Renato Rizzo[1,*]

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Regular paper

An integrated power converter architecture for microgrids with renewable energy sources

The paper deals with structures that allow an intelligent power flows management between the household users, the electric distribution grid and the distributed generation units within microgrids. Power electronics provide the control and flexibility required by the microgrid concept. Correctly designed power electronics and controls insure that the microgrid can meet its customers as well as the utilities needs. In the paper a new high-efficiency integrated power converter architecture for systems with renewable energy sources, in particular photovoltaic, is proposed which structure has as core the new Double Level Boost converter – and also involves a couple of well-known power converter configurations (Buck-Boost converter, Asymmetrical Bridge Rectifier) in its functioning. The design and architecture of the converter are explained evidencing its effectiveness in terms of energy management.

Keywords: Microgrid; renewable energy sources; buck-boost converter; double level boost converter.

1. Introduction

The microgrid concept assumes a cluster of loads and microsources operating as a single controllable system that provides both power and heat to its local area. This concept provides a new paradigm for defining the operation of distributed generation.

To the utility the microgrid can be thought of as a controlled cell of the power system. For example this cell could be controlled as a single dispatchable load, which can respond in seconds to meet the needs of the transmission system. To the customer the microgrid can be designed to meet their special needs; such as, enhance local reliability, reduce feeder losses, support local voltages, provide increased efficiency through use waste heat, voltage sag correction or provide uninterruptible power supply functions to name a few.

The microsources of special interest for microgrids are small (<100 *kW*) units with power electronic interfaces. These sources typically renewables (microturbines, PV panels, and fuel cells) are placed at customer sites. They are low cost, low voltage and have high reliable with few emissions. Power electronics provide the control and flexibility required by the microgrid concept. Correctly designed power electronics and controls insure that the microgrid can meet its customers as well as the utilities needs.

As interest in renewable energy systems with various sources becomes greater than before, there is a growing need for integrated power converters that are capable of interfacing, and concurrently, controlling several power terminals with low cost and compact structure.

The development of structures that allow an intelligent power flows management between the household users, the electric distribution grid and the distributed generation units, represent the main goal to reach in the design of a integrated power conversion architectures.

In particular the most important features that must be guaranteed – through an appropriate structure and an optimal management of itself – are:

- Get as much power as possible from renewable generators – PV panels, wind micro-turbine, fuel cells – during favorable weather conditions and peaks of the grid, in

[*] Corresponding author: R. Rizzo, Department of Electrical Engineering University of Naples Federico II, Via Claudio 21, 8012 Naples, Italy, E-mail: renato.rizzo@unina.it
[1] University of Naples Federico II, Naples, Italy

order to assure a money saving for the consumer and at the same time an improvement in the functioning of the utility grid;

- Provide an alternative feeding sources for loads whenever the power provided by domestic generators is not enough to satisfy the users loads, maintaining the same level of user's comfort;
- Guarantee proper power quality requirements in order to achieve optimal operation conditions – for loads and the utility grid – and the highest efficiency possible.

To achieve configuration respectful of power structure requirements introduced, new architecture having more than one input or output port – known as *multiport converter*s – are developing. These kind of integrated architectures are capable to interfacing and manage several power sources and loads typologies.

Due to the advantages like low cost and compact structure, *multiport converters* are reported to be designed for various applications, such as achieving several bus voltages, in electric vehicles or hybrid electric vehicles [1-3], interfacing the PV panel and a battery in satellite platform power systems [4], PV energy harvesting with ac mains [5] or the battery backup [6], hybrid fuel cell and battery systems [7], [8], and hybrid ultracapacitor and battery systems [9].

From the topology point of view, multi input converters based on buck, boost, and buck–boost topologies have been largely used in [5,6]. Multiport converters are also constructed out of a multiwinding transformer based on half-bridge or full bridge topologies [1],[7]. They can meet isolation requirement and also have bidirectional capabilities. However, the major problem is that they use too many active switches, in addition to the bulky transformer, which cannot justify the unique features of low component count and compact structure for the integrated multiport converter.

An interesting solution for the dc distribution is represented by a new four-port-integrated dc/dc topology, which is suitable for various renewable energy harvesting applications [10]. This structure interfacing photovoltaic (PV) and wind sources, one bidirectional battery port, and an isolated output port. It can achieve maximum power-point tracking (MPPT) for both PV and wind power simultaneously or individually, while maintaining a regulated output voltage [11-13].

