Paper accepted for presentation at 2009 IEEE Bucharest Power Tech Conference, June 28th - July 2nd, Bucharest, Romania

New network topologies for large scale Photovoltaic Systems

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***Abstract*--In order to extend the application of photovoltaic power generation, new integrated solutions with the environment have to be studied and adopted. In the next future, one important solution could be the application of photovoltaic power generator into terrestrial desert surfaces.**

The present paper analyses the possible production of electrical energy by photovoltaic systems in areas characterized by an high level of insolation in order to maximize the global energy conversion. In this context, it has been developed a new and very innovative photovoltaic technology for the realization of solar panel suitable for the extreme condition and at the same time it is studied and analyzed the electrical components and the correct strategy to connect the solar plant to the end users.

The study concerns a preliminary technical analysis on the solar network configuration and presents different PV network configurations, discussing benefits and drawbacks for each one of them.

***Index Term*--Converter topologies, PV-network, PV-farm.**

I. Introduction

THE actual increase of renewable energy utilization is one of the approaches that several countries are currently exploiting and/or are planning to exploit in the next years to reduce the negative effects on the environment of the existing production systems, especially under the future electrical energy provision requirements.

Photovoltaic plants for solar energy profitable utilization plays a key role within this framework, and it has a strategic importance on the capability of concentrating large scale photovoltaic plants – solar farms – in areas characterized by an high level of insolation in order to maximize the global energy conversion. With currently available technologies it could be possible to satisfy the entire world electric energy demand by exploiting only about 4% of terrestrial desert surfaces [1].

Moreover, in those areas of the globe, i.e. desert regions at low latitudes, see Fig. 1, the environmental impact of the infrastructures could be negligible with respect to urban sites, due to the great abundance of surfaces which are not utilized otherwise.

Therefore it should be enviable for the world energy market to invest in the development of innovative solutions, materials and technologies to optimize the utilization of solar energy conversion system in those types of environment. Features like very high temperatures and day-night thermal excursion impose challenging requirements for the development of solar farms, especially as far as photovoltaic conversion systems are concerned.

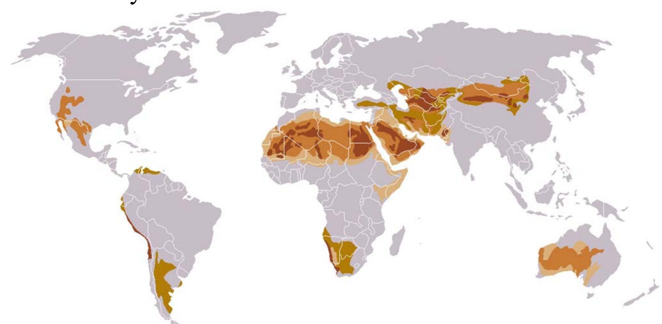

Fig. 1. The terrestrial desert surfaces are underlined.

In this context, it has been developed a new and very innovative technology for the realization of solar panel suitable for the extreme condition (high temperature and thermal excursion). These panel are tested in Sardenia (Italy) and at the moment are installed and under investigation, as near commercial technology suitable for demonstration-level project, in Abu Dhabi (Emirate) for the energy development of Masdar City [2] (Fig. 2). Then, after the choice of the photovoltaic (PV) panels is necessary to study and to analyze the other electrical components, also suitable for the desert conditions, and to identify the correct strategy to connect the solar plant to the end users.

