be unsatisfactory if the inverter sense and control circuits are vulnerable to network disturbances. Potentially, inverters with a flaw such as this could pass through G77 and the associated type test as they currently exist.

It has been suggested that a better approach would be to specify parameters that the whole inverter must withstand. This would be a blanket requirement for the inverter sense, control and operating circuits as well as the relay itself. Such requirements could be measured by tests additional to the existing G77 type tests. These tests could be drawn from the tests contained within IEC255-5. In such a way the entire inverter performance could be addressed within G77. This approach would mirror that taken in other countries, such as the American UL1741.

This would be an approach based on setting safety standards, a normal method to ensure product safety and performance. This approach would not be technology specific and would leave the door open, while ensuring safety, for alternative inverter design strategies, including those utilising semiconductor switching. This approach would also catch any designs that appear nominally safe but are in fact vulnerable to network disturbance. It would also greatly simplify the policing of this important safety issue.

3.2.6 Experimental work

In order to validate this approach experimental testing was performed. The tests specified in IEC255-5 are broadly categorised as Insulation Tests and can be broken down into three separate tests:

- Measurement of insulation resistance
- Dielectric (steady state) voltage withstand tests
- Impulse voltage tests

A test schedule, based on these tests, was drafted and passed to selected Electricity Company representatives for comment. Test voltages were selected to be consistent with equivalent relay tests. Similarly, as for the equivalent relay tests, the inverter was not required to be operating during the tests. The resulting test schedule provides a template for undertaking such tests on an entire inverter (Appendix H).

Following this, an NKF OK4E 100W inverter was put through the tests. This is an "AC module" inverter that utilises semiconductor switching rather than a mechanical relay. The tests were performed at the high voltage test laboratory at E.A.Technology. Results of these tests can be seen in Appendix H.

The experimental work showed that the testing process was found to be straightforward, required fairly standard test equipment and took about 3 hours to complete. The test was seen to be readily applicable to an entire inverter. Furthermore, as can be seen from the test report the inverter withstood all dielectric and impulse voltage tests. This inverter had previously been used to evaluate the G77 type tests where it was observed to pass all the tests. This is then an inverter that has been seen to pass a G77 type test and also the test schedule drawn from IEC255-5.

3.2.7 Comment

There is a strong case that can be made for the reliability and safety of inverter designs utilising semiconductor switching. There is also a clear imperative, from the potential for Guerrilla Solar and the desire for equal access to the market, to consider these alternatives.

Semiconductor switching goes against the history of mechanical relays that have been used to disconnect and isolate rotating plant. However, new innovative and perhaps safer strategies are being built into some inverters. G77 must set the minimum safety requirements, but this should be achieved in a way that is not restrictive to certain design approaches.

As it currently stands, G77 may not provide the degree of protection envisaged. Inverter designs that appear nominally safe but are in fact vulnerable to network disturbance could pass through the existing framework. In addition, the presence or otherwise of a relay to IEC255-5 and the robustness of the control circuits may prove difficult to police.

As an alternative way forward a test schedule has been drafted to address these issues. This has seen to be a straightforward set of tests readily applicable to an entire inverter. By adopting this alternative approach it may be possible to leave the door open to alternative inverter designs, including semiconductor switching, whilst tightening and ensuring the overall safety performance.

3.2.8 Recommendations

(i) That the test schedule drafted during this work be developed and considered as an alternative to the present requirement within G77 for a mechanical relay to IEC 255-5. These tests to form an addition to the existing G77 type tests.

(ii) That in the interim, while the above points are progressed, semiconductor designs are permitted for connection providing they: a) have passed the G77 type test; b) when installed, the system is fitted with an external relay between the inverter(s) and the point of connection to the grid. This relay to be to IEC255 and to operate on loss of mains only.

3.3 DC injection

3.3.1 Cause

If all connections to the network are made to passive devices (such as resistors, capacitors or inductors) or via a transformer then this precludes the injection of DC current into the distribution network. However, the network is now active and with modern electronics it is possible to design inverters that can interface directly to the network. These use digital control of the sampled output current to limit the emission of DC. So called 'transformerless inverters' are increasingly being used for PV systems because of technical and economic advantages: lower cost, smaller in size and weight and higher efficiency. However, the absence of a transformer implies an inherent risk (however small) of a residual DC output current.

The origin (or potential origin) of the DC component stems from two mechanisms [8]: a device failure connecting the grid to an internal DC link voltage (this would most likely blow the mandatory fuse) or a slight asymmetry between positive and negative half waves.

Earlier work [4] has suggested that because the DC component from an inverter is normally distributed with zero mean, the net DC bias from a large number of inverters should be zero. However, further work at STaR (Southampton

Test and Reference facility) has shown that what was previously thought to be pure DC from inverters is in fact very low frequency AC – typically between 0.2 and 0.5 Hz. While this registers as a DC current on normal measuring instruments, upon further inspection it could be clearly seen to oscillate. Subsequent to this finding, a definition of DC was added to the final version of G77:

> 'DC: a unidirectional current in which the changes in value are either zero or so small that they may be neglected. As ordinarily used the term designates a practically non-pulsating current.' [Emphasis added]

3.3.2 Consequences - impact of DC on an AC network

DC currents (like harmonics) are regarded as 'pollution' on the network. There are three possible adverse effects:

(i) Saturation of transformers
A DC current will disturb the operation of the 'upstream' distribution transformer. It can shift the transformer's operating point so that it is operating outside the normal hysteresis cycle. This could saturate the transformer, which would result in a high primary current that may trip the fuse and thus cause a power outage to that section of the network. Secondary effects may be to reduce the life of the transformer and increase losses.

(ii) Cable corrosion
DC causes cathodic corrosion of the cable, possibly shortening the life of the cable quite dramatically. This could constitute a safety hazard because of the Protective Multiple Earthing (PME) that is used for the majority of domestic electrical supplies in the UK.
The supply cables have a combined neutral and earth, which is earthed at various (multiple) points along the network. The PME is not allowed to be used outside of the equipotential zone due to the possibility that a fault could raise the potential of the earth or remote structure relative to the PME, thus exposing a person to differential potentials within touch zones. Such a fault could result from the corrosion of the neutral / earth producing a potential difference between the installation and the earth (the earth may now be a higher resistance path than the original). This would therefore constitute a safety hazard to people outside the equipotential zone i.e. outside the building.

(iii) RCD's
The operation of RCD's may be adversely affected by the presence of DC offset currents. These residual current devices provide protection in low voltage circuits and so this should be examined.

It is not yet known what significance low frequency AC, as opposed to true DC, has in terms of the impact on the network.

DC injection from inverters is not viewed as a significant hazard on other countries' networks and their standards reflect this. A report produced by the IEA PVPS programme [8] concludes that 'the pulsed DC component may reach significant levels without jeopardising the proper operation of the transformer' and 'a general requirement for isolation transformers for PV inverters is not justified'. However, the effect of DC on the UK network is believed to be different because the transformers used in the UK are more susceptible to DC and because of the PME system that is unique to the UK.

Some research has been carried out by EA Technology, on behalf of the DNOs, on the impact of DC on the network. Unfortunately this information has not been released for publication. The Electricity Association are currently monitoring DC traction systems (motors) that are connected to the network as these are known to be a problem.

3.3.3 Existing control

Engineering Recommendation G5/3 "Limits for harmonics in the UK electricity supply system" [9] deprecates (disapproves) the use of equipment that produces a DC component in the AC supply. This effectively states that DC should be zero.

3.3.4 Proposed control

In developing G77, some members of the Working Group expressed the view that the allowed DC component from inverters should be 'zero' as in G5/3. However, it was not wished to place too onerous a constraint on manufacturers by precluding the use of transformerless inverters. The following recommendation is made in G77:

> 'It is recommended that a transformer be installed between the inverter and the DNO's distribution system to prevent DC from entering the distribution system. However, if a DC detection device is installed at the point of connection on the AC side then the transformer may be omitted; provided that the output of the inverter(s) is disconnected if the level of DC injection exceeds 5mA.'

3.3.5 Equivalence

Other devices that are connected to the network inject high levels of DC. In a sample report of power quality in buildings, produced by BSRIA [10], the following DC levels were found in an office building:

Lighting	0.34 A DC (0.53% of rms current)

Computers (each)	laptop 0.04 A DC (7.7% of rms current)
	Desktop 0.03 A Dc (11.2% of rms current)

There is no existing limit for DC (other than G5/3). The proposed limit of 5mA in G77 is based on IEC 61000-3-2 [11], which sets limits for harmonic current emissions for equipment below 16A. Class C equipment (lighting) sets a limit of 2% of the input current (at the fundamental frequency) for the 2nd harmonic. For a 60W filament lamp (standard reference item) 2% current input equals 5.21mA at 230V. Note that the absolute limit for a 60W lamp is applied to G77 rather than the percentage limit specified in IEC 61000-3-2. A 5mA limit for a generator of several kWs is rather more onerous than the same limit for a 60W light bulb.

3.3.6 An achievable limit?

The preliminary testing of inverters at STaR (Southampton Test and Reference facility) has shown that inverters without a transformer do not pass the 5mA level. The only exceptions (so far) are the very small AC Module inverters, which are typically of 100 – 200W. Therefore, despite the fact that G77 does not prescribe the use of an isolation transformer, in practice this is required for current design practices. This adds significantly to the cost of the inverter. One inverter manufacturer stated that the isolation transformer used in their product comprises approximately 15% of the total material cost. This is because a very high efficiency transformer must be used to maintain the overall high efficiency of the inverter.

