IEA INTERNATIONAL ENERGY AGENCY

Grid-connected photovoltaic power systems: Summary of IEA/PVPS Task V activities from 1993 to 1998

Task V
Report IEA-PVPS T5-03:1999
March 1999

PVPS

PHOTOVOLTAIC POWER SYSTEMS PROGRAMME

IEA PVPS
International Energy Agency
Implementing Agreement on Photovoltaic Power Systems

TASK V
Grid Interconnection of Building Integrated
and Other Dispersed Photovoltaic Power Systems

Report IEA PVPS T5-03: 1999

GRID-CONNECTED PHOTOVOLTAIC POWER SYSTEMS : SUMMARY OF TASK V ACTIVITIES FROM 1993 TO 1998

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CONTENTS

FOREWORD

The International Energy Agency (IEA), founded in November 1974, is an autonomous body within the framework of the Organisation for Economic Co-operation and Development (OECD) which carries out a comprehensive programme of energy co-operation among its 23 member countries. The European Commission also participates in the work of the Agency.

The IEA Photovoltaic Power Systems Programme (PVPS) is one of the collaborative R&D agreements established within the IEA, and, since 1993 its participants have been conducting a variety of joint projects in the applications of photovoltaic conversion of solar energy into electricity.

The members are: Australia, Austria, Canada, Denmark, European Commission, Finland, France, Germany, Israel, Italy, Japan, Korea, Mexico, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States.

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in co-operation with experts of the following countries:
Australia, Austria, Denmark, Germany, Italy, Japan, the Netherlands, Portugal, Switzerland, the United Kingdom and the United States

The report expresses, as nearly as possible, an international consensus of opinion on the subjects dealt with.

ABSTRACT AND KEYWORD

This report summarises the important findings from the first stage of activities of IEA PVPS Task V - Grid Interconnection of Building Integrated and Other Dispersed Photovoltaic Power Systems. From 1993 to 1998, review of existing techniques and rules, theoretical and experimental investigation for the important issues for grid interconnection of photovoltaic power generation were conducted and recommendation for further work was issued.

Keywords: Photovoltaic power generation, Grid interconnection, Utility distribution system, Guidelines and regulations for grid interconnection of PV systems, PV inverters, Harmonics, AC modules, Grounding, Ground-fault detection, Overvoltage protection, EMC, Islanding, External disconnect, Re-closing, Isolation transformer, DC injection, Distribution system fault

EXECUTIVE SUMMARY

Background and Objectives

As generally understood, grid interconnection of photovoltaic (PV) power generation system has advantage to utilise generated power effectively. It enables constant and automatic adjustment of electric power from the utility grid side and the PV system side. On the other hand, the technical requirements from both the utility power system grid side and the PV system side should be satisfied to ensure the safety of the PV installer and the reliability of the utility grid. Clarifying the technical requirements for grid interconnection and solving the problems are therefore very important issues for widely application of PV systems. The requirements for grid interconnected systems are deeply related with the configuration and operational concept of power distribution systems of each country and their technologies and social systems.

The International Energy Agency (IEA), Implementing Agreement on Photovoltaic Power Systems (PVPS) Task V : Grid Interconnection of Building Integrated and Other Dispersed Photovoltaic Power Systems, had started its activity from 1993 to investigate the grid interconnection issues through international collaborations. The main objective of Task V was to develop and verify technical requirements which may serve as the technical guidelines for grid interconnection of building integrated and other dispersed PV systems. The development of these technical guidelines intend to safe and reliable interconnection of PV systems to the utility grid at the lowest possible cost. In task V, PV systems to be considered were set as systems connected with a low-voltage grid, which are typically of a size less than fifty peak kilowatts.

This summary report shows the outline of our achievements for five year Task V activities from 1993 to 1998 to have an overview of our results and future considerations. We have issued detailed Task reports for whom interested in our work.

Task V Activities

In order to achieve objectives of Task V, three sub-tasks ware established and collaboration work between participating experts in Task V were conducted.

Sub-task 10 : Review of existing PV grid interconnection guidelines, grid structure and previously installed PV experiences
Sub-task 20 : Theoretical studies on various aspects for grid interconnection and configuration of PV systems
Sub-task 30 : Experimental tests using the Rokko Island and/or other test facilities

Sub-task 10 had four items to study. First item was to review existing technical guidelines or local regulations for the interconnection of PV system with the utility network. This survey enabled us to understand the general requirements for safety and reliable interconnection. The result of survey was summarised as Task V internal report open to IEA participating countries, “Grid-connected photovoltaic power systems: Status of existing guidelines and regulations in selected IEA member countries (Revised Version)”, Task V Report IEA-PVPS V-1-03, March 1998.
Second item was to review utility distribution network configurations to understand the difference of grid interconnection requirements from country to country. The result of survey was also summarised as Task V internal report open to IEA participating countries,

"Information on electrical distribution systems in related IEA countries (Revised Version)", Task V Report IEA-PVPS V-1-04, March 1998.
Third item was to review the status of technology for interconnecting equipment, inverters and protective devices, to identify the applied measure to satisfy the requirement for grid interconnection. Specifications and characteristics of many inverters and protective devices were collected and summarised as Task V internal document.
The forth item was to review operating experience of grid interconnected PV systems to identify any known problems regarding to PV system operation.

The scope of work for sub-task 20 was to analyse present day and possible future problems regarding to the grid interconnection of PV systems and to draft possible recommendation for improvement. Because of the limit of time and resources, we had to select subjects according to its importance, and following subjects were considered.

- Harmonics
- AC-Module
- Multiple inverters and AC grid
- Grounding of equipment in PV systems
- Ground-fault detection and array disabled for PV systems
- Overvoltage protection
- Islanding
- Electro-magnetic compatibility (EMC) of inverter
- External disconnect
- Re-closing
- Isolation transformer and DC injection

The results of work was given in the formal IEA PVPS Task V report, "Utility aspects of grid connected photovoltaic power systems", Task V Report IEA-PVPS T5-01, December 1998. Scope of work, theoretical results, experimental results, conclusions and recommendation for future work were described for every subjects. Therefore this subtask 20 report is easy to access to the information and useful for the readers with the technical background.

In sub-task 30, actual experimental test for PV system grid interconnection were conducted using test facility in Rokko Island Test Facility in Japan. These tests were intended to show the actual phenomena of grid interconnection problem and to be the reference of subtask 20 work. Actually, only a few tests were related to subtask 20 work, variable data for reference were obtained. Subjects of tests conducted in Rokko Island are listed below.

- Harmonics from PV systems
- Islanding
- Short circuit fault in distribution system
- DC/AC mixing fault
- Output power variation of many PV systems
- Temperature measurement of PV array

The results of work was given in the formal IEA PVPS Task V report, "Demonstration Test Result for Grid Interconnected PV systems", Task V Report IEA-PVPS T5-02, 1999.

Conclusions

IEA PVPS Task V finished first stage of work to identify grid interconnection issues of PV systems and to draft possible recommendation for improvement. During the progress of this Task, some countries provided new guidelines of grid interconnection and some countries revised their guidelines due to the deepening of knowledge for requirements for grid interconnection of PV systems. Introduction of grid connected dispersed PV systems are also progressed. AC modules, new concept of PV module with tiny inverter have been developed and now sold in some countries. These may be some of the outcomes of Task V activities.

We still have remained issues not fully solved like islanding issues, interconnection of many PV systems in limited area, cost evaluation of grid interconnected PV systems and so on. These issues will be studied in the continuous work in Task V.

Finally, this summary report is intended to have an overview of our accomplishment for the people who just want to understand outline of our work to get the idea of issues for grid interconnection of PV systems. For the people who are interested in detailed technical requirement for grid interconnection like utility people and manufactures, please refer to the Task V reports published separately.