Figure 1 reports the configuration achieved. The four-port topology is derived based on the traditional two port half-bridge converter, which consists of two main switches S_1 and S_2. One more input power port can be obtained by adding a diode D_3 and an active switch S_3. Another bidirectional power path can be formed by adding a freewheeling branch across the transformer primary side, consisting of a diode D_4 and an active switch S_4. As a result, the topology ends up with four active switches and two diodes, plus the transformer and the rectification circuit.

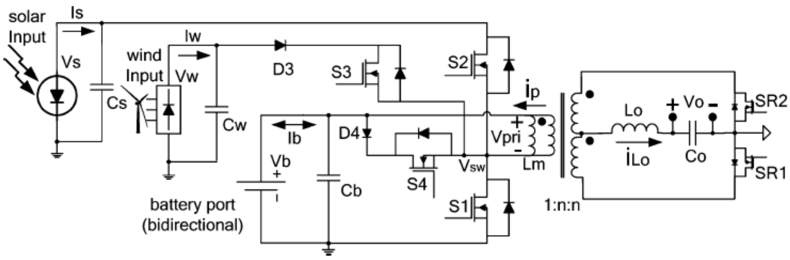

Fig. 1. Integrated four ports dc/dc converter architecture [9].

It should be noted that since the wind turbine normally generates a three phase ac power, an ac/dc rectifier needs to be installed before this four-port dc/dc interface and after the wind turbine output.

One of the criticality of this structure is represented by the lack of ac input ports useful to make possible a feeding to the loads from the utility grid whenever there is no power coming from the distributed renewable generators. Moreover, there are no possibilities to get one more dc output – with different voltage – maintaining the same number of components. An insulation transformer is also required by the structure.
A possible converter topology including photovoltaic and wind power and combining the function of the *grid-tie* system and *uninterruptible power supply* for critical load applications is reported in fig. 2. The system employs six-arms converter topology with three arms for the rectifier-inverter, one arm for battery charging/discharging and two arms for power conversion on the photovoltaic module and wind turbine generator [14]. The operation mode depends on the grid status, the various condition of photovoltaic, wind turbine generator and battery bank.

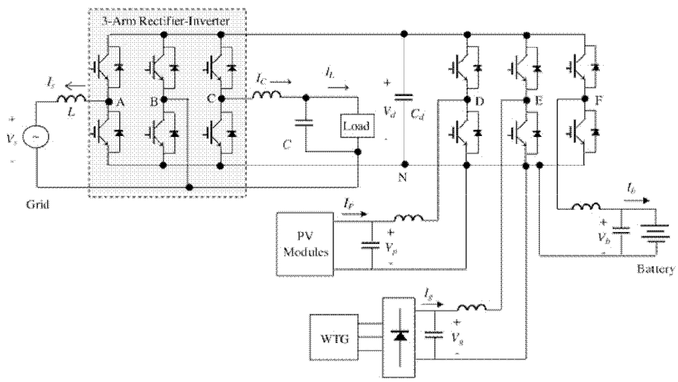

Fig. 2. System topology combining grid-tie and uninterruptible power supply function [14].

As shown in fig.2, the ABC arms constitute a common neutral line single-phase rectifier-inverter, whereas the DEF arms are, respectively, designed for the power conversions of photovoltaic PV, wind turbine generator WTG and the charging\discharging operation of the battery bank. In the grid-tie operating mode, the A-arm is used to regulate the dc-link voltage and ensure a unity power factor by controlling the current of the grid. As the grid failure has been detected the A-arm is not operated under the UPS operating mode. The C-arm is designed for inverter operation and controlled to provide the load a low distorted, sinusoidal voltage all the time. The PV and WTG, respectively, use the D-arm and E-arm to boost their terminal voltages up to the designed voltage level of the dc-link. The F-arm is utilized to control the charging of the battery bank in the grid-tie operation mode and it is used to regulate the dc-link voltage and allow the charging and discharging of the battery bank under the UPS operating mode.

The last topology permits an intelligent management of the power flows between the user system and utility grid, contemplating a wide range of solutions to assure constantly the optimal functioning of entire network. However the structure analyzed requires a large number of components – two active switches per arms – and complicated control algorithms.

3. The time-varying architecture concept

As seen previously the design of integrated power structure capable to achieve several converter functions required the use of a large number of components – switches in particular – that complicate the system and concurrently increases cost for its realization.

