Improving and Experimenting a Recently Introduced AC PV-Module

R. Carbone, A. Tomaselli, A. Pinnarelli

***Abstract*—** In some previous papers, the authors have introduced and discussed an innovative AC PV-module, which constitutive characteristics seem to make it particularly interesting for using in modern low voltage (LV) distribution grids, as low-power distributed generator from renewables. It is essentially based on a conventional DC PV-module endowed by the following additional and innovative components: (i) a mini and distributed on-board energy storage system, (ii) a cascaded H-bridge multilevel inverter with line-frequency switching and (iii) a passive, single-axis solar tracker with negligible additional consumption of power and high reliability. Some first numerical analyses of this PV-module have evidenced that it also has some drawbacks, with respect to conventional ones: increased costs, caused by the increased number of static switches of the cascade H-bridge multilevel inverter and a significant worsening of the quality of the power generated under critical solar irradiation conditions, essentially because of a non optimal control strategy of the inverter. In this paper, the recently introduced AC PV-module is improved and numerically re-experimented. In practice, a new circuit topology of the multilevel inverter is introduced together with a new control logic. The main objective is that of guarantee both lower costs and a good quality of the energy generated by the new AC PV-module also in case of very critical solar irradiation conditions. Differently from conventional H-bridge topology, the new topology of the multilevel inverter here introduced is based on an appropriate number of "DC-units", that are connected in series at their output terminals for supplying a single H-bridge inverter; compared to previously introduced configuration, it has the advantage of reduced number of static switches as well as the number of gate drivers. Furthermore, for the inverter control logic, a Selective Harmonic Elimination (SHE) algorithm is implemented to find the optimal solution set of switching angles of static switches of the DC-units that are also operated by following a "swapping" control logic, able to guarantee a uniform charge/discharge of batteries. Numerical simulations are operated by using the MATLAB/Simulink tool to show the usefulness of the proposed circuit modifications.

***Keywords*—**AC PV-Modules, Photovoltaics, Distributed Generation, Smart-Grids, Energy-Storage.

I. INTRODUCTION

THE increasing demand for electrical energy and, at the same time, the need for reducing CO2 emissions are changing traditional strongholds of power systems that are, now, more and more integrated by "distributed generation" (DG), that is to say small and medium size generator plants managed by end-users (now called "prosumers", to underline that they are both consumers and producers) and essentially based on renewables.

In order to not compromise reliability and quality of the supply, modern power systems have now to become "smarter", for properly managing power received from both centralized and distributed sources; of course, this could be accomplished by means of sophisticated control and communication technologies but also energy-storage systems can have a central role [1-5].

In fact, electricity generated from renewables by distributed plants, unlike to that generated by fuel consuming centralized plants, is highly "intermittent" and this worsens the problem of optimally matching electricity availability with electricity demand of end-users. Without solving this problem, reliability, quality and stability of modern power system are seriously compromised. Reliable, high-efficiency and cost-effective energy storage systems - undoubtedly – can play a crucial role for a large-scale integration on power systems of DG and for enabling the starting and the consolidation of the new era of so called smart-grids. At the moment, a large number of energy storage technologies and systems are available and effectively viable; nevertheless, existing storage technologies can be complimented with innovative researches in order to find new, more reliable and cost-effective solutions. Furthermore, distributed generators from renewables should be intrinsically high-reliable, high-available and not-disturbing, as much as possible.

In this scenario, the main goal of the paper is that of improving a recently introduced AC PV-Module [6, 7] that takes advantages of an on board energy storage system. In fact, differently from a conventional AC PV-module, it is endowed by a properly designed mini and distributed energy storage system, based on commercial rechargeable batteries.

In [4], the authors have introduced the idea of utilizing batteries in grid-connected PV plants as a profitable distributed energy storage system, in alternative to more costly distributed active MPPT devices. In practice, in large grid-connected PV plants, batteries can be used as passive and distributed MPPTs by locating them in parallel with a proper number of PV sub-fields and by maintaining a centralized inverter with centralized active MPPT function. In choosing the capacity of the battery system, the criterion to

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be followed is that of making a passive MPPT system that has to be effective but also inexpensive, in order to result as a valid alternative to the aforementioned, more complex and expensive, active MPPTs (that is to say, a number of power electronic DC-DC converters properly distributed inside to PV-plant electrical schemes).

Once introduced the aforementioned distributed energy storage system on-board of the PV-module, thanks to the consequent availability of a certain number of physical DC-voltage levels, the PV-module can utilize a cascade H-bridge multilevel inverter with line switching-frequency, instead of a conventional PWM inverter with high switching-frequency.

Additionally, an innovative on-board solar tracker is proposed to be also introduced on-board, for rotating, from a minimum to a maximum angle, only the cells of the PV-module, avoiding to rotate also the PV-module container and its remaining heavy components. Because of this last feature of the innovative AC PV-module is not of interest for the analysis of its performances in terms of quality of the output voltage, it will not discussed more in the following (for more details please see [6]).