1. INTRODUCTION

With the participation of experts from 11 countries, first stage of PVPS Task V activity was carried out from 1993 to 1998. The objectives of this task were the extraction of technical problems in the case of small size building integrated PV systems are interconnected to low voltage distribution lines, to study and propose a possible solution for these problems.

As generally understood, grid interconnected photovoltaic power generation enables constant and automatic adjustment of power from the grid side and the PV side. When the generated power from PV modules is insufficient to the load power consumed by the installer, required power is supplied from grid. When the power generated by PV exceeds the power consumption excessive electricity is supplied to the system side and would be consumed by the other customers. The problem in grid interconnection is the optimisation of the system, this being the demand from both the PV system side and the power system side. One of the technical factors which is also the key issue in system optimisation from the PV system side, is to utilise the renewable energy from the sun effectively and having it function effectively as the energy supply system. One of the most important key factors in increasing the popularity of the grid interconnected PV system is that it should guarantee the technical requirements necessary to ensure the safety of the PV installer and the reliability of the utility grid, and that the PV system is available with the least economical burden.

The requirements for grid interconnected systems are, however, deeply related with the configuration and operational concept of power distribution systems of each country and their technologies and social systems. When Task V was started, some countries had already provided guidelines related to grid interconnection of PV systems. Other countries had grid interconnection guideline not specified for PV systems but including all type of dispersed generation systems or does not have such guidelines. During the progress of this Task, some countries provided new guidelines of grid interconnection and some countries revised their guidelines. Review of guidelines are still progressing or about to start in near future in some countries according to the deepening of the knowledge for problems of grid interconnection of PV systems. The guidelines remain, therefore, active in a sense.
Grid interconnection guidelines and regulations reflect the diversified accumulated rules concerning the quality of electricity and the safety of the power distribution system of each country. Regarding those guidelines and regulations, it is also necessary to consider that, due to technical development, there are possibilities of introduction of entire new systems or reinforcement of distribution system itself.

In the process of this Task, the data of the actual conditions of the guidelines for the grid interconnection in each country was collected in the first two years study, and summarised as the Subtask 10 Item 1 Report. (This was revised in fiscal 1998 as the latest edition.) Information was also collected regarding the power distribution networks of each country and the power distribution line control methods of each electric utility company since they affects the requirements for guidelines. This was summarised in the Subtask 10 Item 2 Report. These two reports were utilised in the Task V as the background toward understanding the guidelines. Since they are valuable for further general use, they have been distributed publicly. They are not, however, guaranteed to have precise accuracy. It is, therefore, recommended that these reports be used as the personal levels of the participants and that the original be examined if required.

According to the technical investigations, certain items in these two reports are handled in a different manner in different countries, despite the probability that they are able to be handled in the same manner. Some of differences are considered to be caused by the difference of the distribution networks. It is also possible to assume that priority is given to reduce the negative effect on the most simple conditions and least economical burden by considering that quantity of PV systems interconnected to the utility grid is low right now.

Further information was also collected including the specifications of grid interconnection devices provided by the manufacturers as of today and response time of control system or protection devices. Data of diverse limitations, grid interconnection related problems and technical experience was also collected. This information is handled as internal data and is available only to those experts participating in Task V as they fluctuate with the time factor and are related to the internal information of the related personnel.

In the initial stage of activity of Task V Subtask 20, the discussions by the experts concentrated in extracting the technical subjects for study as the problems in grid interconnection. Selection of subjects for consideration were tried through a questionnaire directed to each expert. However, the proposed subjects were extremely broad in range. Problem recognition also varied reflecting the different conditions of the participant countries and the different experiences of the experts. After several discussions and the introduction of the data of the demonstration test conducted in advance in Subtask 30, the technical subjects were finally summarised in 11 items. Study of each subject and the report production were distributed among the experts and carried out enthusiastically. This is currently being summarised as the result of Subtask 20.

Grid interconnection related demonstration tests were carried out at the Rokko Test Centre for Advanced Energy Systems in Japan, KEMA in the Netherlands, Sandia National Lab. In USA, etc. The data from Rokko Test Centre was summarised as Subtask 30 report. The Rokko Test Centre enables the testing of electrical behaviour under a wide range of conditions by connecting numerous inverters to a simulated distribution line, thereby providing diversified data related to the phenomena when relatively large number of units are installed in the future.

Experts from many countries and who are engaged in various activities participated in Task V. This included experts from national or public research organisations and engineers from the private sectors. Task V was, therefore, achieved by contributions from all its participants, including the remarkable efforts of the leaders of each sub-task, the experts in charge of each report, and the experts in charge of technical subjects.

The result of Task V was then reinforced through discussions at a Workshop in September, 1997. These discussions took place between a number of manufacturers, people engaged in a commitment for international standardisation, and those engaged in the electric power industry. The importance of a common recognition concerning PV was re-confirmed at the Workshop, especially the importance of sharing knowledge with power generation/distribution related people. Also, in addition to the fact that the Workshop contributed to this re-confirmation very significantly, we wish to specify that the participants agreed in realising the importance of this type of opportunity with a deepened content continuously for the future of PV.

It may be possible to define that the research on grid interconnection problems as an international joint project has now achieved its first stage, it has not, however, been completed. This field still requires several more reviews and improvements.
Although the scale of the PV system is significantly small in comparison to other power generation systems, numerous dispersed instalments are expected, thereby providing the

unique feature of popularisation. Consisting of multiple systems, this type of power supply system is an entirely new entity.

Depending on the future technical development of the PV system, several variations may be designed and commercialised, for instance, the AC module which is being introduced into the market today, or a system consisting of numerous small inverters.
Also, technical development has enabled technical system management using extensive data processing through data communication networks. Consequently, the demand side management (DSM) field, including peak demand cut, is now focused. Its mutual interconnection with PV may be considered as a project. It may also be necessary to study the relationship between the harmonics caused by numerous items of electronic equipment and the PV system.
Optimum effort will also be required in grid interconnection to realise overall cost reduction in the PV system. Many demands in the initial stages of PV system development result in a large burden being placed on the PV system. It is, therefore, understandable that the technical approach toward the introduction of a small quantity of systems must differ from that for the introduction of a large quantity of systems.

Grid interconnection between systems with relatively unstable quality (this may occur in some areas in the developing countries) and the PV system will require a different approach wherein some roughness is accepted. One of the objectives of Task V was to produce a future concept considering these trends. However, this subject is in the preparatory stage, one reason being a lack of experience in operating agent (OA). We expect there will be other opportunities to study this matter in the future.

Finally, we wish to add the roles of the PVPS Agreement under the IEA-CERT and the relation with the result of this Task. The practice of Task V and its related discussions enabled an assurance of relatively high standards by providing an opportunity to present the wide ranges of experiences of each participant country. It is seen to have provided a good effect in producing drafts for guidelines, etc., in relation to the grid interconnections that are now underway in some countries.
The discussions raised technical problems thereby stimulated and promoted technical development in quite a few cases. This conformed to the principle objective of the IEA. On the other hand, regarding the content of the reports summarised in Task V, certain content may have not been approved by the authorities of their own country since most content is based on the arrangement of each expert. This means that the entire reports may have not been conformed by the representative opinions of the participant countries.
Also, unlike ISO and IEC, the IEA does not propose specific rules and guidelines as the opinions of the Task. Consequently, specific regulations will not be proposed as the agreement of the Task V participant countries, albeit some suggestions are reported. Since the characteristics of the IEA differ from those of the academic conference or institute, quite a few members are not experts in a specific field. Regarding the relation to the result of the research field, therefore, some supplements and their relevancy may be required. Nevertheless, this report is expected to be official since individual viewpoints and discussion records are seen to provide important suggestions and effective stimulation for future examination and it is hoped that the Ex. Co. and those related will agree.
We wish to emphasise that this report is the product of the contributions of every expert involved in this Task V and, therefore, take this opportunity to extend our sincerest gratitude to them all.

