IEA INTERNATIONAL ENERGY AGENCY

Impacts of power penetration from photovoltaic power systems in distribution networks

Task V
Report IEA-PVPS T5-10: 2002
February 2002

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

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Impacts of Power Penetration from Photovoltaic Power Systems in Distribution Networks

February 2002

Prepared by:

Arne Faaborg POVLSEN
ELSAM A/S
Business Development & Optimization
Overgade 45, DK-7000 Fredericia, Denmark
Email: afp@elsam.com

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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 conducted various joint projects on the 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.

This report has been prepared under the supervision of PVPS Task V by

Arne Faaborg POVLSEN
Elsam A/S,
Business Development & Optimization,
Overgade 45, DK-7000 Fredericia, Denmark
Telephone +45 7622 2000, Fax +45 7622 2450

in co-operation with experts of the following countries:

Australia, Austria, Denmark, Germany, Italy, Japan, Mexico, the Netherlands, Portugal, Switzerland, the United Kingdom and the United States

and approved by the Executive Committee of the PVPS programme.

The report expresses as accurately as possible the international consensus of opinion on the subjects addressed.

ABSTRACT AND KEYWORDS

This paper attempts to answer the question of the upper limits to the amount of PV penetration into a power system as well as the financial aspects of PV penetration.

The subject is analysed in Subtask 54 "Capacity of PV Systems" under Task V of the IEA-PVPS Implementing Agreement.

The subjects of Subtask 54 all focus on the maximum possible capacity that can be achieved from PV systems connected to a power system.

This paper mainly covers Subject 54.1 "Maximum PV Penetration Level" analysed in Subtask 54. The subject deals with the upper limits to the amount of PV power that can be fed into a power system. What sets the limits? What are the possibilities of stretching the limits?

The second subject - Subject 54.2 "Financial Aspects of PV Penetration" - evaluates the financial aspects that high concentrations of PV introduce in a power system. This subject is only slightly referred to in this paper. The subject is discussed further together with the third and last subject analysed in Subtask 54: Subject 54.3 "Power Value and Capacity Value of PV Systems. This subject deals with the economic value of the power produced from PV. This subject is presented in a separate paper.

KEYWORDS:

Photovoltaic power generation, Grid interconnection, Utility distribution system, Penetration level, Voltage limits, Distributed generation.

EXECUTIVE SUMMARY

This paper attempts to answer the question of upper limits to the amount of PV that can be fed into a power system without causing problems to the power systems? What sets the limits? What are possibilities of stretching the limits? And finally, what are the financial aspects of high concentrations of PV in a power system?

The main conclusion is that the impacts of PV penetration are rather modest. PV and distributed generation must be considered in the future network planning. Network planners should actually have considered PV and distributed generation long time ago.

In the short term, the most feasible solution to stretch the limits to PV penetration is to review the procedures for adjusting the MV/LV transformer tap changer positions. The costs of such a solution are likely to be rather limited.

In the longer term, it is expected that more flexible and accommodated consumption (demand side management) will remove the barriers of limits to PV penetration.

Concerning the financial aspects of PV penetration, PV is likely to offer benefits that far exceed the inconveniences to the utilities. No fundamental novel requirements are needed for the network operators. On the contrary, PV offers benefits to the power system, e.g. peak power shaving in areas with significant use of air-conditioning.

1. INTRODUCTION

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. These technical guidelines are intended to ensure the safe, reliable and low-cost interconnection of PV systems to the electric power network. Task V considers PV systems connected to the low-voltage network with a typical peak power rating of 1 to 50 kilowatts.

After the completion of first stage, Task V was extended to complete work on a new Subtask 50 entitled “Study on Highly Concentrated Penetration of Grid-connected PV Systems”. Subtask 50 contains four subjects. They are::

Subject 51: “Reporting of PV system grid-interconnection technology”
Subject 52: “Research on Islanding”
Subject 53: “Experiences (performances) of high penetration PV systems"
Subject 54: “Capacity of the PV systems”

This report deals with one of the topics of Subject 54, “Capacity of the PV systems". The amount of installed power generating capacity from PV systems is steadily increasing. The PV systems are typically installed in residential areas and connected to the existing low voltage (LV) networks.

The instantaneous power production from PV often exceeds the instantaneous power consumption in residential areas with a high concentration of PV systems. In many cases, the imbalance in power creates a net power flow backwards through the MV/LV transformers, i.e. the power flows from the LV network to the medium voltage (MV) network.

This report attempts to answer the question of upper limits to the amount of PV that can be fed into a power system without causing problems to the power systems? What sets the limits? What are possibilities of stretching the limits? And finally, what are the financial aspects of high concentrations of PV in a power system?