After recalling also most important issues related to reliability and power quality of modern low voltage (LV) distribution grids, also giving some ideas for their solution, the schematic and performances of the aforementioned AC PV-module are briefly recalled. Then, a new circuit topology for the multilevel inverter is introduced together with a new control technique. Numerical simulations are operated by taking advantage of the MATLAB/Simulink tool, in order to compare performances of the modified inverter, under both nominal and very critical solar irradiation conditions.

II. Power Quality on Smart-Grids

For power systems, power quality, including reliability and safety, has been already considered a central aspect in the past and for the incoming "smart-grids", undoubtedly, it will have a more and more pregnant role because of this aspect is accentuated by the presence of a very large (and increasing) amount of power electronic converters, that are absolutely needful for interconnecting both modern distributed generators and loads with grids. These apparatus are well known both for working as generators of disturbances (i.e. harmonics and interharmonics) and, at the same time, also for being highly (and negatively) sensitive to them. First of all, balancing of generation and consumption (including losses on grids) is a central task for obtaining a high level of power quality. Because of the inherent complexity of smart-grids, power balancing needs the possibility to significantly control (or influence) both generation and consumption. Undoubtedly, this can be achieved by means of complex and sophisticated methodologies based on modern ICT technologies, also supported by aforementioned high-performance power electronic apparatus, advanced metering infrastructure (AMI, also commonly referred to as "smart-meters") and together with market policies economically stimulating "smart-consumptions", that is to say consumptions that are, moment by moment, compatible with generation [1]. Nevertheless, the complexity of the problem suggests to consider also some additional profitable tasks and, in the opinion of the authors, among those that are nowadays debating in the specialized literature, some of them can have a particular relevance.

Firstly, energy-storage systems can be an effective keyword [2, 5]. In fact, electricity generated from renewables by distributed plants, unlike to that generated by fuel consuming centralized plants, is highly "intermittent" and this worsens the problem of optimally matching electricity availability with electricity demand of end-users. Without solving this problem, reliability, quality and stability of modern power system are seriously compromised. Then, reliable, high-efficiency and cost-effective energy storage systems can play a crucial role for a large-scale integration on power systems of DG and for enabling the starting and the consolidation of the new era of smart-grids. A non-exhaustive list of benefits of the energy storage properly located on modern power systems with DG could be as follows: it can increase voltage control, frequency control and stability of power systems, it can reduce outages, it can allow the reduction of spinning reserves to meet peak power demands, it can reduce congestion on the transmission and distributions grids, it can release the stored energy when energy is most needed and expensive, it can improve power quality or service reliability for customers with high value processes or critical operations and so on. Furthermore, energy storage is on the basis of so called "micro-grids", that is to say: small distribution grids that interconnect multiple customers with multiple distributed generators (typically from renewables) and with a central or distributed energy storage systems. Micro-grids have the potential advantage to be established and operated both in parallel with the transmission grids, in some no-critical conditions, and in a scheduled "islanding" mode during abnormal conditions such as outage in bulk supply or during an emergency. Then, this type of grid structure offers significant improvements in power supply efficiency, reliability, power quality and cost of operation, in comparison to traditional distribution grids.

Secondly, distributed generators from renewables should be intrinsically not-disturbing, as much as possible. It is well known that electricity generation from wind and/or solar energy is accomplished by means of complex and sophisticated apparatus (power electronic converters) which main electrical circuits are strongly based on the use of power electronic devices (diodes, thyristors, GTOs, BJTs, Power MOSFETs and so on), that are asked to work as static switches; rectifiers and inverters are well known to play a very strategic role. High-frequency controlled power electronic converters (like PWM inverters) are, undoubtedly characterized by high performances but, at the same time, they also originate important disturbing phenomena, like: low values for power factor (PF), low-frequency and high-frequency harmonic components on voltages and currents, high switching power losses, EMI and so on. Most of these disturbances can be eliminated and/or properly attenuated by introducing sophisticated and expensive additional apparatus, like active filters, operated by means of complex control strategies. In the opinion of the authors, modern technologies on the field of power electronics have the potential for conceiving innovative power electronic apparatus, for interconnecting distributed generators in smart-grids, with intrinsically reduced disturbing phenomena, that is to say with high PF, very low switching frequencies, very low THD and with no EMI [7-12].

As final consideration, it is relevant to underline that also the energy conversion rate can be an in important keyword for modern distributed generators from renewables, being, at the moment characterized by very low values, because of some specific issues that characterize both wind and solar energy conversion technologies. As non-exhaustive examples, wind plants are characterized by a "capacity factor" typically in the range of 20-40%, while for PV-plants it typically remains in the range of 10-20%. There are, therefore, considerable possibilities for developing researches aimed for profitably improving the efficiency of these power generators [6, 13].

As evidenced in next sections, the introduced low-power AC PV-module seems well aligned with the aforementioned paradigm.

III. Fundamentals on AC PV-Modules

An AC PV-module is a conventional DC PV-module with an integrated DC to AC converter (inverter), installed on its backside; typically, an individual module generates in the range of 100-300 W of AC power (Fig. 1) [14-17].

