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"ENEL's PV Programme"

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These are preliminary lecture notes, intended only for distribution to participants.

OF BATTERY CHARGE REGULATORS IN STAND-ALONE PV SYSTEMS

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ABSTRACT - Performance of photovoltaic systems with electrochemical storage is affected by the adopted battery charge regulator and the problem of an optimum charge regulation in small PV plants is still an open question. To determine the optimum regulation type a monitoring activity has been carried out by ENEL and Conphoebus. Photovoltaic systems, with identical electrical characteristics but using different types of charge regulators, have been compared for a long time, at Conphoebus test facilities, in order to evaluate performance of each charge regulation strategy under identical meteorological conditions, initial battery state-of-charge and electrical load. Furthermore different types of charge regulators, presently available on the market, are adopted in PV plants run by ENEL in order to assess their efficiency and reliability: performance data of different systems have been evaluated.

1. INTRODUCTION

Battery charge regulators are included in most photovoltaic systems to protect the batteries from overcharge and excessive discharge, extend battery life and maintain battery voltage within a range acceptable for the load operation. Moreover regulators are used to transfer energy from the PV array to the battery and towards the load with the maximum efficiency. A good regulator must carry out the aforementioned tasks offering also :

- reliability;
- simplicity of manufacture;
- low cost.

The most utilized kinds of charge regulation in PV systems with electrochemical storage are:

- direct connection regulation, between PV generator and storage (see Fig. 1a) using the self-regulating capacity of properly designed PV modules when they are connected to the electrochemical storage: increasing the battery voltage increases PV array voltage and, therefore, decreases PV array current; this regulation is convenient when the PV system is placed in locations where the ambient temperature does not vary dramatically (so the PV maximum-power voltage remains fairly constant) and when the electric load doesn't require a fair constant input voltage;
- ON-OFF regulation, which consists of a complete connection or disconnection of PV generator from storage when the battery voltage gets the preset levels; the PV generator can be left in open circuit condition (ON-OFF series regulation, see Fig. 1b) or shunted to a power dissipation device (ON-OFF shunt regulation, see Fig. 1c);
- multi-step regulation, which prevents battery overcharging by a partial connection or disconnection of PV generator from storage when the battery voltage reaches the preset limits; the regulation can be realized by means of a partial connection or complete disconnection of whole strings (see Fig. 1d) or part of a string;
- chopper regulation, which maintains a fairly constant output voltage, by means of electronic devices that modulate the charge current according to the battery voltage level (see Fig. 1e);
- MPPT regulation, in which a Maximum Power Point Tracker forces the PV array to always work at its maximum power point even if the irradiance and temperature change (see Fig. 1f).

Regulators, which present simpler manufacture (like direct connection and series types), are less expensive and more reliable. On the other hand, more complex regulators, like chopper and MPPT types, present higher charging efficiency, extend battery life, but make the overall system more expensive and less reliable, because of the added circuitry.

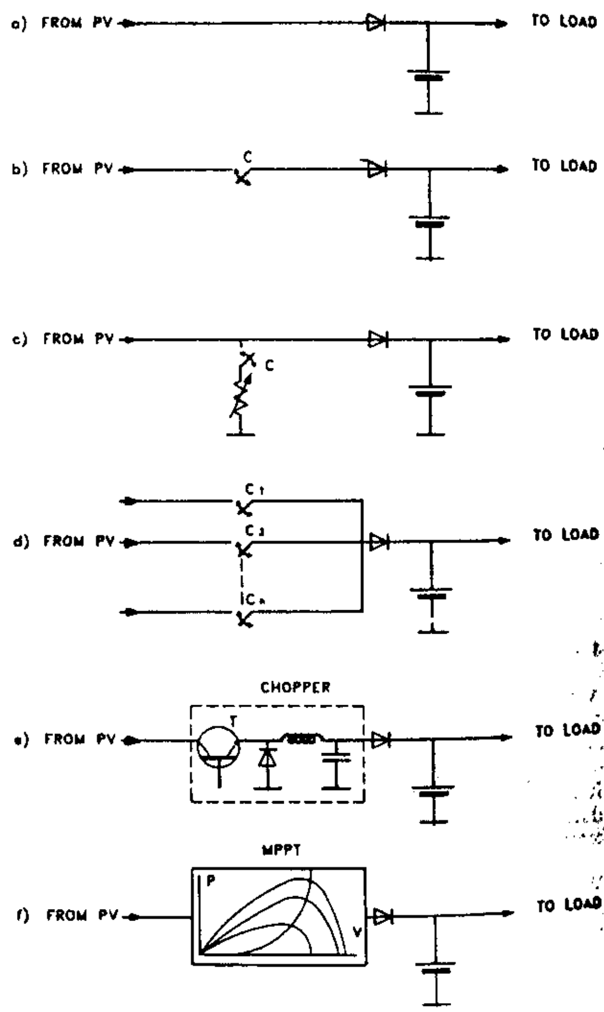

Fig. 1 Battery charge regulation for stand-alone PV systems with electrochemical storage: a) direct connection; b) ON-OFF series regulation; c) ON-OFF shunt regulation; d) multi-step regulation; e) chopper regulation; f) MPPT regulation

In order to determine the optimum regulation type the performances of stand-alone PV systems, having identical electrical characteristics but different types of charge regulation, have been evaluated under identical meteorological conditions, initial battery state-of-charge and electrical load. The work has been conducted at Conphoebus test facilities on behalf of ENEL-DSR-CREL, which has adopted different types of charge regulators for the installations in Alpine Huts /1/ and in Stromboli Island in the frame of the Scattered Dwelling Project /2/. The research has then been aimed at assessing the efficiency and reliability of various types of regulators presently available on the market.

2. COMPARISON BETWEEN 3 DIFFERENT CHARGE REGULATORS UNDER IDENTICAL TEST CONDITIONS

In order to analyze the performance of different charge regulators, during actual operations, three photovoltaic systems with identical electrical characteristics (24 Vdc rated voltage, 4 module pv generator, appropriate load and battery) have been set up in Conphoebus test facilities.

2.1 Description of the systems to be compared

The three photovoltaic systems adopt different types of charge regulators (see Tab. 1):

- ON-OFF series charge regulation is adopted in system 1; it controls the battery by means of a complete connection or disconnection of PV generator from storage when the battery voltage reaches the preset levels;
- two-step series charge regulation is adopted in system 2; it controls the battery connecting or disconnecting half PV generator from storage when the battery voltage reaches the preset levels; the second half is disconnected if the voltage reaches again the threshold;
- direct connection regulation is adopted in system 3; to obtain an optimal self-regulation PV modules must be chosen taking into account battery nominal voltage and average ambient temperature of installation site; Fig. 2 shows different self-regulation characteristics adopting PV modules with 36, 30 and 27 cells in series. A module configuration with 30 cells in series was chosen, because several test runs, conducted during some seasons, have actually indicated that this kind of module, connected with a 12 V battery, presents an optimal self-regulation capacity in the Mediterranean climate. One year operation of a PV system, using this regulation type, resulted in the PV generator presenting a conversion efficiency variable between 8.1% (during July) and 11.9% (during December and January) (see Fig. 3). The system has always charged the battery regularly and deficit occurred only in January (125 hours) and in December (59 hours); the maximum values of the battery got 31.8 V (in February), while its daily average value varied between 24.7 V and 26.2 V; in any case, during the same period, no evident electrolyte gassing was observed.

Tab. 1 - Main characteristics of tested systems

SYSTEM	1	2	3
PV GENERATOR			
Cells in series	36	36	30
Modules in series	2	2	2
Total modules	4	4	4
Total Voc [V]	40.0	40.0	35.5
Total power [Wp]	190	190	160
BATTERY			
Elements in series	12	12	12
Nominal Voltage [V]	24	24	24
Capacity C10 [Ah]	150	150	150
CHARGE REGULATION	ON-OFF series	Two-step series	Direct coupling

The compared regulation types were selected because they seem to offer more advantages than the others when used in stand-alone PV systems. In particular system 3, which adopts the regulation by means of direct coupling between PV generator and battery, for its simplicity seems the best solution for PV systems installed in remote areas, where difficulties in system maintenance could limit system operation.

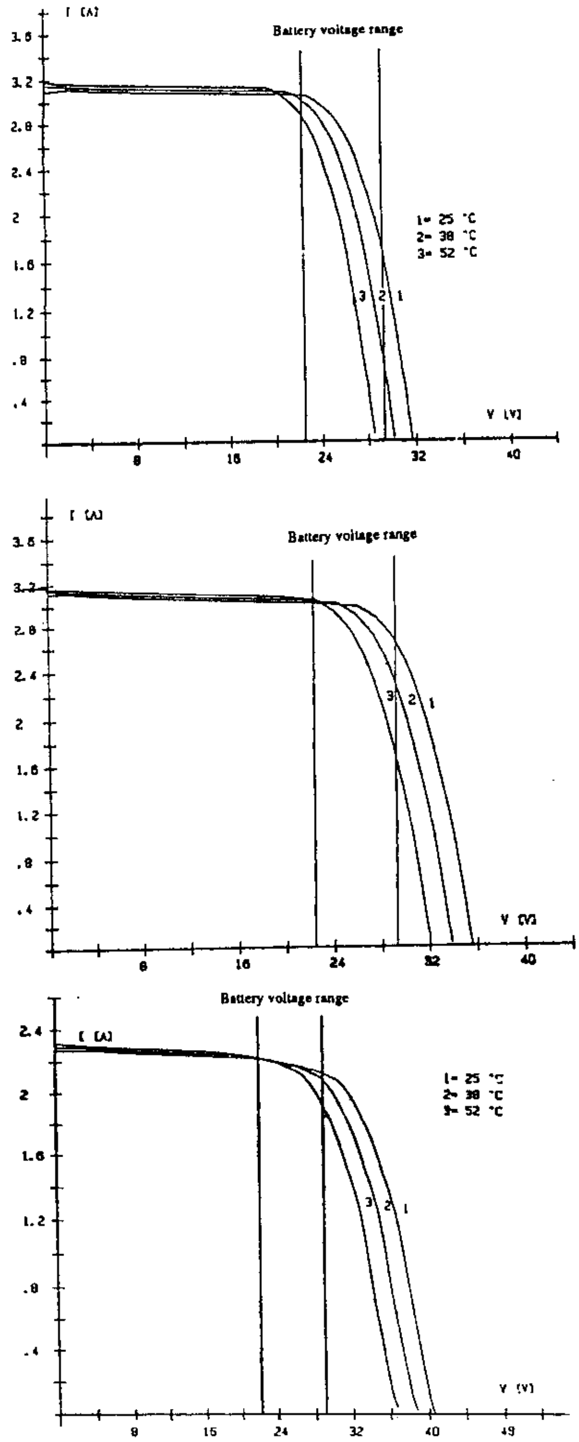

Fig. 2 Self-regulation capacity of modules with different number of cells in series: a) 27 cells; b) 30 cells; c) 36 cells

operation, a data acquisition equipment was used to monitor the main electrical and meteorological parameters. Measurements were taken every 20 seconds and their average recorded every 15 minutes. Finally the data were processed to prepare the output.

2.2 Comparison among different charge regulators during a sunny day

Fig. 4 shows the different profiles of charge current in system 2 and system 3, on a sunny day: generator-battery direct coupling allows the battery to be charged more regularly, thus avoiding high voltage fluctuations and frequent inversions of battery current, which reduces efficiency in transferring energy between PV generator, battery and load. System 3 has presented fewer battery current inversions (BCI) and has produced 36% more energy per unit of installed power than the system 2. On the same day, the maximum voltage level reached in the system 3 (31 V) is higher than that got by the system 1 and 2 (29 V), but this high value does not damage for the battery, because when the maximum value is reached the PV generator works near open circuit condition and the charge current is very low (no appreciable gas development was observed). Moreover such a voltage is affordable by the usual 24 Vdc appliances.

2.3 One month comparison among different charge regulators in no-load conditions

For one month, in two different periods, the systems were operated without load, in order to test system limits in the high charge current / low load demand condition.

Before starting the tests, the battery of each system was discharged until electrolyte density reached the value 1.18 g/cm^3 (Vb = 23V). During the tests the main electrical and meteorological parameters were monitored.

Fig. 5, Fig. 6 and Tab. 2 account for the fact that the direct coupling allows higher charging efficiency than the other regulation strategies: more energy was generated and a higher state of charge was reached (see electrolyte density profile), still maintaining the battery maximum voltage within acceptable value.

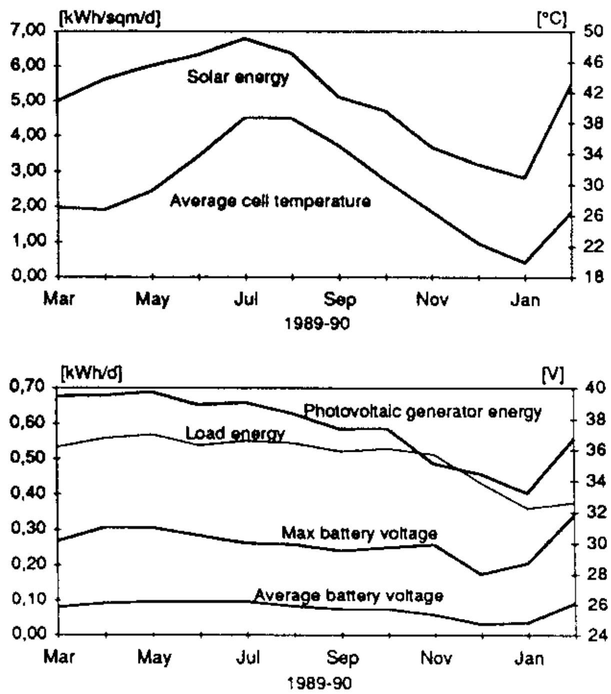

Fig. 3 One year operation of a PV system adopting direct connection regulation

normal operation

The systems under test have been compared during normal operation in different seasons.

During operation in summer period the system 3 produced, per unit of installed power, 18% more energy than the systems 1 and 2 which produced the same energy (see Fig. 7). The battery current inversion per day (BCI) were equals 55 for the first system, 21 for the second one, 6 for the third one.