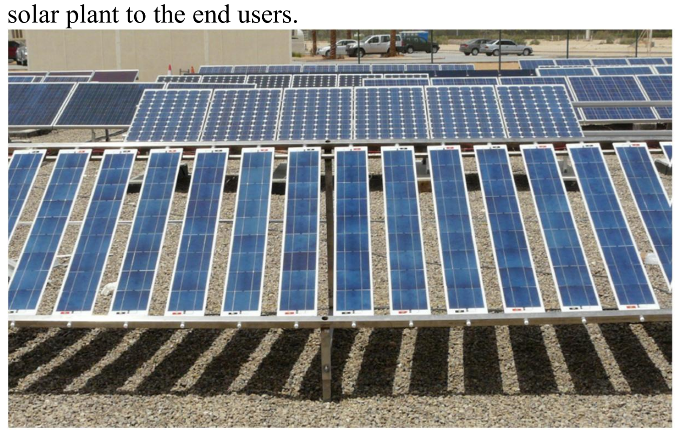

Fig. 2. PV panels under test in Abu Dhabi.

The goal of the present paper consists in the analysis of possible lay-out designs of large scale PV solar farms and networks provided with the capability of being adapted to

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978-1-4244-2235-7/09/$25.00 ©2009 IEEE

extreme climatic and environmental conditions, typical of the aforementioned areas highlighted in Fig.1.

Section 2 discusses the main issues related to the application of photovoltaic conversion systems with particular care at installation in hostile environments; Section 3 presents new technological achievements in the field of PV plants and the benefits which could be obtained by using these type of technologies for the development of a PV solar farm is desert areas; and eventually Section 4 presents different PV network configurations, discussing benefits and drawbacks for each one of them.

II. State of Art of PV Plant Applications

Due to their modularity, photovoltaic plants are used for applications which could range from less than one Watt to several MWatts and they are able to operate as standalone systems as well as grid-connected systems.

Global solar irradiance consists of direct and diffuse irradiance. When skies are overcast, only diffuse irradiance is available. While solar thermal power plants can only use direct irradiance for power generation, photovoltaic systems can convert the diffuse irradiance as well, and hence they can produce electrical power even with cloud-covered sky.

Only a few photovoltaic demonstration systems in the MWatt range were built in the last decades and in general they are built by a lot little system connected together to the network. Currently different large systems are planned or under construction. Reliable general conditions given by fed-in laws in Germany and Spain support the creation of new large systems, and it is expected that the continuous increase of the number of such plants will result in the next years in a sensible decrease of overall costs.

Desert areas at low latitude sites represent a great opportunity in this frame: there is an extraordinary availability of unutilized surfaces with a very high insolation. However, the high thermal excursion between day and night, together with the very high temperatures achieved during the day, impose the need for considerable modifications and adaptation to the technology of the PV plant components with respect to system used in low-medium scale applications and in urban areas at medium latitudes [1].

Off the shelf technologies and components, in fact, are not designed to work in extreme environmental conditions; very often the operative temperature range of available systems is significantly different from the one which characterizes low latitude desert areas, and hence they could not be exploited there without any type of adaptation.

Moreover, unfortunately, some of the hypotheses made about the high potential of energy production from PV systems many times come to be wrong. In fact, the PV energy production is based on calculations that, even though are precise, analyze ideal situations and, for this reason, can be encountered in few cases.

Therefore, some of the factors that can strongly affect the production of a PV system are the following:

- the direct shadows and the horizon profile;
- the installation angle of active surface;
- the temperature of the PV modules and inverters that depends on external conditions;
- the quality of the energy supplied by the distributor.

A. *Main problems of PV module technology*

Only a limited part of the overall light radiation energy which reaches the solar cell is actually converted into exploitable electrical energy. The conversion efficiency for off the shelf silicon solar cells generally ranges between 13% and 20%, while special laboratory products can reach values of about 32,5% (Fig. 3).

Such a low efficiency is due to several different factors, which can be grouped into the following four categories:

- *reflection*: not all the photons which hit the cell can actually pass through it, because some of them are reflected by the cell surface, and some of them hit the contacts metallic grid;
- *photons energetic levels*: in order to break the link between electron and nucleus, and not all the incoming photons have got this necessary amount of energy. Furthermore, there are also some photons which brings too much energy and generate electron-hole couples, and the exceeding energy is converted into heat.