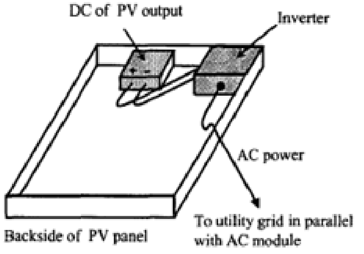


Fig.1. Schematic of an AC PV-module [14]

The main features of using AC PV-modules can be summarized as follows:

- the minimum PV-plant size of one AC PV-module provides a low barrier to the PV market entry;
- the minimum array increment of one AC PV-module allows for maximum plant flexibility;
- the maximum power point (MPP) of each module can be tracked individually, so optimizing the generation of the whole PV-plant, with minor problems for shading or non optimal solar exposure as for typical PV-plant based on strings of conventional DC PV-modules;
- plant generation losses caused by unequal generation of single modules are lower;
- module and string mismatch losses from long series strings are eliminated;
- AC PV-modules are inherently safer than conventional ones;
- no special module/string combiners, DC wiring or DC ground/fault protection devices are needed.

However, there are of course also some disadvantages.

The main one is that for systems with significant power (over about 50 kW), a central inverter can be acquired very cheaply. Other drawbacks are potential reduction in global system efficiency because of the use of several low power high-frequency switching PWM inverters. Also costs of these inverters could be a serious problem. In fact, since conventional PV modules are available with the operating voltage in the typical range of 20-50 V, electronic inverters needed for building AC PV-modules must have a high voltage gain capability. Furthermore power conversion from low voltage DC to higher voltage AC must be achieved as efficiently as possible; in fact, the power level delivered from the module is very sensitive to the point of operation with the load (or grid), so the inverter should therefore incorporate a Maximum Power Point Tracking (MPPT) function, in order to optimize the power generated by the AC PV-module.

Apart from getting the maximum possible power from the AC PV-module, the inverter should also inject the current into the grid in a "soft way", that is to say with a low harmonic content and with a high power factor, in compliance with specific international standards (IEC 61000-3-2 or IEEE-1547 or the U.S. National Electrical Code - NEC – 690). Standards also deal with additional issues like grounding and detection of islanding operation, in order to protect persons and equipment. Regarding islanding, the inverter must remove the PV generator from the grid when this last is out of order (on purpose or by damage), and it can supply only local loads. The US NEC 690 standard demands that the PV modules shall be system grounded and monitored for ground faults, when the maximum output voltage of the PV modules reaches a certain level, e.g., 50 V. System ground involves the negative (positive) terminal of the PV-module(s) being connected to ground. This can be troublesome for many high-power transformer-less systems, since a single-phase inverter with neutral-to-line grid connection already is a system grounded on the grid side. The IEEE and the IEC standards put limitations also on the maximum allowable amount of injected DC current into the grid, in order to avoid saturation of the distribution transformers. This can be achieved by including a line-frequency transformer between the PV-generator and the grid. Topologies without a line-frequency transformer generally have higher efficiencies and may be cheaper; however, in this case a direct connection of the PV generator to the grid occurs without galvanic isolation and this may cause fluctuations of the potential between the PV-module(s) and ground with some additional safety problems for persons.

From the owner (investor) point of view, inverters must be cost effective, with a high efficiency over a wide range of input solar irradiation and of climate conditions and, furthermore, it must be highly reliable (long operational lifetime) since most PV-modules are guaranteed for 25 years on 80% of initial efficiency. The main limiting components inside the inverters are the electrolytic capacitors used for power decoupling between the PV module and the grid, whose lifetime strongly depends on operational temperature combined with humidity levels, salty and corrosive conditions. The power range of inverters for photovoltaic AC modules is usually within 100 W to 500 W, which covers the most commercial PV-modules; the input DC voltage is normally between 20 V and 50 V. An exhaustive overview of most diffused inverters for AC PV-modules can be found in [18-23].

In the next section only a brief summary of the cascaded H-bridge multilevel inverter category is done, due to the fact it is on the basis of the proposal for our innovative AC PV-module.

IV. Recalling the Innovative AC PV-Module

Avoiding some more details that can be found in [6, 7], the schematic of the proposed innovative AC PV-module is that of Fig.2. Like conventional ones, it is essentially based on a DC PV-module, endowed, on its backside, of a power electronic inverter; however, differently from a conventional AC PV-module, it is also endowed by a properly designed mini and distributed energy storage system, based on commercial rechargeable batteries. Furthermore, thanks to the consequent on-board availability of a certain number of physical DC-voltage levels, it also utilizes a cascade H-bridge multilevel inverter with line switching-frequency, instead of a conventional PWM inverter with high switching-frequency. A line-frequency transformer is needed to properly boost the output AC voltage to the rated level of the grid; it can be profitably used also to obtain galvanic isolation. In the specific case we are now discussing, our AC PV-module should include: 72 PV-cells, divided into 6 groups of 12 cells in series, with about 12x0.6 = 7.2 V of output open-circuit voltage; each group of 12 series-connected PV-cells should have in parallel a battery-based "mini" (and distributed) energy storage system, realized by commercial rechargeable batteries with 1.2 V of nominal voltage (i.e. AAA Ni-Mh batteries with a capacity of 2000 mAh). Five batteries in series are proposed to be utilized for each group of 12 series-connected PV-cells, basing on the optimal choice of their whole output voltage, that has to be very close to the MPP voltage (about 6 V) of each group of PV-cells, so working as an effective, reliable and passive (non expensive) distributed MPPT system [4].