Apart from the challenge of designing an inverter that can pass this limit there are two further areas of concern:

(i) The accuracy with which the DC component can be measured
(ii) Possible drift over time

5mA equates to 0.025 % of the rms output current for a 5kW system. One inverter manufacturer commented: 'this limit is simply not measurable with but the best equipment available. You might measure 5mA even if in reality there is nothing at all because of the noise of the measurement.' Another inverter manufacturer suggested that the 0.5% level specified in UL1741[12] (the equivalent US standard) was ‘at the realms of possible design’ and that 5mA would be impossibly expensive to detect. Claims that such a small current would be very difficult to measure are supported by BS EN 61000-3-2. This sets limits for harmonic current emissions and states that:

> ‘Harmonic currents less than 0.6 % of the input current measured under the test conditions, or less than 5mA, whichever is greater, are disregarded.’

G77 requires that the output of the inverter is disconnected if the level of DC injection exceeds 5mA. This implies that the output is continuously monitored to check whether it complies and is not covered by the type test which only checks the DC output at a particular instance in time. There is concern that an inverter that is once approved for connection may, six months later, no longer be acceptable. As yet there is little experience of installing PV systems in the UK to meet the G77 standard and it is possible that all transformerless inverters installed now could automatically disconnect in say two years time because they no longer comply. Furthermore, it is possible that the current sensor used as part of the closed-loop control would itself need continuously recalibrating to maintain such a sensitive measurement. The measuring instrument could be offset due to age and / or temperature. Therefore, the current could drift outside 5mA and fail to be detected.

The design of an inverter that can achieve the performance required in G77 is being researched at the Department of Electrical & Electronic Engineering, University of Newcastle upon Tyne. The Department is currently one year into a three year research programme funded by EPSRC (the Engineering and Physical Sciences Research Council), with industrial partners (including NADA) and contribution in kind from the DNOs. The aim of the programme is to identify all the factors within the inverter that could, potentially, lead to DC and harmonic emission and to then explore ideas for eliminating / reducing these emissions. Ideas being explored include a possible self-calibrating inverter such that the DC output always tends to zero and is not liable to drift, and a method for desychronising inverters such that the cumulative effect on the network is zero.

3.3.7 Summary

The impact of G77 will be to force inverter manufacturers to use an isolation transformer, which in turn keeps the price of inverters high and precludes the use of AC modules.

The limit of 5mA of DC specified in G77 is not based on strong evidence that such a level constitutes a hazard. It is a precaution based on concern that DC like harmonics is causing a degradation of the network, but this effect has not been quantified. Furthermore, other devices that are already connected, such as lighting, inject significant quantities of DC into the network.

There is concern that a current of 5 mA (0.025 % of the rms. current for a 5 kVA system) is simply not measurable and, furthermore, that an inverter that passed the type test may easily drift outside this limit six months later. These issues are being investigated by the Department of Electrical & Electronic Engineering at the University of Newcastle upon Tyne. The research project is due to run for another two years although preliminary results may be available before then.

The following recommendations are made:

(i) The rationale for setting the DC limit of 0.5 % in UL 1741 is investigated

(ii) Research is carried out to assess whether this would be a suitable limit for the UK. It is necessary to monitor the DC component that already exists and quantify the potential impact of additional DC injected into the network (including the consequences of injecting very low frequency, as opposed to pure DC).

(iii) The effect on residual current protective devices should be taken into account.

4 HAZARD ASSESSMENT

4.1 Aim

The aim of this study was to identify and assess all hazards associated with photovoltaic embedded power generation along with an initial look at controls that could be applied and equivalence to other situations. This would be the first step in a full analysis including quantification of residual risk once alleviating measures were in place.

A risk assessment of islanded operation of PV inverters is being undertaken as part of another project (PV Strategic Network Study, ETSU S/P2/0310/00/00). The DNOs are very concerned about islanding, but it is thought to be an extremely rare event and it may be receiving unbalanced consideration when there are other, higher, risk, hazards not yet identified. The aim of the study was to carry out a more holistic exercise in order to identify and consider a much wider range of hazards such as component failure, grid supply failure and other events that might create a hazard. It is critical that any hazards associated with using PV as an additional source of power generation are understood and the risks effectively controlled before there is a rapid escalation of implementation in the UK.

4.2 HAZID approach

Following the Piper Alpha tragedy that took place in the UK offshore oil and gas industry, the UK government established the Better Regulation Task Force as recommended by Lord Cullen in his accident review. This Task Force has been working with the oil and gas industry to help materially improve safety. One main outcome has been the establishment of a Hazard Management System that is founded on a number of principles.

- Transparency
- Accountability
- Targeting
- Consistency
- Proportionality

The Hazard Management System is broken down into a number of practical steps that can be applied to situations to help identify then manage the hazards and risks. These steps are:

IDENTIFY	Identify and agree hazards, hazardous events to both individuals and product
ASSESS	Assess frequency and consequences of hazardous events
CONTROL	Identify measures to prevent hazardous event occurring
RECOVER	Identify measures to limit consequences if hazardous event occurs

Although the Hazard Management approach was developed primarily for the oil and gas sector, it can equally be applied - albeit in an abbreviated form - to the electricity industry. Specifically it was felt appropriate to use the same methodology to help determine the risks associated with the grid-connection of photovoltaic systems.

4.3 Method

The approach adopted was to execute a facilitated brainstorm so as to identify the hazards, possible hazardous events, their causes and potential consequences. Where existing controls were available, these were recorded; where control exist for comparable hazards these were identified and their equivalence discussed. Controls were reviewed both with regard to their potential to prevent the hazardous event occurring and to limit the consequences if it does occur.

Hazards to PV and power supply equipment and quality of power supply were addressed in addition to hazards to people. Hazards to people considered risks to people on the premises where the PV equipment is installed, people maintaining the power supply network and other third parties.

Codes and standards, good practice and engineering judgement [13] are significant contributors to risk decision making, particularly where the hazards are well understood.

The 5 principles outlined in the Better Regulation Task Force Review [14] were used as guidelines:

Transparent	Controls must be simple and clear
Accountable	Stakeholders must have been consulted
Targeted	Controls must set clear goals incorporating future flexibility, and not adopt a scatter gun approach
Consistent	Controls must conform to EU and existing regulations
Proportional	Controls must strike the right balance between risk and cost

A two day workshop was held in October 1999 in the Shell Centre, London. The range of stakeholders was represented with participants from the Electricity Association, the DNOs (London Electricity and SWALEC), Solar Century, SunDog, Halcrow Gilbert and Shell UK. Hazard management and electrical engineering expertise was provided to facilitate the process.

The system configuration used to initiate the discussion is shown in Figure 2. It is based on the arrangement shown in IEC 61277.

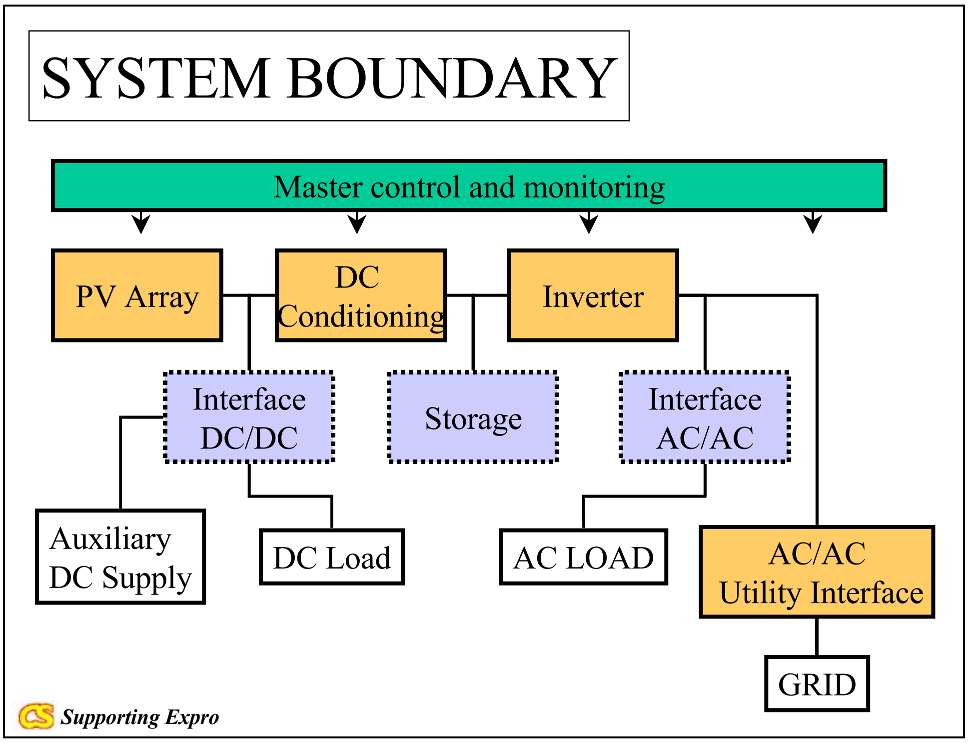

Figure 2- Conceptual PV Arrangement

The following technical specification was considered as representative:
Rated Output: up to 5kVA
Phases: single phase
Output Voltage: to national Standards

Energy Storage: not provided

This was considered as the base case. No stipulations were made concerning the precise design of the inverter or the arrangement of the components making up the PV system. No fundamentally different issues were raised for systems where energy storage was present.