2. THE CLASSIC POWER SYSTEM

In a classic power system, the generated power is assumed to feed into the system at the highest voltage level (A) and the power is consumed at the lowest voltage level (I-J).

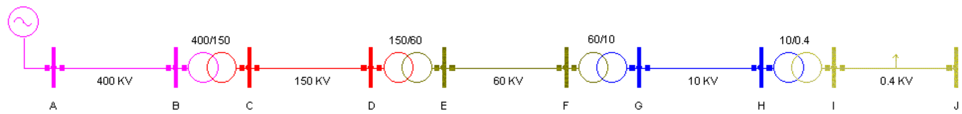

Figure 1 Classic power system

Thus, the power direction through a transformer would always be from the higher voltage level to the lower voltage level. The only exceptions from this are the power plant step-up transformers, which are not shown on the diagram.

With the growth in distributed power generation, the power flow becomes more complicated. Many CHP plants feed directly into the MV networks and many wind turbines even to the LV networks.

It is often necessary to build separate reception networks in areas with a high density of e.g. wind turbines to avoid interference with the consumer networks.

2.1 Voltage restrictions

The electricity supply companies must fulfil certain obligations when supplying electric power to the customers. Some of these are the requirements to power quality at the delivery point, e.g. voltage limits, voltage fluctuations, interruptions and harmonics.

In a classic power system, the power flow causes the voltages to drop through the power system from the highest voltage to the lowest voltage.

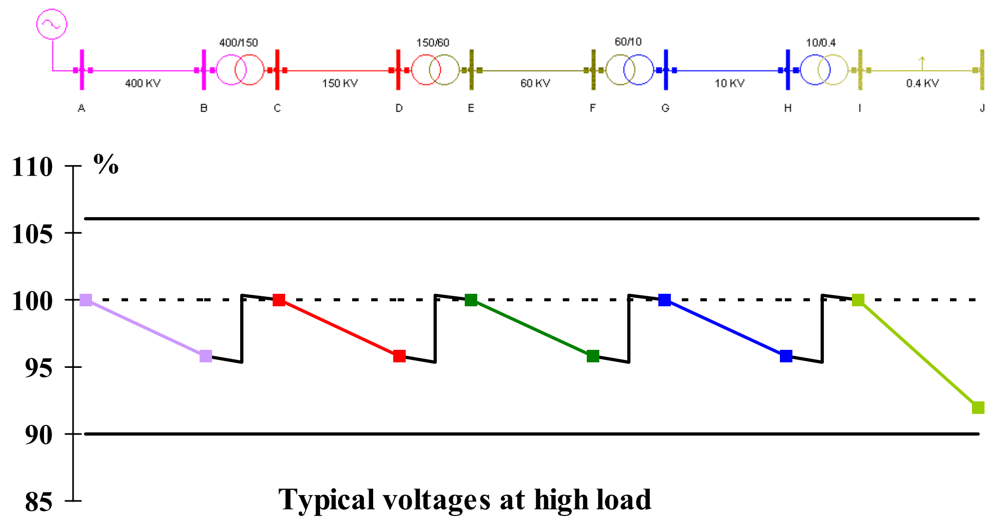

Figure 2 Voltage limits and typical voltages at high load in a classic power system

The supply voltage at the delivery point (I-J) must lie within ±10% of the nominal voltage for European LV networks according to EN 50160. Stricter limits may apply nationally, both in Europe and elsewhere.

Accepted voltages typically lie between 90% and 106% of the nominal voltage. These limits are indicated by the horizontal lines in Figure 1.

The respective transformers compensate for the voltage drops at the individual voltage levels. The transformer ratios are slightly different from the ratios between the nominal system voltages. These differences result in positive voltage jumps at the transformer points.

2.2 Load-dependent voltage variations

The voltage drops through the power lines are reduced when the load is reduced, e.g. during nights or summer holidays.