It is clear that such functions should be carefully defined in order to find an optimal trade-off between the complexities of the converter structure – due to the typology and quantity of converter functions required – and the advantages for the users and distribution grid.
Once defined and minimized the converter functions required – according to the features of system – the idea is to investigate if is possible to combine such converter functions into a smaller number of switches and passive components.
Important considerations can be done if we consider that the most of integrated converter structures are characterized by the non-contemporary necessity of different power converters functions.
This concept will be clearer considering as example a system having a photovoltaic generator. During the night hours there is no power coming from the photovoltaic generator that means in such hours photovoltaic converter – dc\dc or dc\ac depending on the typology of output required – is unused. In this condition it is possible to think of using photovoltaic converter to achieve a different power converter function, for example deliver power to loads using another source. Moreover, also its single components – switches and passives – could be used to realize a different power converter structure that improves the reliability of the system connecting other sources to the loads. This goal could be reached just changing few connections within the converter architecture: in this way savings in the realization cost of the structure and a topology simplification could be obtained.
Obviously as said before implies that switches used are compatible with more power converter functions – and the architecture to obtain such functions – in terms of typology and technical specifics required – e.g. switching frequency, repetitive peak current, collector to emitter breakdown voltage etc. Similar considerations can be done regarding passive components: compatibly with their characteristics also the passives can be used to achieve different power converter architectures, according to the converter function required.
This is the concept of components - sharing: it represents the starting point for the design of the proposed converter.
Moreover, the less number of switches permits to use – at the same cost of realization – higher quality switches. That means a double improvement in the efficiency of system: in fact reducing at the minimum the number of switches required, the number of commutations per period of the entire structure are reduced and due to faster-higher quality switches used, the losses in the commutations are lower.
Ultimately, an integrated power converter structure that changes its architecture to operate constantly in the optimal mode – depending on the power requested by loads, the weather conditions or TOD rates, etc – could be a feasible way to reach an higher efficiency united to a lower cost of the structure, reaching the targets set.

4. The Proposed Power Converter Integrated Architecture

The design targets have been defined starting from the study of the functionality required by a domestic electric system designed to operate in a possible future dc distribution system and having a dc distributed generation unit – as PV array – to produce *in loco* a share of energy required by the domestic users. A couple of dc bus – at different voltage levels – are used to deliver the power to the loads, supposed in dc according to a possible future scenario.

The system is conceived to use *in loco* all the energy produced. This choice takes in consideration the long distance between different load centers typical of some electric network. That means by the production and the complete use of the energy in the same area, is possible to avoid the huge losses share due to the energy transit on the grid. We only consider the flow of energy from the grid to the system whenever is necessary to deliver a certain *surplus* of power to the loads. In the design of the system is also considered a battery pack to absolve, in different operation conditions, the functions of storing device and UPS – uninterruptible power source – for privileged loads as lights, security system, etc. Obviously the amount of energy producible-storable depends on the size of the photovoltaic's and battery and on the stochastic events as weather conditions. As much is the energy available in loco as less is the participation of the grid in the feeding of the household loads.

The possible voltage levels of functioning of the structure are defined taking in consideration some technical aspects and safety requirement. The outputs voltage levels are defined considering the necessity to feed different kinds of loads. In fact it is reasonable think of an higher voltage dc bus to provide energy for heavy dc loads – household electrical appliances as oven, hairdryer, fridge –while a lower voltage dc bus provides energy to most consumer electronics – laptops, mobiles, televisions – and LED light fixtures. On the other hand a photovoltaic voltage output respectful of safety requirements for a domestic plant was hypothesized. Moreover, voltage levels obtainable from the utility grid – according to the standards – were considered in the design.

Table 1 : Voltage levels of the structure

INPUT VOLTAGE		OUPUT VOLTAGE
PV generator	40 V dc	48 V dc
Grid	240 V ac	190 V dc

According to the functions required, the sources considered and the operating voltage of the structure, a simple design for this system should involve several kind of basic converters - as boost, buck and rectifier converters - including at least ten power semiconductors, a certain number of gate driver circuits, and probably nearly as many passive component.

The *proposed integrated power converter architecture* presented in the following, was conceived keeping in mind considerations previously done and once analyzed a wide range of possible solutions. Its peculiarities and functioning will be discussed in detail.

The proposed structure – characterized by a time-varying architecture according to components-sharing concept – has as core the new *Double Level Boost* converter [15] – and also involves a couple of well-known power converter configurations – *Buck-Boost converter, Asymmetrical Bridge Rectifier* – in its functioning.