Where existing controls were available, these were recorded. Where controls exist for comparable hazards these were identified and their equivalence discussed. Controls were reviewed both with regard to their potential to prevent the hazardous event occurring and to limit the consequence if it does occur.

4.4 Hazards identified for PV embedded generators

A range of potential hazards were identified for PV embedded generators:

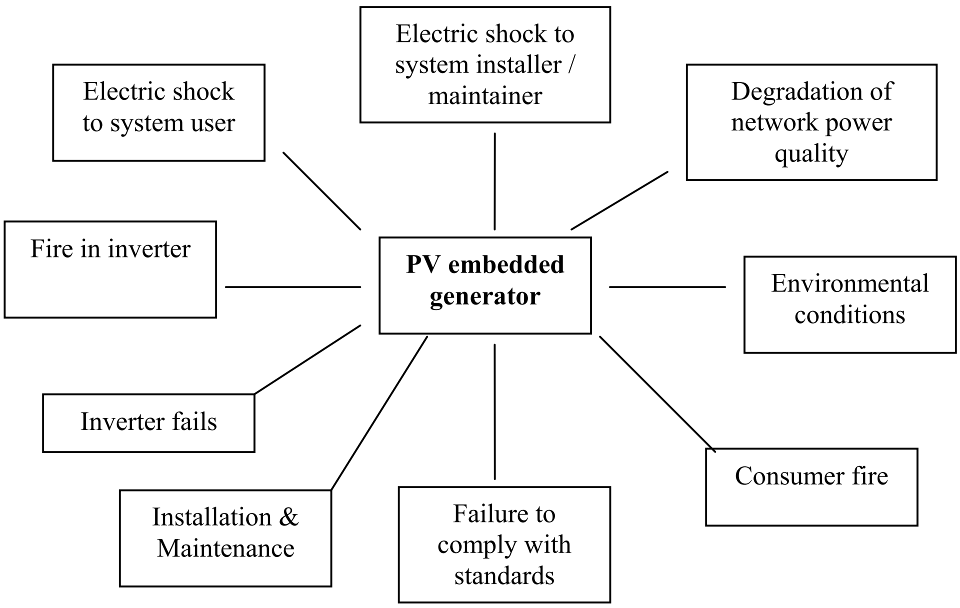

Figure 3: Hazards associated with PV embedded generation

The key results are summarised in Table 3 (a complete record of the HAZID workshop is presented in Appendix E).

Table 3: Summary of results form HAZID exercise

Hazard	Cause	Controls
DC[4] Electric shock to system user	Failure to effectively isolate all sources of energy	Technically possible to put isolator at PV array and at inverter. Additionally possible to use double insulated cables. Required in wiring regs and draft IEC regs. No British standard exists and there is no recognised qualification for installers. Legal requirement to contact electricity company, but this can be difficult to enforce. Solutions being captured in IEC 60364-7-712 which is being drafted.
	Failure of DC component or DC wiring	Core sizes and cable types will be addresses in IEC guidance.
	Lack of understanding of DC potential hazards to system users	
	Use of wrong equipment. DC equipment not readily available. AC switches do not work in DC service	Selection of components should be by competent installers. For DIY markets, a complete package of components is proposed.
	AC supply into DC system	
AC Electric shock to system user	Shock from PV array frame in the event of neutral failure with PME arrangements	Risks assessed as part of G77 development
AC Electric Shock to system maintainer / installer	Failure to isolate effectively all sources of energy. Maintainer may not realise there are 2 isolators so the system is still energised. (Note Dutch practice where local panels are plugged directly into the mains with a switched plug)	G77 has only one typical connection detail. Alternative arrangements are technically feasible.
	Inverter not effectively isolated from AC supply. On loss of mains, if the PV system is not	

[4] Note: The effect of DC on the human body is different to AC. A DC current contracts muscles and prevents releasing the source and thus generally constitutes a greater threat at the same voltage

Hazard	Cause	Controls
	disconnected, supply could be backfed into the main If islanding possible and protection device fails, or takes too long to operate Use of items not approved for connection in the UK	 *See separate study* IEC is addressing global market. PV industry is assessing inverter compliance against G77
Damage to equipment connected to power system	Lightning hitting PV array; possible induced current from nearby equipment	No risk or difference in risk. Inverters already tested to industry standard
Fire in inverter	Out of synchronised power supply on auto-reconnection	Specification of inverter must withstand 180 ^{0} out of phase if inverter takes greater than 0.5 s to disconnect. If outside of specification, inverters individually tested.
Inverter fails	Cross polarity as a result of incorrect installation	Training of installers
Degradation in network power quality	Over voltage due to protection failure at end of line	Some inverters have duplicate trip protection. Increased failure rate of users' equipment. Voltage will exceed statutory limits. On detection, failure of inverter will be identified and inverter is replaced
	Under voltage	Limits set in G77
	Over frequency	Limits set in G77
	Under frequency	Limits set in G77
	Harmonic voltages	Limits set in G77
	DC supply into mains	G77 recommends that transformers are installed between the inverter and the ac connection to act as a DC block. Transformers are sometimes included in the inverter, but to be fully effective the transformers must be after the last stage of DC output. Alternatively, continuous DC monitoring arrangements are permitted. G77 also specifies a maximum dc current

Hazard	Cause	Controls
	Voltage spikes from AC side Voltage dip due to distribution network disturbance (short term loss of supply)	(5mA). This is tested in G77 inverter tests. Inverter is normally fused on AC side Most domestic electrical equipment is designed to operate through short-term disturbances. Internal protection matches output voltage and phase to that of incoming mains supply.
Installation & Maintenance	Falls, electrocution etc Falls during cleaning PV array	No different to other DIY risk on roof
Consumer fire	Increased isolation points if batteries being supplied. Live DC wiring Fire spread via PV array – lack of fire resistance	
Environmental conditions	Fatigue loads from wind etc. No established practices. Planning regs. not invoked	Tested in accordance with roofing tests
Failure to comply with standards	Difficult to comply with standards?	

4.5 <u>Recommendations</u>

A number of opportunities for improvement were identified in the HAZID Workshop; these are grouped under three common themes below:

Accreditation/Training

(i) Develop an overall system for guiding and ensuring the safe and technically appropriate growth of the PV industry in the UK including:
   a) Identification / establishment of competent bodies as a technical focus for PV issues;
   b) Consolidation of standards applicable to PVs and establishment of interim technical guidelines where inadequacies are identified;
   c) Establishment of best practice for design and installation;
   d) Establishment of an agreed syllabus for training and its recognition by existing recognised bodies;

(ii) Develop a standard application form on which users can apply to the local DNO for network connection of a PV system. This form, for use either by registered installers or individuals, should also include a Contact List for the DNOs PV connection representative.

(iii) Product literature and training of installers should identify and highlight specific hazards associated with DC currents.

(iv) Product literature should include suggested standard fixing details to assist installers in mounting the PV units safely and securely.

(v) Contacts should be established with suppliers to the DIY market to determine the sort of package that would be acceptable to be offered to that market.

Technical Proposals

(vi) Include a fuse on the DC side as part of standard details for multiple string arrangements. (suggested change to IEC 60364-7-712) [15]

(vii) Produce typical connection details for all the points at which it is likely that a PV installation could be connected to a consumer's system, and evaluate the safety of each and the limits of rating for which the arrangement may be suitable.

(viii) The present Quantitative Risk Assessment (QRA) study into the 'islanding' phenomenon should include an assessment of the frequency with which this is likely to occur.

(ix) Tripping of the PV system on variation of voltage or frequency outside the proposed 'window' may be better considered a network control function rather than a safety function. Complete loss of supply is seen as having more safety connotations. Agree functional requirements for when a mechanical isolation is required for safety reasons with the G77 committee.

(x) Where a transformer is not used to block the path for DC current into the AC mains, additional evidence is needed on the effectiveness of the inverter designs used to prevent DC supply into the AC mains. Evidence should consider any changes in the DC transmission with age of the device (e.g. from accelerated life tests) to allow the requirement for ongoing continuous DC monitoring to be reconsidered. A common consensus was not achieved on this point because some electrical loads already in widespread use may already have a similar effect on the grid DC component and the need for ongoing monitoring was seen inconsistent with the approach taken with harmonics. This point therefore requires further investigation and review.

(xi) Data on inverter tests, which address the consequences of surge voltages with the DC side live, should be collected. These tests are to consider the likelihood of inverter damage from disturbances in the mains.

'Emergency Services' issues

(xii) Discuss with the Fire and other Emergency services the nature of PV arrays and associated circuits, and issues relating to isolation and fire fighting in buildings equipped with a PV installation.

5. INDUSTRY CONSULTATION

5.1 Programme of consultation

A programme of consultation has been ongoing since 1996, organised by Halcrow Gilbert, under the title of the RECs' Consultative Group. However, it was felt that there had been insufficient dialogue to allow the views of the PV industry to be taken into account. One of the objectives of this project was to provide a forum for the PV industry to contribute towards discussions concerning G77 and other related issues. Consultation took place both formally (through a series of meetings) and informally (through e-mails and telephone conversations):

- September 1999: RECs Consultative Group meeting , London
- October 1999: Type test workshop, University of Southampton
- October 1999: HAZID workshop, Shell Centre, London
- December 1999: PV industry consultation & PV-UK meeting, London
- March 2000: Joint PV / ESI Workshop: 'Installing PV to G77', London

5.2 Results

The results of the market survey of inverters, the technical research relating to G77 and the HAZID exercise were used to stimulate discussion. In effect a wide range of issues have been considered and debated, reflecting the different interests of the various stakeholders. These are summarised below.