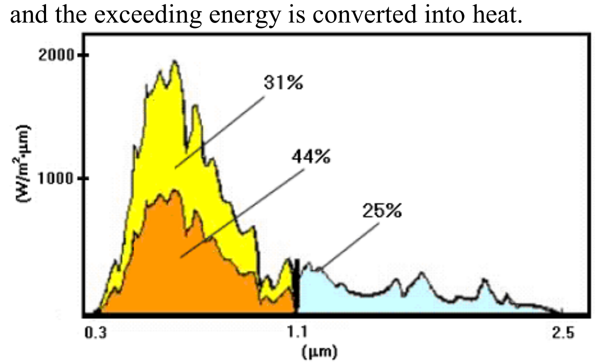

Fig. 2. Breakdown of solar cell available energy: actually convertible portion in orange; non-convertable portion in blue; portion which contributes to the cell heat increase in yellow.

- *Ricombination*: not all the electron-hole couples are collected by the junction electric field and then sent to the exteranl load, as they can ricombine with opposite charges encountered along their path from the generation point toward the junction.
- *Parasitic resistances*: charges generated and collected into the depletion region must be sent outside. The collection is performed by the metallic contacts, placed both on the front and rear side of the cell. Even if during the manufacturing it is performed an alloy process between silicon and aluminium that compose the contacts, there is still a given interface resistance which causes a dissipation, and hence a reduction of the power transferred to the load., The efficiency is furtherly decreased concerning polycrystalline silicon cells, because of the resistance met by the electrons on the boundary between two elementary parts, and even much more concerning amorphous silicon cells, because of the resistance due to the casual orientation of single atoms.

Moreover, if the cell temperature gets higher than the nominal (defined in the Standard Test Conditions equal to 25°C) is possible to have a decrease in the conversion efficiency of around 5÷8%. This phenomenon happens because the whole potential conversion of the solar radiation in electrical energy by the PV modules is limited to only a part of the total radiation spectrum; the exceeding radiation does not give a contribution to the conversion and it is converted in heat increasing the cell temperature.

A further problem of the current technology is associated to the decrease of PV panel performance in time. Generally the performances of a solar panel are characterized by a 1% decrease per year [1], and this is mainly due to thermic variations among the different points of the cell, which could cause microfractures which reduce the mobility of free electrons: such microfractures generate a resistance for charges and hence they reduce the electrons capability to move and reach the electrode.

Microfractures of solar cells can also be caused by torsions and flexions of the envelope materials due to wind, atmospheric agents, thermal dilatations, etc… Being the cell strictly in touch with these materials is considerably solicitated.

B. Main problems of converters technology

The possible configurations of a PV plant mainly depends on the type of electric grid the plant is connected to, the number and type of converters, and the plant size, in terms of kWp. In particular the main problem is the quality of the voltage waveform in the connection point. Often it is not taken in account but it is fundamental for the efficient operating of PV system connected to the distribution network. The standards fix that the PV system has to be disconnected automatically from the network, see Fig. 4, if the voltage waveform is outside from the standard limits. Therefore, the static converter, in presence of distorted loads (such as big motors or inductive loads in general) or in case of network characterized by low short circuit power could continuously disconnect itself affecting the production efficiency.

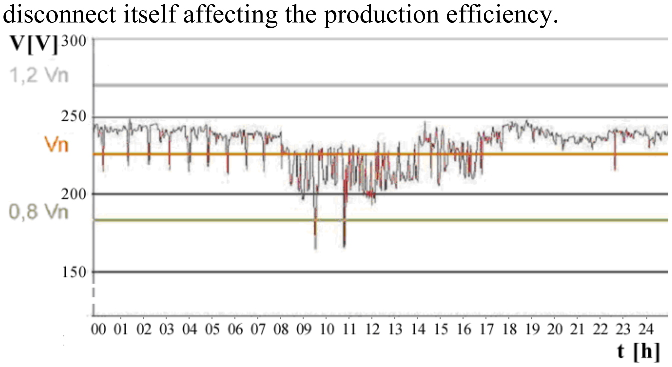

Fig. 4. Trend of the effective value of the network voltage during a day and for a low-power user. 1.2Vn and 0.8Vn represent the maximum values according to the standard, beyond which is necessary to disconnect from the distribution network.