The inverter is a cascade H-bridge multilevel inverter [10-12], with 6 H-bridges of power BJTs (or general-purpose MOSFETs) so obtaining a thirteen-level inverter.

Performances of the aforementioned circuit have been already tested in [7], by simulating it with the help of the MATLAB/Simulink tool; a selective harmonic elimination (SHE) control technique has been implemented and the following assumptions have been made:

- the internal resistance of batteries is constant during the charge and the discharge cycles and doesn't vary with the amplitude of the current;
- the parameters of the model, deduced from discharge characteristics are the same also for charging;
- the capacity of the battery doesn't change with the amplitude of current (no Peukert effect);
- the model doesn't depend from temperature effects;
- the Self-Discharge of batteries doesn't occur;
- batteries have no the memory effect.

Normal working conditions (presence of solar irradiation and on-board batteries at 100% of their state of charge, SOC) are considered together with very critical working conditions ("long" solar irradiation absence). The main simulation results can be summarized with the help of Fig.3 and Table I.

Some considerations on these results will be done on section VI, for comparing them with those obtained by simulating a new and simplified circuit of the multilevel inverter, also operated with a new control technique.

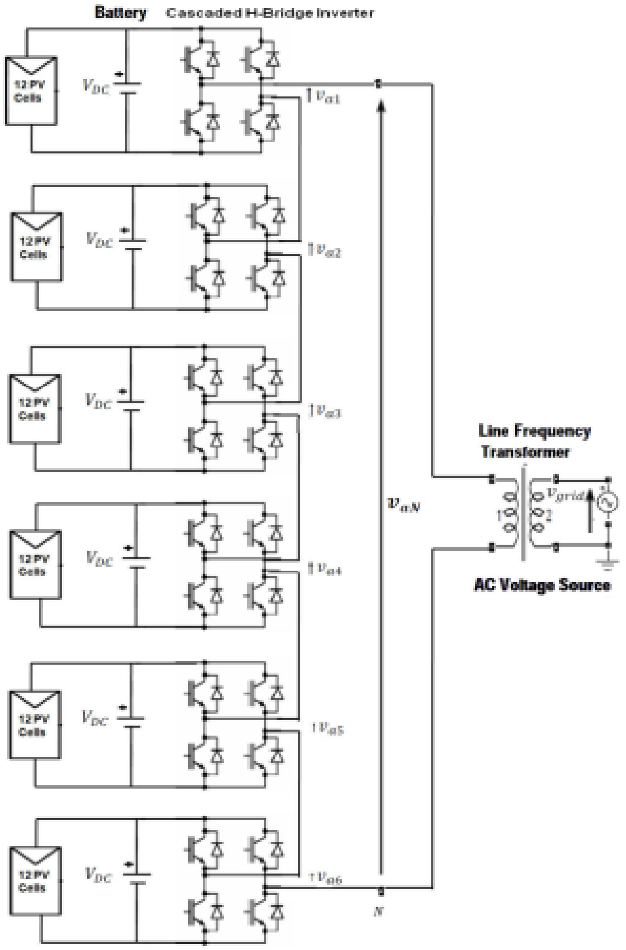
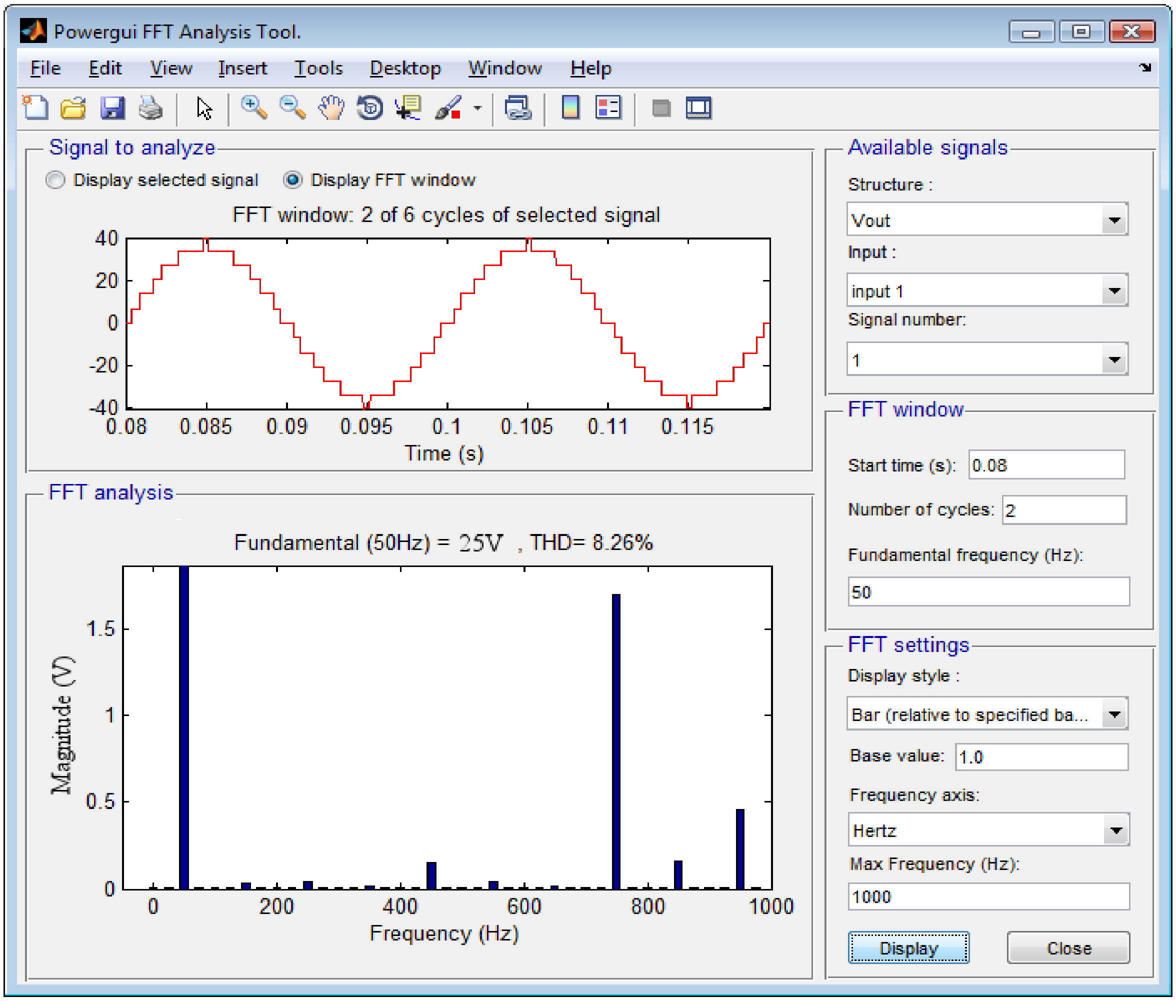