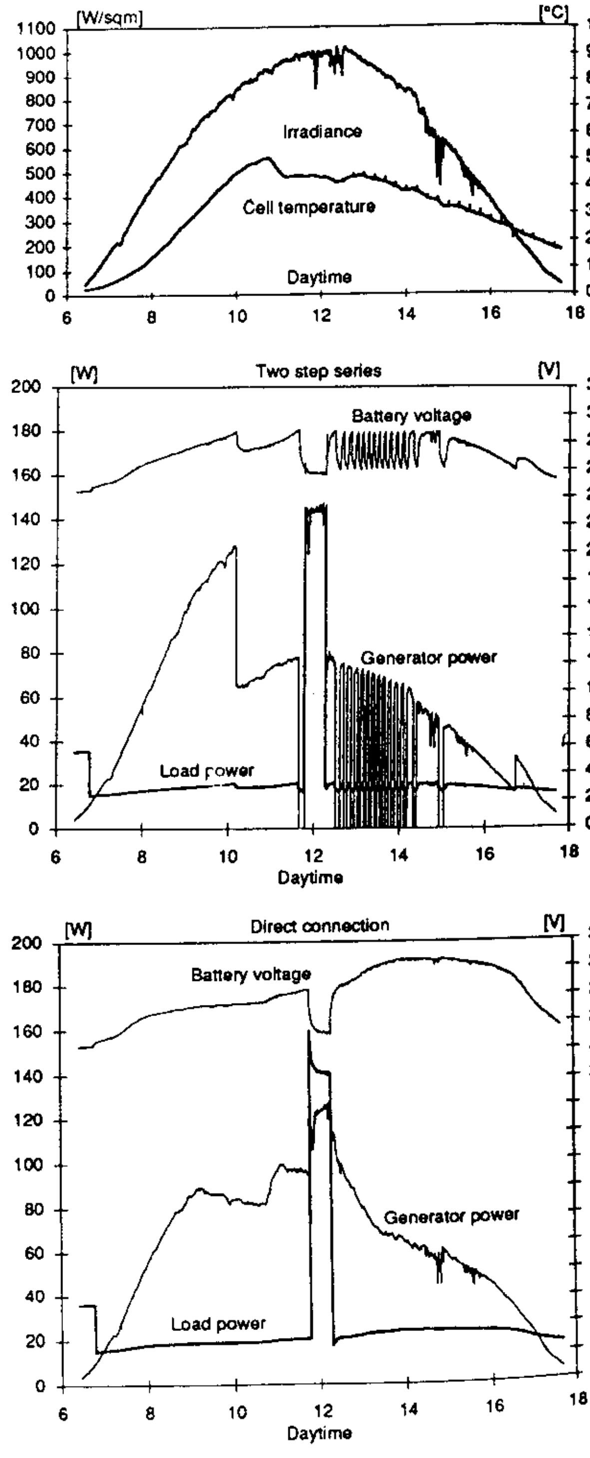

Fig. 4 - Comparison among different charge regulators during a sunny day (23/03/90).
On plane sol. radiat.. = 6940 Wh/sqm;
Average cell temp. = 29 °C;
2 step regulator: Pg = 617 Wh, Pc = 549 Wh, BCI = 40
Direct connection: Pg = 709 Wh, Pc = 574 Wh, BCI = 4

During operation in winter period the system 3 produced, per unit of installed power, 10% more energy than the systems 1 and 2 which produced almost the same energy (see Fig. 8). The battery current inversion per day (BCI) were equals 14 for the first system, 8 for the second and the third ones.

3. PERFORMANCE OF DIFFERENT CHARGE REGULATORS ADOPTED IN ENEL'S PV PLANTS

Different types of battery charge regulators have been adopted by ENEL for stand - alone PV plants, namely in 7 mountain huts and in 30 houses in the island of Stromboli, near Sicily.

The plants for the huts equipped with ON-OFF regulators have shown that the battery is not allowed to reach the initial S.O.C., thus reducing in practice the available battery capacity /1/.

At Stromboli, ten of the plants are equipped with electromechanical two-step series charge regulators, eleven plants adopt a four-step regulation by means of a programmable logical controller (PLC) and nine plants use chopper regulation. During two year operation, all the adopted regulators have presented a good reliability. The conversion efficiency of the systems which adopt PLC and chopper was quite similar and about 10% higher of the systems adopting two-step regulator (see Fig. 9). Anyway, the system efficiency is strongly affected by the user, depending upon the balance of produced and consumed energy.

4. CONCLUSIONS

According to the performance of several small stand-alone PV systems operated by ENEL, the use of simple battery charge regulators is recommended, since chopper regulators does not show drastic advantages as compared with step regulators. Furthermore the test activity carried out by Conphoebus shows that the charge regulation obtained by means of direct coupling between properly designed PV generator and battery offers reliability and efficiency. This regulation could therefore be considered the best solution for small PV systems especially if they are installed in remote areas, where difficulties in system maintenance could limit plant operation.

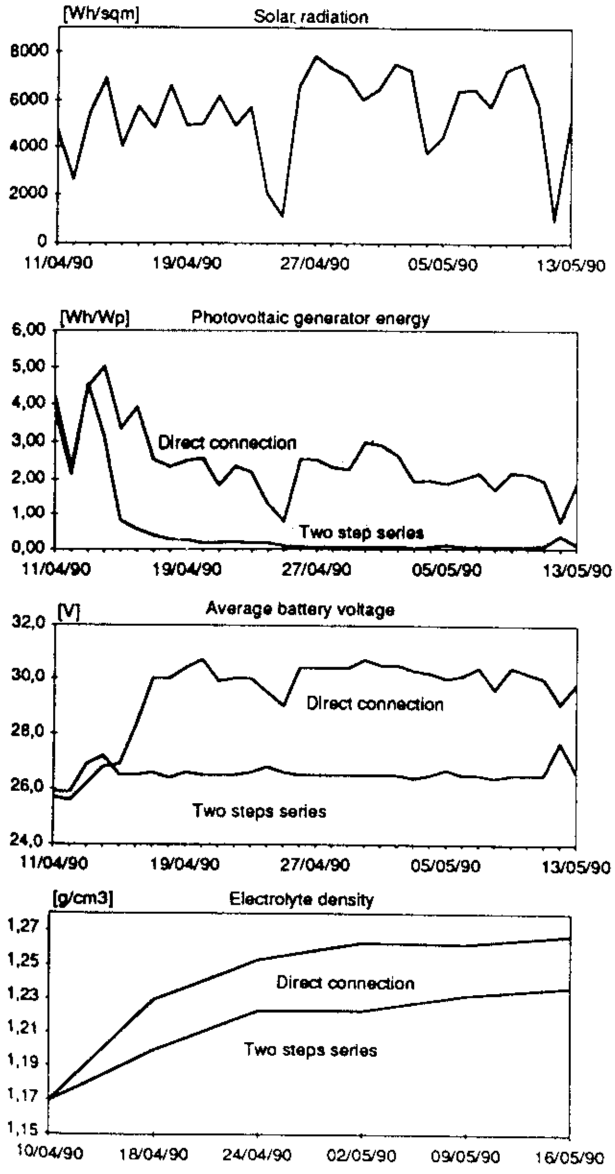

Fig. 5 One month comparison among different charge regulators in no-load conditions (April - May 1990)

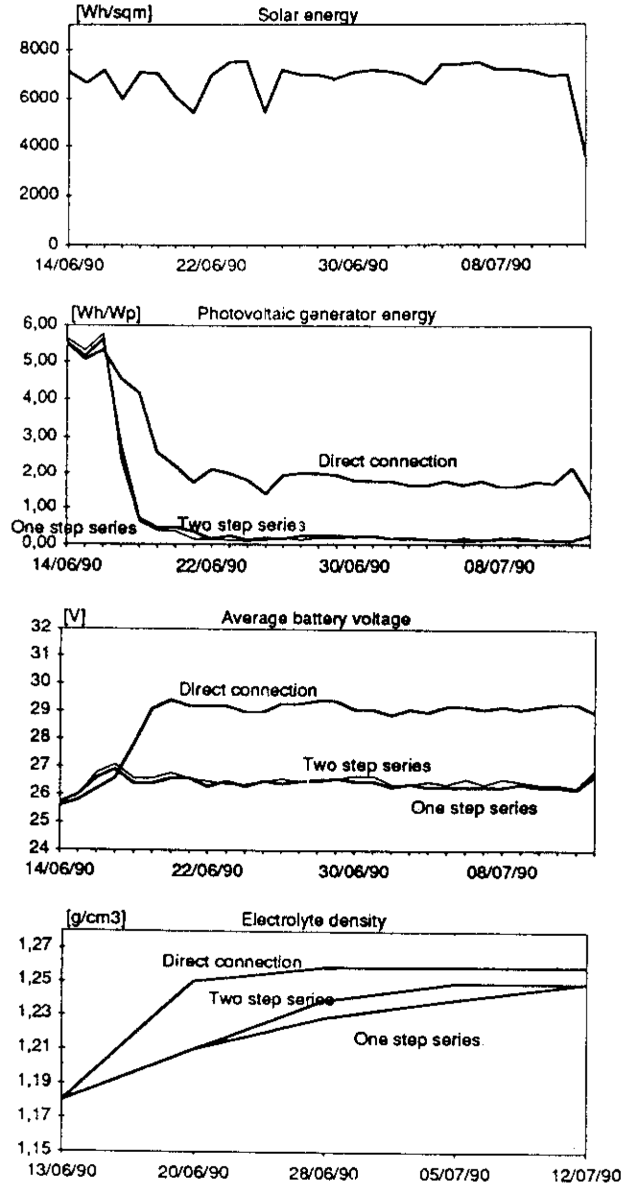

Fig. 6 One month comparison among different charge regulators in no-load conditions (June - July 1990)

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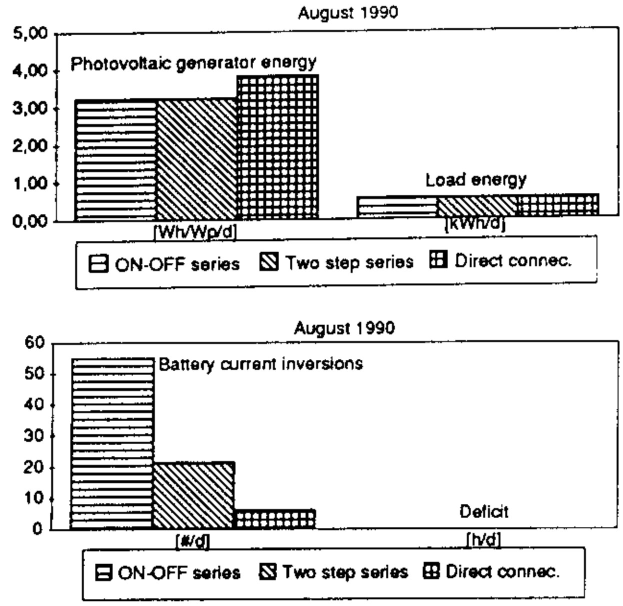

Fig. 7 Comparison among different charge regulators in actual operating conditions in a summer period

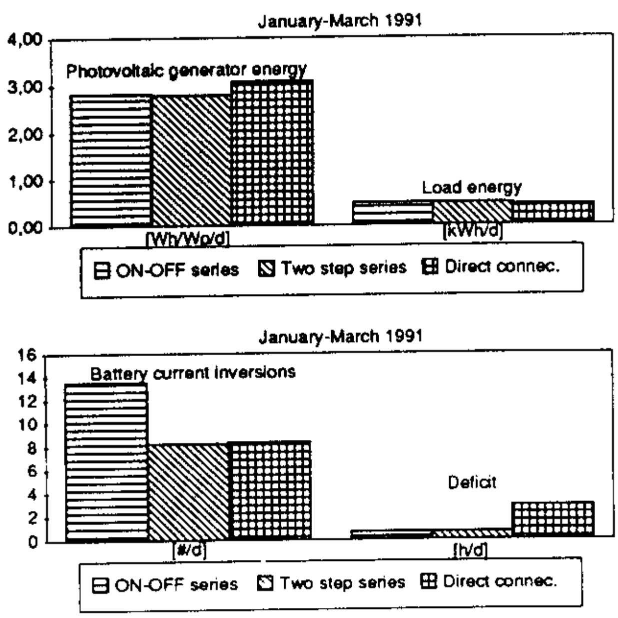

Fig. 8 Comparison among different charge regulators in actual operating conditions in a winter period

referred to the system 2

PERIOD			April '90	June '90
On plane irradiance		[Wh/sqm/d]	5457	6800
Cell temperature during insulation time	med	[°C]	20.4	39.3
	max	[°C]	56.1	58.4
SYSTEM 1				
Generated energy		[Wh/Wp/d]	0.54	0.80
		[%]	-2	-3
Charge current		[Ah]	122	165
		[%]	-3	-3
Battery voltage	med	[V]	26.5	26.5
	max	[V]	28.9	28.9
SYSTEM 2				
Generated energy		[Wh/Wp/d]	0.55	0.82
		[%]	--	--
Charge current		[Ah]	126	170
		[%]	--	--
Battery voltage	med	[V]	26.6	26.4
	max	[V]	29.1	29.0
SYSTEM 3				
Generated energy		[Wh/Wp/d]	2.42	2.33
		[%]	337	192
Charge current		[Ah]	423	384
		[%]	236	132
Battery voltage	med	[V]	29.5	28.7
	max	[V]	32.1	30.6

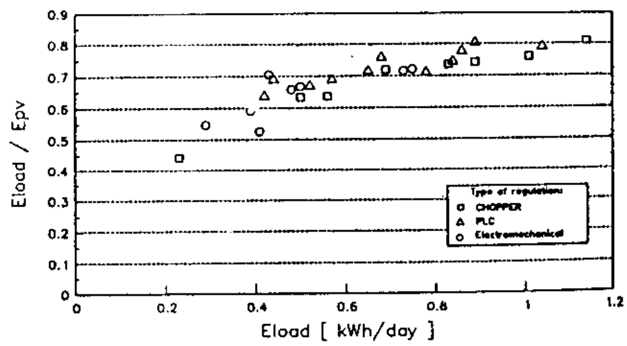

Fig. 9 Ginostra PV plants - Efficiency vs energy consumption

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ENEL's 3-MW PV POWER STATION PRELIMINARY DESIGN

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ABSTRACT. In the context of the Italian National Energy Plan, ENEL, the Electricity Authority, is developing a first utility scale PV generation plant, to be located in the region of Naples.
This paper presents the main technical characteristics of the plant at its preliminary design phase, and the available information of the principal components.

1. INTRODUCTION

The design of a grid-connected photovoltaic power plant is basically quite simple. It involves setting up a d.c. generator of a given size and power, coupled to a d.c. - a.c. static converter. However, the transition from the theoretical design to its implementation in practice involves a series of technical problems that are not always easy to solve and are not catered for by conventional plant engineering. The salient feature and the weakest point in photovoltaic conversion is, as it is known, the low degree of conversion efficiency of present-day photovoltaic modules. This aspect, which has only a slight bearing on the designing of small photovoltaic plants, becomes decisive when it comes to setting up power plants of MW dimensions.
The considerable amount of land required for such plants means the designer has some new and unusual structural and architectural problems to deal with. The possible solutions are many, but their effect on the cost of the system is significant. Moreover, low conversion efficiency also affects the electrical design of the project, inasmuch as setting up large power generators involves handling, assembling, and wiring tens of thousands of modules, which obviously means high labour costs.
By setting up this photovoltaic power plant, ENEL aims above all to ascertain the present costs of implementation and to improve design criteria, as well as the costs of future projects, so as to make them as competitive as possible compared to conventional power plants.
Let us now take a closer look at the design criteria applied.

2. DESIGN PARAMETERS

The designing of a grid-connected plant calls for knowledge of the main meteorological data in respect of the site under consideration (i. e., solar energy, temperature, wind speed). The system has to be so designed that it will guarantee a given annual production of electric energy and peak power throught the year.
The design parameters to be defined are:
- The tilt angle
- The system's conversion efficiency.

Both the above quantities have to be laid down so as to ensure that the maximum energy is produced for a given amount of installed generating power.
Various more or less sophisticated methods can be used to calculate the optimal tilt angle. In the case of the plant in question, use has been made of the methodology indicated in (1).
The chosen value of 20° is based not only on energy, but also on practical considerations, as follows:

- Module self-washability
- Reduction of the area taken up by the plant
- The possibility of supplying only slightly below rated installed peak power in winter time.

As regards the electrical efficiency of the system, (ratio between the DC and the AC rating) the aim has been to obtain the best, compatible with a number of constraints, imposed both by the current state of the art in respect of photovoltaic modules and by Italian safety regulations. The first step to reduce the ohmic losses of the array, given the same power output, it's to fix the rated voltage as high as possible.
In the case of photovoltaic plants, there are practical limitations on the use of high voltages for the following reasons:

- The output voltage from the plant depends on the number of modules arranged in series; it has been estimated that when the number of modules connected in series exceeds a hundred, the reliability of the system begins to diminuish (2).
- If the plant's voltage exceeds 600 V, steps have to be taken, in accordance with Italian safety regulations, to isolate the plant from the public and also from maintenance staff.