Moreover regarding the converters it is of fundamental importance:

- the knowledge of the final utilization of the plant output power, e.g. to be directly injected into the electric grid or to supply energy storage systems,
- and the climatic and environmental conditions of the operative site.

Among off-the-shelf converters it is possible to identify two main categories of devices: DC-DC converters (choppers) and DC-AC converters (inverters). In particular, the latter ones can be used to make available to any system connected to the electric grid (operating with AC current) the electrical power provided by the PV plant. Anyway the word inverter is used also to call the multi-stage DC-AC conversion made by chopper or choppers plus inverter.

In addition to the capability of conditioning the voltage and current parameters, PV converters functions include also the optimization of final plant efficiency, and the safety control of the plant. The most important features of a converter for PV applications are its reliability, its efficiency characteristics and its range of the DC voltage operation. Other features of PV converters that are impacted by external environment conditions are: the range of operative temperature, the Maximum Power Point Tracking (MPPT) [3] and the degree of protection (IP).

Traditional devices are designed to work properly in specific environmental conditions; whenever the maximum operative temperature is overcome, the converter stops working, as an auto-protection effect. Generally this happens close to the achievement of the maximum power output, with the consequence of a considerable reduction of the global efficiency. For this reason the converter are often put in climatic chamber but this, obviously, reduce drastically the energy efficiency. Moreover, the Maximum Power Point (MPP) which has to be tracked to adapt the circuit to the maximum efficiency of the cells, depends not only on the type of cell technology, but also on the insolation and the temperature of the modules [2]. Eventually, particular temperature and humidity conditions may generate condensation phenomena and the device must be provided with a degree of protection such that the effects of humidity and condensations are minimized.

The experience in operation and maintenance of large-scale PV systems especially in extreme environmental conditions shows that the inverter continue to be the source of nearly all the problem with PV systems. Inverter have improved considerably but remain the weak link [1]. For this reason, for example, in desert PV plant the converters are usually installed in conditioned rooms, nevertheless these problems are emphasized and the efficiency of the whole system reduced.

III. A New Photovoltaic System

A new technology of photovoltaic (PV) system that represents the ultimate innovation in the field of solar energy production is patented worldwide [4] by Soltechna. It is the result of years of research and development and testing, in Italy and abroad.

The PV-system (Fig. 5) is constitute by PV-panels, composed by several modules with 9 cells each one connected in series, by axial rolling panels sun tracking systems installed on a particular framework.

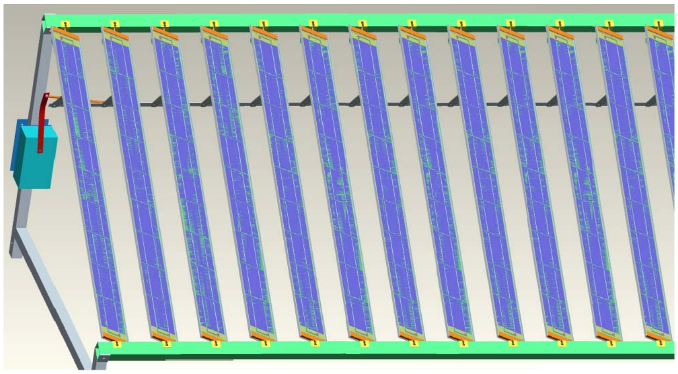

Fig. 5. The innivative PV system.

The innovation of the PV-system is expressed by three main themes: the PV-panel with cells liquid cooling system; the sun tracking system and the water-proof (and sand-proof) support framework.