2. SUMMARY OF TASK V ACTIVITIES

2.1 Objectives of Task V

Task V is a working group of the International Energy Agency (IEA), Implementing Agreement on Photovoltaic Power Systems (PVPS). The title of the working group is "Grid Interconnection of Building Integrated and Other Dispersed Photovoltaic Power Systems"

The main objective of Task V is to develop and verify technical requirements that may serve as pre-normative technical guidelines for the network interconnection of building-integrated and other dispersed photovoltaic (PV) systems. The developments of these technical guidelines aim at a safe, reliable and low cost interconnection of PV systems with the electric power network. Task V considers PV systems connected with the low-voltage network with a typical peak power rating between a hundred watt and fifty kilowatt.

Task V has three subtasks:

- 10 Review of PV guidelines, grid structures and PV experiences
- 20 Theoretical studies on utility aspects of PV systems
- 30 Experimental tests using the Rokko Island and/or other test facilities

Subtask 10 defines the status quo of grid connected PV systems. A survey on present day guidelines gave information on the interconnection of PV systems with the utility network. A second survey showed the different network structures of the participation countries. Subtask 10 identified present day and possible near future problems regarding the network connection of PV systems.

The scope of work of subtask 20 was to analyse these problems and to draft possible recommendations for improvement. Some problems, however, appeared to be too complex and additional experimental work had to be done. These experiments are co-ordinated in subtask 30.

In subtask 30, experimental studies using Rokko Island test facility were conducted. Experiments were conducted for many aspects like harmonics, islanding, PV system output variation, dc-ac mixing and others. These experiments were conducted as the reference to grid interconnection of PV systems and some of the subjects were not directly related to the subtask 20 activities.

2.2 Summary of subtask 10

For Sub-task 10 (Review of previously installed PV experiences), existing grid-interconnection guidelines or related regulations for PV systems, difference of distribution systems to consider the background of guidelines, actual characteristics of inverters and related protection equipment and actual operating experiences of grid interconnected PV systems were studied by March 1998.

Existing guidelines and regulations for grid interconnection of PV systems in Task V participating countries were summarised as Task V internal report, "Grid-connected photovoltaic power systems: Status of existing guidelines and regulations in selected IEA member countries (Revised Version)", Task V Report IEA-PVPS V-1-03, March 1998. Difference of distribution systems in each Task V member country was also summarised as Task V internal report "Information on electrical distribution systems in related IEA countries (Revised Version)", Task V Report IEA-PVPS V-1-04, March 1998.

Actual characteristics of inverters and related protection equipment and actual operating experience of grid interconnected PV systems were summarised as Task V internal documents.

2.2.1 Grid-Interconnection Guidelines

According to the research on guidelines of each participating countries of Task V, following information related to guideline were clarified.

- Type of generation (Energy sources covered in the guideline)
- Classification of interconnection voltage (Difference of guidelines with interconnection voltage)
- Limitation of generation capacity per customer
- Correspondence to reverse power flow
- Requirements for facility
  - Electrical system
  - Power factor
  - Harmonics
  - HF Noise
  - Flicker
  - Protection co-ordination
  - Protection and safety
  - Necessity of isolation transformer
  - Restriction on inverter
  - External disconnect switch
  - Location of switch
  - Reclosing procedure
  - Detection of islanding phenomena
  - Voltage fluctuation
  - Short-circuit capacity
- Safety and wiring of DC side
- Metering
- Lightning protection
- Authorisation procedure
- Standard configuration and electrical layout
- Islanding Protection

In general it can be said that no common guidelines for the connection of PV systems to the utility grid exist in the participating countries. Every country has its own set of rules, and in many countries these rules vary in different regions. This reflects the fact that in many countries it is up to the utilities individually to define rules for connecting independent power generators to their grid.

Safety is the most important issue in all regulations. At this moment it seems that the problem of possible islanding (i.e. continued operation of a PV inverter even when the grid is off) is a crucial issue and needs further study as it could immediately lead to severe accidents. Topics such as cabling and earth fault detection seem to be well known and can be readily adopted from guidelines governing conventional electrical systems. However, the exception of DC currents flowing from the solar panels leading to possible dangers that are different from those associated with AC currents.

For the promotion of photovoltaic it is of great importance to set internationally recognised standards which allow identical PV systems to be connected to the grids of different countries. During the progress of Task V activity, both utilities and manufactures have been aware of the problems of grid interconnection of PV system which leads some country to revise their guidelines and regulations. The guideline summary report is the important information source to allow comparisons to be made of the various approaches to the problems and dangers specific to PV.

2.2.2 Distribution System Configuration

It is important to know the distribution system configurations, distribution system equipment, required protection relays and so on because they are strongly related to the requirement for grid interconnection equipment. Therefore, distribution line configuration for each participating country of Task V were studied and summarised.

Following information were obtained.

Voltage level and network scheme
- HV transmission
- HV distribution
- MV distribution
- LV distribution

Capacity of transformers - Feeders - Capacitors
- Transformer
- Feeders per transformer
- Impedance
- Average length
- Number of switches per feeder
- Number of sectionalise per feeder
- Capacitor for p.f. improvement
- Average number of customer per feeder per phase for LV
- Power rating of customer for LV

Protective device
- Protective device installed in the public network
- Reclosing
- Protective co-ordination with independent producer

Type and setting levels of the interface devices installed in the independent producer's network

Operation criteria
- Voltage fluctuation
- Voltage regulation
- Temporary supply
- Work method for fault repair

It is worth noting that some data contained into the report have to be considered as referred to mean or typical conditions. As a consequence, data referring to some countries, where

many local utilities exist and therefore network characteristics and procedures normally carried out can differ from region to region, should be carefully treated.
In general, it can be said that the voltage of LV grid in Europe have similar value while USA and Japan have different voltage level for LV grid. Distribution system configuration are different from country to country, and protection scheme is also different. This is one of the reason why the grid interconnection guideline for PV system is different in each country.

This electrical distribution system report is useful to understand the difference of electrical grid configuration and the difference of approach to the grid interconnection requirements.

2.2.3 Inverter and Related Protection Equipment

Characteristics of grid-interconnected PV systems are greatly dependent on performance of inverters and protective devices. These interconnecting devices should be designed to comply with existing guidelines and regulations on grid interconnection. Therefore, the survey of interconnection devices makes it possible to identify the status of existing applied measures for PV system grid interconnection. This survey is also intended to identify remained technical issues on interconnection equipment including cost reduction and to clear the concepts for requirements and devices for grid interconnection in future. This survey will eventually lead to improve understandings of technical requirements for grid interconnection of building integrated and other dispersed PV systems. The survey was done by circulating and summarising questionnaire on interconnecting equipment including inverter specifications, protective devices specifications etc. More than 50 responses were obtained including 5 inverters for AC modules, new concept PV system integrating inverter to PV module. Followings are the summarised results.

Inverter design and specifications

Type of Conversion

Most of all converters are self-commutated PWM inverters with current control.
Some voltage controlled self-commutated PWM inverters and line-commutated inverters are listed.

Nominal AC voltage & Standard grid connection

Europe
- 230 V (1 phase/3 wires), 380 V (3 phase/3 or 4 wires), 400 V (3 phase/3 or 4 wires) 50 Hz

Japan
- 100 V (1 phase/2 wires), 200 V (1 phase/2 or 3 wires, 3 phase/3 wires) 50/60 Hz

USA
- 120 V (1 phase/3 wires), 240 V (1 phase/2 or 3 wires), 480 V (3 phase/4 wires) 60 Hz

Harmonic current

Less than 5% in total and less than 3% for each harmonics.
There are inverters complied with EN/IEC/VDE or G5/3 standards.