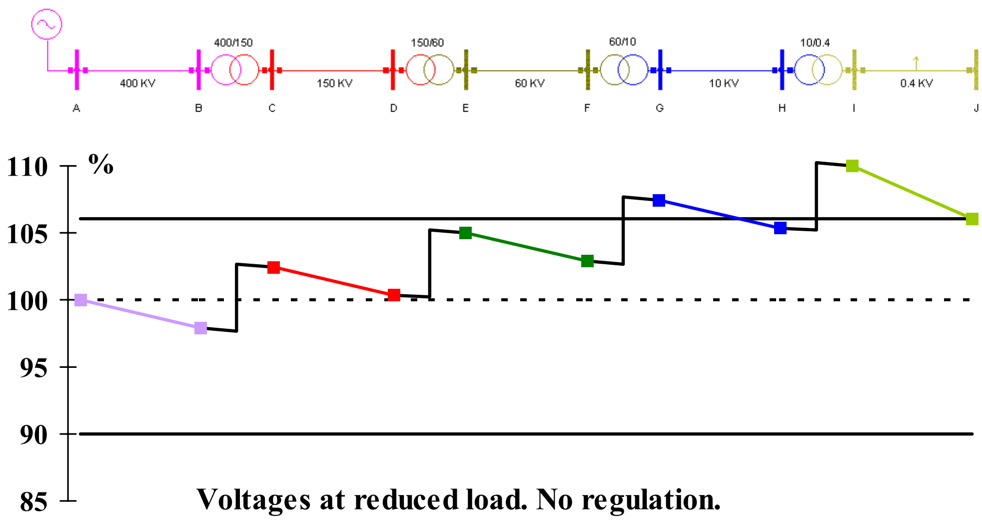

Figure 3 Voltages at reduced load if no voltage regulation is applied

At reduced loads, the voltages would go beyond the upper limit if the transformer ratios were the same as for high loads.

Therefore, the transformer ratios change automatically by automatic tap changers when the voltages change on the secondary side of the transformers.

2.3 Automatic voltage regulation

The automatic tap changers fix the voltages on the secondary side of the transformers as close as possible to the nominal system voltage. The maximum deviation from the nominal system voltage is only ± one step in tap changer position (typically ±1,5%).

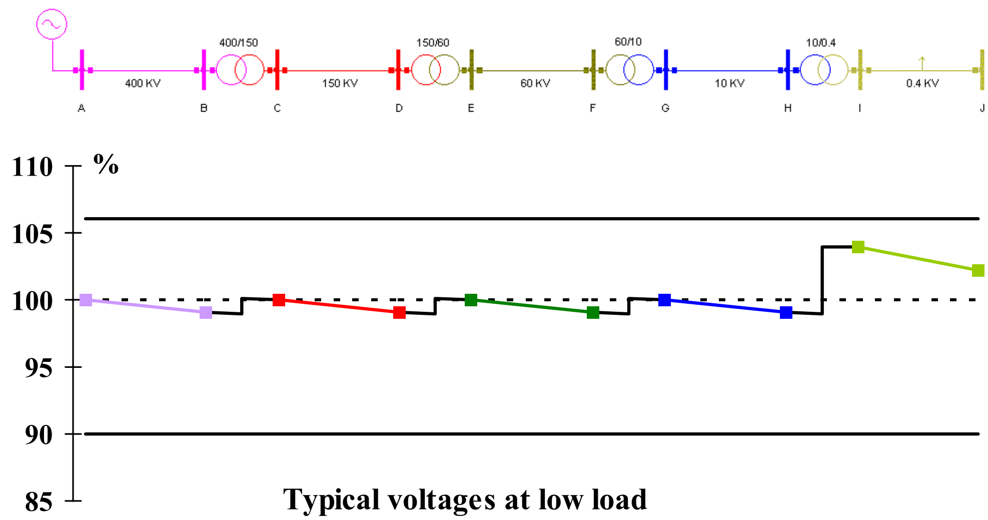

Figure 4 Voltages at low load if voltage regulation is applied

The MV/LV transformers are normally *without* automatic tap changers but have *manual off-load* tap changers. Typically, the tap changer positions of the MV/LV transformers are set once and never changed again except when the networks are extended or modified.

The manual tap changer settings of the MV/LV transformers must be chosen so the voltage is always below maximum voltage (+6%) at minimum load, and always above minimum voltage (±10%) at maximum load.

3. POWER SYSTEMS WITH PV PENETRATION

3.1 Simplification of the study

The study of PV penetration can be simplified and limited to the MV and LV networks as the voltage at the MV side (A) is always very close to 100% due to the automatic voltage control of the HV/MV transformers.

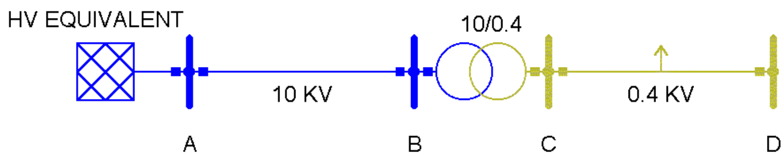

Figure 5 Simplified power system

Only when a large amount of PV power is fed into the network, the HV network must be considered as well. In such cases, the range of the automatic tap changers of the HV/MV transformers would need to be reviewed.