The PV-panel, that represent the core of the PV system, comprises an external liquid-tight casing that is permeable to light, housed in which is a plurality of photovoltaic cells totally immersed in a fluid. For the fact of being immersed or embedded in the fluid, the heat generated by the cells is then transferred directly to the fluid keeping low and rather uniform the cells temperature. This increases the efficiency of the photovoltaic cells themselves, drastically reducing the amount of micro-fractures that are generated in the cells on account of the thermal gradients to which the cells are subjected. For this reason, this system come with an unusual performance warranty: about 90% over 30 years, compared to 80% over 20 years of the traditional solution. In addition, the fluid, once transferred outside the PV-panel, can be sent into a heat exchanger, in this way recovering the heat possessed by the fluid itself. The refrigerating fluid is a particular silicone liquid and makes the described photovoltaic panel to have higher efficiency than that of known panels. Likewise, this liquids have a high resistance to exposure of solar radiation over time, and good convection capacity and they are neither pollutant nor toxic. These panels can provide only with this aspect until 20% higher efficiency compared to others fixed PV panels on the market in its life.

The single-axis sun tracking system, thanks to the low inertia moment of the PV panel, presents a lower structure cost per Watt and allows to improve more than 12% the efficiency of the solar conversion respect to fixed PV system [5].

Moreover it is very reliable. In addition, unlike conventional sun tracking system, the particular structure of the PV-panel does not require foundations, concrete fillings or ground excavations assuring minimum environment impact. The panel frame in fact is simply set on the ground and can be removed or replace very easily, leaving the original ground unchanged. Moreover, its limited height allows a pleasant insertion of the frame in the natural landscape.

Other important advantages are associated to the use of the high-quality materials and the absence of void in the structure (filled up by the cooling liquid) that give the frame an extended mechanical strength, enabling the structure to bear accidental shocks and to avoid tensional stress due to thermal excursion guaranteeing superior reliability.

Finally as the result of a specific manufacturing process allowing the possibility to disassemble completely all component, each part is easily maintainable and is recyclable and no-toxic to both, men and environment.

This new PV-system is composed by panels with 34Wp power that present low voltage (around to 4.5V) and high current (around to 8A) in respect to other PV-panel; that makes this solution very profitable and most favourable for large scale PV-farm.

The specific design of the PV-panels, with very low weight, of the tracking, and of the framework make this panels suitable to operate in aggressive environments such as coastlines or desert.

IV. PV Solar array configurations

Hereafter different possible configurations for a solar PV farm are presented and discussed. For each configuration the main advantages and drawbacks are addressed, in order to preliminarily evaluate the most suitable solutions for applications in extreme environmental conditions, as the ones in low latitude desert areas, with reference to the new innovative PV system.

A. Network A. Typical configuration of a PV plant exploited in Europe

The typical configuration of a PV plant exploited in Europe regarding plants connected to the public Low Voltage (LV) and Medium Voltage (MV) network is reported in Fig. 6 [6]. In that case the overall photovoltaic field is divided into several sub-fields, each one corresponding to a dedicated inverter for the connection to the LV AC bus. Furthermore a converter for the connection to the MV plant, and hence to the public network, is foreseen.

This configuration is exploited both for small plants and medium-large ones, connected to the public network which constitutes a node of infinite power. In case of plants connected to the LV bus, the configuration is the same but the transformer T1 is not foreseen.

Concerning large PV systems, the use of topology A leads to the following considerations:

- It is necessary to have an high power node which constitutes the voltage and frequency reference for installed inverters;
- It is necessary a subdivision of PV generator into subfields directly connected to the national grid, due to the maximum size of currently off the shelf inverters;
- The single MPPT dedicated to each subfiels optimizes the functioning point of the PV field, as it optimizes the performance of each subfield (it is possible to reach 250kWp). It should be evaluated the benefits provided by the reduction of the dimensions of the subfield optimized by the single MPPT, taking into account the partial shadowing problems;
- The final efficiency in case of low power is low: the low irradiance phase is not optimized, until no inverter input power balancing systems are used.
- The string must be designed taking into carefull account the inverter mimimum activation voltage.