5.2.1 Technical issues relating to the requirements of G77

The guidelines set out in G77 set limits which inverter manufacturers must achieve. At present there is only one inverter manufacturer in the UK (NADA, formerly trading as MicroTech) although at least two other companies (Futronics and Sollatek) are developing a product suitable for the grid-connection market. Design limitations will have price implications for the manufacturers of inverters and hence a knock-on effect on the total system cost. There are concerns that if (as appears to be the case) G77 is more stringent than comparable standards in other countries then it may put the UK PV industry at a competitive disadvantage. G77 also, in its present form, prevents the use of AC modules because of the requirement for a mechanical relay to IEC 255. It is expected that AC modules will capture a large proportion of the building-integrated PV market in the near future and to restrict the use of AC modules in the UK would be a serious blow to the UK PV industry. The debate concerning the two contentious issues, mechanical disconnect and DC injection, is presented more fully in chapter 3.

G77 contains a 'typical circuit diagram'. While it is recognised that other arrangements are possible there was concern that the circuit diagram in G77 would be taken as the approved way for wiring an installation. It was suggested that alternative wiring arrangements could be included in G77. In particular there is a need to consider the opportunity for connecting a PV array directly to the ring mains. In the Netherlands up to 600 W can be 'plugged in' directly with 16 A protection. The safety of this approach needs to be evaluated for the UK and guidelines developed if necessary. With a large future market for AC modules it is likely that many PV systems in the future will be connected in this way.

The potential hazard of somebody outside the building i.e. outside the equipotential zone, being in contact with an array that was earthed to the PME source was discussed although there was a general consensus that the existing regulations are appropriate.

5.2.2 Type testing of inverters

The scope and protocol for type testing was discussed. The type test does not cover environmental testing or efficiency but it is expected that the inverter manufacturer will cover such tests before sending his product to STaR, for instance to meet the CE mark. Eventually it is anticipated that there will be a comprehensive European standard covering all aspects of an inverter's performance. A manufacturer is not required to send more than one sample or to randomly select a sample for type testing, as it is not in the manufacturers interests to deliberately mislead and there is no evidence to suggest that this has been a problem.

A type-approved inverter may not always contain the same software setting, for example voltage protection. It was suggested that a separate test certificate is issued by the test centre for each different setting. If necessary the DNO could request a print out of the software settings at commissioning.

It was observed that type approval is only part of G77 compliance. For example, the type test does not check whether a mechanical (as opposed to a solid-state) relay is used or the location of the transformer. It is therefore the installers' responsibility to self certify when completing the commissioning.

The type test procedure developed at Southampton has been witnessed and approved by representatives from the DNOs although no inverters have yet been certified. NADA have adopted this test procedure to test their own products. Testing of a NADA inverter (that has been used on the Scolar programme) was witnessed and approved by representatives from some of the DNOs in February 2000.

5.2.3 Simplified and standardised connection procedure

At present the DNOs generally require inspection of an installation prior to connecting to their network. As the number of PV installations applying for connection proliferates this will soon become impractical and an excessive burden on the DNOs' work load. It was appreciated that a single quality assurance certificate, produced as a result of factory testing, would not be sufficient as equipment may have been damaged en route or poorly installed. It was suggested that a standard commissioning form could be produced, for completion by the installer. One copy would be sent to the DNO and one copy possibly to PV-UK who would keep a database on the PV installations in the UK. (A pro forma for applying for connection and commissioning is included as Appendix F to this report, together with a contact list for the various DNOs – Appendix G).

It was suggested that the PV-UK website could / should be used to share information so that installers can find out which DNOs have accepted which inverters for connection. Although the DNOs have had G77 in its draft form for the past two years the willingness of the DNOs to accept inverters for connection seems to have varied considerably. This situation should alter when more inverters have been type tested, but in the interim there is no reason why PV-UK, as a trade association, can not be used to share such information.

5.2.4 Training and accreditation of installers

However carefully the guidelines for installing PV systems are developed; connection to the network will depend ultimately on the competency of the electrical installer. At present there are very few installers experienced with wiring PV systems in the UK and as it varies in several fundamental aspects from other electrical installations (e.g. the requirement for DC wiring) there is a need for training. This has proved to be a major constraint in the installation of systems under the Scolar programme. This was discussed at the HAZID workshop – see chapter 4 – and has already been taken forward by a Special Working Group within PV-UK. It was recognised that there are several key elements: developing training material and a syllabus, running a training course, and finally accreditation of trained installers. It is important that all three strands of work are developed in turn.

5.2.5 Role of PV-UK

It was suggested that as the PV industry continues to expand, the British Photovoltaic Association (PV-UK) would be best placed to co-ordinate the work, act as a central database and disseminate information within the industry.

It has been recognised for some time that for PV-UK to be active and credible as a trade association it must be independent and on a firm financial base. The type of activity suggested here clearly would add to credibility of the Association but the cost of doing so remains an issue until more income to the Association is secured.

5.2.6 Opportunity for improving power quality

To date work has focused on minimising the possible negative impact of PV inverters on the network, and this is the role of standards such as G77. However, it has been suggested that static inverters could be used to actually improve the power quality.

G77 specifies that the power factor shall be in the range of 0.95 leading to unity relative to the DNO's supply. This is because a low power factor (signifying a larger proportion of reactive power) would produce heating and losses on the network. While inverters can produce an output within this range, they can equally be adjusted to produce a lagging power factor to compensate for the reactive power that already exists on the network. The DNOs require the use of capacitors where connection of equipment causes power of an unacceptable quality. However, using inverters to perform this task simply requires a software adjustment rather than new hardware. Also, the inverter setting could be continuously monitored and controlled remotely to maintain optimum power quality. In a similar way, an inverter can be used as an active harmonic filter since the phase difference can be controlled.

The issue seems to be one of control: the DNOs have no control over embedded generators connected to their network and are thus wary of the quality of power injected onto their system. However, with the rapid growth in embedded generation predicted, access to the 'wires' will become more and more open. Embedded generation could be viewed as an opportunity rather than a threat, if it is used strategically. Of course, it is true that given the present penetration of PV in the UK the issue is somewhat hypothetical, but in the future the use of inverters to improve power quality may be an attractive option.

5.2.7 Other embedded generators

A similar process to the drafting of G77 is now being undertaken for other small generators such as fuel cells or micro-CHP. When the development of G77 began it was discussed whether it could be guidelines for the connection of small generators via inverters in general, but it was decided to limit its scope to just photovoltaic inverters. Although much of G77 will be useful for the development of parallel standards, the Electricity Association argue that it can not be applied directly, as some other embedded generators may not be inverter-connected.

5.2.8 Metering and Tariffs

Although outside the scope of this work, commercial and tariff issues associated with the export of electricity from PV systems to the local network were discussed. Now that the potential for installing PV systems on buildings in the UK is being realised (through organisations such as Solar Century and programmes such as Scolar) this is likely to receive increasing attention in the near future, especially as the impact of the New Electricity Trading Arrangements (NETA) is felt.

Regarding metering, it was noted that the half-hourly meters, which are required by some DNOs, are comparatively very expensive for small generators such as PV. As for the negotiation of a tariff the value of PV-generated electricity was debated. From the utility perspective the increase in embedded generation invokes extra work for the DNO in terms of managing, controlling and integrating the network and this should be reflected in the tariff rates. Furthermore there should be a connection charge since PV generators are effectively using the grid as a back up and it is not a free resource. From the perspective of the PV industry, the new Utility Bill results in a difference in the value of ‘green’ as opposed to ‘brown’ electricity and this should also be reflected in the tariff offered to PV generators.

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Engineering Recommendation G77

6.1.1 Publication of G77

A final draft of Engineering Recommendation G77 has been produced by the Electricity Association and was circulated to its members for approval in February 2000. This has now been approved by the DNOs and the EA expect to issue the final document in May.

The publication of G77 represents a milestone in the development of photovoltaic embedded generation in the UK. While two technical areas, namely the requirement for mechanical relays and the control of DC injection, continue to be debated (see sections 6.1.4 and 6.1.5) there is a general consensus on the guidance given in G77. Its success is largely due to the constructive debate and discussion that has taken place between the electricity industry and PV industry.

Due to the current limited experience in connecting PV systems in the UK and the continuing input from this and parallel projects, it was decided to allow an 18 – 24 month monitoring period after publication of G77. The EA will monitor its implementation and revise, if necessary, before seeking its inclusion in the Distribution Code.

6.1.2 Simplified connection procedure

G77 is designed to simplify the process of connecting PV systems to the network and ensure that a uniform approach is adopted across the UK. To further this aim, it was recognised that a standard form for applying for connection and commissioning of an installation would be very useful. Such forms have been developed and reviewed by members of the DNOs. Though they will not be attached to G77, they have been informally approved by the EA. It is recommended that these forms are published on the PV-UK website so that they are easily accessible to PV installers. In addition a list of contact points for each of the DNOs has been compiled so that PV installers know whom to contact when applying for connection. It is recommended that installers establish contact with the appropriate DNO at an early stage of the project design.