Fig. 2. Electrical scheme of the recently introduced AC PV-module with the distributed energy storage system and with a thirteen-level cascade H-bridge (CHB) inverter



○ Display selected signal ● Display FFT window

Fundamental (50Hz) = 25V , THD= 8.26%

Structure : Vout

Input : input 1

Signal number: 1

Start time (s): 0.08

Number of cycles: 2

Fundamental frequency (Hz): 50

Display style : Bar (relative to specified ba...

Base value: 1.0

Frequency axis: Hertz

Max Frequency (Hz): 1000

Fig. 3. AC output voltage of the AC PV-module, under normal working conditions and with the implementation of SHE control technique

Table I. AC output Voltage and Power generated by the AC PV-module under critical working conditions

	Time width of solar irradiation absence equal to 180 seconds								
	SOC 100%	**SOC 90%**	**SOC 80%**	**SOC 70%**	**SOC 60%**	**SOC 50%**	**SOC 40%**	**SOC 30%**	**SOC 20%**
THD [%]	8.47	8.35	8.34	8.35	8.38	8.42	8.50	8.73	10.02
RMS [V]	22.78	22.49	22.33	22.16	21.92	21.57	20.98	19.82	16.69
Power [W]	174.2	169.8	167.4	164.7	161.3	156.1	147.8	132.0	94.02

V. Introducing a Simplified Multilevel Inverter together with a New Control Logic

With respect to conventional PWM inverters, the main drawbacks of the cascade H-bridge multilevel inverter introduced in [7] are: higher costs, caused by the high number of static switches and a significant worsening of the quality of the power generated under critical solar irradiation conditions, essentially caused by the inverter control logic that does not guarantee a uniform charge/discharge of the on-board battery groups.

In order to overcome these issues, a new inverter, based on a reduced number of static switches, is introduced together with a new control logic.The new simplified thirteen-level inverter scheme is represented in Fig.4. Now, it consists of a number (in the specific case, 6) of “DC-units”, each of which is simply based on a single static switch and a diode (instead of the four switches of the H-bridges present in the previous inverter circuit); they are connected in series at their output terminals and are able to generate a DC-link bus voltage, V_{aN}. This last is simply “inverted”, at the line frequency, by means of only one H-bridge inverter, so obtaining the desired AC output voltage.

No modifications, with respect to previous circuit solution (Fig.2 and [7]), are introduced with reference to the grouping of the PV-cells and of the on-board battery groups.

Also in this case, the DC-units are driven by implementing the aforementioned "*Selective Harmonic Elimination"* (SHE) algorithm, in order to eliminate, under nominal working conditions, low frequency harmonic components on the AC output voltage.