For all the reasons mentioned, the operating voltage of ENEL's plant has been fixed at 330 V (i.e., about 400 V no-load), thus allowing

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d.c. generator within bounds, it has been decided that all wiring be designed not to exceed a current density of about 1A/mm^2, at peak power.
In addition to ohmic losses, photovoltaic generators suffer internal losses due to the lack of homogeneity in the electrical characteristics of the numerous photovoltaic modules of which they are made up. More or less complicated criteria to optimize the matching of modules in series and in parallel can be adapted (3). The basic principle is to connect in series the modules that supply very similar currents, and in parallel the modules or strings of modules that have very similar voltages. In this case, too, practical considerations have meant that modules are classified and subdivided as little as possible, in order to complicate on-site assembly as little as possible. In the case of the ENEL plant, the modules will be subdivided into two current and voltage classes balancing cost of installation and array efficiency.

3. ELECTRICAL DIAGRAM OF THE PLANT

Particular attention has been paid to the electrical layout. First of all, the 3-MW power plant has been subdivided into 10 sub-field, each with a gross power of 330 kW peak. Each sub-fields is electrically independent of the next, since it is connected to the 20-kV network by means of its own converter. All the sub-arrays therefore operate electrically in parallel on a buried 20-kV loop running throughout the area of the photovoltaic plant.
Each sub-array is broken down into two galvanically separate sections, and is connected to the converter in accordance with the diagram in Fig.1.b.
This 4-wire layout is functionally identical to the -3-wire system with the center tapped to ground, as described in Fig.1a.
Of the two alternatives, the choice fell on that in Fig. 1b, which offers the advantage of operating as a floating photovoltaic plant, isolated from the ground. The main plus point here consists in the fact that ground fault causes the circulation of only very weak fault current.

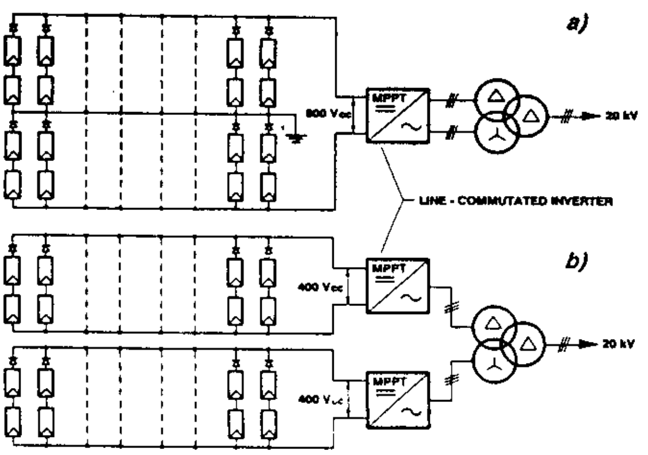

Fig. 1. 3MWp PV power plant - Possible electric lay-outs of one sub-field (330 kWp)

The ENEL photovoltaic plant will be equipped with polycristalline silicon modules. During 1990, both Italian and non-Italian manufacturers were invited to submit tenders for the supply of the 10 sub-arrays into which the plant is subdivided.
The electrical diagram proposed by ENEL provides for a 72 cell module with a power of about 90÷100 Wp and a voltage at maximum power of about 17 V d.c. The diagram is given in Fig. 2b. The module is twice the size of the 36-cell type available on the market. Obviously, the 72-cell module has the following advantages over the smaller kind:

- Higher power density (W/m^2), given the same cell output.
- Saving in material
- Only half the amount of work required for assembly and wiring of the modules.

Some of the manufactures approached stated they were prepared to supply modules with the characteristics indicated by ENEL, while others were prepared to provide either 36-cell or 72-cell modules, but with twice the output voltage required (i.e., 35 V d.c.).
Consequently, assuming all the sub-arrays operate at the same voltage of 330 V d.c., there will be sub-arrays with source circuits consisting of 20 or 10 modules connected in series of the large type, and sub-arrays with 20 module strings in series of the small type.

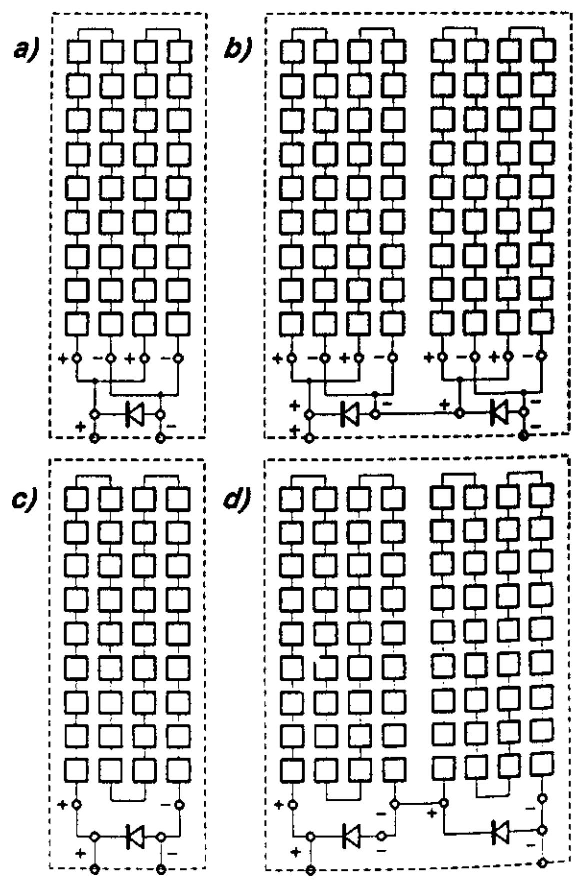

Fig. 2. 3MWp PV power plant - Electric lay-outs of the pv modules to be installed

The energy generated by each sub-array will be converted into a.c. and stepped up to medium voltage (20 kV) by means of a line-commutated inverter and a step-up transformer. The inverter consists of two three-phase bridges connected to the two secondary windings of the step-up trasformer, as show in Fig. 3. The targetted efficiency of each converter is 92% at full load. Each bridge is equipped with MPPT control logic. This logic, developed by ENEL (4) makes possible maximum feed into the network of the power generated by the sub-arrays. In one of the sub-arrays, it is planned to install a further forced-commuted inverter, to operate alternately with the line-commuted one. This unit, which will

prototype.

6. INTERFACE OF THE SUB-ARRAY WITH THE MEDIUM-VOLTAGE NETWORK

All the sub-arrays will be supplying the energy produced in the 20-kV network.
A special, buried loop-line therefore runs throughout the central area, linking in parallel the primary windings of the step-up transformers of the static converters (see Fig. 4). At the interface with the network, suitable filters to compensate for the harmonics and banks of capacitors for power factor control will be installed.

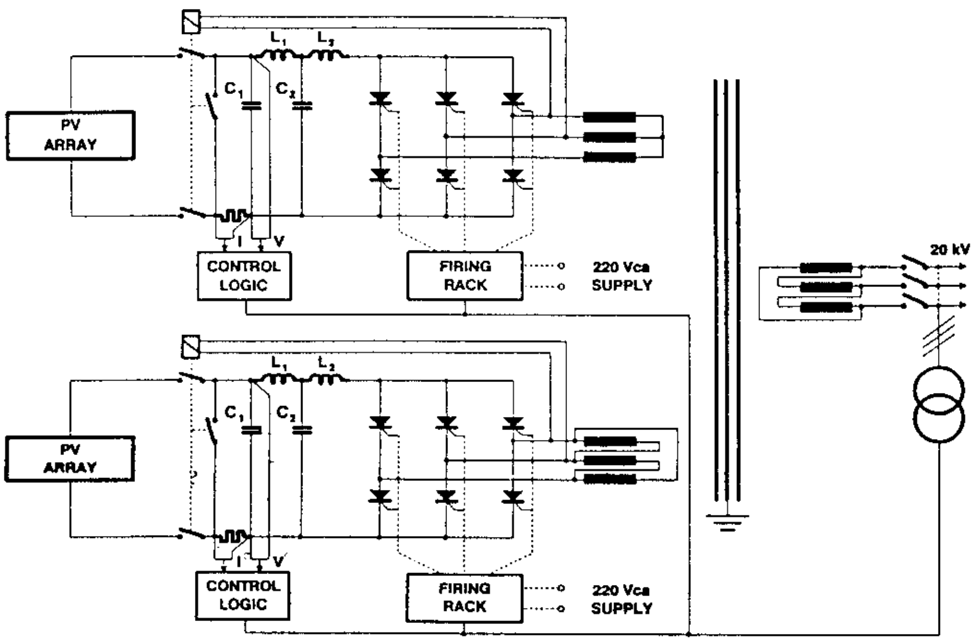

Fig. 3. 3MWp PV power plant - Lay-out of the converters

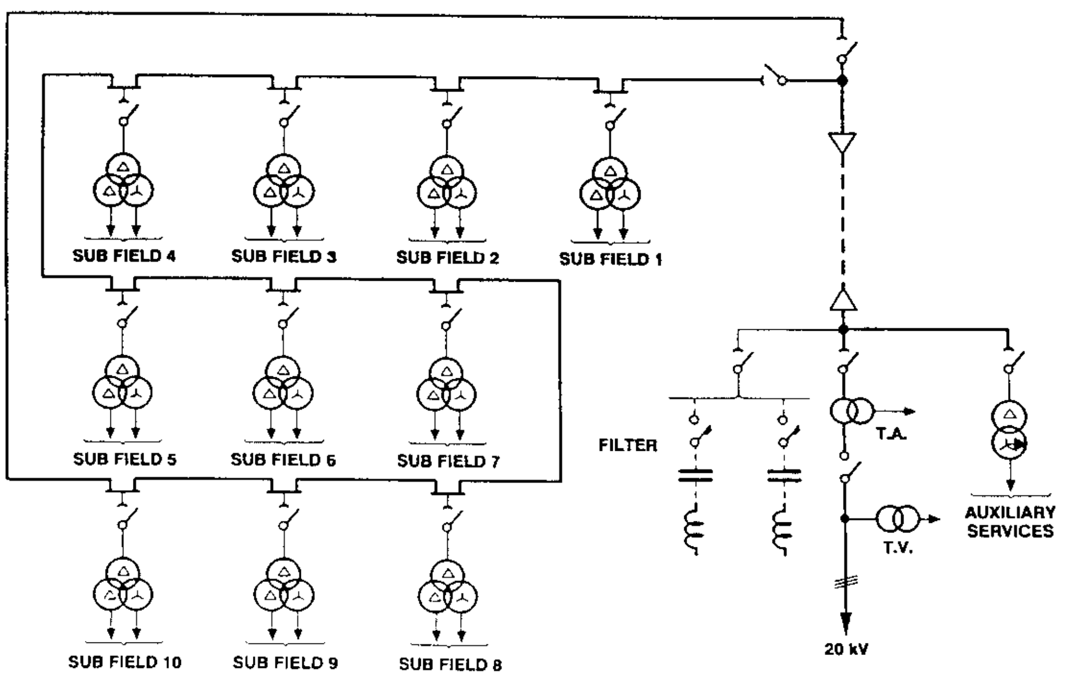

Fig. 4. 3MWp PV power plant - Topographic lay-out of 10 sub fields

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The ENEL 3-MW photovoltaic power plant will be set up during the period 1991-93. Three sub-arrays are expected to come on stream by the end of '92, and the remainder thereafter. The plant will be located in the Province of Salerno (Italy). The design criteria adopted for the plant are aimed at cost optimization. It is considered that, given the experience gained in such a project, it should be possible to modify or confirm the validity of such criteria with a view to setting up other multi-MW power plants in the future.

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ENEL'S TEN YEARS' EXPERIENCE IN THE USE OF PHOTOVOLTAIC GENERATION UNITS TO SUPPLY ISOLATED DWELLINGS WITH ELECTRICITY

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ABSTRACT: In 1982 ENEL launched a technological development program for the nationwide application of photovoltaic systems, with the aim of supplying small loads to consumers and tradesmen in isolated areas not yet covered by the national electricity service.
This Report describes the main project data of the systems built by ENEL (about 250 installations) and the performance figures, where available.

1. INTRODUCTION

In 1982 ENEL launched a technological development program for the nationwide application of photovoltaic systems, with the aim of supplying small loads to consumers and tradesmen in isolated areas not yet covered by the national elec:ricity service.

The program was structured to enable investigation of feasibility, cost, production, reliability and the level of satisfaction of users' needs. These parameters applied both to very small photovoltaic plants (able to supply not more than 1000 kWh/year), and larger plants able to produce up to 6000 kWh/year. This subdivision was made because of the necessity to provide two types of plant:
1) Plants for users requiring only modest loads, making it possible to supply electricity at 24 or 48 V dc.
2)Plants for more demanding users, requiring mono- or tri-phase AC supplies at 220-380 Vac

From 1982 to 1992, both types of system were developed to meet a number of practical applications, some of which are now in the process of being installed.

2. INSTALLATIONS

In the period 1984-1992, the following installations were completed:
- Seven plants for supplying Alpine refuges [1]
- Eight plants for supplying WWF field bases [2]
- One for the Ministry of Agriculture.
- Thirty plants for supplying homes situated in the Ginostra area of the Island of Stromboli (Sicily) [3]
- Sixteen plants for supplying homes situated in the Bazzina area of the Island of Alicudi (Sicily).

In the period 1992-1993, the following plants will be completed:
- One hundred and forty plants for supplying small tradesmen in the Southern Italian regions of Abruzzo, Molise, Puglia, Campania, Basilicata, Calabria and Sardinia (Valoren Project).
- Seven plants for supplying business users in the Ginostra area on Stromboli, Sicily.
- Eighteen plants for supplying Alpine huts.

The above plants have a peak power between 0.3 kW and 6 kW, with nominal operating voltages of 24 dc or 220 ac.

3. DESIGN CRITERIA

The plant are designed on the basis of a constant guarantee to users of a high degree of reliability in power supplies. From the quantity point of view, this is expressed as a total maximum number of hours per year for which power supplies cannot be guaranteed.

ENEL plants are normally designed to allow between zero and 100 hours per year in which supplies are not available; the exact figure in this range is dictated by users' individual requirements [4].

Non-availability depends also from random interruptions in supply due to breakdowns occurring in the plant, and failures caused by users.

To keep the levels of non-availability within the project's designed range requires extremely high plant reliability. To guarantee this, it is necessary that:
- The basic electrical design of the plant is simple and correct.
- The protections with which the plant is fitted are calibrated in accordance with the plant's general criteria.
- Both the reliability and life of the components are the highest possible.

As well as the technical criteria involved, the design of the plant is also influenced by the total implementation cost. The final design criteria thus derive from an acceptable compromise between cost and reliability.

To gain experience the ENEL demonstration program in this sector therefore varies from case to case, with the result that plant designs differ as regards the installed power, the technical solutions adopted in the basic layout, and the ways in which battery charge is controlled.

The following sections cover the main components of the stand-alone plants, and briefly describes ENEL's experiences.

4. SUBSYSTEMS: ACQUIRED EXPERIENCE

4.1 Photovoltaic Modules

Ten years' experience in the use of crystal modules (single and multi) has produced very positive results, in the sense that these components can without doubt be regarded as the most reliable of all those used in the plant. They need practically no maintenance. The photovoltaic fields used have a power of between 350 Wp and 6000 Wp depending on user requirements.

4.2 Batteries

The stationary Pb accumulators are of the type normally used in ENEL plants. The cells used have a capacity of between 300 Ah and 1500 Ah, depending on the power of the plant. The reliability of this component has been satisfactory in all the applications described in this Report.

Controlling the state of the accumulator is still a problem as regards both estimation of the state of charge and estimation of the life remaining after installation.

The above information can be obtained (approximately) by monitoring systems which, although certainly available on the market, are too sophisticated to be applied to the small systems described here.

One practical problem, but relevant also from the economic point of view, concerns the "housing" of the accumulators in the open air. The containers designed by ENEL are certainly adequate in resolving the technical problems connected with the installation of the accumulators (safety, maintenance, etc.). The cost is still very high and can only be reduced by standardization. Maintenance of the plants has not been particularly demanding, although it has always been necessary to assign ENEL technicians for the periodic site checks.