4.1 Architecture

The idea of using the same switches and passive components to absolve different operation modes is achieved through the structure of fig. 3. The structure proposed presents as power sources a photovoltaic panel, a battery and the electric ac utility grid. The static switches *PvON_OFF_1* and *PvON_OFF_2* ensure the connection and disconnection of the photovoltaic source to the converter. Through the switch *GridON_OFF* is possible to get power from the ac utility grid.

The battery is connected through the low voltage bus. The use of a battery stack is expected in order to store the energy during the production *surplus* of renewable generator or whenever is useful get low-cost energy from the grid. The energy stored will be delivered to the loads during the operation phases of the system in which is required to cover a gap of power requested or when an *UPS* for low voltage loads is required.

The topology includes different kinds of semiconductor devices. In particular, three fully controlled switches – S_1, S_2 and S_3 – and three uncontrolled switches – D_1, D_2 and D_3 – are used. The fully controlled switches suitable for a practical realization of the structure are

IGBT (Insulated Gate Bipolar Transistor). They are controlled through different logical according to the operation mode achieved.

The structure also involves passive components: the capacitors C_1 and C_2, the inductor L. An inductor L_f, part of the LC output rectifier filter, completes the power electronics structure.

The high and low voltage loads are modeled through proper resistors *R_HVload* and *R_LVload*: values are determined considering the possible amount of power requested by loads.

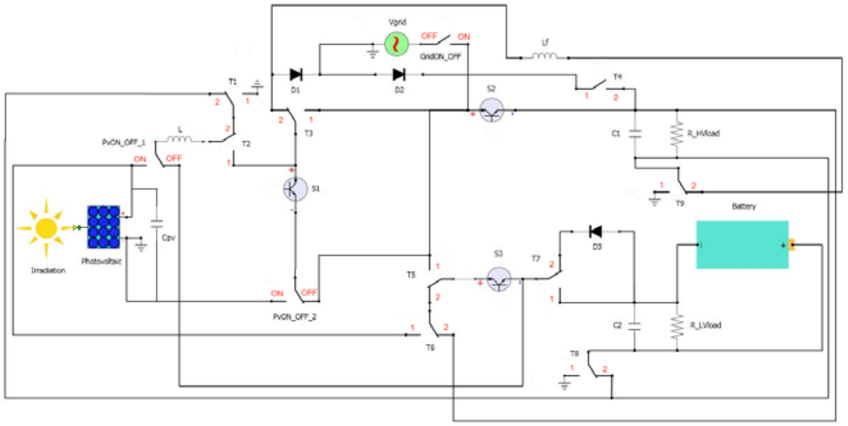

Fig. 3. Proposed Integrated Converter Topology.

Changing the connections between the components using simple transfer switches – *T-switch* – is possible to get different kinds of structures:

- *Double Level Boost*, to deliver the power coming from a lower voltage dc source – *photovoltaic generator* – to the loads *R_LVload* and *R_HVload*;
- *Boost-Rectifier,* in order to get a power share from the ac utility grid power when a *deficit* of production does not make possible to cover the entire load requests;
- *Buck-Rectifier*, in order to get the entire power requested from the ac utility grid when there is no power coming from renewable generator.

The different functioning modes are obtained setting each *T-switch* between the position 1 and 2. The *T-switch* status is not independent switch to switch but the commutation happens simultaneously for a defined group of switches: the most of transfer switches can be controlled with a common command signal that changes the state of a group of them in order to realize the desired converter architecture. Taking in consideration as said, a practice realization of this architecture may involve the use of electromechanical contactors or power transistor to achieve the transfer switch functions.

Ultimately, it is possible to achieve different power converter configurations depending on the converter function to realize. In the following the analysis of the energy strategy management and the configuration assumed by the system during the different mode, will make clearer the functioning and the peculiarity of the entire structure.

4.2 Energy management strategy

The architecture introduced in the previous paragraph was conceived taking in consideration the features required by a household system operating in a possible future scenario. The definition of an optimal management of the power flows into the system would represent a further validation of the proposed converter architecture. Will be shown that the structure features permit an energy management strategy that makes this configuration extremely useful in the range of household applications.