Additionally, a "d*uty-cycle swapping"* control technique is introduced for driving the static switches of the DC-units, in order to avoid the presence of low frequency harmonic components on the AC output voltage, also under very critical conditions ("long" solar irradiation absence). In practice, because of, in simulating the unmodified circuit of Fig.2 in case of "long" solar irradiation absence, it was found that a strong third voltage harmonic component came out as a consequence of the unbalanced discharge of the on-board batteries, now it is proposed to drive the DC-units so that, at each half cycle (of the line-frequency), the *duty-cycle* of each DC-unit is not the same of the previous half cycle; instead, it is chosen equal to the *duty-cycle* of another DC-unit in the previous half cycle.

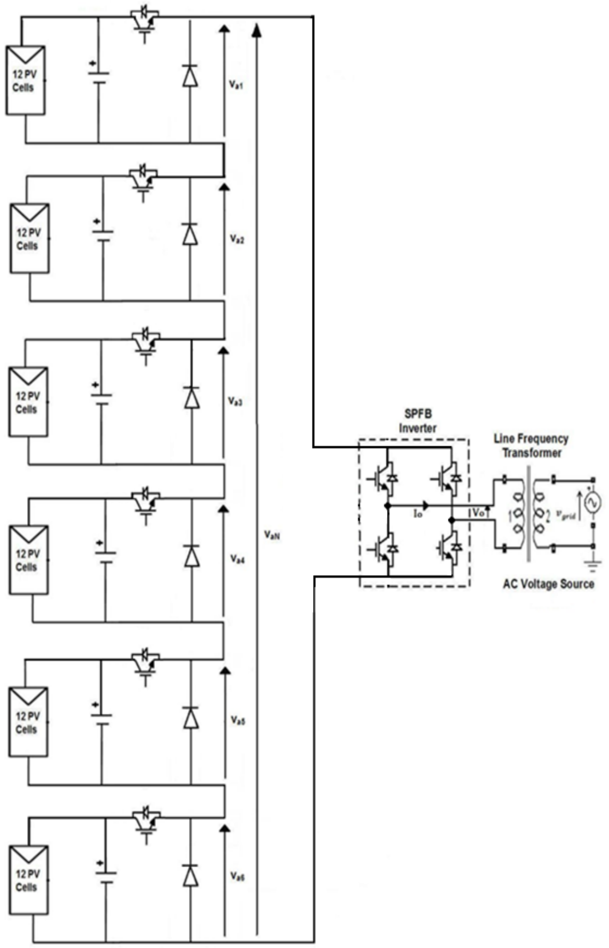


Fig. 4. Electrical scheme of the AC PV-module with the simplified inverter circuit (with reduced number of static switches)

In our specific case of a thirteen-level inverter, by applying this new control logic for all the 6 DC-units of the circuit, after 6 half cycles (of the line-frequency) all the DC-units have been operated for the same "whole working time" and, as a consequence, all the 6 groups of on-board batteries have lost the same quantity of charge (so obtaining the desired balanced discharge).

In a very similar way, under normal working conditions (presence of solar irradiation), the batteries are charged in a balanced mode.

In next section, the new circuit of the simplified multilevel inverter is numerically tested also implementing the SHE control logic together with the newly introduced "d*uty-cycle swapping"* control.

The obtained results are analyzed together with with those previously obtained for the unmodified inverter circuit, for developing some comparative considerations.

VI. Numerical Experiments and Comparisons with Performances of the Unmodified Circuit

After introducing on the inverter circuit and on its control logic the modifications discussed on the previous section V, numerical simulations of the new electrical scheme of Fig.4 have been performed by using the MATLAB/Simulink tool, under normal and critical working conditions.

Figg. 5 and 6 refer to some results obtained under normal working conditions, that is to say, with the on-board batteries fully charged (SOC=100%), in presence of solar irradiation and with the AC PV-module generating the rated power (on the rated load).

Table II and Fig.7, instead, refer to results obtained under critical working conditions: a "long" (180 seconds) solar irradiation absence is considered together with a non optimal SOC of the on-board batteries (variable from 100% to 20%), with the AC PV-module supplying the unchanged rated load.

By analyzing these new results together with those previously obtained by simulating the cascade H-bridge multilevel inverter circuit (unmodified circuit), the following comparative considerations can be developed.

Under normal working conditions, performances of the simplified circuit are practically identical to the unmodified one, so making fully appreciable the reduction of its costs and the improvement of its reliability, obtainable thanks to the significant reduction of the number of the inverter switches.

In case of a "long" solar irradiation absence:

- the RMS value of the AC voltage generated by the PV-module is sufficiently high also starting from a very low initial charge of batteries (SOC = 30–40 %);
- the THD of the AC voltage generated by the PV-module, practically, does not worsen with respect to that obtained under normal working conditions;
- the on-board battery groups are discharged uniformly;
- practically, no low frequency harmonic components appear on the AC generated voltage;
- specifically, no sensible third harmonic component appears on the AC generated voltage.