Initially, high concentrations of PV will be analysed for LV and MV networks (local concentrations) only. High concentrations that also affect the HV network (regional concentrations) are assumed to be less urgent at this moment. In addition, the problems at high voltage levels are not much different in nature than the problems at low voltage levels.

3.2 Voltage limits in a simplified power system

The manual off-load tap changer of an MV/LV transformer is normally set once in a fixed position. The selected position is to ensure that the voltage limits are respected at both minimum and maximum load.

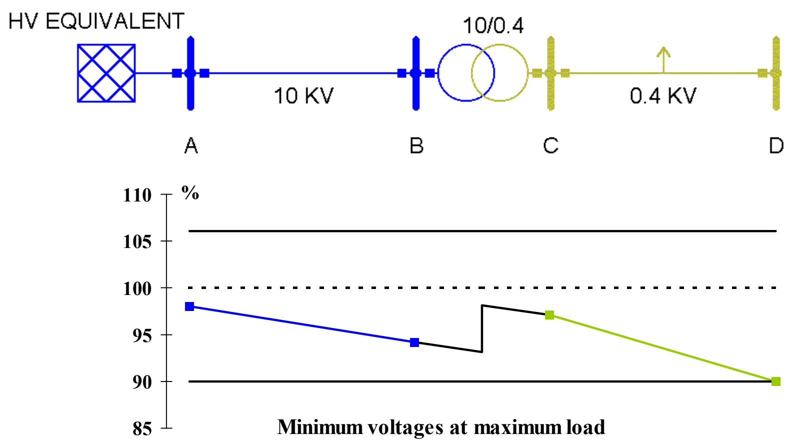

Figure 6 Minimum voltages at maximum load in the simplified power system

The voltage at the beginning of the MV line (A) is kept close to 100% by the automatic tap changer of the HV/MV transformer. To allow for a variation equal to ± 1 step in tap changer position, the voltage is set to 98% at maximum load and 102% at minimum load.

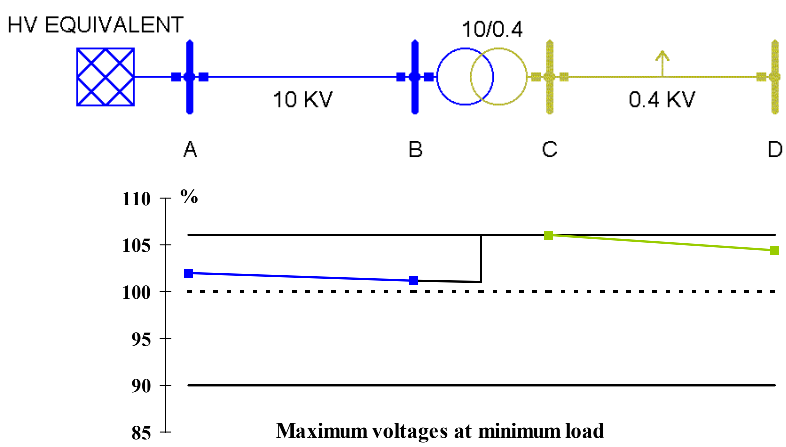

Figure 7 Maximum voltages at minimum load in the simplified power system

Of course, the voltage curves from A to B and from C to D are not straight lines if the loads are evenly distributed along the power lines. They are parabolas. However, the shapes of the curves have no influence on the results of the analyses as long as the voltages at the beginning and the end of the lines are correct.

3.3 Load conditions during PV penetration

PV penetration is of course much more suitable for power systems when the power generation from PV coincides with heavy load situations. Such conditions are typical in areas with significant use of air-conditioning.

PV penetration is less suitable for areas such as the northern countries where the use of air-conditioning is limited. In such countries PV penetration often coincides with low power demands from both households and industry due to holiday seasons.

4. INVESTIGATED CASES OF PV PENETRATION

Usually, the MV/LV transformers are evenly distributed along an open MV ring (Figure 8). The voltage changes along the MV ring are most significant farthest away from the HV/MV transformers (B1).