4.3 Charging Regulators of the Batteries

In the plants developed by ENEL, a number of devices have been tested for battery charging (see Fig.1), including directly connecting the photovoltaic field with the battery. All the methods used proved successful, but obviously the self-regulating system was preferred, which offers reliability at low cost [5].

What choice to make from among the various types of regulators, apart from the cost, depends on the particular conditions in which the accumulator has to work (continuous or discontinuous charge, the temperature of the environment, accumulator type, whether the capacity is high or low relative to the power of the photovoltaic field).

A good compromise between the various types of regulators is shown in Fig. 1 bis, for the following reasons:

- high reliability
- high charging capacity
- low self-consumption
- low cost.

4.4 Power conversion

As described below, ENEL has carried out experiments in supplying power to users by means of both Direct Current and Alternating Current.

In some cases it has been shown convenient to install small converters dedicated only to feeding a part of the equipment used, leaving the remaining in Direct Current.

In the more powerful plants ENEL has made a total conversion of the power, by means of autonomous converters designed ad hoc for photovoltaic systems.

The converters have a high performance level also at low charge, an extremely low self-consumption (a load sensor enables the machine to be kept on standby when the load applied is practically null), and a high level of overloading.

This equipment has been installed recently, and no data are available yet regarding reliability over time.

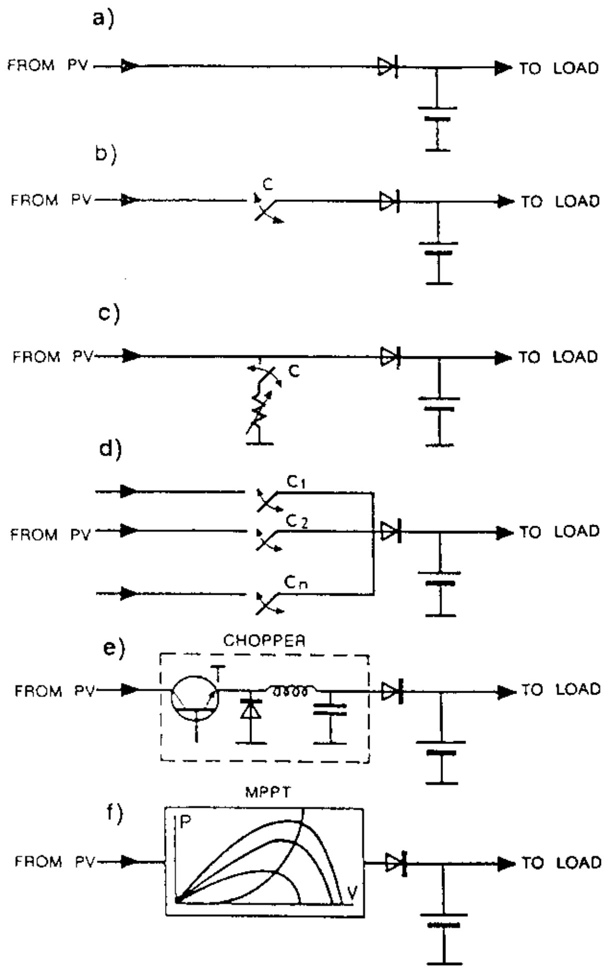

Figure 1: Battery charge regulation for stand-alone PV systems with electrochemical storage: a) direct connection; b) ON-OFF series regulation; c) ON-OFF shunt regulation; d) multi-step regulation; e) chopper regulation; f) MPPT regulation

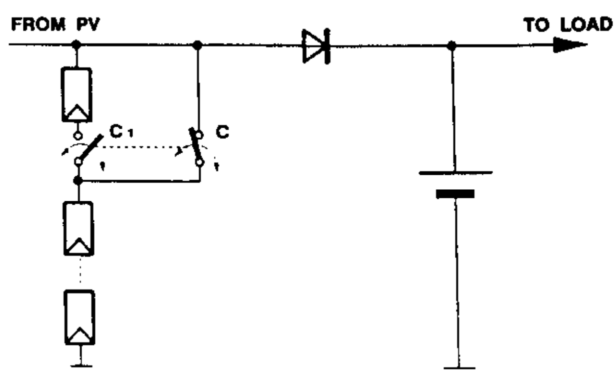

Figure 1 bis: ON-OFF shunt regulation of one PV module

The scheduled maintenance of this equipment must always be carried out by specialist technicians, either from ENEL or the manufacturer.

4.5 Monitoring

All the systems installed by ENEL are fitted with power meters (for Alternating and Direct Current), for the calculation of the power consumed by users.

ENEL has also designed and developed a special data acquisition system, which provides more detailed information on the behaviour of the plant and the reliability of the supply. This system, which is known as GMF, provides a complete energy balance report on the plant, i.e.: [6]

- The solar energy acting on the photovoltaic field
- The electrical power produced by the photovoltaic field
- The power consumed by the user
- The number and duration of the periods when the user is not supplied

The design of the GMF system required considerable care, particularly as regards reliability and the reduction of self-consumption. These measuring systems, installed for long periods in certain ENEL installations, have made it possible to characterise their behaviour completely, as described below.

In some cases, commercial data loggers have been used, integrated in the GMF systems in order to make the energy balance calculations through the continuous recording of the voltages and currents in the various sections of the plant.

5. SOME OPERATING RESULTS

The most interesting aspect, clearly confirmed by the operating results of ENEL plants, is that the stand-alone plants must almost always be designed to supply more than the actual needs of the load, particularly when the latter is for consumers. The intake of power by this type of user, as is well-known, is rarely the same on any given day, and is linked to the particular lifestyle of the people involved, to periods of absence and to the number of occupants of the premises being supplied, and so on.

The random nature of the load inevitably means that the photovoltaic plant is often larger than strictly necessary, as it must be designed to supply power to the user "in the worst case" both as regards the consumption by users and the meteorological conditions.

The above situation is well-documented by the records of the energy balances of the thirty plants installed in the Ginostra area of Stromboli. All the plants are identical (they have an installed power of 350 Wp), supply power to the user at 24 V dc, and benefit from the same levels of insolation, as they are all located in a relatively small area (about 2 sq km).

The bar chart (see Fig. 2) shows users' consumption (average daily value of the power consumed and produced over two years). It is evident that only a few users fully exploit the potential of the plant, while the majority consumes only a small part of the electrical power available.

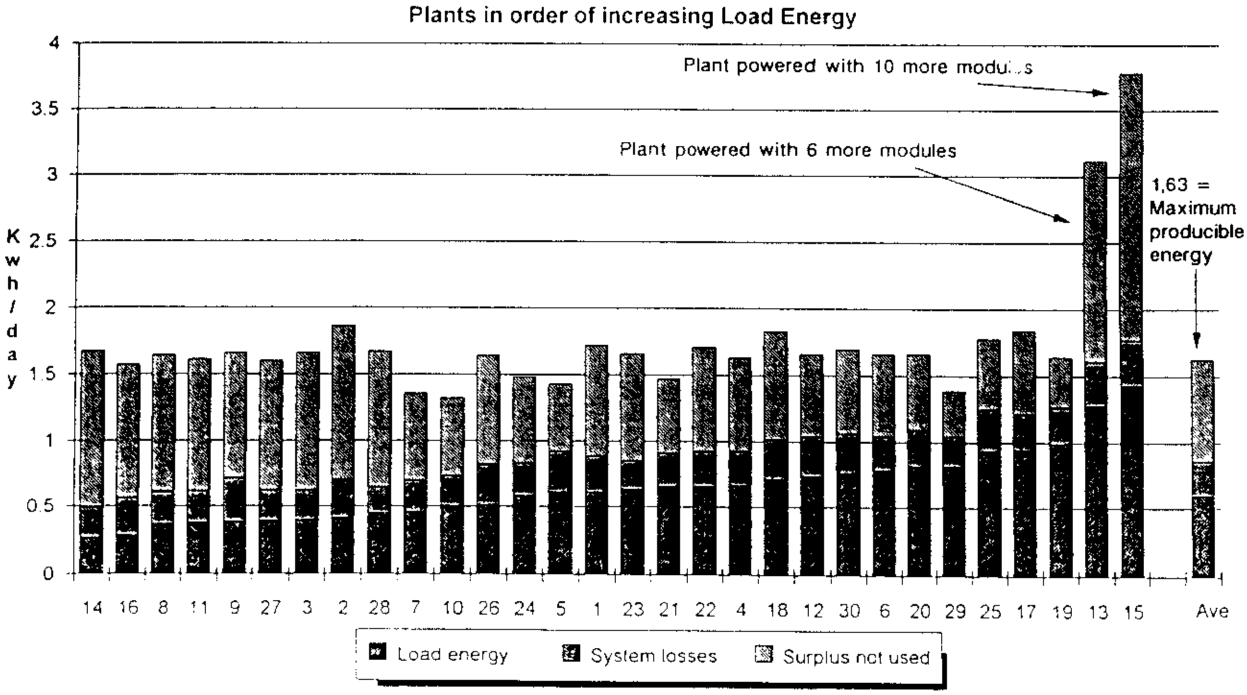

Figure 2: Energy balance in the first 2 years operation period of the 30 Ginostra PV plants

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6. CONCLUSIONS

The production of decentralized electrical power at the rural premises of consumers or tradesmen is feasible even with stand-alone photovoltaic plants.

ENEL's ten years' experience in the field confirms this.

Choice of the way the power is supplied (traditional means or photovoltaic) depends on environmental and/or economic considerations. It is clear that the photovoltaic plant replaces, in this application, the traditional means of supplying electrical energy current (overhead lines or underground cables), or the Diesel generator. The "avoided" cost of the photovoltaic installation may therefore be that of the line or cable or the least quantifiable facet of reduced environmental impact, visually or acoustically.

The current cost of the plants described here is about 20 - 30 ML/kWp, and this will probably be slightly reduced by ENEL in the immediate future as the components used are further standardized.

ENEL will subject the operational costs of these plants to further analysis, particularly as regards the plants equipped with the static converter developed as part of the VALOREN project.

In the near future, ENEL will therefore also be able to count on photovoltaic systems to resolve particular problems in supplying power to users facing high connection costs, and to users located in areas that are subject to environmental controls, where the use of overhead cables is to be avoided

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1 MW Photovoltaics Project
Planning, Construction and Operation of Photovoltaic Power Plants

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RWE Energie AG has been conducting a 1 MW Photovoltaics Project since 1986 in the course of which three large-scale grid-integrated photovoltaic power generation plants have been/are being planned, constructed and commissioned. The first facility, which is located in Kobern-Gondorf on the Moselle River, has been in operation since October of 1988. The design capacity of this plant with its peak power output of 340 kWp was selected so as to enable a comparison of various technologies on an international scale. The results obtained during operation of the first plant were incorporated in the planning of the second power plant, which is located on Lake Neurath and was commissioned as a pilot facility in September of 1991. The objective of this 360 kWp facility is to demonstrate the cost reduction potential of large-scale photovoltaic power plants. The findings of the studies and analyses conducted are discussed in the article below. In summary it can be said that in the long term photovoltaic technology can be an interesting as well as viable option for future power generation. The performance and reliability of power plant components have been proven in continuous operation, however further technical development and continued substantial cost saving are required before this technology can be employed on a commercial scale. The development potential is present, however intensive work in all systems engineering areas is required in order to achieve the above objectives.

1. Role of Large-Scale Photovoltaic Facilities in Power Generation

In Germany in 1990, approximately 18.8 billion kWh of power has benn harnessed from the regenerative power generation sources of power generation companies and private and municipal power generators into the public power grid. This quantity corresponds to 4.3 % of total consumption in Germany. The greatest portion thereof, i.e. 3.6 %, came from hydroelectric power generation. Amounting to only 0.0002 %, photovoltaic power generation accounted for a negligible portion of total power generation. Yet 37 utility-operated solar generators and another 100 privately operated facilities providing for a combined capacity of approximately 1.6 MW fed ca. 650,000 kWh into the public power grid. Consequently, in 1990 eight times as much power originated from solar energy than in 1988. By 1993, the installed photovoltaic capacity is estimated to reach 8 MW (1).

A land-use analysis conducted in Germany's western states clearly shows the enormous potential of photovoltaic technology. If, for example, only one third of the areas presently classified as marginal-yield and fallow tracts were used for the construction of commercial-scale photovoltaic plants, these facilities would cover ca. 25 % of total German power generation, i.e. eight times the amount presently provided by hydroelectric facilities. Yet increasing the proportion of photovoltaic power generation of total power requirements comparable to that presently provided by hydroelectric facilities would mean that ca. 1,000 MWp photovoltaic generators would have to be constructed annually. A comparison with Germany's present annual production capacity, which amounts to ca. 10 MWp, shows just how long-term such an objective would be.

It is probably too early to strive for such magnitudes. We simply want to express that we should make every effort to promote the continued development and improvement of this technology. New concepts have to be developed and corresponding standards are required before the technology can be introduced further. In the last analysis, ecological, economic and political exigencies will determine the contribution of photovoltaic technology to power generation in the future.

2. Results of the 1 MW Photovoltaics Project

Two of the facilities planned in the 1 MW photovoltaics project are operational and have already produced a number of interesting results.

2.1 Plant Design

Both facilities are directly grid-integrated. Whereas the first facility in Kobern-Gondorf features a rated power range of 1 to 100 kW for the purpose of comparison of components on an international scale, the second facility located on Lake Neurath was designed to demonstrate the cost reduction potential of such facilities. The differing objectives of the two facilities become appearent when comparing the block diagrams (cf. Fig. 1 and Fig. 2) and specifications (cf. Table 1). A detailed facility description is presented in the references (2; 3).

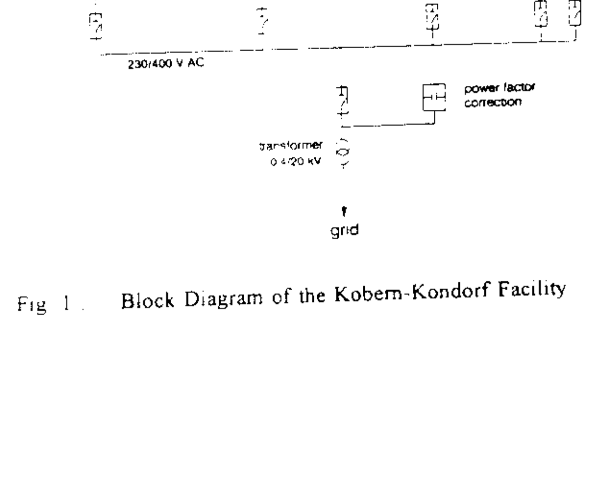

Fig. 1. Block Diagram of the Kobern-Kondorf Facility

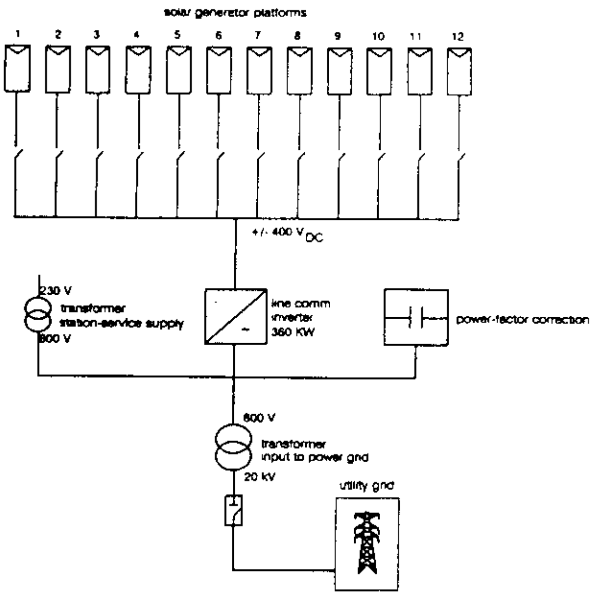

Fig. 2: Block Diagram of the Lake Neurath Facility

	Kobern-Gondorf	Lake Neurath
Peak power output	[illegible]40 kWp	360 kWp
Voltage level	42 - 400 V	800 V
Solar modules		
Number	7,740	3,772
Power output	12 - 80 Wp	50 - 280 Wp
Conversion efficiency	4 - 13 %	10 - 12 %
Size	0.3 - 0.6 m²	0.4 - 2.3 m²
Support structure		
Size	10 - 30 m²	300 m²
Number	210	12
Inverters		
Number	9	1
Rated power output	1.3 - 80 kW	380 kW

Table 1: Comparison of Specifications

2.2 Solar Modules

Continued development of the solar module is of paramount importance for the future, as reducing its costs, improving its conversion efficiency, and enhancing its reliability are prerequisite for the economical operation of photovoltaic facilities. Comprehensive studies are being conducted of solar modules in order to evaluate various technologies under practical conditions. The analyses and operating results to date point to three essential unresolved problems

- poor insulation resistance
- insufficient power output and insufficient reliable system voltage in connection with amorphous silicon modules and
- inadequate module sizing

In the operation of large-scale photovoltaic facilities, to set up the highest practicable system voltage aims at minimizing associated costs and losses. Many of the ca. 7,700 solar modules implemented in Kobern-Gondorf showed considerable insulation deficiencies when the facility was inspected for the first time. These deficiencies were due to manufacturing defects, i.e. conductors routed too close to the frame, and design errors, i.e. solar cells placed too close to the edge, in combination with improperly sealed edge covering. In extreme cases, several of these deficiencies resulted in electric arcs between the solar cells and the grounded frame in generators with a higher voltage. The arcs caused the glass melting, as a consequence destroying the modules.