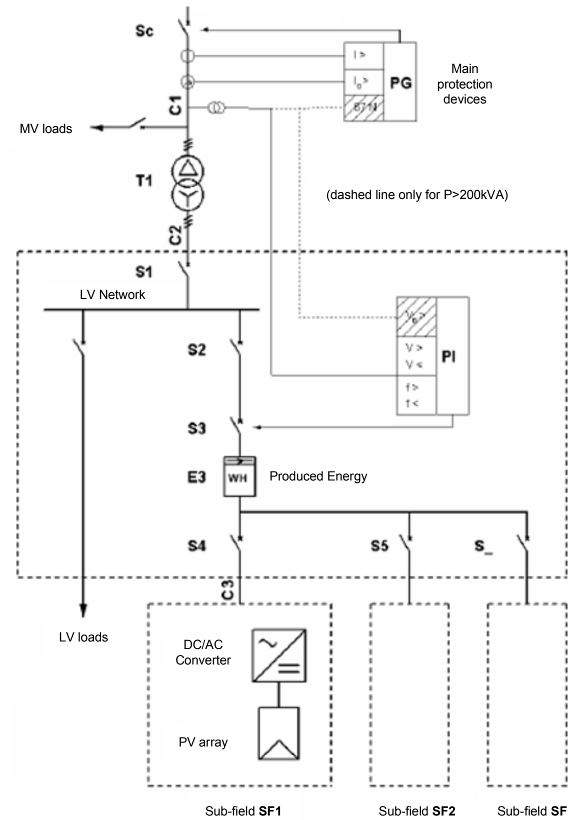

Fig. 6. PV plan operating in parallel to the distributor MT network, in accordance with CEI 11-20, V1 standard.

This network is very spread and represents the first topology of PV-network developed in the world but it does not answer all the requests of optimization of a very large PV-system in desert areas. The main issue correlated to this network consists in the reduced efficiency due to, among other reasons, the necessity of placing the converters in climatized rooms. Some other limiting factors to the realization of this solution are the cabling complexity together with the high sensitivity of the inverters to both voltages on DC side imposed by strong thermic excursions, and voltages and frequency on AC side due to local networks characterized by small robustness.

B. Network B: PV-modules connected to a single DC bus

A possible network configuration for large plants is shown in Fig. 7. In this case, all the PV modules are connected to a single DC bus, together with a usefull number of high power inverters. The inverters implements the MPPT logic.

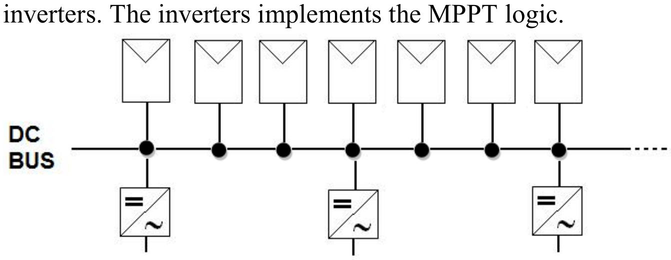

Fig. 7. Network B

Such a configuration allows the utilization of high power inverters with high efficiency. However it is characterized by the following problems:

1. the DC bus voltage is strongly dependant on atmospheric conditions: inverters must then be designed in order to work also at low voltages;
2. currently off the shelf inverters have maximum size of 1-2MW. In case of an higher power the same components are used in parallel. High power converters are also characterized by great dimensions, with consequent transportation problems;
3. it is necessary to carefully study inverters parallel connection: the power breakdown among them, their synchronization, and the most suitable logic in case of stand alone network;
4. inverters must be controlled in order to work as much as possibly in the proximity of the maximum efficiency condition: it is required a control logic capable of activating the proper number of inverters;
5. In the DC bus flows high currents;
6. during the design of the conductors for the different subfields it shall be taken into account the fact that a shortcircuit is fed also by all the other subfields. The sizing of the protection on the DC side (diodes and/or fuses) becomes particularly demanding because a double directional protection is required at the beginning and at the end of the cable which connect the single PV string to the DC bus;
7. the presence of additional protections and, in particular, of diodes required to protect the single PV-field strings connected in parallel, reduce the efficiency of the plant, as the protection devices imply voltage drops and hence power losses.