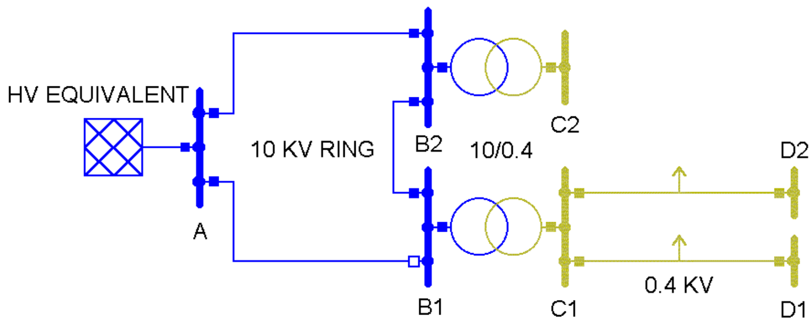

Figure 8 Typical configuration of the MV/LV power system

Three cases of high PV penetrations are investigated:

- high PV penetration from a single LV line (in the order of 30-80 kW_P)
- high PV penetration from all the LV lines connected to a single MV/LV transformer (in the order of 200-400 kW_P)
- high PV penetration from all the MV/LV transformers connected to a 10 kV ring (in the order of 1-2 MW_P)

The next step would be high PV penetration from all the MV rings connected to a HV/MV transformer (in the order of 5-10 MW_P). However, as mentioned earlier, that investigation is left out to begin with.

4.1 Choice of network parameters

A typical number of five LV lines per MV/LV transformer are chosen. In Figure 8 only two LV lines are shown.

In the same way, a typical number of five MV/LV transformers per one *half* MV ring are chosen (10 MV/LV transformers per ring). In Figure 8 only two MV/LV transformers are shown.

Typical average values are chosen for line impedances, line lengths and transformer sizes. Only the relative values are important for the analyses as the limits of PV penetration are expressed in proportion to the load.

The minimum load is set to 25% of the maximum load.

4.2 PV penetration from a single LV line

The first case considered is PV penetration from a single LV line.

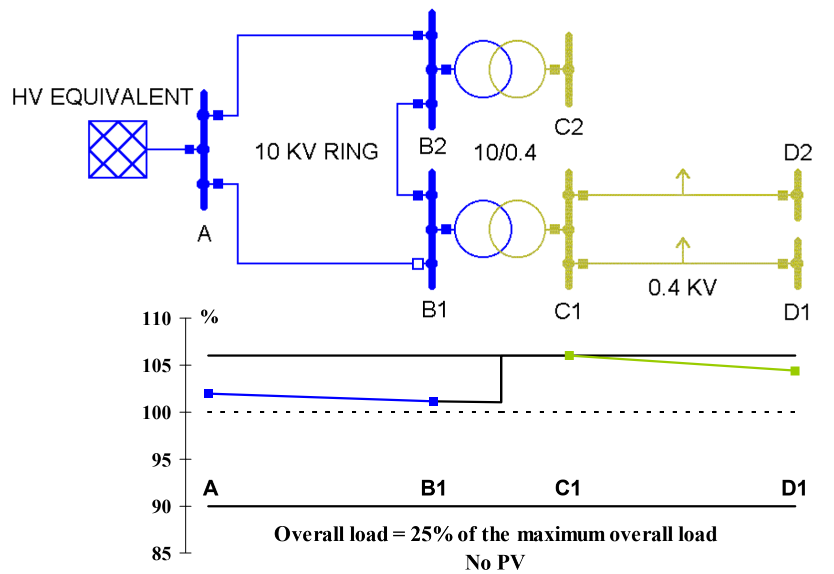

Figure 9 No PV is acceptable at minimum load (25% of maximum load)

No PV is possible at minimum load as the voltage at C1 is already at its maximum (106%) at minimum load.

However, the over-voltage caused by PV penetration would only increase to 106.1% if the PV penetration level were equal to the minimum load on the LV line.

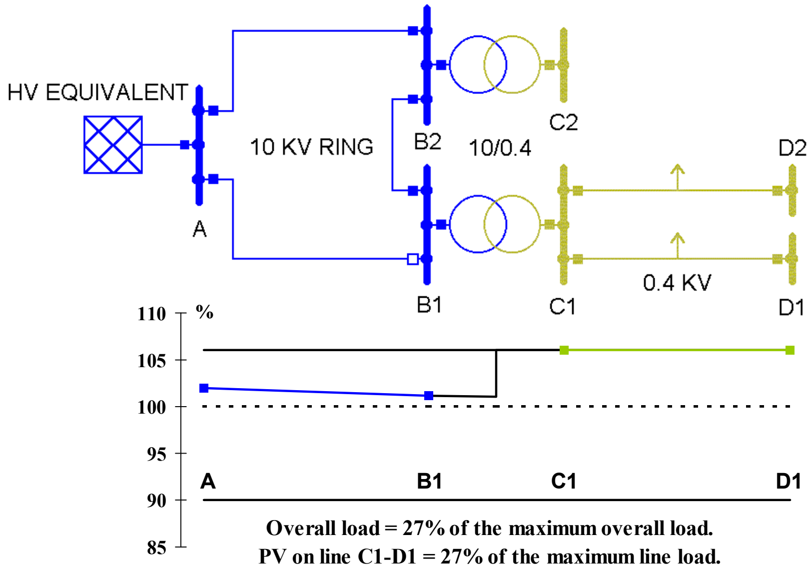

Figure 10 An amount of PV penetration equal to the load is acceptable at 27% of the maximum load