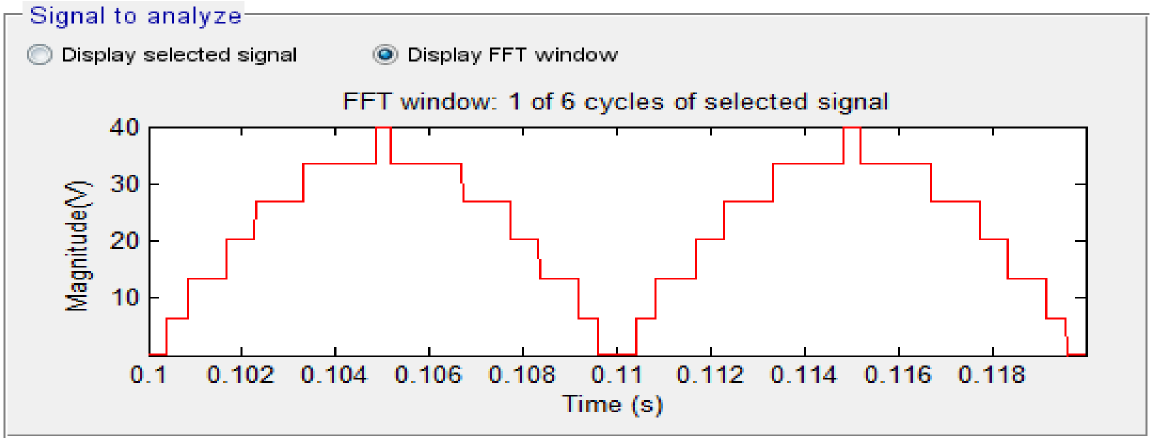
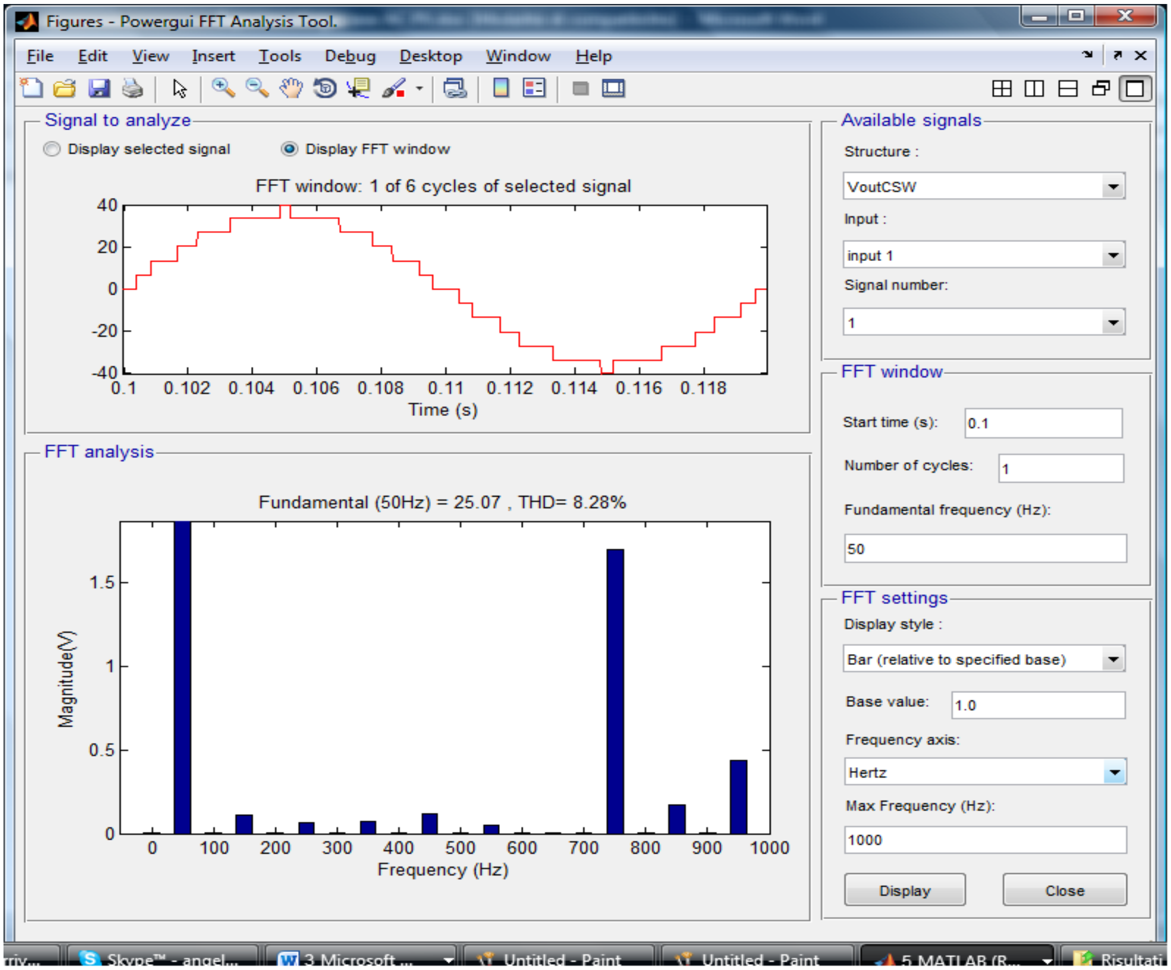