Control methods of harmonics

Mostly current controlled PWM (pulse width modulation) with or without filtering.

EMC standards/directives with which inverter complies

Europe: EN, IEC, VDE, CISPR
Japan: VCCI (Japanese Voluntary Directives)

Value of AC power factor in each power output point

Almost constant in each power output point except for very low power. (around 1)

Control method of power factor

Mostly synchronising current phase with line voltage at zero crossing.

Control method of voltage fluctuation
Japanese inverters have reactive power supply or output power suppression option.
Most of other inverters have no control on voltage fluctuation.

Isolation transformer
Utility frequency transformer or high frequency transformer are employed.

Control system
Almost all are employing Maximum Power Tracking.
Many inverters have power factor control (Some of them are optional).

Operations AC voltage and frequency ranges
Voltage: Almost rated voltage +/- 10%
Frequency: Majority is utility frequency +/- 1%, Maximum +/- 10%.
Others are +/- 1 Hz, +/- 3%, +/- 5%, etc.

Conditions for start-up and stop
Start-up: Mainly by DC voltage level increase.
Stop: Mainly by DC or AC output power decrease. DC current, DC voltage decrease are also employed.

Control power source
Depend on the inverter design. Either DC side or AC side is used. Some inverters can be powered from both DC side and AC side.

Protective Devices

Required protective devices, protection level and operation time
AC side: Overvoltage, Under voltage, Over frequency, Under frequency, Overcurrent, Fuse (in Europe), Metal oxide varistor (in Europe and USA), Optional AC disconnecter (in USA)
DC side: Ground fault detection, Over current, Fuse(in Europe), Over/Under voltage, Metal oxide varistor(in Europe and USA), Optional DC disconnecter(in USA)

Presence and specification of overvoltage protection/device
Transient: Varistor, TSV-Diodes, Metal oxide varistor (in Europe and USA)
Dynamic: Over-voltage relay or software detection

Necessity protective devices for preventing islanding phenomenon
Europe
- Almost yes : frequency relay, voltage relay, harmonic increase, frequency shift

Japan
- Yes : Combination of both passive measure and active measure

USA
- Not required: Some inverters have frequency shift measure

Disconnection procedure at abnormal state
Gate blocking and trip of breaker (or opening of contactor).

Restart
Almost automatic.
Restart time: 30 sec (Austria), 180 sec, adjustable (Italy), 150 sec, 160 sec, 0-300 sec adjustable (Japan), first zero crossing, 6 sec, 120 sec after utility return to spec. (USA), 5 sec, 15 sec, 2 to 4 min (Switzerland), 20 sec (UK)

Others

Location of protective device
Almost included in inverter

Prices of inverter and protective devices

Depends on output power and quantity to be sold. Cost 1000 to 3000 (5000) $/kW for under 5 kW devices. Less than 1000 $/kW for large power inverters. AC module could be 1$/W.

Remained issues on interconnection devices including cost reduction

- Noise reduction
- Full evaluation of islanding prevention measures
- Transformer-less designing
- To customise control board and other components
- Islanding prevention measures with a number of interactive inverters
- Wiring-working-less construction
- Minimisation of heat dissipation
- Minimisation of checking procedure
- Inclusion of external disconnecter into the inverter
- External transient protection may be needed in some installation
- Standard EMI specifications could define minimum standards

2.2.4 Operating experiences for existing PV systems

It is useful to review the operating experience of existing grid connected PV systems for identifying the actually encountered problems. Survey was mainly focused to review of faults and failures. By understanding the cause of failure countermeasures and required modification of design could be clarified. The survey was done by circulating and summarising questionnaire on fault in low voltage grid and fault in PV systems. Around 2400 systems were surveyed. Followings are the summary of results.

Grid conditions (low voltage grid)

Frequency and duration of power outage

From some seconds to some hours per outage, few times per year

Failure or malfunction of protective device(s) of an interconnected power plant

No information available

Faults and failures for PV Systems

PV array

total number of incidents: around 90

Human error or design error: string not connected, wiring error, loose terminal, partial shading, module overrating, theft

Manufacturing error: condensation in junction box, corrosion, insulation failure, broken glass, defective diode

Others: lightning

Inverter

total number of incidents: over 470

Human error or design error: poor MPPT

Manufacturing error: malfunction of control circuit, defective fuse, other manufacturing error

Others: unspecified and internal cause, damage by transients from grid, power limitation

notes: Many problems occurs at the first production stage.

Utility interface

total number of incidents: 8

Static switch, MV grid, frequency shift due to thermal failure

Other component failure
loose terminal in junction boxes, varistor burnt, burned contacts in circuit breaker in front of battery (stand alone system), break of battery case (stand alone system)
Technical trouble to local grid or loads by introduction of PV system
voltage rise after long feeder
Transient overvlotage protection
damaged inverter
Lightning strike
module destroyed
Grounding fault
many faults in systems with old module design
Grounding fault detectors or insulation monitors
frequent tripping under high humidity, GFCI (grounding fault current interrupter) worked well with transformerless inverter
Experience of islanding
No actual islanding was reported
Troubles due to DC injection
No actual information
Troubles due to reclosing
No report was obtained
Trouble due to electromagnetic interference
some old inverters caused disturbances on radio and TV, no problem with new design
disturbance on telephone
Experience of multiple inverters on one feeder of the grid
Several countries have experience and working well so far

It was found that failure in inverter is the most frequent incidents. This is mostly caused by the lack of experience in first production stage and newly designed inverters have good reliability.
Only a few faults or failures caused by interconnection of PV systems are reported so far. However, this fact is not always indicate that there is no problem for grid interconnection of PV systems. It is difficult to make clear the cause of problem when some failure occurred because we do not have precise measuring devices for incidents in actual products. Some unexplained inverter failure might be caused by disturbance from grid, reclosing, and other interconnecting issues.

2.3 Summary of subtask 20

In subtask 20, several topics were studied on the utility interface of grid connected PV systems. These topics were selected after a careful brainstorm session and country by country evaluation. Summaries of the selected topics are described below. Detailed information on the topics is given in the subtask 20 report "Utility aspects of grid connected photovoltaic power systems", Task V Report IEA-PVPS T5-01: 1998.

2.3.1 Harmonics

Problems
The harmonic problem has assumed a particular relevance starting from the 1960s with the increasing use of static converters, which directly effect the quality of the electricity supply.

In general, the harmonic problem can be defined as that particular disturbance that, originated by the presence of non-linear components in the electrical systems, determines a permanent modification of the voltage and current sinusoidal wave shapes, in terms of sinusoidal components at a frequency different from the fundamental.

Findings
PV generators are connected to the distribution network through static converters and are therefore potentially able to cause harmonics, so downgrading the quality of electricity and altering the performances of other equipment sensitive to voltage harmonics. On the other hand, static converters themselves are sensitive to harmonics and may operate incorrectly as a result of the harmonic voltage distortion.

The chapter investigates the harmonic phenomena as applied to PV systems, taking into account aspects relevant to the generation (emission) and to the effects (susceptibility), gives an overview of the present international rules relevant to harmonics and reports some measurements realised in Denmark from November 1996 to September 1997 about the impact from the PV installations on the local voltage distortion.

Conclusions
The work done has also showed the necessity to further investigate the effects on harmonics in case of multiple PV systems operation

2.3.2 AC Modules

Problems
An AC Module is an integrated combination of a single solar module and a single inverter. The inverter converts the DC energy from the module into an AC energy and feeds this energy into the AC network. The main advantage of AC Modules is the modularity. Complicated DC wiring is not required and the solar power is directly available as AC-power.

This modularity allows for very simple systems that can easily be expanded by simply paralleling several AC Modules at the AC side. An AC Module is an electric product and comparable to other appliances. It is expected that AC Modules will become available at the hardware store, and that people will buy and install them without consulting a certified electrical engineer.