Only a small increase in the overall load will allow for a considerable amount of PV. At 27% of the maximum load (only 2 %-points above the minimum load), an amount of PV equal to the load on the LV line is possible without over-voltage. In reality that situation corresponds to a no-load situation as indicated by the horizontal voltage profile along the LV line.

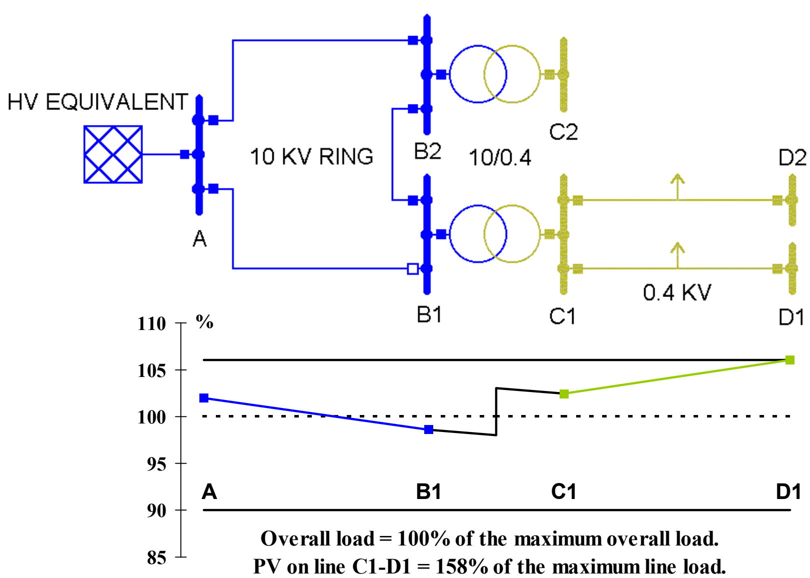

Figure 11 An amount of PV penetration equal to 158% of the load is acceptable at maximum load

At maximum load, the allowable PV penetration is as much as 158% of the maximum load.

In situations where the penetration from PV amounts to less than the load, the limits are given by the voltage at the beginning of the LV line (C1).

In situations where the penetration from PV amounts to more than the load, the limits are given by the voltage at the end of the LV line (D1).

4.3 PV penetration from all the LV lines in an MV/LV transformer

Again, no PV is possible at minimum load. The over-voltage caused by PV penetration would be 106.6% if the PV penetration were equal to the minimum load on the 5 LV lines (no-load situation).

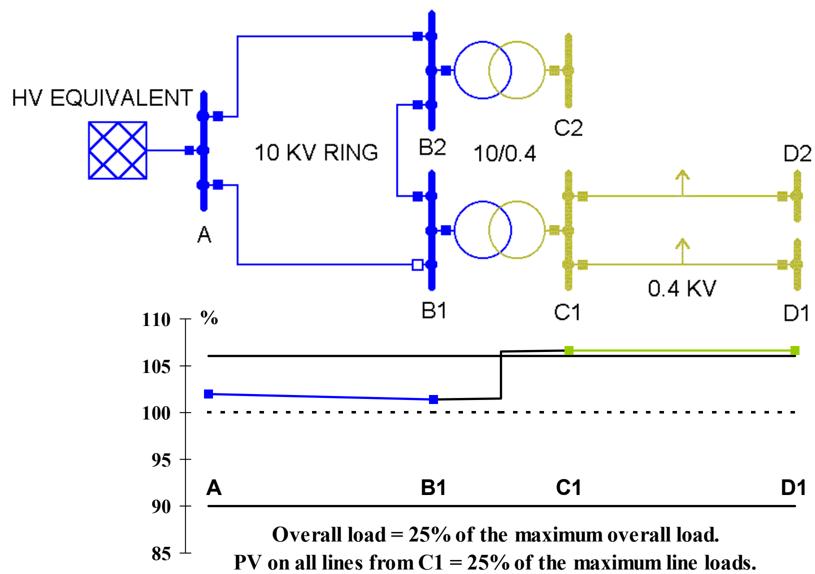

Figure 12 An amount of PV penetration equal to the load from all the 5 LV lines from an MV/LV transformer causes an over-voltage of 106.6% at minimum load

Note that the capacitive currents in the no-loaded LV lines cause a slight voltage increase in the transformer windings!