The management strategy definition involves any important factors as:

- *Amount of power produced by the photovoltaic generator* [$\mathbf{P_{GEN}}$];
- *Amount of power requested respectively by HV loads* [$\mathbf{P_{HV}}$] *and LV loads* [$\mathbf{P_{LV}}$];
- *Operating conditions of the utility grid and TOD rates*;
- *State of charge of battery and power available* [$\mathbf{P_{BATT}}$].

The management philosophy is based on a "sources hierarchy" that introduces a priority order in the using of energy. This priority order imposes to use – in the feeding of loads – firstly the energy produced from the renewable generator, then the storage system and, as last possibility, the energy coming from the utility grid. In this way the use of grid is limited as much as possible and concurrently, the amount of energy coming from the photovoltaic is always exploited first of all the others.

A priority order is also established regarding the loads: the typology of loads that could be connected to the low voltage output – lights, alarm systems, VoIP phones, internet routers etc – can be reasonably considered as priority loads because of their importance to ensure proper safety and security standards to the users. That is it why an uninterruptible power source function is provided – through a battery – to the low voltage load.

The functioning mode achieved by the proposed structure is substantially linked to the amount of power available to the input ports and the amount of power requested to the output ports of the converter. Hence, depending on these quantities, the converter assumes different architectures in response to the different situations that may occur. The possible cases are analyzed in the following.

➢ **CASE I: $\mathbf{P_{GEN} \geq P_{HV} + P_{LV}}$ - *Power entirely delivered from PV generator***

Photovoltaic generator provides a feeding to both loads; moreover through the LV bus, a surplus of power generated can be stored in the batteries pack. The structure works in *Double Level Boost Mode*. Utility grid is disconnected. Considering a photovoltaic panel as renewable generator, *case I* could occur during the sunny days of year.

Table 2 : Case I: Power entirely delivered from renewable generator

$\mathbf{P_{GEN} \geq P_{HV} + P_{LV}}$			
	PHOTOVOLTAIC	**GRID**	**BATTERY**
Status	*Producing*	*Disconnected*	*Charging if $P_{GEN} > P_{HV} + P_{LV}$*

➢ **CASE II: $\mathbf{P_{BATT}+P_{GEN} \geq P_{LV}+P_{HV}}$ *and* $\mathbf{P_{LV} < P_{GEN} < P_{HV}}$ - *Power entirely delivered from photovoltaic generator and battery***

The power coming from photovoltaic does not satisfy the request of both the loads. In such a case the battery could cover a share of power requested – through the low voltage loads feeding – as much significant as bigger is the difference $\mathbf{P_{GEN}}$ **-** ($\mathbf{P_{LV}+P_{HV}}$). If the difference between $\mathbf{P_{GEN}}$ and ($\mathbf{P_{LV}+P_{HV}}$) is small, the battery has to provide just a little share of the power requested whereas if such difference increases, the battery could be used to feed almost the entire low voltage load while almost all the energy coming from the photovoltaic is used by the high voltage loads. Anyway, this functioning mode implies that the sum of the power made available by the photovoltaic $\mathbf{P_{GEN}}$ and the battery $\mathbf{P_{BATT}}$ is at least equal to the power requested by loads. Vice versa a participation of grid is required. In the *case II* the structure still works in *Double Level Boost Mode*. Utility grid is still disconnected. *Case II* may happen during a partly cloudy day.

As said previously, *case I* and *II* implies the functioning of the proposed integrated power converter architecture in the *Double Level Boost mode.* The resulting architecture is shown in fig. 4.

Table 2 : Case II: Power entirely delivered from renewable generator and batteries

$P_{BATT}+P_{GEN} \geq P_{LV}+P_{HV}$ and $P_{LV}< P_{GEN}<P_{HV}$			
	PHOTOVOLTAIC	**GRID**	**BATTERY**
Status	*Producing*	*Connected*	*Discharging*