This “plug and play “ idea of AC Modules has raised several questions by experts from electrical safety bodies and utilities. Plug and play means that the AC Module is equipped with a standard AC-plug that allows for a direct plug-in to a regular outlet in the electrical installation of a building. Some national and international safety standards do not allow this, other standards are unclear

Findings
A survey revealed that only a restricted number of countries are actually developing and/or using AC Module systems. Other countries have no objections to AC Modules but wait for other countries to gain hands-on experience. Nevertheless it is expected that AC Modules will be used World-wide within a few years.

The most important unresolved question is how to connect an AC Module to the network. Manufacturers are, of course, in favour of allowing the AC Modules to be connected to a regular outlet. This allows easy installations and reduces the costs. Safety standards, however, do not always allow this and/or utilities do not like the idea of having generators connected at normal feeders of an electrical installation. There is also a non-technical but realistic aspect to this discussion. When AC Modules become available at the hardware store, people will buy AC Modules. It can be expected that people will not install a separate feeder just for one or two AC Modules, mandatory or not, and will connect the AC Module to a regular outlet.

The Netherlands have issued a pre-draft guideline that AC Modules (or other types of small generators) may be connected to normal feeders if the generated power is below approximately 500 W. This philosophy is also under discussion in Switzerland. However, some countries for example Australia and USA, have strict regulations not to allow AC Modules or other types of small generators to be connected to a regular feeder; a separate feeder is always necessary.

There are two certification standards for AC Modules available in the world. Both these standards provide a set of rules to guarantee the electrical, mechanical safety of an AC Module. The Dutch standard is issued by KEMA, in the USA the standard is issued by Underwriters Laboratories (UL). UL and KEMA are working to harmonise both these standards.

Conclusions
AC Modules have recently been introduced as a commercial product, application can be found in a limited number of countries. It is expected that this number will grow dramatically in the next few years.

Although AC Modules have been available on the market for some years now, there is still a lot of discussion on methods for interconnecting AC-Modules with the network. Is a separate feeder necessary for the connection of an AC Module with the AC-grid, or is the “Dutch-way” an option? Also, the method of interconnection is an important topic; is there a need for an AC-marshalling box or is an AC-cord with (special) plugs an option, and what about the connection to the AC-mains supply, bolted terminals or a separate plug?

When AC-Modules will become as popular as expected, these issues have to be settled. Present day standard should be (better) adopted for AC-Modules.

2.3.3 Multiple Inverters and AC Grid

Problems

As small PV power generation systems become more common, it will be necessary to investigate several effects that are not significant for single inverter systems. For example, if a large number of dispersed PV generators are connected to a branch of the low voltage distribution system, then the reverse power flow to the higher voltage power system will substantially increase during periods of light load and maximum daylight. This may cause a significant voltage rise in the distribution lines, particularly at the ends. Also, the PV systems will supply a part of the fault current in the event of a distribution line fault. This additional fault current will decrease the fault current flowing at the substations and might cause fault detection relays in substations to malfunction. It is thus necessary to identify effects that may occur when connecting large numbers of PV systems, and to establish countermeasures.

Findings

- The voltage at the customer’s terminals may exceed the upper statutory limit because of reverse power flow from PV systems during light-load hours in the daytime. Leading power factor operation of the PV system is an effective countermeasure to prevent the voltage rise without reducing effective power.
- If each customer supplied by a distribution transformer installs PV systems with a capacity equal to or above their contracted power, the reverse current flowing through the transformer could exceed the transformer capacity because of simultaneous power generation change of the PV systems and transformer design concept. It would be necessary to consider replacement of the transformer or installation of an energy storage facility in such situation. If a diversity figure is used such as ADMD (after diversity maximum demand) for distribution system design purposes, restricting generation to the ADMD could be an effective countermeasure.
- In the event of short-circuit fault condition in the distribution line, the increase in short-circuit capacity of the distribution line and the malfunction of over current relays (OCRs) or fuses in the distribution system may occur as part of short circuit current is supplied from PV systems. It would be necessary
- to develop a new fault detection system for the PV system. A method of detecting the voltage phase change occurring in the fault condition may be one useful option.

Conclusions

The effects anticipated to occur when a large number of PV power generation systems are interconnected with distribution lines were investigated (excluding harmonics and islanding that are covered in other chapters). The theoretical results and experimental result regarding the effects and countermeasures are reported. Recommendations for future work are as follows.

- Development of a new fault detection for PV systems to detect a short-circuit fault occurring at an end of a long distribution line, with a high resistance, or during distribution line overload.
- Further studies on the effect on distribution line voltage variation caused by the wide-spread application of PV power generation, covering different application areas and the number of interconnected systems.
- It would also be important to study and encourage the application of various distribution line support systems which make the best use of the added values offered by PV power generation.

2.3.4 Grounding of Equipment in PV Systems

Problems
When rules for early power generation and electrical distribution systems were being developed in the late 1890 to early 1900's, grounding requirements were limited to lightning protection. In the United States, the National Electrical Code (NEC) and it's grounding requirements was first published in 1897. Most other countries throughout the world, often independently, developed other versions of electrical codes to address safety and grounding issues for electrical generation and distribution systems. The resulting grounding techniques and requirements vary from country to country. Optimised grounding for personnel protection does not optimise fire safety of a system and grounding for fire safety does not optimise personnel safety. Grounding to provide protection for equipment would require a third set of requirements. Photovoltaic (PV) systems, as distributed current sources, require additional grounding considerations. Distributed leakage paths, multiple fault paths and new roles for fuses and circuit breakers are among a few of the new issues that need careful consideration for PV applications. Codes for PV have closely followed the national practice for AC power systems in each country, but many PV codes are being developed as separate documents, rather than being included into existing codes. Grounding of batteries associated with PV power sources adds another consideration when grounding the PV array.

Findings
System and equipment grounding practices and requirements vary widely with applications, among the countries, and sometimes within individual countries and a survey of participating IEA countries revealed requirements and practices. Codes in the USA require equipment grounding of all systems, and system grounding for systems with voltages over 50 volts (open circuit module voltage). European and Japanese codes require equipment grounding, but do not require system grounding and most of their PV systems do not have grounded current-carrying conductors on the DC side.

Conclusions
The grounding of power systems is complicated by the introduction of current-limited PV sources interconnected with batteries and conventional voltage-source electromechanical generators. Two universal conclusions for grounding were: a) most codes and standards generally require equipment grounds for all metal surfaces that might become energised, b) when system grounds are used, single-point grounds are required. The ungrounded system provides the best fire hazard reduction because multiple ground faults are needed to create a fire hazard. Ungrounded systems allow easy ground fault detection and simple PV array disable.

The grounded PV system generally provides the best personnel protection from electrical shock because the voltages to ground are well defined. The system grounding ensures a solid or known PV array ground through properly sized conductors. The distributed capacitance to ground, of the PV modules and wiring, does not build static charges and the system voltage is stable and known in the grounded PV system. With proper design, both grounded and ungrounded PV systems can achieve good personnel, fire and equipment safety.

2.3.5 Ground-fault Detection and Array Disable for PV Systems

Problems

Installed PV systems rarely perform exactly in the manner indicated by electrical schematics. Accumulative leakage currents associated with the large PV array, long runs of wiring, surge protection, diodes, junction boxes that collect moisture, and conduit often make actual ground-fault detection difficult. Leakage currents in early PV systems were often sufficient to cause false indications of ground faults and contributed to many hours of system down time. The leakage currents associated with all of the distributed PV source components and wiring also pose unseen and unfamiliar hazards to personnel, or may contribute to ground faults that increase fire danger and personnel hazards.