6.1.3 Approved inverters

The UK manufacturer, NADA, has successfully type tested one of their inverters to the standard outlined in G77. Although the process for type testing at STaR (at the University of Southampton) has been approved, STaR have not yet certified any of the inverters tested.

In the interim, a survey of the inverter market was undertaken. A list of all the inverter manufacturers was compiled, together with contact details for these manufacturers. The technical performance of these inverters was analysed against the key criteria in G77. This will be a useful tool for installers in selecting an appropriate inverter, until more inverters have been type tested and certified. It is recommended that these results are published on the PV-UK website so that they are easily accessible.

Using a type approved inverter is only part of G77 compliance. For example, the type test does not specify the disconnect relay or the location of the isolation transformer. Where an inverter does not meet the requirements of G77 it may be possible to add other components, such as a disconnect relay or isolation transformer, such that the requirements are satisfied. Quotes were obtained for such components. However, it was found that they add significantly to the total cost of the inverter (especially for one-off purchases).

6.1.4 Mechanical vs. solid-state disconnect

G77 presently requires that the automatic disconnection be performed by the use of a mechanical relay to IEC 255-5. However, there is a strong case for the reliability and safety of inverter design utilising semiconductor switching.

For example, the OK4-100 inverter produced by NKF (which uses semiconductor switching) passed the equivalent US standard test UL1741 which is a very comprehensive series of tests for inverters [16]. This inverter has also been observed to pass both the G77 type test and a new set of tests, developed during this project, applying the standards contained within IEC255-5 to the whole inverter.

Furthermore, G77 may not provide the degree of protection envisaged. An inverter containing a relay rated itself to IEC255-5 but with flawed grid monitoring and control circuits vulnerable to network disturbances, could pass through G77 and the associated type test as they currently exist. In addition, the presence or otherwise of a relay to IEC255-5 and the robustness of the control circuits may prove difficult to police.

It has been suggested that a better approach would be to specify parameters that the whole inverter must withstand. This would be a blanket requirement for the whole inverter. Such requirements could be measured by tests additional to the existing G77 type tests. In such a way the entire inverter performance could be properly addressed and policed within the G77 framework. This approach would mirror that taken in other countries, such as the American UL1741.

The test schedule, drawn from the tests contained within IEC255-5 and validated during experimental testing, was seen to be a straightforward set of tests readily applicable to an entire inverter.

By adopting this alternative approach it may be possible to leave the door open to alternative inverter designs, including semiconductor switching, whilst tightening and ensuring the overall safety performance.

It is recommended that:

(i) That the test schedule drafted during this work be developed and considered as an alternative to the present requirement within G77 for a mechanical relay to IEC 255-5. These tests to form an addition to the existing G77 type tests.

(ii) In the interim, while the above points are progressed, semiconductor designs are permitted for connection providing they: a) have passed the G77 type test; b) when installed, the system is fitted with an external relay between the inverter(s) and the point of connection to the grid. This relay to be to IEC 255 and to operate on loss of mains only.

6.1.5 DC injection

The limit of 5 mA of DC specified in G77 is not based on strong evidence that such a level constitutes a hazard. It is a precaution based on concern that DC, like harmonics, is causing a degradation of the network but this effect has not been quantified. Furthermore, other devices that are already connected to the network, such as lighting, are responsible for injecting significant quantities of DC into the network.

The UL1741 test specifies a DC limit of 0.5 % of the rms. current (equating to 109 mA for a 5 kVA, 230 V system). This was submitted to the relevant international standards committee (IEC TC 82) in 1998 for consideration as an IEC standard and is currently being reviewed. There will be pressure on the UK to conform to this standard unless a valid justification for setting a more stringent limit is put forward.

The following recommendations are made:

(i) The rationale for setting the DC limit of 0.5 % in UL 1741 is investigated

(ii) Research is carried out to assess whether this would be a suitable limit for the UK. It is necessary to monitor the DC component that already exists and quantify the potential impact of additional DC injected into the network (including the consequences of injecting very low frequency, as opposed to pure DC).

(iii) The effect on residual current protection devices is investigated.

6.1.6 Future changes to G77

AC modules are particularly suited for integration into buildings because of their modularity (allowing easy system expansion) and simplicity of connection (potentially available as a DIY product). They are typically rated between 100 to 300 W. The present requirement in G77 for a mechanical relay and a DC limit of 5 mA (which effectively necessitates an isolation transformer) precludes the use of AC modules in the UK. By outlawing their use there is concern that the ‘guerilla solar’ movement in the US could be replicated in the UK – that is systems being installed without the knowledge or consent of the DNO. It is therefore a matter of urgency to resolve these issues.

The argument for testing the entire inverter to the same requirements specified for a mechanical relay was present at a meeting to the G77 Consultative Group on 2 May 2000. It was agreed that the test schedule, laboratory data and other supporting data would be pulled together into a formal report for submission to the Electricity Association by the end of June. The Electricity Association will then distribute this report to its member companies for consideration. While it has not been possible to incorporate changes to the text of G77 prior to its publication it may be possible to enclose an addendum if a consensus is reached.

6.2 Identification of hazards

A Hazard management approach, that has been tried and tested in the oil and gas sector, was used to identify all potential hazards associated with embedded photovoltaic systems. The methodology focused the attention on the hazard and hazardous event rather than on the consequence or controls. This helped to provide a broader view of risk management rather than focusing solely on the risk associated with islanded operation, which has already been studied in depth.

Many of the potential hazards are already covered under G77, the IEE wiring regulations or by research carried out under this project. However, a number of specific areas were highlighted that could be improved:

- Develop guidelines and training for installers of PV systems
- Evaluate the safety of alternative connection arrangements
- Include a fuse on the DC side as part of standard details for multiple string arrangements (Suggested change to the Wiring Regs)
- Collect data on the likelihood of inverter damage from disturbance in the mains

- Discuss the nature of PV arrays with the Fire & Emergency services

6.3 Further work

The PV industry in the UK has grown, and is growing, very rapidly. It is important that the development of guidelines and standards keeps pace with this to ensure that systems are installed safely and appropriately and there are no unnecessary barriers to market expansion. The following recommendations for further work are based on the results of research and consultation carried out within this project:

(i) Monitor the implementation of G77
It is not presumed that, now G77 is ready for publication, everything about the connection of PV systems is known. It is recommended that the use of G77 is monitored by contact with installers and DNOs and through the DTI large-scale BIPV and domestic field trials. It is proposed that the Consultative Group meet at 6 monthly intervals throughout the 'bedding in' period to review G77 in the light of experience. The Consultative Group will also provide a forum for resolving the issues of mechanical disconnect and DC injection.

(ii) Conduct research to measure or model the impact of DC on the network, especially low-frequency AC. Of particular concern is the possibility that RCDs (residual current devices) within the home could be saturated.

(iii) Input to IEC Technical Committee No. 82 ("Solar Photovoltaic Energy Systems"). UL1741,'Electrical Safety of Static Inverters and Charge Controllers for use in PV Power Systems', has been approved as a new work item (Ref. 82/210/NP). It is important that the UK plays an active role in the development of this and other proposed international standards so that they reflect the needs and concerns of UK industry.

(iv) Underpinning research to the IEC /IEE Wiring Regulations work. A further section (7-712) on photovoltaic power supply systems is being drafted under the chapter on 'special installations'. Topics that need to be considered include alternative installation diagrams, AC modules local connection to building, DIY installation and selection of system components e.g. DC switches, cables.

(v) Develop installation guidelines and training programme for installers. One of the key outcomes of the HAZID exercise was the urgent need for appropriate guidelines and training for installers. This has been taken forward by a special working group within PV-UK. The following areas of work have been identified:

- Produce an authoritative installation guide that pulls together all the relevant information on the installation of a grid connected PV system in the UK. While much of this information already exists, it is spread across a number of different documents. Also the relevant chapter in the Wiring Regs. (7-712) does not stand as an independent document and supplementary text is required.
- Produce a short, more readable guide to the above suitable for DIY installers. This would summarise the information, clearly defining the particular safety issues and point the reader towards sources of further information. This could be supplied as part of DIY kits.
- Prepare a syllabus and material for a training course based on the above material.
- Develop a process for accrediting installers. This might involve National Inspection Council for Electrical Installation Contracting (NICEIC) once the guidance is adopted into the IEE Regs.

(vi) Provide information for the Fire and emergency services on the nature of PV arrays and associated circuits and issues relating to isolation and fire fighting in buildings equipped with a PV installation.

While the focus of this work has been on developing appropriate guidelines for installing PV systems in the UK, consultation within the industry highlighted a wider range of issues such as the role of PV-UK, opportunities for improving power quality, guidelines for other embedded generators (based perhaps on G77), metering and tariffs.