The main problems of this network are connected to the high DC bus voltage fluctuations due to the irradiation and temperature variations, to the conductors sizing, especially the ones of the DC bus, and to the big power and size of the inverters that have to be inserted in climatic rooms with consequent riduction of the system efficiency. The modularity of this kind of network is low. Eventually, issue correlated to the application in extreme environments, mentioned in the discussion of Network A features, are still present.

C. Network C: Modular network (separated DC bus) composed by 1-2 MW PV-Chopper-Inverter modules .[1]

The architecture shown in Fig. 8 is a modular one: it is composed by 2MWp PV sub-fields and it is characterized by an higher reliability.

Each subfield is composed by strings in the PV field that are connected to the DC-bus by means of choppers with power ranging between 2kW and 5kW, and that implement the MPPT logic, allowing the optimization of each subfield efficiency.

All the choppers are connected to a DC bus together with two inverters of size equal to 1MW and 2MW.

Inverters are controlled in such a way that they work as much as possible in the proximity of the maximum efficiency condition, by activating the proper inverter depending on the load. On the AC side they are connected to a single AC bus.

[1] It is necessary to accurately identify the size of the field and of the conver ters with respect to products (e.g. cables, protections, atc…) available off the shelf.

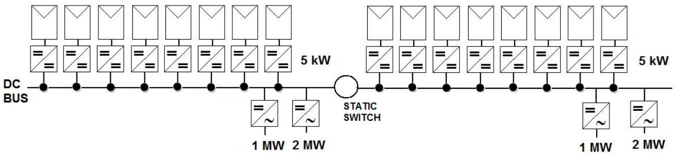

Fig. 8. Network C.

Configuration C is characterized by some advantages with respect to configuration B:

a. the DC bus voltage[2] is not modified by irradiance and/or temperature variations because it is kept almost constant by interface choppers between PV strings and DC-bus.
b. there is redundance for each inverter sub-network: in caso of an inverter failure it is possible to operate at reduced or full regime with the remaining inverters;
c. it is possible to optimize the MPPT for each 2-5kWp string;
d. the choppers can be installed closed to the PV-panel togheter with the single axis trackink system;
e. it is a modular system;
f. the current in each single DC bus is lower with respect to configuration B, and hence the design of the system is simpler and cheaper;
g. there are less problems in the design of protections and cables on the DC bus thanks to the modularity of the configuration, even if the connections (and their protections) between the modules shall be carefully designed;
h. the duration of operativity period is higher because the choppers have less problems associated to minimum operative voltage with respect to inverters.

The realization of 2MW sub-networks it is possible to operate with the same network and to guarantee a usefull level of system redundance: in case of an inverter failure it is possible to operate in reduced power regime or in full regime with the remaining inverters. However it shall be noticed that an higher number of inverter turns into higher costs.

This configuration, however, is characterized by some of the same problems of configuration B (in particular the aforementioned drawbacks number 3 and 4), furthermore it is necessary to add switches for the disconnection of the chopper (e.g. in case of maintenance operations);

Regarding the total efficiency, even if two conversion steps are used, it can be higher than the one of Network B, because the problems due to the accetable minimum voltage of the inverter can be reduced in this case, resulting in a PV sytem continuous functioning guaranteed also at high temperatures.