Apart from reliability, the power output or solar-to-electricity conversion efficiency or utilization ratio is the second essential criterion for evaluating a solar module. Table 2 shows the range of theoretical efficiencies, the actual efficiencies measured by us, both indicated for solar radiation of 1,000 W/m² and a solar cell temperature of 25 °C, and the utilization ratio of a single solar module versus an entire generator.

	Solar module			Solar-generator
	theoretical η factor	measured η factor	utilization ratio	utilization ratio
polycrystalline	8.9 - 10.7	7.5 - 9.6	7.0 - 8.8	7.2 - 8.8
mono-crystalline	10.1 - 13.3	9.0 - 12.2	9.3 - 11.4	8.2 - 11.8
amorphous	4.1 - 5.6	2.1 - 4.3	1.9 - 4.3	1.9 - 3.6

Table 2: Conversion Efficiency and Utilization Ratio of Solar Modules and Generators

A comparison of values for mono-crystal and polycrystalline silicon shows that the conversion efficiencies actually measured deviate from the manufacturer's values by 1 to 1.5 percentage points. This differential generally corresponds to the maximum deviation from the manufacturer's rated power output. The yearly utilization ratio of solar modules, i.e. the ratio of power output to incident solar radiation amounts to 0.5 to 1.0 percentage points less. This is explained by thermal influences and pollution. By contrast, the utilization ratios of the solar generators rated (in perfect running order) deviate only marginally from those of the individual module. In summary it can be said that the actual yearly utilization ratio of single-crystal and polycrystalline solar modules is ca. 2 percentage points below those values indicated by the manufacturer.

This applies to solar modules made of amorphous silicon in absolute terms as well, however the relative deviations are naturally greater on account of the generally lower conversion efficiency of these modules. Consequently, the measured module efficiency and utilization ratio of some amorphous technologies amount to only half of the manufacturer's values. According to results obtained to date, current figures pertaining to the performance and insulation resistance of solar modules made of amorphous silicon cannot be considered to constitute an adequate planning basis for facility design (4).

The third criterion for evaluating a solar module, apart from conversion efficiency and reliability, is absolute power output or size. Table 1 above shows that by employing large-area modules developed by NUKEM GmbH in the Lake Neurath facility, the number of solar modules could be reduced by half, with power output remaining approximately the same. Power output amounts to 240 to 270 Wp for an area of 2.3 m². Table 3 shows that, as a result, construction costs (including material and personnel) are reduced considerably as compared with conventional solar modules.

	Large-area module		Standard module	
	per module	per kW	per module	per kW
Number of modules	---	4	---	20
Mounting screws	4-6	18-24	2-4	40-76
String cabling (m)	2-3	8-12	0.3-0.5	6-10
Platform cabling (m)	1-2	5-7	0.7-1.25	14-25
Mechanical installation(h)	1	4.7	0.35	7
Electrical installation (h)	1	3	0.3-0.5	6-10

Table 3: Comparison of Large-Area Modules and Standard Modules

2.3 Inverters

In the 1 MW Photovoltaics Project, a total of 10 inverters in both facilities within a rated power range of between 1.3 and 360 kW are being investigated. Three different concepts are being compared with regard to conversion efficiency, MPP control precision, harmonic behavior, fundamental reactive power and simplicity of electric circuitry. The results obtained during the first years of operation are detailed in (5); consequently only a summary is given below:

- The efficiency of large inverters is better than that of small inverters on account of their lower relative stand-by losses.
- The utilization ratios of large inverters are ca. 10 percentage points higher than those of small ones on account of better partial-load behavior.
- All large inverters achieve efficiencies higher than 90 % when power output exceeds 20 % of the rated power output.
- In commercial-scale facilities the line-commutated inverter is presently the best trade-off between price and performance.
- In small-scale facilities, self-commutated inverters with pulse-width modulation and pulse repetition frequencies of a few kHz appear to be the best solution.

	5 kW	100 kW	380 kW
Efficiency at 20 % of rated output	70 - 87 %	90 - 95 %	> 95 %
Efficiency at rated output	87 %	92 %	97 %
Utilization ratio	70 - 80 %	93 %	95 - 97 %

Table 4: Comparison of Inverters

2.4 Structural Engineering

Four different support structures are being investigated in the two test facilities. Whereas support members measuring 10 to 30 m² are employed in Kobern-Gondorf, considerably larger structures measuring over 300 m² have been constructed for the facility on Lake Neurath on account of the slope there, which corresponds to the optimal orientation of the solar surfaces. An analysis (cf. Table 5) of the specific material and personnel costs associated with the various structures shows that enlarging the module area to 300 m² results in a savings in foundation costs, however not with respect to the amount of steel required. Satisfactory values are obtained for the large-area module only. Large-area support structures can be used only in combination with a particular slope, consequently the optimal solution is considered to lie in a standard setup consisting of ca. 30 m² supports equipped with large-area solar modules.

		Standard modules			Large area modules
		10 m²	30 m²	300 m²	300 m²
Steel	kg/m²	31	23	25 - 35	22
Foundations	no./m²	0.1	0.067	0.033	0.033
Concrete	m³/m²	0.07	0.06	0.03	0.03
Erection time	h/m²	7 - 9	7 - 9	7 - 9	3 - 4

Table 5: Support Structures

One essential criterion in the design of the support structures are the wind and snow design load factors as specified in the building code. The values would have to be reconsidered for commercial-scale facilities as facilities of this type generally do not pose a hazard to humans. These facts might enable the reduction of safety factors or conservative design loads.

The second essential criterion in the design of the support structures is the safe deflection of the individual support members. Relatively exacting standards have to be met here so as to prevent damage to the solar modules. As a rule, this results in structures which are costly. If solar module costs could be reduced, then increased risk of potential damage to them could be accepted so as to ease deflection requirements.

3. Cost Analysis

A detailed cost analysis was conducted in parallel to the technical studies. Greatly varying technologies were employed, particularly in the facility in Kobern-Gondorf, consequently the investment costs associated with the individual systems vary greatly. Table 6 shows a comparison of a Kobern-Gondorf-type 100 kW system with an optimized 350 kW facility on the basis of the technology employed at Lake Neurath. The additional development and planning costs required to implement the individual technical innovations are not taken into consideration, neither are the additional costs for the scientific monitoring and evaluation of the facility. Considerable savings were achieved in connection with erection and cabling/wiring costs. The decisive factor for these savings is the compact design of the facility and the advantages of installing large-area modules. The cost savings associated with power conditioning are a result of increasing the inverter unit rating by a factor of three. By employing the processes developed at Lake Neurath, savings of ca. 30 % of the investment costs in future facilities can be achieved as compared with those required for the Kobern-Gondorf facility.

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	100 kW system		350 kW system	
	DM/kW	%	DM/kW	%
Solar modules	12,500	55.8	10,000	61.3
installation (mech.)	1,570	7.0	1,250	7.7
Cabling/wiring	1,900	8.5	1,000	6.1
Power conditioning	2,060	9.2	1,100	6.7
Grounding	340	1.5	150	0.9
Support structures	2,030	9.1	1,800	11.0
Infrastructure	2,000	6.9	1,000	6.1
Total	22,400	100.0	16,300	100.0

Table 6: Investment Costs Associated with Photovoltaic Systems

4. Outlook

During the planning, construction and operation of the two photovoltaic facilities at Kobern-Gondorf and Lake Neurath, valuable findings have been obtained for the project planning of other photovoltaic facilities. Apart from the ongoing reduction of the manufacturing costs of solar modules, the findings of our studies indicate cost reduction potentials in the following areas. In the mechanical and electrical installation of solar modules through the prefabrication of large-size units and by replacing screwed connections with adhesive connections; in inverters through the continued improvement of the inverter unit rating; and in the support structures by easing design load and deflection requirements.

Together with the Spanish electric power company Union Electrica Fenosa, RWE Energie AG is presently planning a photovoltaic facility with a power output of 1,000 kW, to be located in the vicinity of Toledo, Spain. Plans have been made to demonstrate the potentials indicated above in this facility. Construction is planned to commence in September of 1992. Commissioning is planned for the end of 1993.

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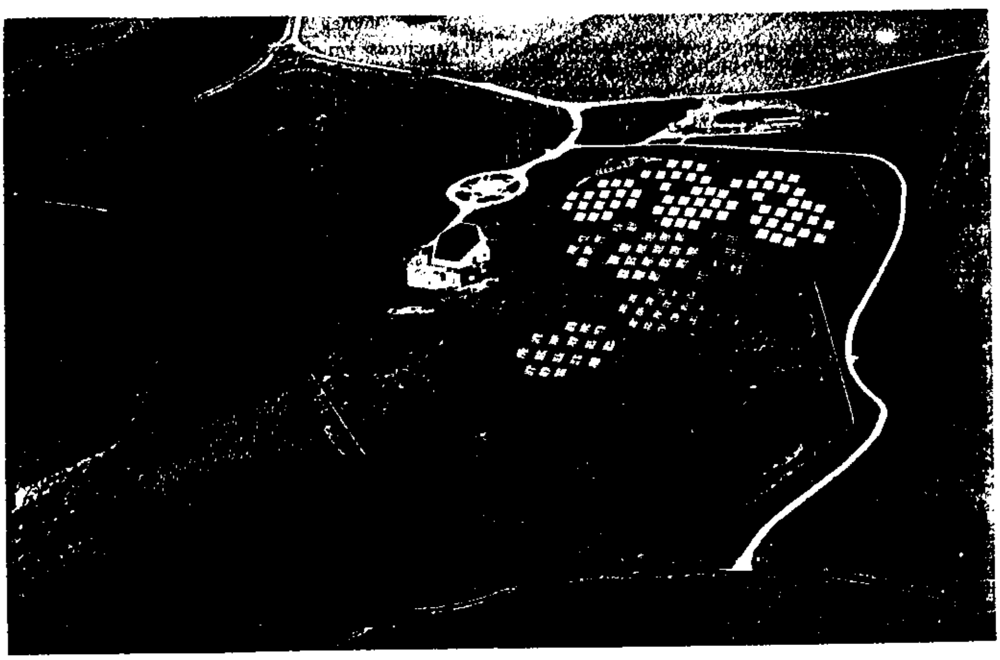

Photovoltaic Plant Kobern-Gondorf

PROGRESS REPORT ON THE 3.3 MWp PHOTOVOLTAIC PLANT BEING SET UP BY ENEL AT SERRE (SOUTHERN ITALY)

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ABSTRACT: Plans for a 3.3 MWp PV plant at Serre were finalized by ENEL in 1991. The plant is presently under construction and will be completed by mid 1994. It consists of ten indipendent sub-arrays of 330 kWp each, equipped with semi-crystalline modules, connected in parallel to the MV grid by means of line-communitated MPPT inverters. The main features of the plant, procurement criteria, current situation and cost analysis are presented in the paper.

1. INTRODUCTION

ENEL's decision to build the photovoltaic power station at Serre was taken in 1990 mainly with the aim of checking the technical-economic feasibility of photovoltaic power plants designed for use by electric utilities.

The project also had the aim of providing a boost to the national photovoltaic industry, as well as enabling technical know-how to be acquired in an energy sector in a phase of expansion.

The general project for the plant was completed during 1991, when also the technical specifications required for the acquisition of the components were defined, and orders for the equipment and assemblies were placed.

2. GENERAL DESCRIPTION OF THE PLANT

The main feature of the power stations's architecture (see Fig.1) is the subdivision of the plant in ten electrically independent subfields of 330 kWp each, linked to a MV ring terminating at a central cabinet [1].

Each photovoltaic subfield is fitted with an autonomous MPPT inverter with step-up transformer, housed in a small cabinet barycentric to the subfield concerned.

A central building houses the equipment for interfacing with the electrical network, the supervision and data acquisition system and the auxiliary services.

2.1 Modules

The photovoltaic modules are made of semi-crystalline silicon, with 36 or 72 4" or 5" cells per module.

The total number of modules is about 60,000, corresponding to over 2,600,000 cells.

2.2 Photovoltaic Subfields

The ten 330 kWp subfields are mounted on fixed metal supporting structures, with an angle of inclination of 20 degrees [2] (see Fig. 2).

The structures are in the form of lattice frameworks, they require, for the overall plant, over 700 tons of steel (210 kg/kWp), and are anchored in foundations requiring about 2600 cubic metres (0.79 m^3 /kW) of reinforced concrete (35 kg Fe/m^3) per subfield.