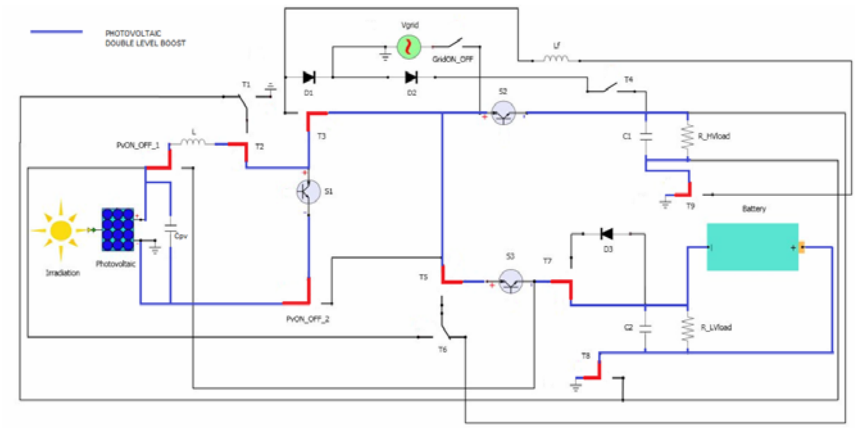

Fig. 4. Proposed Integrated Converter Topology: Double Level Boost mode.

The blue line of fig. 4 remarks the active path of the structure and the components involved during this mode. The thicker red line shows the connection achieved through the transfer switches. Starting from the fig. 3, table 3 underlines the status of each transfer switch. Not involved switches are indicated with *ni*.

Table 3 : Double Level Boost mode: transfer switches status

PvON_OFF_1	PvON_OFF_1	GridON_OFF	T1	T2	T3	T4	T5	T6	T7	T8	T9
ON	ON	OFF	*ni*	1	1	1	1	*ni*	1	1	1

- **CASE III: $P_{LV}<P_{BATT}+P_{GEN}< P_{HV}$ *and* $P_{GEN} \approx P_{LV}$ *- Power to LV loads delivered from photovoltaic generator/battery, power to HV loads delivered from utility grid***

If power coming from the photovoltaic $\mathbf{P_{GEN}}$ plus the one made available by the battery $\mathbf{P_{BATT}}$ is less than the power required, a participation of the grid in the feeding of loads is required. In such a case power coming from photovoltaic may cover approximately the low voltage loads request. Battery has the important function to guarantee the equilibrium between the power coming from the photovoltaic $\mathbf{P_{GEN}}$ and the power required by the low voltage loads $\mathbf{P_{LV}}$. It can provide or store energy respectively in cases of $\mathbf{P_{GEN}<P_{LV}}$ or $\mathbf{P_{GEN}>P_{LV}}$. Definitively, in such a case the grid provides the feeding to the high voltage loads while power coming from renewable generator is delivered to the low voltage loads through a simple Boost converter. Battery pack could cover a share of $\mathbf{P_{LV}}$ or storing energy. The structure works in *Boost-Rectifier Mode*. This situation may occur during a partly cloudy day or during a typical winter day.

The resulting architecture in *Boost-Rectifier Mode – case III* is shown in fig. 5.

Table 4 : Case III: Power to LV loads delivered from photovoltaic generator/battery, power to HV loads delivered from utility grid

$P_{LV}<P_{BATT}+P_{GEN}< P_{HV}$ and $P_{GEN} \approx P_{LV}$			
	PHOTOVOLTAIC	**GRID**	**BATTERY**
Status	*Producing*	*Connected*	*Discharging if $P_{GEN}<P_{LV}$* *Charging if $P_{GEN}>P_{LV}$*

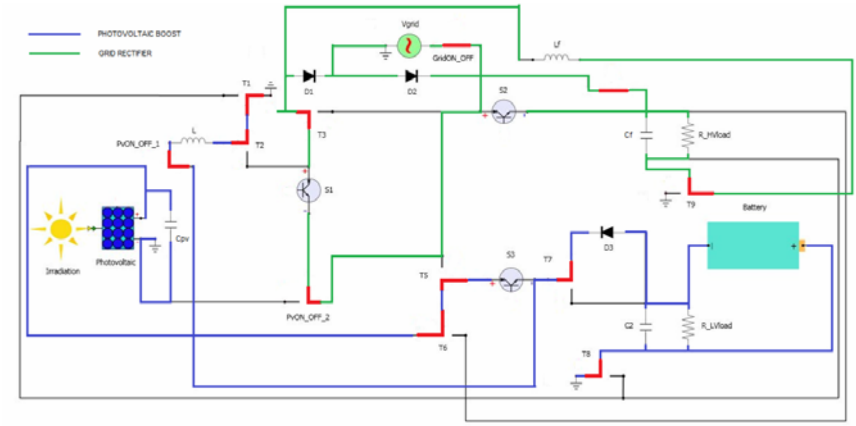

Fig. 5. Proposed Integrated Converter Topology: Boost-Rectifier Mode.