At 45% of the maximum load, an amount of PV equal to the load is possible from all the LV lines without over-voltages.

At maximum load, an amount of PV equal to 120% of the maximum load is possible.

4.4 PV penetration from all MV/LV transformers in an MV ring

No PV is possible at minimum load. The over-voltage caused by PV penetration would be 107.3% if the PV penetration were equal to the minimum load on all the MV/LV transformers.

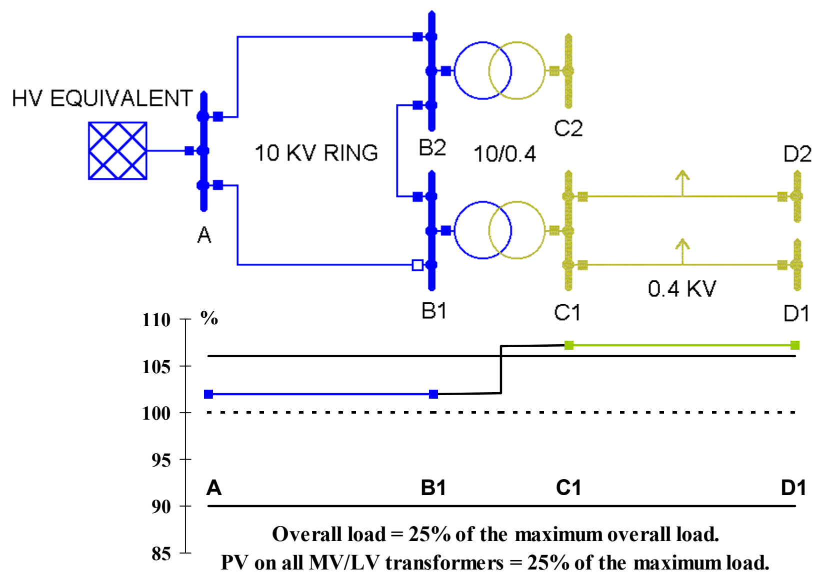

Figure 13 An amount of PV penetration equal to the load from all five MV/LV transformers of a half MV ring causes an over-voltage of 106.6% at minimum load

Actually, an amount of PV equal to the load is never possible when the PV power penetrates from all MV/LV transformers. This is due to the fact that the MV/LV power system is not designed for a total no-load situation.

At maximum load, an amount of PV equal to 75% of the maximum load is possible. In reality that amount corresponds to the minimum-load situation.

5. OVERVIEW OF THE LIMITS TO PV PENETRATION

Figure 14 shows the overall limits of PV penetration as analysed in 4.2 – 4.4.