Fault currents may occur between active conductors in the circuit called line-to-line or bolted faults, and active circuit conductors-to-ground called ground faults. Utility-interconnected PV systems are often installed in close proximity to utility power lines and accidental cross connection is a possibility that must be addressed. Unintentional connections or faults may result in insulation failures and line-to-line (bolted) faults or line-to-ground (ground) faults. The ground-fault protection of the PV system must be consistent with the ground-fault protection used on the connected AC power system. The AC circuit ground-fault protection requirements are generally part of electrical system installation codes for the application.

Findings

A review of PV system experiences and requirements related to ground faults for grid-tied applications was included as part of a survey of participating IEA countries. The survey included hardware compatibility reviews and ground-fault detection requirements as well as detection methods and disable methods. New developments such as the rapidly evolving AC PV module will not require the use of ground-fault detection on the PV-side DC circuits, since the DC voltage is self-contained within the module and inverter, and there is no external access to the DC circuits. Additionally, the tests associated with listing or certifying the self-contained AC PV modules will assure both fire and personnel safety. . It is very unlikely that any conditions will require DC ground-fault detection in AC PV module applications.

The evolution of building-integrated PV systems using DC wiring circuits, PV source circuit combiners and inverters will require ground-fault detection and PV array disable devices for fire and personnel safety. Issues such as backfeeding that may result from inadvertent four-quadrant operation of an inverter, transformer insulation breakdowns or internal circuit failures must be addressed for building-integrated systems

Conclusions

Comparisons of the fire and personnel safety of the grounded and ungrounded PV systems along with considerable research, showed the advantages and disadvantages of each with respect to ground-fault detection. Users and operators must be aware of the grounding methods used and the ground-fault detection and array disable methods. The work included comparisons of PV array ground-fault detection requirements and array disable experience, along with hardware, standards, listing guidelines and practices used for PV system installations. The results of simulated ground faults, simulated transients and lightning, and measured performance for the selected grounding methods are reported and referenced.

2.3.6 Overvoltage protection

Problems
PV systems are installed on roof tops, facades of buildings, special construction like sound barriers on motor ways. PV-system have, by definition, a large exposure to the open sky and are therefore subjected to atmospheric influences. A lightning strike is one of the most severe atmospheric influences. To protect a PV-system for a direct lightning stroke is very difficult due to the very high energy content of the lightning stroke. However, a PV system must and can be designed to withstand the effects of indirect lightning strike.

Another cause for transient overvoltages in PV systems is the AC-network. These overvoltages originate from switching phenomena, fault clearance in the power network, and/or lightning induced voltages in overhead lines of the utility. These transient overvoltages are not special for PV systems and are applicable for all types of equipment connect to the distribution network.

Findings
Overvoltages due to indirect lightning strokes can be controlled with a proper design of the grounding structure of the PV-system. The main objective is to reduce loops between the DC and AC wiring and the ground structure. This can be solved to have a grounding wire running down from the metal support structure of the array, DC wiring, inverter, AC wiring to the ground structure at the main fuse box. If an external lightning protection system is available this should be connected to the metal support structure of the array. This deliberately formed ground loop allows currents to flow, but reduces the presence of overvoltages to a minimum. Since these currents flow in a well defined path, no hazards are present.

Conclusions
A simple and cost effective grounding structure is defined for PV-systems. This reduces all possible overvoltages to very acceptable and controllable levels.

2.3.7 Islanding

Problems
Islanding is the continued operation of a grid-coupled inverter (or generator in general) in cases where the utility grid has been switched off, cut off or the distribution lines have been damaged so that no electric energy is delivered from the utility side. In such a situation the safety of persons and/or the safety of equipment might no longer be guaranteed.

Findings
A lot of anti-islanding methods have been identified in the literature and have been tested in practice. They can be divided into 2 groups:

- Passive methods:
  a detection circuit monitors grid parameters (e.g. voltage, frequency, voltage phase jumps, voltage harmonics); these methods do not have any influence on grid quality

- Active methods:
  a detection circuit deliberately introduces disturbances (e.g. active or reactive power variation, frequency shift) and deduces from the reaction to these disturbances if the

grid is still present. The grid quality is somehow affected; however, ordinary devices like TV sets have a much bigger (negative) effect.

There are hardly two countries with identical legislation as far as islanding is concerned, but there is some common ground: in all countries a PV inverter (or some external protective device) is required to monitor voltage and frequency. However, the set-points for shutdown and disconnection from the grid are not generally agreed upon.

Conclusions
Islanding seems to be the most controversial topic with grid-coupled PV systems. However, theoretical studies show that islanding can only happen under very special and unlikely circumstances if basic safety methods are implemented. These basic methods are

- monitoring of grid voltage
- monitoring of grid frequency

As these parameters can be monitored very easily it is recommended to include the sensing circuits in the inverter electronics to reduce system costs. Some countries like The Netherlands, Germany, Switzerland and Austria have tried this approach and have made very good experiences.
It is further recommended to perform a scientific risk analysis based on real load patterns in real distribution systems to determine the probability of islanding. Such an analysis could form the common ground from where generally accepted anti-islanding methods could be derived. At present the dangers of islanding seem to be over-estimated; in some countries this has led to legislation demanding very costly or too sensitive anti-islanding methods.

From the technical point of view it seems to be possible to include effective and reliable anti-islanding methods in the inverter electronics which would make PV systems more simple to install and bring costs down.

2.3.8 Electro magnetic Compatibility

Problems
Electro-magnetic compatibility is the ability of an electric or electronic device or system to operate according to its purpose in its electromagnetic environment without negatively influencing other equipment by conducted or radiated electromagnetic emissions.

Therefore a manufacturer of PV inverters has to make sure that his device has a certain immunity against external electromagnetic phenomena. At the same time it must not produce emissions disturbing other electronic devices.

Findings
All industrialised nations have some form of legislation which sets limits to the maximum allowable level of electromagnetic emissions. These limits are usually a result of long discussions and are well-proven in practice. The compliance with these limits is tested in well-defined test set-ups with standardised test instruments. The relevant standards for Australia, Europe, Japan and the US have been compiled and referenced. Where possible, the relevant immunity standards (if such exist) have also been cited.

Conclusions
The problem of EMC is not a PV-specific topic. Therefore it does not make sense to create new standards for PV equipment like inverters as the existing standards are generally valid. The only remaining topic: the test set-up for measurements of emissions on the DC lines has to be defined more clearly as conventional devices usually do not have DC connections.

2.3.9 External disconnect

Problems
This topic examined the necessity for PV systems to have an external manual ac disconnect switch to allow the Utility to disconnect the PV system in the case of maintenance on the ac network or fire hazard etc., to comply with Health and Safety Regulations

Findings
Nearly all countries required a means of physically disconnecting the PV generator from the mains for maintenance of the inverter and the ac network to which it is connected. The traditional means to achieve this was a mechanical switch mounted in an external position such that the Utility could operate it before carrying out maintenance on the ac network. This had evolved for a situation of a relatively small number of large generators.

It was generally agreed that as small generators became more common, the task of isolating every unit at an external switch would become impossible to implement reliably, and moreover it did not take into account units that were illegally connected, and thus not registered with the Utility. For this reason, and the relatively high installation costs for such a switch, it was proposed to investigate other solutions.

Some countries, such as Germany the Netherlands and Austria, were coming to the view that in certain circumstances protection relays and operational procedures could be relied upon. This was backed up by a risk assessment study in Germany by the Employer's Liability Insurance Association to IEC guidelines.

Conclusions
It was generally agreed that if anti-islanding devices were used for the external disconnect function, they would have to be relay devices with a physical opening of contacts rather than an electronic semiconductor switch.

For PV it is anticipated that the situation evolving in Germany and the Netherlands will become more widely adopted, where the external switch is not mandatory, and the Utility relies on the relay 'islanding' protection and their practices for checking and grounding the conductors, assuming that they are live, before carrying out maintenance. This relies on the involvement of the Utilities.