The blue line of fig. 5 remarks the *Boost* section of the structure and the components involved. Similarly, the green line remarks the *Rectifier* section. The thicker red line shows the connection achieved through the transfer switches. Starting from the fig. 3, table 5 underlines the status of each transfer switch.

Table 5 : Boost-Rectifier Mode: transfer switches status

PvON_OFF_1	**PvON_OFF_1**	**GridON_OFF**	**T1**	**T2**	**T3**	**T4**	**T5**	**T6**	**T7**	**T8**	**T9**
ON	ON	ON	1	2	2	2	2	1	2	1	2

➢ **CASE IV: $P_{GEN} = 0$ – *Power entirely delivered from utility grid***

There is no power coming from photovoltaic generator: both high and low voltage loads are fed by the power coming from utility grid. The structure works now in *Buck-Rectifier Mode*. Through the rectifier the grid feeds the high voltage loads while a Buck converter, connected to the high voltage output, step down the voltage in order to deliver the power also to the low voltage loads. In this situation the battery pack can be charged by grid.

This is a typical functioning of the system during the night: utility grid provide entirely the power requested and charge the batteries if necessary, during the low load - low rates hours of the day for the grid.

The resulting architecture in the *Buck-Rectifier Mode – case IV* is shown in fig. 6.

Table 6 : Case IV: Power delivered from utility grid

$P_{GEN} = 0$			
	PHOTOVOLTAIC	**GRID**	**BATTERY**
Status	*Diconnected*	*Connected*	*Charging*

Table 7 : Buck-Rectifier Mode: transfer switches status

PvON_OFF_1	**PvON_OFF_1**	**GridON_OFF**	**T1**	**T2**	**T3**	**T4**	**T5**	**T6**	**T7**	**T8**	**T9**
ON	OFF	ON	2	2	2	2	2	1	2	2	2

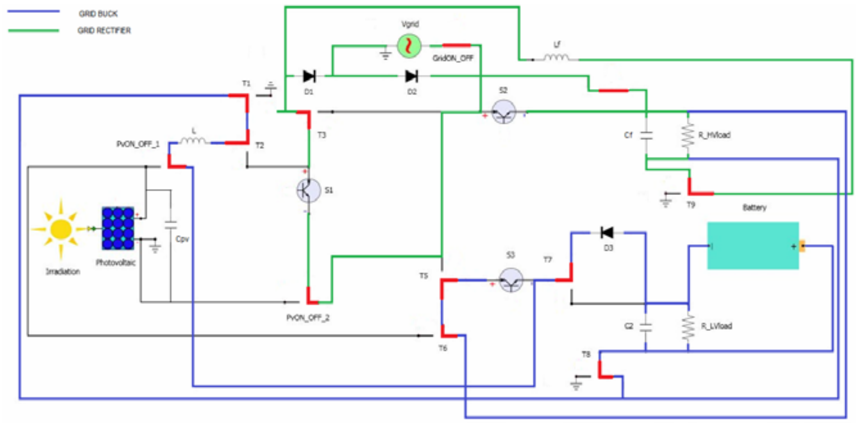

Fig. 6 – Proposed Integrated Converter Topology: Buck-Rectifier Mode.

The blue line of fig. 6 remarks the *Buck* section of the structure and the components involved. Similarly, the green line remarks the *Rectifier* section. The thicker red line shows the connection achieved through the transfer switches. Starting from the fig. 3, table 7 underlines the status of each transfer switch.

As previously said, the battery provides also an uninterruptible power source to the low voltage loads whenever there is no power coming from both the grid – black out events – and photovoltaic – no sun – sources.

The energy management strategy of the system is the starting point in the designs of an appropriate automatic control for the entire converter structure. The last aspect is an important future step in the development of the system.

5. Conclusion

Power electronics provide the control and flexibility required by the microgrid concept. Correct controls insure that the microgrid can meet its customers as well as the utilities designed power electronics needs. In the paper a new high-efficiency integrated power converter architecture for dc microgrid systems with renewable energy sources, in particular photovoltaic, has been presented which structure has as core the new Double Level Boost converter – and also involves a couple of well-known power converter configurations (Buck-Boost converter, Asymmetrical Bridge Rectifier) in its functioning. The design and architecture of the converter have been detailed evidencing the flexibility and correctness of the system. The proposed structures allow an intelligent power flows management between the household users, the electric distribution grid and the distributed generation units within microgrids. The analysis of the proposed solution evidenced its effectiveness in terms of energy management.

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