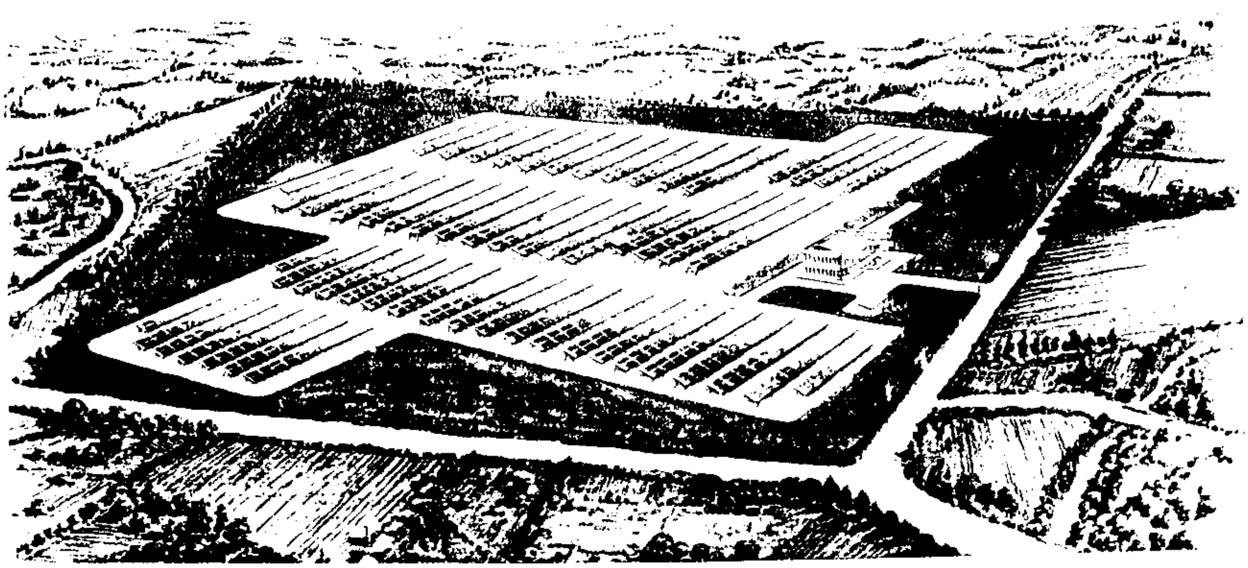

Figure 1: Artistic View of ENEL's 3.3 MWp PV Plant

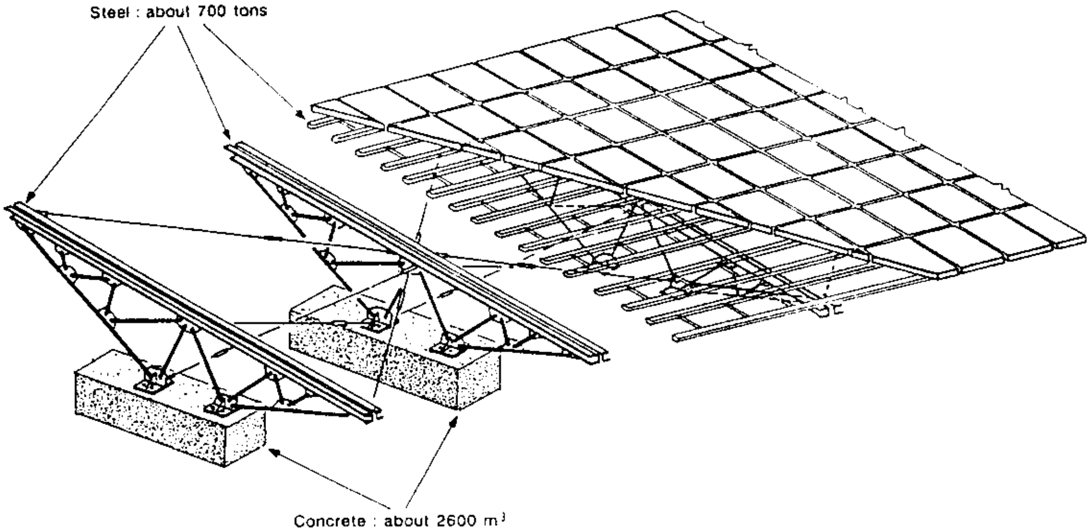

Figure 2: Sketch of the supporting structures

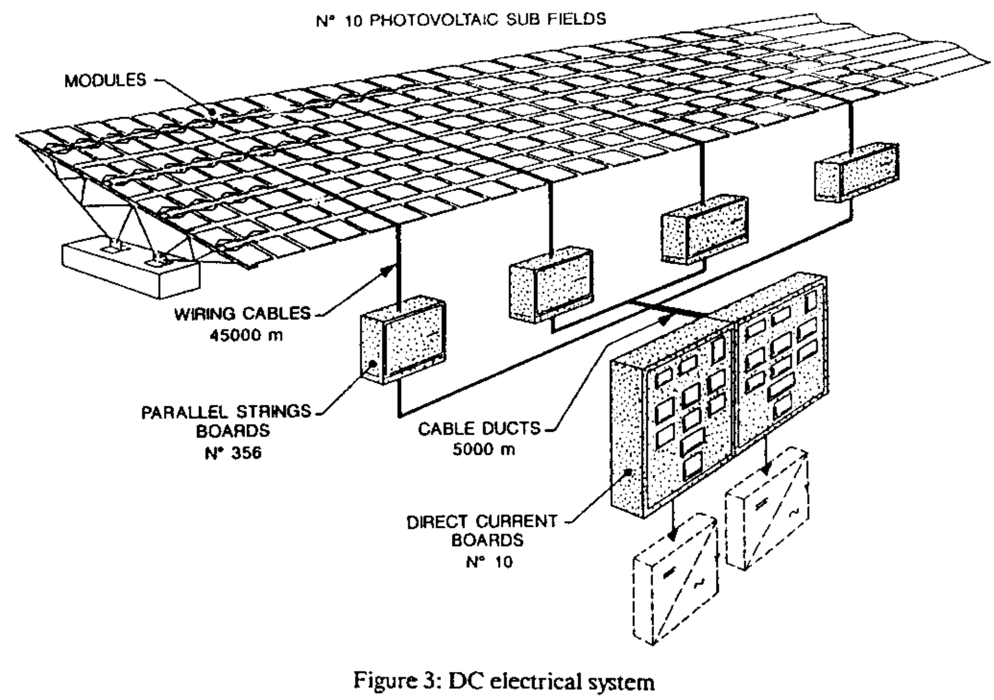

Figure 3: DC electrical system

2.3 DC Electrical System

The DC electrical system (see Fig. 3) is made up of connections between the modules, in series of 10 or 20, with a string voltage of about 330 Vn (440 Voc). Groups of 80 or 160 modules terminate at peripheral small cabinets for parallel connections (about 35 per subfield).

From these cabinets, a number of cables laid in cable-ducts reach an electric board housed in a small cabin, positioned barycentrically in each subfield. This board supplies the adjacent subfield inverter.

The DC electrical system is insulated from ground.

The total length of the DC cables is about 5000 m per subfield (500 of which laid in buried cable ducts).

2.4 Inverters

The ten inverters are of the line communtated type, with a nominal power of 550 kVA.

Each inverter comprises two galvanically insulated power units (see Fig. 4) fitted with tyristors connected to the LV side of the step-up transformer.

The inverters are fitted with a control system that enables them to function in MPPT or at impressed voltage, and allows the sweeping of the I-V characteristics.

The efficiency is 95% at Pn and above 90% at 25% Pn.

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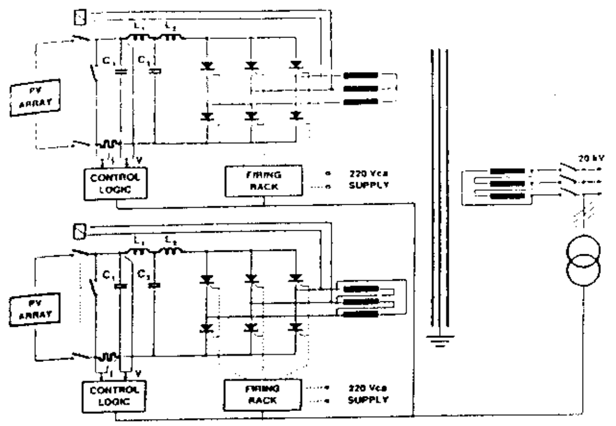

Figure 4: Each inverter consists of two galvanically insulated tyristor bridges, connected to a transformer

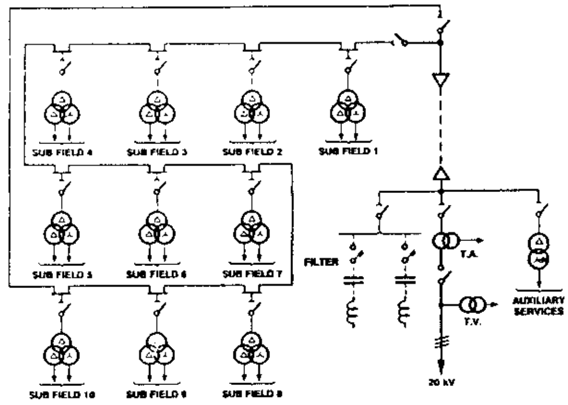

Figure 5: AC electrical system (n° 10 step-up transformers connected to a 20 kV cable; central filtering and power factor compensation; grid interface)

2.5 AC Electrical System

Each subfield inverter is connected to a double secondary transformer D-Y, with a primary D, 550 kVA rated. This is connected, via a MV switch, to a buried 20 kV cable ring of about 2500 m, which terminates at the MV cabin for interfacing with the electrical distribution network.

This cabin also contains the system for filtering the harmonics and compensating the reactive power, and the auxiliary AC and DC services (see Fig. 5).

2.6 Centralized Supervision and Data Acquisition System

For experimental and demonstration purposes, the power station is equipped with a centralized supervising, monitoring and data acquisition system, which makes it possible to observe, online, the functioning of the plant, execution of electrical manoeuvres, and the acquisition and processing of both electrical and meteorological data (see Fig. 6).

2.7 Civil Construction Work

Preparation of the site involves the removal of 10,000 m^3 of earth in order to create three flat areas, which cover a total of 70,000 m^2. The cover coefficient is about 0.45. The perimeter fencing extends for about 1,500 m. The asphalted roads inside the area, which are 4 m wide, extend for about 1,200 m. Suitable drainage work will be provided. The ground network will require 5,000 kg of copper.

The buildings provided comprise a prefabricated cabin for each subfield, which houses the DC electrical subfield and the inverter, and a central building that houses the interfacing with the network and the auxiliary services and, for demonstration purposes, the supervision and a meeting room.

The buildings occupy a total of about 1,000 m^3 for the electrical systems, 400 for working areas, and about 900 for research and demonstration activities.

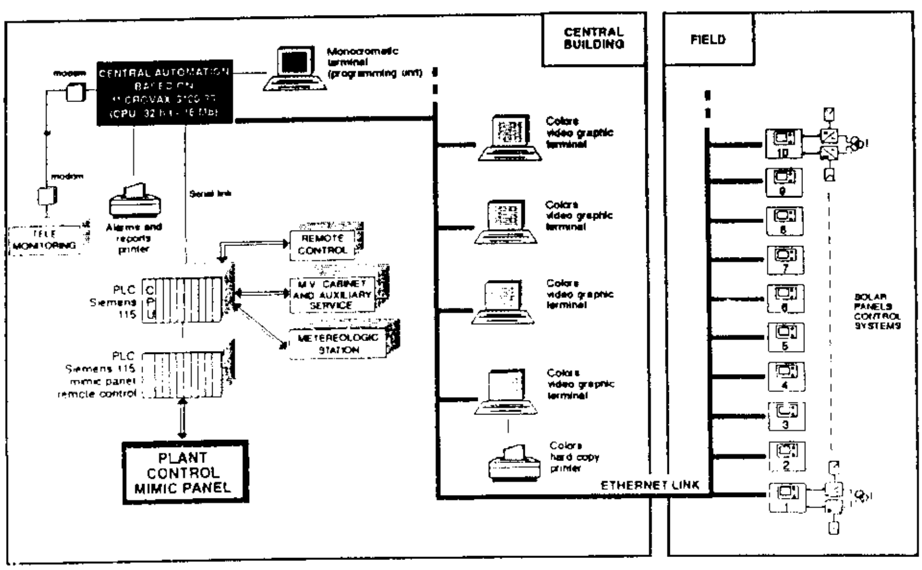

Figure 6: Centralized supervision and data acquisition system

3. PROCUREMENT CRITERIA

Supplies for the 3.3 MW power station are subdivided in three items: modules, inverters and BOS.

It has been decided that the modules, following an international technical-economic survey, be supplied by five Italian and foreign manufacturers of multi-crystalline silicon modules.

A sample shipment of these modules, which are manufactured according to ENEL specifications, has been made for type testing (CEC-JRC 503 certification and additional insulation tests).

The acceptance tests are effected at the factories of the suppliers: they are carried out on samples, selected according to standard sampling tecniques, and are based on a predefined classification of defects that involves the acceptance, reworking or rejection of the lot being examined.

The final testing is performed during the preassembly of the modules in panels, with 100% in situ checks of the electrical characteristics, prior to mounting on the supporting structures.

The inverters are manufactured in accordance with a detailed ENEL design and are supplied following a tender. A prototype is subjected to type testing, and the ten units supplied are checked at acceptance trials.

The balance of system, which comprises the executive project, all the components supplies, all the site work and the start-up phase, has been awarded following a tender based on a general ENEL plan.

Type and acceptance testing are provided for all qualifying components, along with periodic checks of the site works, up to the final testing and plant start-up phases.

4. CURRENT SITUATION AND SCHEDULE

During September 1992 type testing was in progress on a number of photovoltaic modules, while other lots of modules were undergoing acceptance trials.

It is expected that half the total number of modules will be supplied by mid 1993.

As regards the power conditioning, type tests are in progress on the prototype inverter, and the ten units ordered for the plant will be available by mid 1993.

As regards the BOS, to date, the plant executive project has been completed and approved, and the on-site work was begun in September 1992; the plant will come on stram gradually: 1300 kWp will be connected to the grid by August 1993, 1000 kWp by December and the remaining 1000 kWp by mid 1994.

5. COST ANALYSIS

The total cost of the plant is estimated at a value of about 7000 ECU/kWp, of which about 5% covers equipment and systems concerning research or demonstration.

The breakdown of the total capital cost into the various components is shown in Fig.7: the modules contribute for about 60% of the total.

AKNOWLEDGMENTS

The authors wish to thank Carlo Gavazzi Systems, Cesi and Fit-Ferrotubi for their cooperation

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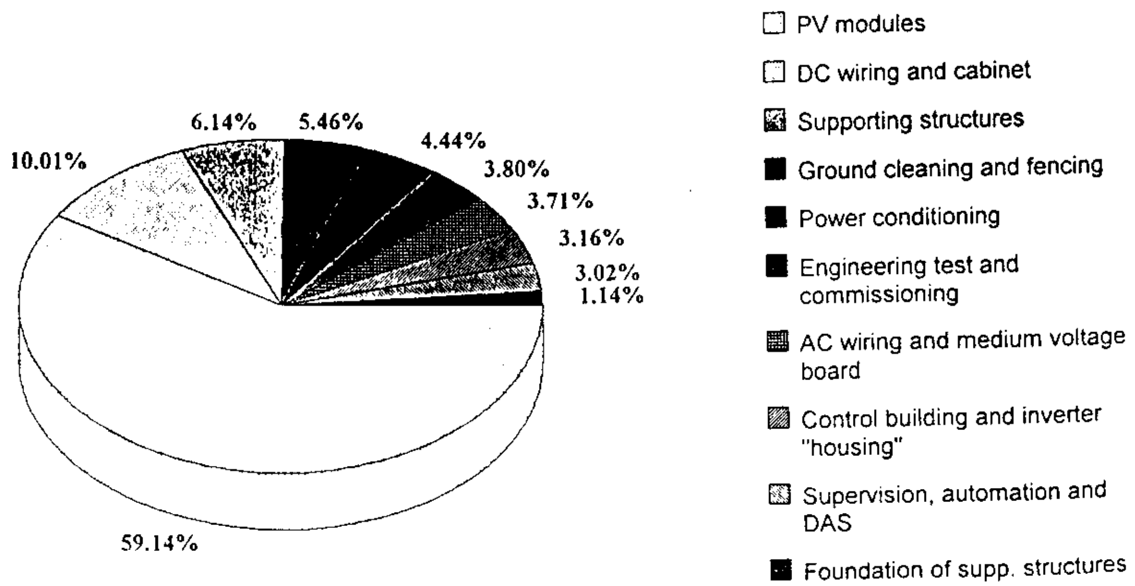

Figure 7: Breakdown of the total capital cost of ENEL's 3.3 MWp PV plant

MAXIMUM POWER POINT TRACKER FOR PHOTOVOLTAIC POWER PLANTS

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ABSTRACT

The paper describes two different closed-loop control criteria for the maximum power point tracking of the voltage-current characteristic of a photovoltaic generator. The two criteria are discussed and compared, inter alia, with regard to the setting-up problems that they pose.

Although a detailed analysis is not embarked upon, the paper also provides some quantitative information on the energy advantages obtained by using electronic maximum power point tracking systems, as compared with the situation in which the point of operation of the photovoltaic generator is not controlled at all.