Fig. 5. DC whole voltage (V_{aN}) of the PV-module with the simplified circuit of the inverter, under normal working conditions



Fundamental (50Hz) = 25.07 , THD= 8.28%

Available signals
Structure : VoutCSW
Input : input 1
Signal number: 1

FFT window
Start time (s): 0.1
Number of cycles: 1
Fundamental frequency (Hz): 50

FFT settings
Display style : Bar (relative to specified base)
Base value: 1.0
Frequency axis: Hertz
Max Frequency (Hz): 1000

Fig. 6. AC output voltage of the PV-module with the simplified circuit of the inverter, under normal working conditions

Table II. AC output Voltage and Power generated by the PV-module, under critical working conditions, by introducing the new "d*uty-cycle swapping"* control technique on the inverter with the simplified circuit

	Time width of solar irradiation absence equal to 180 seconds with Swapping								
	SOC 100%	**SOC 90%**	**SOC 80%**	**SOC 70%**	**SOC 60%**	**SOC 50%**	**SOC 40%**	**SOC 30%**	**SOC 20%**
THD [%]	8.29	8.30	8.30	8.30	8.30	8.30	8.30	8.31	8.33
RMS [V]	22.91	22.59	22.44	22.29	22.11	21.83	21.39	20.55	18.51
Power [W]	176.2	171.3	168.9	166.8	163.9	159.98	153.5	141.7	114.22

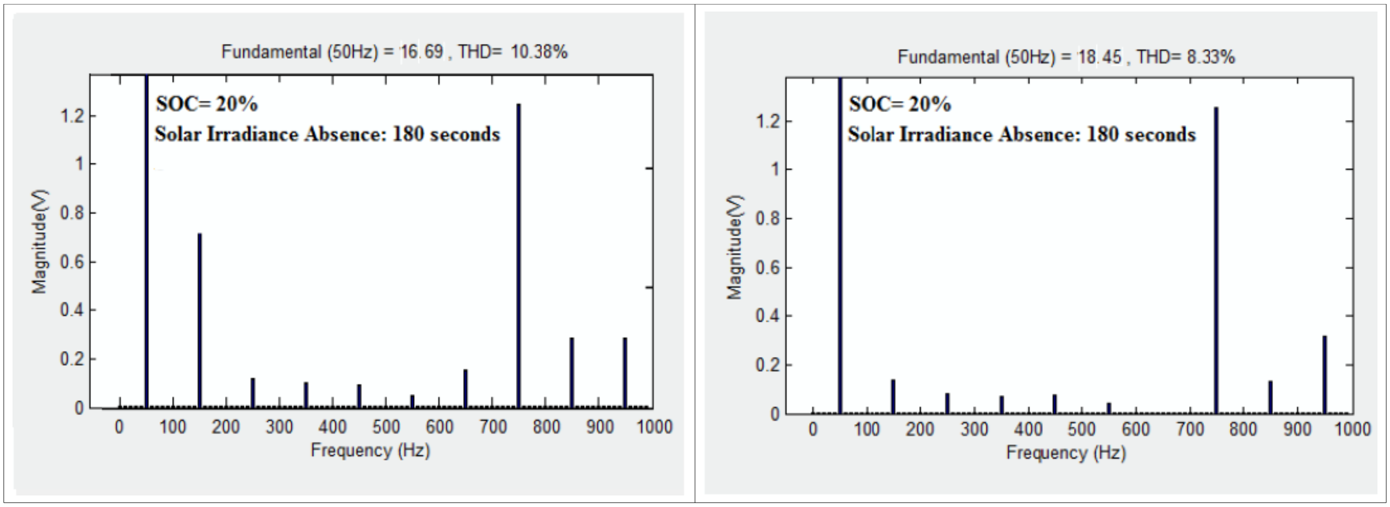


Fig. 7. Spectra of the AC output voltage of the AC PV-module, under very critical working conditions (180 seconds of solar irradiation absence and on-board batteries with SOC=20%), for both the unmodified inverter circuit operated with no "*swapping*" control technique (fig. on the left) and for the simplified inverter circuit operated with the "*swapping*" control technique (fig. on the right)

VII. CONCLUSIONS

In order to improve a recently introduced AC PV-Module, a simplified electrical topology for the on-board multilevel inverter has been introduced and discussed. With respect to the previously discussed cascade H-bridge multilevel inverter, the new topology presents a significantly reduced number of static switches; in this way, costs are significantly reduced, also improving the circuit reliability. Furthermore, a new control logic has been also introduced for driving the inverter static switches: a "d*uty-cycle swapping*" logic is utilized to guarantee a balanced charge/discharge of the on-board battery groups of the AC PV-module. This last feature is on the basis for a significant improvement of the quality of the power generated by the PV-module also in case of "long" solar irradiation absence. Numerical simulations operated by using the MATLAB/Simulink tool have confirmed the aforementioned advantages of the introduced simplified inverter circuit.

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