As far as applications in extreme environment are concerned, there is the need for placing only the inverters in climatic rooms, with consequent reduction of the global efficiency, and the problems correlated with voltage and frequency fluctuation on AC side due to weak local networks are still present.

[2] The selection of this voltage value has to be based on the availability of DC switches.

V. Conclusions

Network A solution is undoubtely the most suitable and the most validated one regarding PV plants up to few MWp connected to robust national grids which guarantee voltages and frequencies and with reduced voltage fluctuations on DC bus.

Concerning instead larger PV plants (more than some MWp) the most suitable solution seems to be the one represented by Network C. In particular, the utilization of small size choppers and high power inverters allows reducing the problems associated to inverter minimum and maximum voltage.

The utilization of the chopper downstream the PV panel is also suitable to increase the low voltage which characterizes the PV systems and in particular the previously described innovative PV-system profitable for desert areas.

The chopper utilization closed to the PV panel is then properly suitable to the new PV-system here presented. In fact, as it is required to install a command and control system for the sun tracker, it is useful and cheap to develop together with the PV panel power converter itself.

Anyway, the usage of modular networks consitutes by the same components considerably increases the reliability of the system and reduces the maintenance costs for the overall PV plant.

Solution C is therefore the one to be preferred, as it is modular, every “mini” central – 2 or 3MW – is optimized depending on the reliability level desired, the design of the DC network is replicated, and the structures of the modules are connected in the same point. Eventually, the problem of the connection between different “mini” networks is easily solvable exploiting the currently available tecnology even if the presence of the static switch has a strong impact on the control system in terms of optimization of the overall PV plant efficiency.

Eventually, the need for climatic rooms for the inverters and the problems correlated with voltage and frequency fluctuation on AC side due to weak local networks are still present. As far as the former issue is concerned, an interesting analysis is the evaluation of cooling technologies more efficient than the currently utilized ones [7].

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VII. Biographies

Giacomo Carcangiu, from many years he focused his attention on renewable energy projects (in particular Photovoltaic Energy) and finally joined Soltechna company in 2007 as C.E.O. and co-owner. Together with Mr. Sardo Marcello, he leads the R&D Department of Soltechna.

Carlotta Dainese received the M.S. degrees in Aerospace Engineering from the Politecnico di Milano, Italy, in 2006. Currently, she is a research fellow at the Energy Department of Politecnico di Milano, engaged at Consorzio L.E.A.P. Her research interests include: photovoltaic energy conversion (innovative projects for photovoltaic array applications), energy conversion from biomass and residual fuels, wind energy, energetic audits and strategies for energetic savings, waste to energy technologies and analysis of waste integrated management strategies.

Roberto Faranda received his Ph.D. degree in Electrical Engineering from the Politecnico di Milano in 1998, and at present is an Assistant Professor in the Department of Energy of the Politecnico di Milano. His areas of research include power electronics, power system harmonics, power quality, power system analysis and distributed generation. He is a member of the Italian Standard Authority (C.E.I.), the Italian Electrical Association (A.E.I.), IEEE, and the Italian National Research Council (C.N.R.) group of the Electrical Power System.

Sonia Leva (M'01) received the M.S. and Ph.D. degrees in electrical engineering from the Politecnico di Milano, Milan, Italy, in 1997 and 2001, respectively. Currently, she is Assistant Professor in Elettrotecnica in the Department of Energy, Politecnico di Milano. Her research interests include electromagnetic (EM) compatibility, power quality, the foundation of the EM theory of the electric network, and the renewable energy. She is member of the Italian Standard Authority (C.E.I.), and of the IEEE Working Group "Distributed Resources: Modelling & Analysis".

Marcello Sardo received his degree in Civil Engineering from Politecnico di Torino in 1999. After a six-year period of working in a building-construction company, from 2006 he focused his attention on renewable energy projects and finally joined Soltechna company in 2007 as C.E.O. and co-owner. Together with Mr. Carcangiu Giacomo, he leads the R&D Department of Soltechna.