7 REFERENCES

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[2] Electricity Association Engineering Recommendations G59/1, "Recommendations for the connection of embedded generating plant to the Regional Electricity Companies distribution systems", 1991

[3] EA Technology, "Low-Voltage Grid-Connection of Photovoltaic Power Systems", ETSU Report S/P2/00215, 1999

[4] Halcrow Gilbert, "Co-ordinated Experimental Research into PV Power Interaction with the Supply Network – Phase 1", ETSU Report S/P2/00233 1999

[5] Engineering Recommendation G77: Recommendations for the Connection of Inverter-Connected Single-Phase Photovoltaic (PV) Generators up to 5kVA to Public Distribution Networks, *due to be published by the Electricity Association in May 2000*

[6] Halcrow Gilbert, "Co-ordinated Experimental Research into PV Power Interaction with the Supply Network – Phase 2", ETSU Report S/P2/00233/2, 2000

[7] IEC 255-5:1977 (BS 5992 Part 3) Electrical Relays, Part 3 Specification for the insulation testing of electrical relays

[8] IEA-PVPS Report T5-01: 1998 "Utility aspects of grid connected photovoltaic power systems": December 1998

[9] Engineering Recommendation G5/3 Limits for harmonics in the United Kingdom Electricity Supply System, Electricity Association 1976

[10] BSRIA: Power quality Survey at **** House (for further information contact Colin Pearson at BSRIA)

[11] BS EN 61000-3-2: Electromagnetic Compatibility (EMC) Part 3 Limits , Section 2:Limits for harmonic current emissions (equipment input current ≤ 16 A per phase)

[12] UL1741 (Underwriters Laboratories) Standard for Static Inverters and Charge Controller for use in Photovoltaic Power Systems, ISBN 07629 0421 6, May 1999

[13] Industry Guidelines on A Framework for Risk Related Decision Support, Issue No.1, 1999. Published by UKOOA

[14] Better Regulation Task Force Review, April 1999. Published by Central Office of information, ISBN:0 7115 0378 8

[15] IEC 60364-7-712 Electrical Installations of Buildings (Part 7: Requirements for special installations or locations - Section 712: Photovoltaic power supply systems), 1997

[16] UL Report on Photovoltaic Static Inverters for NKF Kabel B V, File E188194, Project 97NK35957, 1998

8 ACKNOWLEDGEMENTS

The project was led by Halcrow Gilbert with sub-contractors SunDog (Martin Cotterell), Shell UK (Stefano Gambro) and Solar Century (Daniel Davies). However, the work would not have been possible without the wider participation of the PV industry, representatives from the electricity companies, EA Technology and the Electricity Association. Their time and input into the various meetings and discussions is gratefully acknowledged.

APPENDIX A G77 EXPLANATORY NOTES

CE mark

All electric and electronic equipment to be sold within the European Community must possess a CE mark. It proves to the buyer that the product meets all essential safety and environmental requirements as they are defined in the European Directives appropriate to that product. There are two Directives relevant to power supplies:

i) 73/23/EEC, the Low Voltage Directive
ii) 89/336/EEC, the Electromagnetic Compatibility Directive

The Directives' requirements are not expressed in terms of limits and tests to be performed but mainly describe the effect the Directive should have. Limits and test methods are left over to the market, by means of European standards to be applied.

Power quality

The 'quality' of the output waveform from the inverter is described in terms of five quantities: harmonic emissions, voltage flicker, electromagnetic compatibility, power factor and DC injection (the latter two are considered separately).

i) Harmonics are disturbances on the ideal sine wave at multiples of the fundamental (50 Hz) frequency. They are viewed as a form of 'electrical pollution' on the network since they provide no useful benefits but their existence can cause losses in the distribution system, overheating of network components and possible harm to equipment connected to it.
ii) Flicker, as the name suggests, is associated with lighting and is caused by periodic voltage fluctuations. The eye is particularly sensitive to fluctuations in the range 1 Hz to 10 Hz, where fluctuations of 1 % or less can be detected by the human eye. Concerns over flicker are much greater in other European countries, mainly because of differences in electrical network configurations. Voltage flicker is not likely to be a concern with PV systems because of the high quality of the waveform control.
iii) All electrical and electronic equipment must comply with international standards limiting the electromagnetic radiation and be immune to background electromagnetic radiation.

The inverter type test checks the performance of inverters against international standards for harmonics, voltage flicker and electromagnetic compatibility. In the absence of type approved inverters, compliance with these standards is inferred from the EMC-Directive, which is covered by the CE mark. This is an assumption but a reasonable one considering that the CE mark transfers liability to the manufacturer.

Power factor The power factor indicates the ratio of real power to reactive power. Reactive power can produce adverse effects on the utility's equipment and other loads connected to the network. Therefore the power factor should be as close to unity as possible. G77 requires that: the power factor shall be within the range of 0.95 leading to unity relative to the DNO supply.

Voltage/ Frequency Band The voltage must be 230 V ± 10%, and the frequency 50 Hz +1%,-6%. G77 requires that the PV generator disconnects if the operating voltage and frequency moves outside the tolerance band. It also requires that the voltage and frequency limit settings should not be capable of adjustment by the user.

Loss of mains protection Loss of mains protection is required to prevent the inverter continuing to provide power to the 'local' network after the local network has become disconnected from the main supply system. This condition is known as 'islanding'.

Mechanical relay G77 requires that when the PV system is disconnected the disconnection is achieved by the separation of mechanical contacts to the requirements set out in IEC 255-5:1977.

DC injection In addition to minimising the output of harmonic currents the inverter should not emit direct current (DC) into the distribution system. DC can give rise to technical problems. The problem of DC can be removed by installing an isolation transformer between the inverter and the network. Recognising that this will not always be the case, G77 requires that the inverter disconnects if the output of DC exceeds 5mA.

APPENDIX B Inverter Manufacturers

1. Aixcon Elektrotechnik GmbH
   Tel: 09195 9494-0
   Fax: 09195 9494-290

2. ASP
   Hauptrasse 36b
   CH - 8637
   Laupen/ZH
   Switzerland
   Tel: 055 246 4114
   Fax: 055 246 4116

3. Bahrmann
   Im Vogelsang 1
   71101 Schnaich
   Germany
   Tel: 07031 630202
   Fax: 07031 653946

4. Dorfmuller Solaranlagen GmbH
   Gottl. Daimler Str. 15
   71394 Kernen
   Germany
   Tel: 07151 94905-0
   Fax: 07151 94905-40

5. Fronius
   Guenter Fronius Strasse 1
   A - 4600 Wels - Thalheim
   Austria
   www.fronius.com

6. Futronics Power Designs
   Futronics House
   1 Wheatcroft Terrace
   Much Hadham
   Hertfordshire
   SG10 6AP
   Tel: 01279 843128
   Fax: 01279 841103
   Email: info@futronics.co.uk
   www.futronics.co.uk

7. Hardmeier Electronics
   Weststrasse 115
   Ch - 8404 Winterthur
   Switzerland
   Tel: 052 222 0526

Fax: 052 222 88 48
Email: mail@hardmeier-electronics.ch

8. KACO
Kreuzackerstrasse 35
74081 Heilbronn
Germany
Tel: 7131 58952-0
Email: Kacowerk@aol.com

9. Karschny Elektronik
Caalenberger Strasse 28
30169 Hannover
Germany
Tel: 0511 1317190
Fax: 0511 1317192
Email: mail@alfasolar.de
www.alfasolar.de

10. Mastervolt
Snijderbergweg 93
1105 AN
Amsterdam
Netherlands
Tel: 020 342 2180
Fax: 020 342 2188
Email: info@mastervolt.com
www.mastervolt.com

11. NADA (formerly trading as MicroTech)
Unit 13
Hawks Road
Gateshead
Tyne & Wear
HE8 3BT
UK
Tel: 0191 477 4755
Fax: 0191 477 8733
www.nada.uk.co

12. NKF Electronics
Schieweg 9
PO Box 26
2600 MC Delft
The Netherlands
Tel: 015 260 5905
Fax: 015 261 5489
Email: electronics@nkf.nl
www.nkf.nl/electronics

13. SMA
Rosendahl Industrievertretungen
Adolf Dembach Str.1
D - 47829 Krefeld
Germany
Tel: 02151/456789-0
Fax: 02151/456789-9
Email: ri@sma.de
www.sma.de

14. Solar Fabrik GmbH
Munzinger Str.10
D - 79111 Freiburg
Germany
Tel: 0761 4000-0
Fax: 0761 4000-199
www.solar-fabik.de

15. Solar Konzept
51405 Bergisch Gladbach
Germany
Tel: 02204 8440 40
Fax: 02204 8440 44

16. Sollatek
Unit 4/5 Trident Industrial Estate
Blackthorne Road
Poyle
Slough
SL3 0AX
UK
Tel: 01753 688300
Fax: 01753 685306
Email: solar@sollatek.com
www.sollatek.com

17. Solon AG
Schelesische Strasse 27
D - 10997 Berlin
Germany
Tel: 03061 0709-0
Fax: 03061 0709-99
Email: solonag:solonag.com
www.solonag.com

18. Sun Power Solartechnik GmbH
Marktplaz 2-4
D - 61118 Bad Vilbel
Germany
Tel: 06101 584550

Fax: 06101 584560
Email: sales@sunpower.de
www.sunpower.de

19. Sunways AG
Macairestrasse 5
D - 78467 Konstanz
Germany
Tel: 07531 99677-0
Fax: 07531 99677-10
Email: infor@sunways.de
www.sunways.de

20. Trace Engineering
5916 195th NE
Arlington
Washington
98223 USA
Tel: 360 435 8826
Fax: 360 435 2229
www.traceengineering.com