It is important to recognise that the problem is not specific to PV but also applies to other embedded generators, and so it is sensible to harmonise with other work being carried out in this area.

When more information is available from the anti-islanding work, then these devices should be assessed for their suitability to provide the function of the external disconnect also.

2.3.10 Re-closing

Problems

By re-closing, it is meant the automatic procedure used by the distributor to reduce the duration of the power supply interruption to the users caused by network faults. Therefore, no procedures relevant to the manual re-closing operations carried out by the personnel is considered in this chapter.

Findings

Re-closing is utilised by the distributor on the MV network but, as MV networks are usually operated in an open-ring scheme, it has consequences on the downstream LV network where PV systems are connected.

In fact, the re-closing procedure may lead to out-of-phase parallel conditions with consequent potentially dangerous stress for the inverters, for the loads, for the line-breakers and for the transformers installed on the utility network.

Conclusions

The chapter illustrates the re-closing principle of operation, the effects of the automatic re-closing and gives an indication of the counter-measures that can be adopted in order to overcome the above mentioned problems.

2.3.11 Isolation transformer and DC injection

Problems

Transformerless inverters gain increasing importance for grid-connected PV systems due to technical and economical advantages. Contrary to current technology, which mostly relies on transformers built into the inverter, transformerless inverters offer no inherent protection against a dc component fed into the utility's network.

A dc current fed from the customer's side into the grid can disturb the regular operation of the upstream distribution transformer. It can shift the transformers operating point and cause saturation. This would result in high primary current peaks, which might trip the input fuse and thus cause a power outage to that specific section of the grid. It would furthermore cause increased harmonics.

An overview is given how the participating countries view the requirement for an isolation transformer. The possible impact of a dc current on the operation of a distribution transformer was assessed using literature review and laboratory experiments.

Findings

From the references it can be concluded that dc components from a transformerless inverter may cause saturation effects in the local distribution transformer. However, a disruption of the utility service is to be unlikely. The experiments showed that primary currents from secondary ac and pulsed dc components linearly superimpose.

Under high dc components high primary current peaks occur. Also, a high level of harmonics is generated. The pulsed dc component may reach levels around 10 % of rated current without jeopardising the proper operation of the transformer.

Conclusions

The hazard of dc currents from small PV systems for the local distribution transformer seems to be negligible. A general requirement for isolation transformers for PV inverters is not justified. The very unlikely case of equal dc currents to each winding of a 3-phase transformer could not fully be resolved.

2.4 SUMMARY OF SUBTASK 30

In subtask 30, experimental studies using Rokko Test Centre for Advanced Energy Systems test facility were conducted. Experiments were conducted for many aspects like harmonics, islanding, PV system output variation, dc-ac mixing and others. These experiments were conducted as the reference to grid interconnection of PV systems and some of the subjects were not directly related to the subtask 20 activities. Summaries of the experimental results are described below. Detailed information on the test results are given in the IEA PVPS report “Demonstration Tests of Grid Connected Photovoltaic Power Systems”, Task V Report IEA-PVPS T5-02.

2.4.1. Measurement of Harmonics Distortion Caused by PV Systems

Problems and Objectives

Grid interconnected photovoltaic power generation systems generates harmonics because it has AC/DC converters and isolation transformers. These harmonics may affect the quality of electricity and cause damage to equipment.

As the number of units of grid interconnected photovoltaic power generation systems increase, the total harmonic content in the system may increase when each harmonic from each photovoltaic power generation system superimposes one another or may decrease when each harmonic cancels one another. It is important to examine what is the general tendency of total harmonic when a lot of photovoltaic power generation systems are interconnected to one distribution line. Relation between the number of interconnected PV units and total harmonic current was measured.

Findings and conclusions

It was found that the third and the fifth harmonic current increased with the increase in the number of connected units of inverters. However, the higher harmonics did not always increase or sometimes decreased with the number of units, especially when the photovoltaic power generation inverters manufactured by the different manufacturer (having different control scheme) are interconnected to the same distribution line.

From these results, it can be concluded that third and fifth harmonic current from inverters have almost the same phase displacement and the total harmonic current could be superimposed, while higher harmonics from inverters have different phase displacement even if the same control scheme is employed and total harmonic current could be cancelled. The phenomenon that the third harmonic and the fifth harmonic increase with the number of connected units is considered to be caused by exciting current of the isolation transformers.

2.4.2. Measurement of Islanding Characteristics

Problems and Objectives

Islanding may cause problems such as human safety and equipment maintenance if it continues for a long time. It is therefore important to clarify the conditions under which continued islanding occurs, and verify the necessity of measures for preventing islanding and effectiveness of these countermeasures, especially when a large number of PV systems are interconnected to one distribution line.

Findings and conclusions

When many PV systems whose inverters have only ordinary protective relays such as over/under voltage relays and over/under frequency relays, islanding can be continued for a long time if total output power from PV systems is higher than total load in distribution system. This result shows that some measures for detecting islanding conditions are required. Various kind of islanding detection or prevention function, including passive and active schemes, have been proposed.

Islanding phenomenon does not continue for a long period of time if multiple photovoltaic power generation systems having islanding detection functions for their inverters were interconnected to power distribution line. Especially when inverters manufactured by different manufacturers were interconnected together, that means different schemes of islanding detection were exist, islanding is hardly occur. It was confirmed that mainly the passive scheme detected islanding phenomenon, while the contribution of active scheme islanding detection was not clarified. It was also found that islanding detection time increases when a load which can sustain a distribution line voltage such as induction motor load.

2.4.3. Characteristics under Distribution Line Short Circuit

Problems and Objectives

Photovoltaic power generation systems may supply fault current under the short circuit fault condition in distribution system. Fault current from PV systems could affect the fault detection in distribution system and causing delay of protection. Therefore, it is necessary to verify the effect of the short circuit current from PV systems on system fault detection.

Fault current from PV system was measured under the short circuit condition at the low voltage side of distribution transformer. Measurements were conducted for various output power of PV system.

Findings and conclusions

Some inverters do not supply fault current at all (only maintaining the current before short circuit fault) and stop the operation in a short period of time (within 1 or 2 cycles) by the under voltage relay. Even for inverters supplying fault current, magnitude of fault current is only twice of current before fault and lasts only 1 or 2 cycles. This result shows that output current control of inverter works well.

It was concluded that PV systems do not affect the protection for short circuit fault in distribution system.

2.4.4. Characteristics under AC/DC Mixing Fault

Problems and Objectives

If PV system has no isolation transformer, DC current component may injected to AC circuit of the power distribution system (DC injection), resulting magnetic saturation of utility transformer. This magnetic saturation causes distortion of exciting current and a large amount of harmonics in distribution system. The effect of DC injection could be examined by more severe situation, AC/DC mixing fault condition, in which DC circuit of PV array is directly connected to the AC system. In this AC/DC mixing fault condition, effect of AC current breaks into DC circuit of photovoltaic array can be also examined.

Propagation range of harmonics generated at the AC-DC mixing fault in the power system, the effect on other transformers connected to the same high voltage distribution line and the effect on other inverters for photovoltaic power generation connected to the same low voltage distribution line are examined.

Findings and conclusions

Exciting current of utility transformer starts to increase immediately after AC/DC mixing fault and becomes stabilised (saturated) in several to ten-odd seconds. At this time, magnetic saturation occurs and harmonic current of even orders are generated on the high voltage side of the utility transformer. Distortion of current waveform was also seen in other utility transformers connected to the same high voltage side of distribution line and the isolation transformers of other photovoltaic power generation systems connected to the same low voltage distribution line.