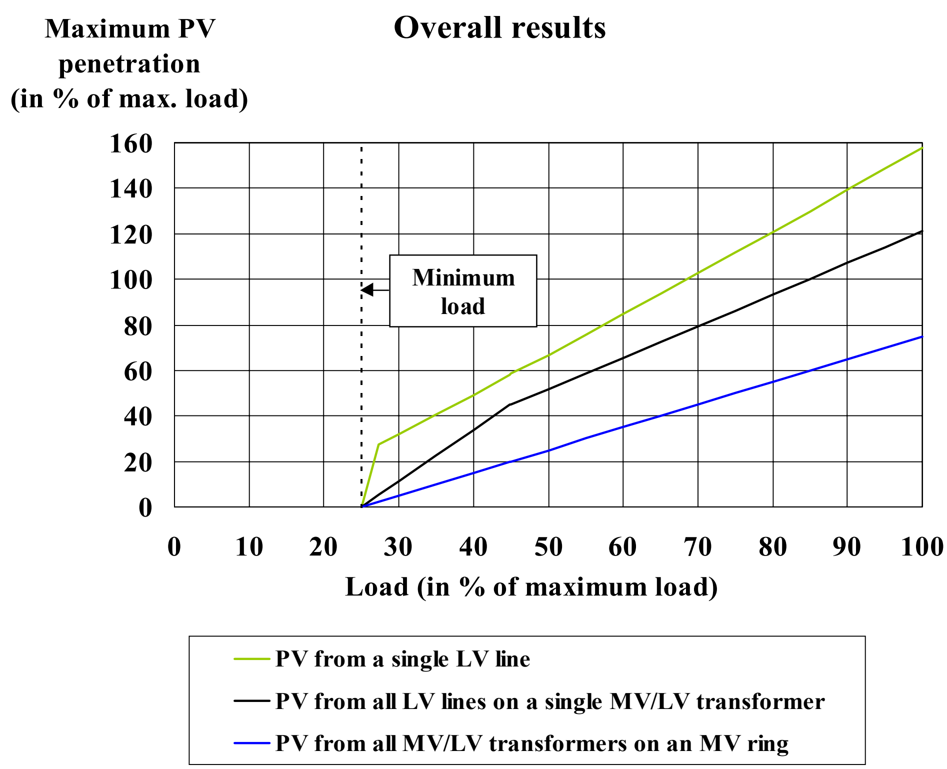

Figure 14 Overall limits of PV penetration into existing power systems

In principle, no PV penetration is acceptable at minimum load. However, the excess voltages are rather limited for PV penetrations up to the minimum load.

In addition, only a small increase in the load from the minimum load opens up for a considerable amount of PV, especially if PV power only penetrates from a single LV line.

Of course, the restrictions at minimum load are only a problem if the power generation from the PV systems coincides with minimum load situations.

6. MEASURES TO STRETCH THE LIMITS OF PV PENETRATION

Measures to increase the amount of PV penetration are only necessary if large power production from PV coincides with minimum load situations. This is the case during the summer holidays in many countries, especially if the use of air-conditioning is limited.

6.1 Separate PV reception networks

A conservative way to avoid over-voltages from PV penetration would be to build separate reception networks for PV systems (i.e. PV networks separated from the consumer networks). Such measures are often seen in the open country with high concentrations of wind power.

The power networks are, however, not very often well established to begin with in the open country.

On the contrary, one of the big advantages of PV is in fact to connect to the existing power networks as well as to use the existing buildings for mounting.

The costs of PV would increase to unacceptable levels if separate power networks were required, especially if the problems only occurred a few times per year.

6.2 Controllable PV systems

Another way to avoid over-voltages could be to let PV systems reduce their power generation in case of over-voltage.

Such a measure would add unacceptable costs to PV systems, especially if the measure is not needed in the majority of cases.

In addition, over-voltage monitoring systems would make PV more sensitive to short-term disturbances in the network.

6.3 Adjusting the transformer tap changer position

A more feasible solution to allow for more PV penetration at minimum load during summer days is to change the MV/LV transformer tap changer positions in the summer period when maximum load situations are not expected.

Such a measure would require an interruption of the electricity supply twice a year for adjustment of the offload tap changers.

The costs of this measure are likely to be rather limited.

6.4 Customer initiatives

One of the most efficient measures to allow for more PV is perhaps the customers' own changes of behaviour.

Experience with PV systems in Denmark shows that the customers change their consumption behaviour when at the same time they become power producers.

Many customers who have PV installed endeavour to move their consumption to moments with high power production from PV. This tendency is especially noticeable if the customers experience different buying and selling prices of electricity.

7. FINANCIAL ASPECTS OF PV PENETRATION

In general, PV is unlikely to present conceptually novel issues requiring fundamental, additional investments in the power systems. PV is more or less just another element of distributed generation contributing to the general competition in generation, transmission and distribution.

The marginal costs per kWh that PV imposes on the power system are likely to be substantially lower than for bulk power. PV penetration implies only minor costs of the measures of stretching the limits for penetration. If PV becomes a significant element in power generation, it must be integrated into the dispatch protocols of the independent system operators.

On the contrary, PV offers benefits to the power systems like all other elements of DG (distributed generation). PV reduces the peak power demand from the network if high PV penetration coincides with peak demand situations.

The benefits appear especially when PV is combined with flexible and accommodated consumption. The major benefits are the independent supply security and the reduction in network losses.

8. CONCLUSIONS

The limits to the amount of PV power that can be fed into a power system are least critical if the PV power penetrates from only a single LV line.

The limits are more severe if PV power penetrates from multiple LV lines connected to the same MV/LV transformer or even multiple MV/LV transformers.

The most severe limits occur in minimum load situations, especially if the power system beforehand is operated to its design limits.

However, an amount of PV penetration equal to the minimum load only causes slight excess voltages in the power network.

Only a small increase in the load from the minimum load opens up to a considerably larger amount of PV, especially if the PV power only penetrates from a single LV line.

The most feasible solution to stretch the limits to PV penetration is to review the procedures for adjusting the MV/LV transformer tap changer positions. The costs of such a solution are likely to be rather limited.

In the longer term, it is expected that more flexible and accommodated consumption will remove the barriers of limits to PV penetration.

It is essential that PV - together with other elements of distributed generation - is considered in the future network planning.

Concerning the financial aspects of PV penetration, PV is likely to offer benefits that far exceed the limited costs of PV penetration.