Lastly, the paper presents two high-efficiency MPPT converters for experimental photovoltaic plants of the stand-alone and the grid-interconnected type.

INTRODUCTION

When designing photovoltaic plants, it is important, both for financial reasons and plant compactness, to obtain maximum conversion of solar energy to meet the load requirement. To this end, it is of interest to:

- Define control criteria for maximum power point tracking of the V-I characteristic of the photovoltaic generator.
- Develop electronic devices that will apply these criteria and provide high-efficiency maximum power point tracking (MPPT).
- Evaluate the energy advantages obtained by using MPPT.

Photovoltaic power plants can be subdivided into grid-interconnected and stand-alone. The former consists of an array connected to the grid via a dc/ac converter. In this case, since the transfer of energy to the grid has to take place via the converter, it is obviously advisable to control the converter in such a way as to extract the maximum power of the PV generator under all operating conditions. Stand-alone plants, on the other hand, generally consist of an array, a storage system (battery), and an inverter (if the load is a.c.). For plants of this kind, the coupling between the array and the battery may be achieved by using an electronic power-conditioning (MPPT) or, more simply, by connecting the array to the battery directly in parallel. If MPPT is used, it may carry out, besides the maximum power point tracking, also the limitation of the battery charging voltage to prevent damage. In the case of direct coupling, however, the only function controlling the transfer of power from the array to the battery consists in avoiding battery over-charging. For this reason, generator sub-arrays may be connected to the battery through shedding switches that, when the battery reaches the charging limits, are gradually opened automatically by a suitable control logic.

Coupling in parallel of the PV array at the battery offers the advantage that it is very reliable, easy to set up, and inexpensive. On the other hand, it has been found that, even with an optimized rated voltage for the battery, there will generally be a mismatch between the actual battery voltage and the corresponding voltage at the maximum power point. This mismatch which is equivalent to a loss of efficiency in the PV generator, depends on the battery charge state, the strength and flow direction of the battery current, and the photocell junction temperature; obviously, it also depends on how clean the panels are, on drift over a period of time due to aging, on faults in PV and battery cells, etc.

Should the interface between the array and the battery consist of an MPPT, this mismatch can be avoided; but there are other problems, such as conversion efficiency, manufacturing costs, and plant reliability.

In the case of stand-alone plants, the choice of either a direct coupling or an electronic interface (MPPT) between the array and the battery, is not easy to decide on, since it involves complex evaluations connected with:

- Conversion efficiency, including the total plant outage time due to an insufficient battery charge.
- Plant design (peak array power, battery capacity, average load, etc.) and the costs involved.
- Srress of the battery due to continual charging and discharging.

As regards the energy balances in PV stand-alone plants, there is still little literature on the subject - although studies are in progress - and the few works published regarding experimental evaluations (1) and computer simulations (2,3,4) refer to a specific case. Probably, when current studies on energy balances and checks on the advisability of using MPPT in photovoltaic plants have been completed, the conclusions reached will differ, depending on the particular application examined. Having a large number of case histories available will therefore make it possible to produce a breakdown of photovoltaic applications, and to identify the specific characteristics of those appications that call for use of an MPPT.

In this connection, this paper briefly presents some partial results of studies still in progress on comparison of the performances of plants with or without MPPT. These results have been obtained with a simulation program that reconstructs, in sufficient detail, the behaviour of stand-alone PV plants supplying small isolated consumers.

The hope for greater clarity on this important subject of energy balances is not, however, confined to interest in studies on the definition of control criteria for maximum power point tracking, and their practical application in high-efficiency converters.

In this connection this paper proposes two different control criteria, both in closed-loop operation, for max.power point tracking, and in presenting two high-efficiency MPPT prototypes for small stand-alone and grid-interconnected PV plants

Generally speaking, to implement maximum power point tracking, it is necessary to have a converter (dc/dc for stand-alone plants, or dc/ac for grid-interconnected plants), in which the input/output voltage transformation ratio is varied by means of a suitable control, which operates either in closed-loop or in open-loop.

The closed-loop control criteria check, instant by instant, that the power extracted actually is the maximum, thus making it possible to deal not only with variations in solar illumination and temperature, but also with drift over a period of time, due to aging, the state of cleanliness of the panels, etc.. With open-loop control, on the other hand, the generator operating point is fixed on the basis of its theoretical rated performance.

The criteria applying to open-loop operation can immediately be understood, since they generally refer to a table that holds the maximum power points relating to given insolation and temperature values: the PV generator operating point is fixed to correspond to the held data of insolation and ambient temperature nearest to the measurements of these two quantities (5).

As regards criteria for closed-loop operation, different strategies can generally be pursued to identify the maximum power operating point.

A first strategy searches for the maximum power point with a suitable logic based on the measurement of the power time-derivative, and with appropriate regulation circuits that allow self-oscillation of a given amplitude and frequency around the general maximum power point (6). Criteria based on this strategy may be called auto-oscillation criteria.

A second strategy is based, on the other hand, on measurement of the slope of the PV generator power-voltage characteristic, a measurement obtained by imposing a small-amplitude oscillation on the operating voltage. Criteria using this strategy may be called forced-oscillation criteria.

Whichever the control criterion chosen, its practical application involves setting up an electronic system to control the converter transformation ratio.

In the case of a grid-interconnected PV plant, one of the simplest, most reliable and highest-efficiency solution is a line-commutated thyristor inverter. This solution, however, may present problems of grid reactive power absorption and of current harmonics [illegible] grid. In the case of stand-alone PV plant, the dc/dc converter is a chopper that may be of the up-converter or down-converter type, or else a combination of both (3,6). In this case, as long as the voltage and current levels make it possible, it is advisable to use a transistor technology, possibly of the MOS-FET type.

STAND-ALONE COMPUTER SIMULATION

With reference to stand-alone plants, in order to evaluate the energy advantages offered by the use of an MPPT compared with the simplest case of direct coupling between the array and the battery, research is under way to compare the behaviour, with or without MPPT, of autonomous photovoltaic plants for supplying isolated consumers.

The study of this problem called for the development of a computer program that, for pre-established insolation, temperature, and load trends, reconstructs in sufficient detail the behaviour of various plant components in the two cases of presence or absence of MPPT, the resulting output giving the trends of the more significant variables and the energy balances. The computer program takes into consideration hourly insolation, ambient temperature, and load trends, and carries out energy balances, updating the state of the plant every 10 minutes.

In the case of direct coupling between the array and the battery (absence of MPPT), account is taken of a logic disconnecting photovoltaic sub-arrays, to limit the battery charging voltage. In the case of presence of MPPT, account is taken of the two alternative ways of regulation, one of which carries out tracking of the maximum power point, while the other limits the battery voltage to the maximum charging value. Furthermore, account is taken of a logic that limits battery discharge by disconnecting the load when the battery voltage reaches the minimum value.

For fixed ratios between PV generator peak power, battery rated power, and annual load energy, the computer program supplies, at pre-established time intervals, the state of the plant, especially voltage and battery charge state, load demands not met, and the photovoltaic energy not utilized.

Since this study is still in progress, we only give here, briefly, some partial comparative results relating to a flat-panel photovoltaic plant for supplying small domestic communities (Sicily; tilt angle=38.5°). These results concern a full year of plant operation. Table I gives, in respect of a few values for the [peak array power/annual load energy] ratio and in respect of two values for the [battery capacity/annual load energy] ratio, the days of plant outage (discharged battery), in both cases of presence or absence of MPPT.

Examining the table, we see that, except in cases in which the photovoltaic array is markedly too small (cases a) and d)), use of MPPT considerably reduces total outage. In particular, we see that, given the same number of days of outage, use of MPPT reduces the size of the photovoltaic array by about 35% in the case of small battery capacity (cf. cases b) and c)), or else by about 15% in the case of medium battery capacity (cf. cases e) and f)).

Case	(kW_p)field / (KWh/year)load	(kWh)battery / (KWh/year)load	outage days with MPPT	outage days without MPPT
a)	8×10^{-4}	8×10^{-3}	79	80
b)	16×10^{-4}	"	33	43
c)	24×10^{-4}	"	20	34
d)	8×10^{-4}	16×10^{-3}	77	78
e)	16×10^{-4}	"	18	24
f)	18×10^{-4}	"	13	17

Table 1. Simulation results for stand-alone plants of the domestic type.

MPPT CONTROL CRITERIA

As already mentioned in the introduction, it is possible to obtain maximum power point tracking of the voltage-current characteristic of a PV generator using controllable-transformation-ratio electronic converters.

As regards closed-loop tracking criteria, it is above all important to note that the power (P)-voltage (V_G) characteristic of the PV generator, corresponding to given insolation and temperature values, generally presents just one maximum point (see Fig.1).

In searching for the maximum point, it is therefore necessary to:
increase V_G if $dP/dV_G>0$ or reduce V_G if $dP/dV_G<0$.

It should be pointed out that, once the transformation ratio between the output voltage Vout and the input voltage V_G of the converter has been indicated with $1/\alpha$ ($V_G = \alpha V_{out}$; α being the control variable), the sign of dP/dV_G coincides with the sign of $dP/d\alpha$. Indeed, since the output voltage V_{out} of the converter is almost constant as α varies (the output voltage is fixed by the battery in the case of a stand-alone plant, and by the grid in the case of a grid-interconnected one), it can be seen that $dV_G/d\alpha > 0$ and therefore:

$$\text{sign}\{dP/dV_G\}=\text{sign}\{(dP/d\alpha)\ (d\alpha/dV_G)\}=\text{sign}\{dP/d\alpha\}$$

As regards the search for the maximum point, this also corresponds to:
increase α if $dP/d\alpha > 0$ or reduce α if $dP/d\alpha < 0$.

Bearing in mind that the slope of the P-α characteristic (equivalent to the P-V_G characteristic) cannot be measured directly without introducing variations in the operating point, the problem of tracking consists, generally speaking, in establishing the converter transformation ratio control criteria, which, based on small operating point variations, reconstructs the value or the sign of the slope $dP/d\alpha$.

Hereunder we present two different control criteria that solve this problem.

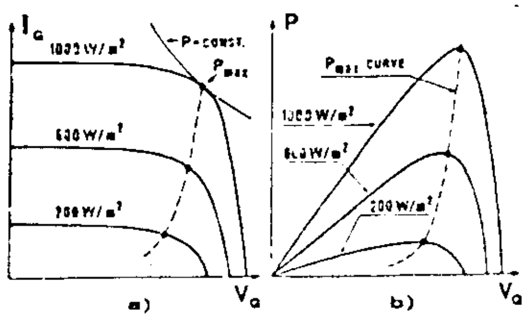

Fig.1 - PV generator electrical output characteristics at three different illumination levels; a): I_G-V_G curves, b): P-V_G curves

Auto-oscillation criterion

With reference to Fig. 2), in the auto-oscillation criterion considered control of the photovoltaic generator voltage is based on an appropriate logic that compares the signs of the derivatives with respect to the time of voltage and of the power delivered.

This logic demands that the increase or reduction in the operating voltage be continued until such an increase or reduction corresponds to an increase in the power delivered. The logic also demands operating in the opposite direction, as soon as there is a reduction in the power delivered. As will be made clear later on, based on this logic and using suitable regulating circuits, an auto-oscillation of given amplitude and frequency is obtained around any maximum power point.

For a dynamic analysis of the control loop, and particularly in order to evaluate how the system parameters and transfer function G(s) (s=Laplace variable) of the regulation circuit influence the amplitude and frequency of the auto-oscillation, the following considerations may be advanced. The converter, on the assumption that it has negligible losses, is described by the following equations:

$$P = V_G I_G = V_{out}\ I_{out} \quad (1)$$

$$V_G = \alpha V_{out}\ ;\ I_{out} = \alpha I_G \quad (2);(3)$$

in which, apart from the quantities already defined, I_{out} is the direct current fed into the battery in the case of a stand-alone plant, or the active component of the alternating current fed into the grid in the case of a grid-interconnected plant.

As regards the PV generator, the non-linear voltage-current dependence $V_G=f(I_G)$ can be expressed, for small variations around any operating point $\{V_G^o, I_G^o\}$, by the equation:

$$V_G - V_G^o = -R_d^o(I_G - I_G^o) \quad (4)$$

in which $R_d^o \triangleq (dV_G/dI_G)^o$ is the differential output resistance of the generator ($R_d^o > 0$).
Equations (1) (2) (3) and (4) give us:

$$P = V_{out}(I_G^o + V_G^o/R_d^o)\alpha - V_{out}^2\alpha^2/R_d^o \quad (5)$$

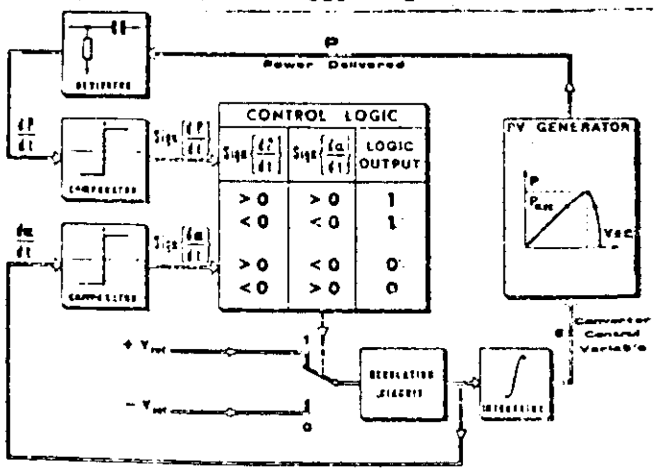

Fig. 2 - Basic diagram of the auto-oscillation criterion

considered that V_{out} = constant (as already stated, V_{out} is fixed either by the battery or the grid), we obtain from (5) the following:

$$dP/dt = [(I_G^o + V_G^o/R_d^o)V_{out} - 2\,\alpha V_{out}^2/R_d^o]\,d\alpha/dt$$

and therefore

$$(dP/dt)/(d\alpha/dt) = K_1 - K_2\alpha \qquad (6)$$

having defined $K_1 \triangleq (I_G^o + V_G^o/R_d^o)V_{out}$ and $K_2 \triangleq 2\,V_{out}^2/R_d^o$. It should be pointed out that $sign\{(dP/dt)/(d\alpha/dt)\} > 0$, on condition that the sign of the two derivatives dP/dt and $d\alpha/dt$ agree; moreover, $sign\{(dP/dt)/(d\alpha/dt)\} < 0$, on condition that the signs of the two derivatives do not agree. Taking this into account, and based on equation (6), it is recognized that the control logic in Fig. 2 requires application to the regulation circuit input of the constant signal $+V_{ref}$ or $-V_{ref}$, respectively, depending on whether $sign\{K_1 - K_2\alpha\} > 0$ or $sign\{K_1 - K_2\alpha\} < 0$.

Following the aforementioned considerations, the control loop is described by the block diagram in Fig. 3. This block diagram shows that the equilibrium point of the system controlled occurs at the α^o value of the control variale, such that $(K_1 - K_2\alpha^o) = 0$, that is, when $R_d^o = V_G^o/I_G^o$. As is known, this condition of equality between differential and apparent generator resistance indicates operation at the maximum power point. As regards choice of the regulator transfer function G(s), it is necessary to ensure the existence of a stable "limit cycle" around the point of equilibrium (which is the maximum power point). In this connection, on the assumption that the transfer function (G(s)/s) is of the "low-pass" type, recourse may be had to well-known analysis criteria for non-linear control systems, based on the "descriptive function" of the non-linear block. In the case in question, these criteria indicate that the existence of a permanent oscillation of the variable α, with an amplitude α_M and a frequency ω, is expressed by the following eq.s:

$$\begin{cases} G(i\omega) = \alpha_M \pi\omega/(4\,V_{ref}) = V_{GM}\pi\omega/(4\,V_{ref}\,V_{out}) \\ \arg\{G(i\omega)\} = \pi/2 \end{cases}$$

As can be seen, while the auto-oscillation frequency depends exclusively on the choice of regulator transfer function G(s), the amplitude V_{GM} of the generator voltage oscillation around the maximum power point depends both on G(s) and on the output voltage level V_{out}.