However, even though the AC/DC mixing fault continues for several minutes, no overheating, vibration or sound were observed for the utility transformers. Also, no effect was observed for the operation of photovoltaic power generation systems connected to the low voltage side of utility transformers located in the vicinity of the utility transformer generating mixing fault. For conclusion, effect of DC current injected to the AC system is negligible.

2.4.5. Output Fluctuation of PV systems

Problems and Objectives

The output of photovoltaic power generation fluctuates with solar irradiance. Solar irradiance varies in second order owing to the movement of cloud except for a very fine day and a totally cloudy day. The fluctuation in output of the photovoltaic power generation causes the fluctuation in power flow, or fluctuation in voltage in the connected distribution line. If many PV systems are interconnected to a limited area, output fluctuation of PV system occur simultaneously then voltage fluctuation in the distribution line becomes larger than the fluctuation induced from load. Moreover, considering that the voltage fluctuation take places in second order, it may causes flicker in distribution system. That kind of fluctuation may become a technological issue for future introduction of photovoltaic power generation.

Power fluctuation from large number of PV systems interconnected to one distribution line within limited area was measured and relation between power fluctuation for individual system and whole system was obtained.

Findings and conclusions

In the case that many PV systems are connected, even if the output fluctuation of each PV system is large, both the magnitude and speed of fluctuation decrease to level off as the whole system. Accordingly, distribution voltage fluctuation due to output fluctuation also decreases.

It is difficult to measure the speed and magnitude of output fluctuation of the multiple interconnected photovoltaic power generation systems in actual installation. It was found that measured value brought by a pyranometer of slow response rate is similar to the actual values of the speed and magnitude of output fluctuation of multiple interconnected photovoltaic power generation systems. Therefore, measurement of the speed and magnitude of output fluctuation can be conducted with a pyranometer of slow response rate.

2.4.6. Measurement of PV Array Temperature

Problems and Objectives

The surface temperature of array is an important factor in evaluating characteristics of photovoltaic power generation systems. However, it is not clearly determined whether the temperature is for output period or for no output period. Therefore, the difference in the surface temperature of array "for the case that inverter is connected to photovoltaic array and output at full capacity" and "for the case that output terminal of array is opened, i.e., no output" was measured.

Findings and conclusions

The surface temperature of array of photovoltaic power generating systems is lower when the array have output power than when the array does not have output. This was confirmed by the measurement with three units of photovoltaic power generating arrays. Although the temperature difference was as low as 5℃ at the most in this measurement, the difference is considered to be bigger under actual conditions.

It should be studied in the future that which is appropriate to measure the surface temperature of array with output or array without output and what is the appropriate interval in evaluating the conversion efficiency of photovoltaic power generating systems.

3. CONCLUSIONS

IEA PVPS Task V has performed important studies on topics related with grid interconnected PV systems. This report, together with other report published by Task V will serve as valuable information dissemination tool for utility people, manufactures and customers to understand the problems and their solutions for grid interconnection of PV systems.
As the time and resources for work were limited, however, some problems are remained unsolved. On the other hand, with the advance of our study, new items related to grid interconnection of PV systems were recognised.
The members of Task V believe that further work should be done within the IEA-PVPS-implementing agreement on grid connected PV-systems.

4. FUTURE WORK

The members of Task V believe that further work should be done within the IEA-PVPS-implementing agreement on grid connected PV-systems. A survey revealed several new topics that need to be addressed. These new topics were identified by carefully looking at the trends in PV-systems design, questions raised by people from both utilities and manufacturers and short and long term plans of the utilities for high density penetration of PV-systems on the grid. The new related topics for study are listed below.

PV-SYSTEM RELATED ISSUES
* AC Modules
* High voltage DC wiring
* Evaluation of electrical PV-system design
    - Various protection methods to prevent electrical shock
    - Overvoltage protection and safety grounding
    - Ground fault detection
    - Array disable
    - EMI
    - Lightning protection
* PV and the privatised market
* Continuous review of PV grid-interconnection guidelines
* PV grid-interconnection to the low quality grid

GRID RELATED ISSUES
* Islanding
* Multiple inverters
* Capacity of the grid for PV
* Power Quality improvement by using PV-inverters
* PV, grid and Storage

ANNEX A LIST OF REPORTS

During its first stage of activity, IEA PVPS Task V published following reports.

- “Grid-connected photovoltaic power systems: Status of existing guidelines and regulations in selected IEA member countries”, Task V Internal Report, IEA-PVPS V-1-01, July 1996
- “Information on electrical distribution systems in related IEA countries”, Task V Internal Report, IEA-PVPS V-1-02, July 1996
- “Proceedings of the IEA Workshop on Existing and Future Rules and Safety Guidelines for Grid Interconnection of Photovoltaic Systems”, September 1997 in Zurich
- “Grid-connected photovoltaic power systems: Status of existing guidelines and regulations in selected IEA member countries (Revised Version)”, Task V Internal Report, IEA-PVPS V-1-03, March 1998
- “Information on electrical distribution systems in related IEA countries (Revised Version)”, Task V Internal Report, IEA-PVPS V-1-04, March 1998
- “Utility Aspects of Grid Interconnected PV systems”, IEA-PVPS Report, IEA-PVPS T5-01: 1998, December 1998
- “Demonstration Tests of Grid Connected Photovoltaic Power Systems”, IEA-PVPS Report, IEA-PVPS T5-02: 1999, March 1999
- “Grid-connected Photovoltaic Power Systems: Summary of Task V Activities from 1993 to 1998”, IEA-PVPS Report, IEA-PVPS T5-03: 1999, March 1999 (This report)

ANNEX B LIST OF PARTICIPANTS

Leaders of subtasks and working items or subjects

Task V has three subtasks, 10, 20 and 30. Subtask 10 and subtask 20 have working items or subjects to accomplish the required work. The leader of subtasks, working items and subjects, who are the main author of each summary in this paper are listed in the tables below.

Subtask 10: Review of existing PV grid interconnection guidelines, grid structure and previously installed PV experiences

Leader: Gunther Rabensteiner, Verbundgesellschaft, Austria
Christoph Panhuber, Fronius KG, Austria

Item	Leader(s)	Company and Country
Grid Interconnection Guidelines	Gunther Rabensteiner	Verbundgesellschaft, Austria
	Christoph Panhuber	Fronius KG, Austria
Distribution System Configuration	Alberto Iliceto	ENEL S.p.A., Italy
	Ettore De Berardinis	ENEL S.p.A., Italy
Inverters and Protection Equipment	Hiromu Kobayashi	CRIEPI, Japan
	Tadao Ishikawa	CRIEPI, Japan
Operating Experience	Hermann Laukamp	Fraunhofer ISE, Germany

Subtask 20 : Theoretical studies on various aspects for grid interconnection and configuration of PV systems

Leader: Bas Verhoeven, KEMA T&D Power, Netherlands

Subject	Leader	Company and Country
Harmonics	Ettore de Berardinis	ENEL, Italy
AC Module	Bas Verhoeven	KEMA T&D Power, Netherlands
Multiple inverters	Hiromu Kobayashi	CRIEPI, Japan
Grounding of equipment	Ward Bower	Sandia National Laboratories, USA
Ground fault detector	Ward Bower	Sandia National Laboratories, USA
Overvoltage protection	Bas Verhoeven	KEMA T&D Power, Netherlands
Islanding	Christoph Panhuber	Fronius, Austria
EMI of inverter and Array	Christoph Panhuber	Fronius, Austria
External disconnect	Jim Thornycroft	Hga, UK
Reclosing	Ettore de Berardinis	ENEL, Italy
DC injection and isolation transformer	Hermann Laukamp	Fraunhofer ISE, Germany

Sub-task 30 : Experimental tests using the Rokko Island and/or other test facilities
Leader: Akio Kitamura, The Kansai Electric Power Company, Japan

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The members of Tasks V are listed below (in country alphabetic order and per 1999):

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Contributing members

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