21. UfE Solar GmbH
Alfred Nobel Str.1
16225 Eberswalde
Germany
Tel: +49 39395 81914
Fax: +49 39395 81442

22. Wurth Solar
Abteilung Systemtechnik
Ludwigsburger Str.100
71672 Marbach am Neckar
Germany
Tel: 07144 9414-20
Fax: 07144 9414-29
www.wuerth-electronik.de

APPENDIX C SUPPLIERS OF DISCONNECT RELAYS

1 **ABB Control**
Stonefield Works, Oulton Road, Stone, Staffs, ST15 0RS
Tel: 01785 82 5050
Fax: 01785 82 5117

2 **AVK SEG UK**
Powersystems House, Manor Courtyard, Hughenden Ave,
High Wycombe, HP13 5RE
Tel: 01494 435 600
Fax: 01494 435 610

3 **Crompton Instruments**
Freebournes Rd, Witham, Essex, CM8 3AH
Tel: 01376 512601
Fax: 01376 518320

4 **GEC**
St Leonards Works, St Leonards Ave, Stafford, ST17 4LX
Tel: 01785 223 251
Fax: 01785 236 800

5 **PBSI**
Bellevue works, Boundary St, Manchester, M12 5NG
Tel: 0161 230 6363
Fax: 0161 230 6464

6 **Precision Controls**
20 Broadhurst Street, Stockport, Cheshire, SK3 8JH
Tel: 0161 476 4606
Fax: 0161 476 5639

7 **Siemens**
Sir William Siemens House, Princess Rd, Manchester, M20 2UR
Tel: 0161 446 5130

8 **Vetech Reyrolle protection**
PO Box 8, Hebburn, Tyne &Wear, NE31 1TZ
Tel: 0191 401 5255
Fax: 0191 401 5575

APPENDIX D SUPPLIERS OF ISOLATION TRANSFORMERS

1 **Carroll & Meynell Ltd**
Portrack Grange Road
Stockton-on-Tees
TS18 2PF
Tel 01642 617 406
Fax 01642 614 178
E-mail Carrmey@aol.com

2 **XP plc**
Horseshoe park
Pangbourne
Berkshire
RG8 7JW
Tel 0118 984 5515
Fax 0118 984 3423
E-mail sales@xpplc.co.uk

3 **Lintron**
Tel 01670 713 312

APPENDIX E RESULTS OF HAZID WORKSHOP

HAZARD	HAZARDOUS EVENT	CAUSE	CONSEQUENCE	EXISTING/POSSIBLE CONTROLS	EQUIVELENCE	ACTION
Current-DC	Electric Shock to System User	Failure to effectively isolate all sources of energy. Impossible to isolate PV array and fuse will not protect this circuit	DC current contracts muscles and prevents releasing source. Current above level capable of causing harm. Increased potential from falling	Technically possible to put isolator at PV array and at inverter. Additionally possible to use double insulated cables. Required in wiring regs and draft IEC regs. No British standard exists and there is no recognised qualification for installers. Legal requirement to contact electricity company, but this can be difficult to enforce. Solutions being captured in IEC60364-7-712 which is being drafted		Develop circulation list of installers to ensure good practice is followed as IEC 60364-7-712 is drafted. Consider developing equivalent accreditation for installers of PV systems as for conventional systems. Jointly develop standard application form and contact list for installation , either by DIY or registered installer and approval by DNO/PES
	Electric Shock to System User	Failure of DC component or DC wiring	DC current contracts muscles. Current will be above level capable of causing harm	Core sizes and cable types will be addressed in IEC guidance. See above		See above

HAZARD	HAZARDOUS EVENT	CAUSE	CONSEQUENCE	EXISTING/POSSIBLE CONTROLS	EQUIVELENCE	ACTION
	Electric Shock to System User	Lack of understanding of DC potential hazards to system users	DC current contracts muscles. Current will be above level capable of causing harm			Include nature of DC hazards in product literature and training of installers.
	Electric Shock to System User	Use of wrong equipment. DC equipment not readily available. AC switches do not work in DC service	DC current contracts muscles. Current will be above level capable of causing harm.	Selection of components should be by competent installers. For DIY markets, a complete package of components is proposed.		Suggest to PV UK that they establish contacts with DIY market to assist in determining contents of package DIY
	AC supply into DC system	Inverter failure	DC system does not always have fuse protection. Fuse on AC side would blow			Include fuse on DC side as part of standard details for multiple string arrangements (in IEC 60364-7-712)
Current-AC	Electric Shock to System User	Shock from PV array frame in the event of neutral failure with PME arrangements	AC shock.	Risks assessed as part of G77 development	Deemed no more than comparable equipment such as outside taps, metal windows by considering the PV array as bonded	

HAZARD	HAZARDOUS EVENT	CAUSE	CONSEQUENCE	EXISTING/POSSIBLE CONTROLS	EQUIVELENCE	ACTION
	Electric Shock to System Maintainer/ installer	Failure to isolate effectively all sources of energy. Maintainer may not realise there are 2 isolators so the system is still energised. (Note Dutch practice where local panels are plugged directly into the mains with a switched plug)	AC shock	G77 has only one typical connection detail. Alternative arrangements are technically feasible		Assess alternative connection details and their technical viability. G77 to review at next meeting (Circa April 2000)
Various	Islanding		May lead to deterioration in power quality and re-connection problems	Islanding is subject to a separate study		
	Electric Shock to System Maintainer/ installer	Can occur if Islanding possible and protection device fails, or takes too long to operate	AC shock	Islanding risks being assessed in detailed QRA		As part of QRA study include an assessment of the frequency of islanding occurring

HAZARD	HAZARDOUS EVENT	CAUSE	CONSEQUENCE	EXISTING/POSSIBLE CONTROLS	EQUIVELENCE	ACTION
	Use of items not approved for connection in UK.	Available on global market and may be imported.	AC shock, Equipment not tested. Potential to feed back into network. Risk to members of public when LV line is down but being back fed from unauthorised users. (Current DNO work practice is to test lines prior to working on them)	IEC is addressing global market. PV industry is assessing inverter compliance against G77.	Portable generators can be misused and connected to the mains but will not work in parallel with mains.	
Voltage Levels	Damage to equipment connected to power system	Lightning hitting PV array. Possible induced current from nearby equipment	Direct hit to PV array destroys array. Voltage surges attenuated in AC system. Surge performance criteria referenced in G77 and	No or difference in risk. Inverters already tested to industry standard		

HAZARD	HAZARDOUS EVENT	CAUSE	CONSEQUENCE	EXISTING/POSSIBLE CONTROLS	EQUIVELENCE	ACTION
	Fire in inverter	Out of synchronised power supply on auto- reconnection	Fire damage	Specification of inverter must withstand 180 deg out of phase if inverter takes greater than ½ second to disconnect. If outside of specification, inverters individually tested.		
	Inverter fails	Cross polarity as a result of incorrect installation		See above for installation competencies	As above	
	Inverter not effectively isolated from AC supply	G77 requires Mechanical disconnection in additional to functionality as in IEC 255. BS7671 provides insufficient guidance regarding the use of solid state as a disconnection method.	The primary safety concern appears to be on loss of mains, if the PV system is not disconnected, supply could be backfed into the main. This requires confirmation.	An additional relay (loss of main or under frequency) could be designed to provide a physical disconnection if the only function is mains disconnection. If over and under voltage (or frequency) is a control function and not a safety function, then this arrangement may be acceptable.		Agree functional requirements for isolation requirements (eg is voltage/frequency tripping control or safety function). Present alternative relay arrangements to G77 for approval
Network Power Quality	Over voltage	Protection failure at inverter at end of line. Some inverters have duplicate trip protection	Increased voltage in distribution system upstream of other inverters.	Increased failure rate of users' equipment. Voltage will exceed statutory limits. On detection, failure of inverter will be identified and inverter is replaced		

HAZARD	HAZARDOUS EVENT	CAUSE	CONSEQUENCE	EXISTING/POSSIBLE CONTROLS	EQUIVELENCE	ACTION
	Under Voltage	Inverter protection will trip at agreed low voltage level. Would require also require co-incident loss of mains	No consequence to PV equipment but potential damage to system users. Potential to assist grid on under voltage in mains	Under voltage limits set in G77		
	Over frequency			Limits set in G77		
	DC supply into AC mains	AC output off spec	DC increases corrosion potential.	G77 recommends that transformers are installed between the inverter and the ac connection to act as a DC block. Transformers are sometimes included in the inverter, but to be fully effective the transformers must be after the last stage of DC output. Alternatively continuous DC monitoring arrangements are permitted. G77 also specifies a maximum DC current (5mA). This is tested in G77 inverter tests	Normal lighting gear injects a DC component and does not require ongoing DC monitoring. Its approval was based on prototype testing. Other inverter operational parameters do not require ongoing monitoring.	Develop evidence to support type testing and review the need for ongoing continuous DC monitoring (Required when transformer not fitted)
	Under frequency			Limits set in G77		

HAZARD	HAZARDOUS EVENT	CAUSE	CONSEQUENCE	EXISTING/POSSIBLE CONTROLS	EQUIVELENCE	ACTION
	Presence of harmonic voltages			Limits set in G77		
	DC injection pulse	Some inverters can use DC injection		Active DC injection inverters not permitted in G77 inverter approval		
	Presence of voltage spikes from AC side		Concern over inverter performance with damaged AC side but DC side still live	Inverter is normally fused on AC side.		Collate data on inverter tests which address consequences of surge with DC side live and present to G77
	Voltage dip	Distribution network disturbance (short term loss of supply)	Possible re-connection on 'out of phase' supply	Most domestic electrical equipment is designed to operate through short-term disturbances. Internal protection matches output voltage and phase to that of incoming mains supply	Not directly comparable since other equipment is 'passive' and not generating'.	
Failure To Comply With Standards		Difficult to comply with standards?	Legal breach. Potential hazards above. Possible violation of insurance liabilities. Potential long term insurance issues may arise.	No additional controls identified		See action above about publicity