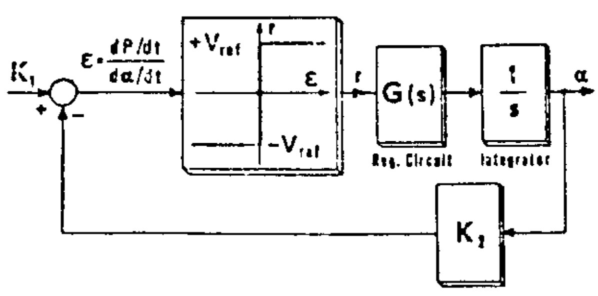

Fig. 3 - Block diag. of the auto-oscillation-criterion control loop

With reference to the block diagram in Fig. 4, the forced-oscillation criterion proposed is based on measurement of the PV generator power-voltage characteristic slope. This slope is measured by superimposing a small-amplitude oscillation on the working voltage. The diagram indicates the triangular waveshape $\Delta\alpha$, having an oscillation period T, superimposed on the converter control variable around any value α_k. The positive measurement +P of the generator power during the positive semi-wave of $\Delta\alpha$ and the opposite measurement -P during the negative semi-wave of $\Delta\alpha$ are sent, alternately, to the integrator input. A sample-and-hold circuit samples the integrator output corresponding to the zero-crossing (with positive slope) of $\Delta\alpha$. In this way, at every T, the increase (positive or negative) in the output signal of the sample-and-hold circuit is proportional to the difference between the areas A_k^+ and A_k^- subtended by the characteristic $P=P(\alpha)$: these areas correspond to the positive semi-wave and the negative semi-wave of $\Delta\alpha$, respectively.

The sample-and-hold circuit output added to the oscillation $\Delta\alpha$ gives, instant by instant, the control variable value. Due to the integrator, the generator operating point shifts in the direction of increase of α if $A_k^+ > A_k^-$, or in the direction of decrease of α if $A_k^+ < A_k^-$.

The equilibrium point of the control loop occurs when $A_k^+ = A_k^-$.

If we ignore the asymmetry of characteristic $P=P(\alpha)$ around the maximum power point (which is legitimate if the oscillation amplitude is sufficiently small), the condition of balance $A_k^+ = A_k^-$ corresponds to the reaching of that maximum power point.

For a dynamic analysis of the control loop, and in particular in order to evaluate how the various system parameters affect the response time the following consideration may be advanced.

The characteristic $P=P(\alpha)$ can be approximated, around any value $P_k = P(\alpha_k)$, with the expression:

$$P = P_k + [dP/d\alpha]_{\alpha k}(\alpha - \alpha_k) + [d^2P/d\alpha^2]_{\alpha k}(\alpha - \alpha_k)^2/2$$

If we call α_M the peak amplitude of $\Delta\alpha(t)$, the difference between the areas A_k^+ and A_k^- indicated in Fig. 4 is expressed by:

$$A_k^+ - A_k^- = [dP/d\alpha]_{\alpha k}\,\alpha_M^2$$

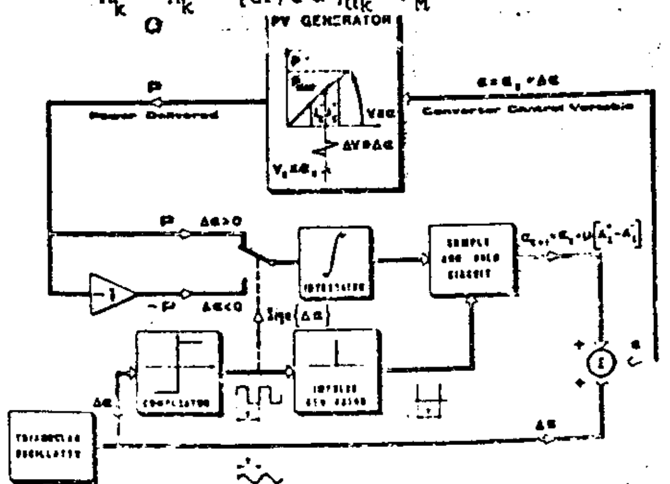

Fig. 4 - Basic diagram of the forced oscillation criterion

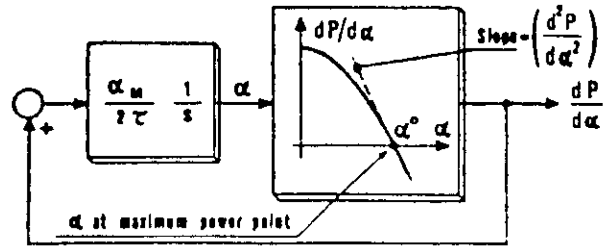

Fig.5-Block diag. of forced-oscillation-criterion control loop

Taking into account the piecewise linear dependence between the variable $\Delta\alpha$ and the time t,($\Delta\alpha(t)$ is a triangular wave) the difference ($\alpha_{k+1}-\alpha_k$) between the successive samples of the integrator output is proportional to the difference($A_k^+-A_k^-$) with the proportionality coefficient expressed by: $\mu = T/(2\alpha_M\tau)$ in which T is the sampling time equal to the oscillation period) and τ is the "integrator time constant". We therefore have:

$$\alpha_{k+1} = \alpha_k + [dP/d\alpha]_{\alpha k}\,\alpha_M T/(2\tau)$$

This relationship between samples of the variables α and $dP/d\alpha$ may be interpreted as a "finite-difference" equation (of the 1st order) associated with the continuous equation

$$d\alpha/dt = (dP/d\alpha)\,\alpha_M/(2\tau)$$

Taking this into account, the continuous system equivalent to the discreet system, for slow dynamics in relation to the sampling time T, can be represented by the block diagram in Fig. 5.

As can be seen, the control loop is of the 1st order and converges towards the value of α at which it is $dP/d\alpha = 0$. The convergence towards the maximum power point is thus confirmed. Lastly, it is pointed out that the loop "time constant" is given by $2\tau/[(d^2P/d\alpha^2)_{Pmax}\ \alpha_M]$.

COMPARISON BETWEEN THE CONTROL CRITERIA

The criteria previously described, although equivalent theoretically, in practice present different problems when being set up. To be more precise, the forced-oscillation criterion is more advantageous than the auto-oscillation one for the following reasons.

The auto-oscillation criterion calls for measurements of the derivative dP/dt, a measurement that poses disturbance problems. Again with regard to the problem of disturbances superimposed on the derivative measurement, the auto-oscillation criterion requires that the oscillation amplitude around the maximum power point be sufficiently high, so as to have an adequate signal/disturbance ratio.

As against this, the forced-oscillation criterion makes it possible to operate with a very small oscillation amplitude around the maximum power point, thus making negligible the differences between the instantaneous power delivered during oscillation and maximum power.

The control logic of the auto-oscillation criterion is, in practice, more complex than is shown in the basic layout in Fig. 4, because it involves dealing with indeterminate situations that occur when dP/dt and $d\alpha/dt$ simultaneously take on values around zero(these uncertain situations occur periodically at the auto-oscillation frequency). Again, taking into account the problems of disturbance superimposed on the derivative measurement, operation of this logic may become critical.

MPPT PROTOTYPES

The main characteristics required for setting up MPPT equipment are not only high reliability and low manufacturing costs, but also particularly high conversion-efficiency.

As regards the dc/dc converter for stand-alone plants, the technology most suitable at present seems to be the one that uses power-switching transistors. In fact, this technology, since it does not require heavy power circuits for forced commutation, makes it possible to obtain much higher conversion efficiency than can be obtained by the more conventional thyristor technology; in addition, transistor technology makes possible very high commutation frequencies (of the order of tens of kHz), which is an advantage for purposes of limiting the size of filters. Furthermore, in the case of photovoltaic plants of moderate power (e.g., up to 10 kW_p), it is possible to use field-effect transistors (MOS-FET) which, by calling for very low gate control power, make it possible further to enhance conversion efficiency and to simplify the design of the driving circuits.

If we pass on to consider the case of dc/ac converters for grid-interconnected plants, one of the simplest, most reliable, and highest-efficiency solutions appears to be a line-commutated thyristor-inverter. This solution may, however, present problems of grid reactive power absorption and of current harmonics introduced into the grid.

Two MPPT prototypes, based on the forced oscillation criterion, have been made at ENEL's Automatica Research Center. One of the prototypes has been in operation for more than a year at the SOLE-1 stand-alone experimental plant (in Sicily). The second prototype is destined for the ADRANO (European Community) PROJECT (7), for direct on-site testing and comparison of different grid-interconnected PV generators.

Fig. 6 shows the schematic diagram of the prototype used at the stand-alone plant. The up-converter system was preferred to the down-converter one, since the former makes it possible to explore the whole V-I characteristic under all insolation conditions. The device was built using field-effect power transistors. Painstaking circuit

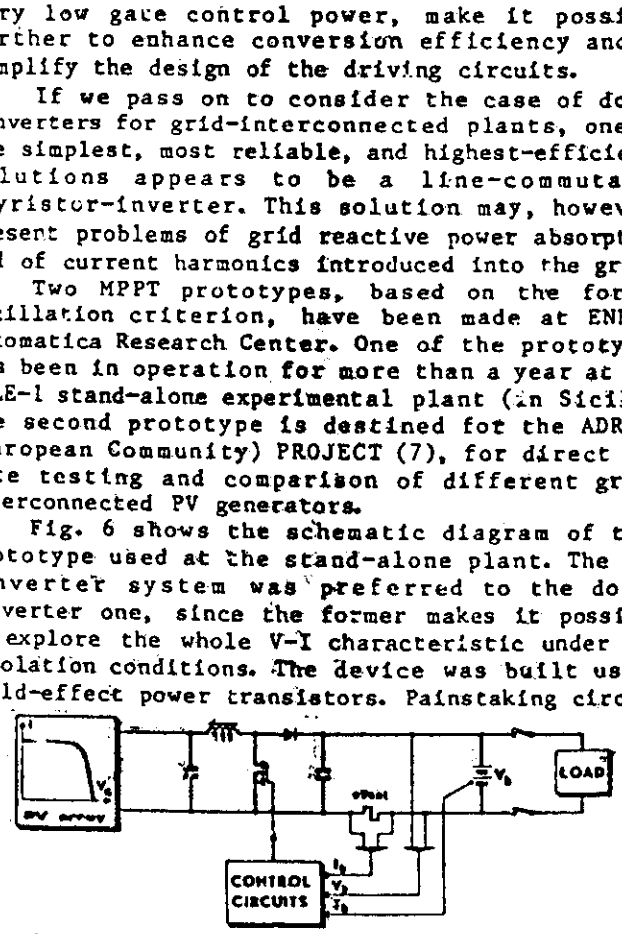

Fig.6-Schematic diag. of MPPT prototype for stand-alone gen.s

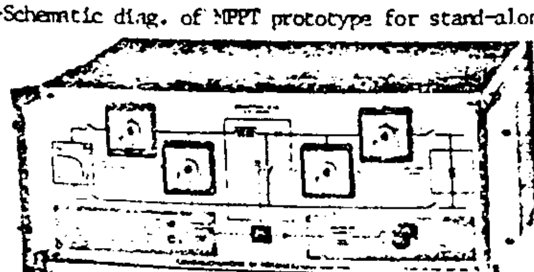
Fig. 7 - 5kW_p MPPT prototype for stand-alone PV plants

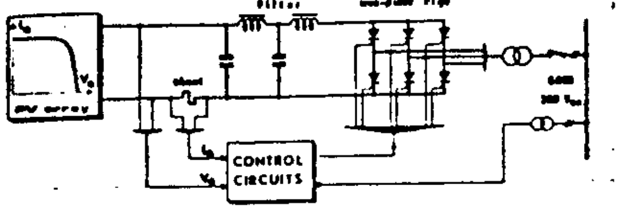

Fig.8–Schematic diag. of the MPPT prototype for grid-interconnected PV generators

design has made it possible to obtain high conversion efficiency, at the same time limiting manufacturing costs. The use of a high commutation frequency (40 kHz) has enabled a light filter to be used, thus limiting both dimensions and weight (see Fig. 7). When the battery charge state approaches 100%, the device automatically shifts from maximum power point tracking to a control that limits the battery voltage to maximum charge voltage, this value being made to vary depending on the temperature of the electrolyte. The main characteristics and performance features of this device are the following:

- Maximum power point tracking virtually guaranteed throughout the insolation range.
- Battery voltage limited to the maximum charge value (this limitation takes into account the dependence of the voltage on the temperature of the electrolyte by means of a special thermo-resistive probe); the automatic commutation between the battery voltage limitation and the MPP tracking has an hysteresis of ± 0.2%.
- Transformation ratio with manual control for recording the whole V-I characteristic.
- Converter rated power: 5 kW.
- Maximum PV generator current: 25 A.
- Battery rated voltage V_{BN}: 48 – 220 V.
- Ripple introduced into the PV generator: peak-to-peak voltage amplitude <0.5% V_{GN}, peak-to-peak current amplitude < 1% I_{GN}.
- Efficiency > 95% for a 10 – 100% power range.

Passing on to consider the prototype for grid-interconnected applications, this has been set up according to the basic layout in Fig. 8. As can be seen, a classic line commutated thyristor inverter with a three-phase bridge has been used. In this case, the relatively low commutation frequency (300 Hz) made it necessary to use a much heavier filter than that employed in the dc/dc converter, and this fact, together with the presence of the output transformer, considerably increased both the dimensions and the weight of the device (see Fig. 9). The main characteristics and performance features of this device are as follows:

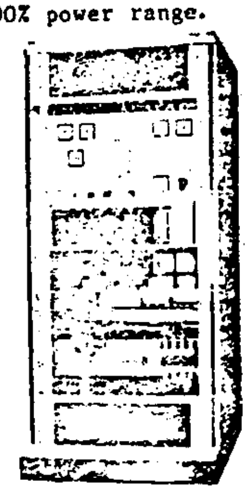

Fig.9 – 5 kW_p MPPT prototype for grid-interconnected PV plants

- Maximum power point tracking virtually guaranteed throughout the insolation range.
- Transformation ratio with manual control for recording the whole V-I characteristic; local and remote control ...
- Rated converter power: 5 kW.
- Maximum PV generator current: 50 A.
- Three-phase grid voltage: 380 V ± 15%.
- Ripple introduced into the PV generator: peak-to-peak voltage amplitude < 0.5% V_{GN}, peak-to-peak current amplitude < 1% I_{GN}.
- Efficiency > 95% over a power range of 20-100%.

CONCLUSIONS

With reference to the case of stand-alone PV plant, the results of the simulation studies indicate that, at least in some significant cases, the use of MPPT considerably reduces the total time of plant outage due to insufficient battery charge.

Closed-loop maximum power point tracking criteria are more advantageous than open-loop criteria, inasmuch as they make it possible to deal not only with variations in insolation, but also with drift, over a period of time, due to aging and/or dirt of the panels, and to fluctuations in ambient temperature and battery voltage, etc..

Of the closed-loop criteria, forced-oscillation is more advantageous than auto-oscillation, inasmuch as, on the one hand, it does not call for derivative measurements which, generally speaking, present disturbance problems, and, on the other hand, it makes it possible to operate with an oscillation of very small amplitude around the maximum power point, thus rendering negligible the differences between the instant power delivered during oscillation and maximum power.

The development of MPPT prototypes for stand-alone and grid-interconnected plants has, on the one hand, shown the real effectiveness of the forced-oscillation criterion, and, on the other hand, has confirmed the possibility of making high-efficiency and reliability converters.

As regards MPPT developed for grid-interconnected PV generators, this device is particularly useful for direct on-site testing and comparison of different PV generators.

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