HAZARD	HAZARDOUS EVENT	CAUSE	CONSEQUENCE	EXISTING/POSSIBLE CONTROLS	EQUIVELENCE	ACTION
Installation	Falls, electrocution etc			No different to any other DIY risk on roof		
Consumer Fire	Fire impacting PV system	Increased isolation points if batteries being supplied. Live DC wiring			Same as premises with UPS. Labels provided at consumer unit. No requirement to notify fire brigade of imbedded generation	Advise Fire brigade of nature of PV arrays and fire fighting issues
	Fire spread via PV array	Lack of fire resistance	PV array tested for roofing fire integrity			
Environmen-Tal Conditions	Wind, rain snow loads	Fatigue loads from wind etc. No established practices. Planning regs not invoked	Dropped objects	Tested in accordance with roofing tests		Recommend including standard fixing details with product literature
Injuries	Cleaning PV array	Falling off roof	Risks of commercial installation covered by CDM Regs. Domestic maintenance as per solar thermal		Directly comparable with solar thermal. No new hazardous identified	

APPENDIX F APPLICATION FOR CONNECTION

Application for the connection of Photovoltaic Generation to the distribution network - single phase PV system up to 5kVA to Engineering Recommendation G77 2000
Part 1 - Initial information *This form is intended for use at the planning stage of a grid connected PV system. This information to be provided to the DNO prior to installation of the system in order that a DNO can assess and make comment on the proposed system.*

Site Details	
Site address (inc. post code)	
Telephone number	
Customer supply / M.P.A.N. number	
Distribution Network Operator (DNO)	
Contact Details	
System owner	
Contact person	
Contact telephone number	
PV System Details	
Installed capacity of PV array	
Location of PV array	
Type (manufacturer & model) of inverter(s) to be used	
Proposed date for installation	
Installer Details	
Installer	
Contact person	
Telephone Number	
Fax Number	

Other Information to be Enclosed	
Copy of system schematic	yes/no
Existing earthing arrangements	yes/no
Copy of inverter type test certificate or other information pertaining to inverter status re. G77 and type test process (inc. loss of mains detection - ROCOF, frequency shift etc)	yes/no

Declaration - to be completed by applicant	
This installation will comply with the requirements of ER G77 2000	yes/no
If NO, see comments below :	
Applicant:	Date:

DNO comments - to be completed by DNO representative following application		
A representative of the DNO will wish to witness the commisioning tests		yes/no
As a representative of the DNO, I give, in principle, permission for the connection of this photovoltaic generator		yes/no
If NO, see comments below :		
DNO:	Contact:	Date:

Application for the connection of Photovoltaic Generation to the distribution network - single phase PV system up to 5kVA to Engineering Recommendation G77 2000
Part 2 - Commissioning application   *This information to be supplied in order to arrange system commissioning / switch on date. Where appropriate Part 1 and Part 2 may be sent at the same time.*   *NB. This form is provided for the purposes of providing information only.*   ***This form does not constitute a connection agreement.***

Site Details	
Site address (inc. post code)	
Telephone number	
Customer supply / M.P.A.N. number	
Distribution Network Operator (DNO)	
Contact Details	
System owner	
Contact person	
Contact telephone number	
PV System Details	
Installed capacity of PV array	
PV manufacturer / module type	
Location of PV array	
Type (manufacturer & model) of inverter(s) to be used	
Serial number of inverter(s)	
Serial number / version numbers of software (where appropriate)	

Installer Details	
Installer	
Address	
Contact person	
Telephone Number	
Fax Number	

Information to be Enclosed	
Final copy of system schematic	yes/no
Computer print out (where possible) or other schedule of inverter protection settings	yes/no

Declaration - to be completed by installer	
That the system has been installed in compliance with ER G77 2000 (UK technical guidelines for inverter connected single phase photovoltaic generators up to 5kVA)	yes/no
That, where necessary, inverter operating parameters have been programmed to comply with Engineering Recommendation G77 - yes/no.	yes/no
The inverter operating parameters are protected from alteration except by prior agreement with the DNO.	yes/no
That the system has been installed to comply with the relevant sections of BS7671 (1992) Requirements for Electrical Installations (IEE Wiring Regulations) and BS7430 (1991) Earthing (Code of Practice for Earthing). An installation test schedule is attached (where requested by the DNO*)*.	yes/no yes/no
If NO to any of the above, comments:	

Name:	Signature:	Date:

APPENDIX G DNO CONTACTS

DNO	Contact	Address
1. TXU Europe Power	Alex Spivey	Ely Road Milton Cambridge CB4 6AA Tel 0870 196 2155 Fax 0870 196 2176
2. East Midlands Electricity	Trevor Richards	398 Coppice Road Arnold Nottingham NG5 7HX Tel 0115 935 7405 Fax 0115 935 7484
3. Midlands Electricity	Chris Chell	Network Management Centre Toll End Road Tipton West Midlands DY4 0HH Tel 0121 557 2811 Fax 0121 522 6175
4. Northern Electric	Barrie Brass	Carliol house Market Street Newcastle upon Tyne NE1 6NE Tel 0191 210 1133 Fax 0191 210 1131
5. London Electricity	Richard Clarke	Asset Management 261 City Road London EC1V 1LE Tel 0171 865 7733 Fax 0171 865 7889
6. Manweb	Peter Thomas	Prenton Way Prenton Birkenhead CH43 3ET Tel 0151 609 2452 Fax 0151 609 2098

DNO	Contact	Address
7. SEEBOARD	Russell Batchelor Asset Management Engineer	Forest Gate Brighton Road Crawley West Sussex RH11 9BH Tel 01293 656458 Fax 01293 656353
8. South Wales Electricity (Swalec)	Ivor Rogers Generations Connections Manager	Newport Road St Mellons Cardiff CF3 5WW Tel 01222 771 279 Fax 01222 771 165
9. Yorkshire Electricity	Ruth Isaac	PO Box 161 161 Gelderd Road Leeds LS1 1QZ Tel 0113 241 5735 Fax 01132 415 594
10. Scottish Power	Ian Hunter	Cathcart Business Park Spean Street Glasgow G44 4BE Tel 0141 568 3773 Fax 0141 568 3557
11. South Western Electricity	Andrew Hood	800 Park Avenue Aztec West Almondsbury Bristol BS12 4SE Tel 01454 452 438 Fax 01454 452 007
12. Norweb	David Hoyle Connection Liaison Manager	NORWEB Hathersage Road Manchester M13 0EH Tel: 0161 257 4641

DNO	Contact	Address
13. Southern Electric	Richard Roe Strategic Planning Engineer	Southern Electric House Westacott Way Littlewick Green Maidenhead SL6 3QB Tel 01628 584123 Fax 01628 584523
14. Scottish Hydro-Electric	Craig Neill Connections Manager	Scottish and Southern Energy Inveramond House Dunkeld Road Perth PH1 5WA Tel 01738 456463

APPENDIX H Insulation tests of an Inverter Unit

Using the Specification for the insulation testing of electrical relays in IEC255-5 (clauses 6, 7, 8), a test schedule was drafted that could be applied to a complete inverter unit. This was circulated to the G77 Consultative Group prior to the testing.

The tests were performed on an OK4E, AC module inverter, by EA Technology. The test report is enclosed. Note that for Test 2.1 (Measurement of insulation resistance) the inverter was switched off and isolated from all other circuits during the test.

Figures 1 to 4 show, diagrammatically, how the tests were conducted.

Figure 1: Between AC Circuits (L&N bonded together) and Case

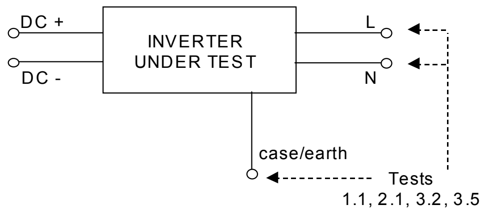

Figure 2: Between DC Circuits (positive & negative bonded together) and Case

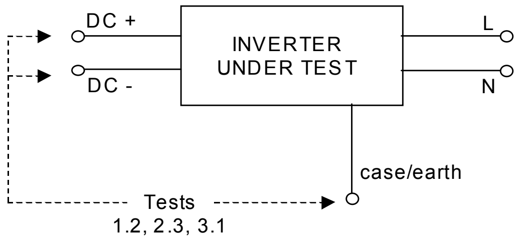

Figure 3: Between DC Circuits and AC Circuits

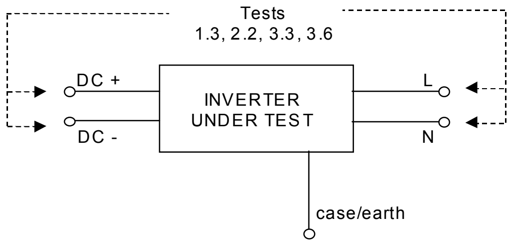

Figure 4: Between Live and Neutral (AC Circuits)