Review of Novel Topologies for PV Applications

Elena Makovenko[1,2(✉)], Oleksandr Husev[1,3], Carlos Roncero-Clemente[2],
and Enrique Romero-Cadaval[2]

[1] Department of Electrical Engineering, Tallinn University of Technology,
Ehitajate tee 5, 19086 Tallinn, Estonia
elena-makovenko@yandex.ru
[2] Power Electrical & Electronic System (PE&ES), University of Extremadura, Campus
Universitario, Avda. de Elvas s/n, Escuela de Ingenierías Industriales, Lab. C2.7,
06006 Badajoz, Spain
croncero@peandes.unex.es
[3] Department of Biomedical Radioelectronic Apparatus and Systems,
Chernihiv State Technological University, Shevchenko Street 95, Chernihiv 14027, Ukraine
oleksandr.husev@ieee.org

Abstract. Renewable energy capacity has been growing rapidly, exceeding
140 GW of installed power in solar Photovoltaic (PV) power generation. Along
with PV installations, the variety of applied power electronics topologies has also
increased, resulting in a key point of future Smart Grids, as long as they allow
new operation possibilities. This paper reviews the emerging topologies for PV
applications that could be used in the generation of new smart inverters. A partic-
ular focus is on impedance-source converters and naturally clamped solutions.
Pros and cons along with areas of application are summarized.

Keywords: Soft-switching inverters · Z-source inverters · Smart inverters · PV
power generation

1 Introduction

Today's development is towards alternative and Renewable Energy Sources (RES) such
as hydro, geothermal, wind and solar energy. These types of energy are of prime impor-
tance because of limited natural resources and the increasing concern about environ-
mental pollution. By use of RESs, consumer dependence on the main grid is lower and
they will not suffer from different types of perturbations such as voltage spikes, sags or
swells; at the same time, reliability is improved by an alternative supply in case of a
blackout in the main grid.

RES that are based on emerging integrated concepts, such as smart grids, smart meters
and smart buildings, are playing an important role in the modern world. They can be also
associated with Fuel Cell Vehicles (FCVs), which are transportation generation systems
with zero emission that reduce negative influence on the environment [1]. RESs are inte-
grated as Distributed Generation (DG), essential in a back-up electric power generating
unit. The presence of DG in industrial or public infrastructures (hospitals, shopping

centers) is very important, because when a grid blackout happens, DG will provide emergency power during that time. Also, home's DG can contribute to avoid or mitigate different negative effects caused by voltage sags or voltage swells. If some Energy Storage System (ESS) is present, it could support extra energy if the energy from RES is insufficient to supply the consumption. It can also store surplus energy if RES is producing more energy than the consumer requires.

Figure 1a shows the general functional structure of back-up DG, which contains the following blocks: RES (PV, fuel cell or wind turbine), bidirectional and unidirectional dc-dc converters to connect the RES and ESS to the constant dc-link voltage bus, the dc-ac converters to connect to the main grid for energy interchanges, and loads connected directly to the dc bus.
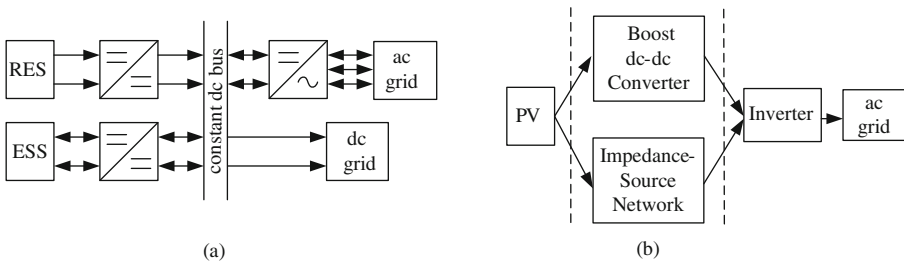

(a)   (b)

Fig. 1.   (a) Functional structure of general back-up DG [1]; (b) grid-connected solar converter.

In case of solar systems the proper design of converters and controllers is essential because the voltage and current characteristics of the PV modules are non-linear and depend on solar irradiance and temperature. The Maximum Power Point Tracking (MPPT) is not an easy task with typical PV modules and the Maximum Power Point (MPP) voltage in the range from 20 V to 50 V. The most simple is conventional Voltage Source Inverters (VSI) or Current Source Inverters (CSI), but they cannot provide very wide input voltage regulation range.

In case of wide input voltage regulation range is demanded the intermediate voltage boost dc-dc converters can be used. Figure 1b shows a generalized concept of the buck-boost dc-ac converter for PV application. The first one is two stage energy conversion that is based on the voltage boost dc-dc converter along with VSI [1]. These converters can use a High Frequency (HF) transformer, as they allow achieving high step-up ratio and provide galvanic isolation between the PV modules and the grid. Second is based on an intermediate Impedance-Source (IS) network. IS based converters are also being considered as good candidates since they are able to obtain an additional voltage boost by applying the shoot-through states.

The aim of this paper is to review the emerging converter topologies for PV applications. This overview is meant as a starting point of enabling technologies; further research will focus on the design of an advanced control algorithm for a selected converter, specifically on distorted, unbalance and unstable grid-connected applications, which would cover scenarios in future Smart Grids where distributed and RES and Cyber-Physical System (CPS) integrated within power electronic systems will be key factors.

2   Technological Innovation for Cyber-Physical Systems

New power grids need to migrate to a new Smart Grid where Information and Communication Technologies (ICT) and CPSs will be of higher importance. These new ICT facilities make it easier to move from centralized to distributed generation, allowing implementation of new benefits in a more optimized electric grid management, dividing the distribution grid in micro or even nano-grids, and giving back-up support. The success of this new grid paradigm will also be related to the correct use of a distributed energy resource, principally based on renewable resources, which should be controlled by ICT, thus the result will be a Cyber-Physical System (CPS).

The PV inverter is the key element in the grid integration of PV systems because it enables an efficient and flexible interconnection of different elements to the electric power system. The electronic control platforms integrated in these inverters usually have communication interface to send measurements and state variables and to receive operation set-points. At the same time, these control platforms have sufficiently free resources to be employed in the CPS used to optimize the whole electric system operation. For a long time, the function of the PV inverters was merely to inject power into the main grid with a unitary power factor as the control reference [2]; however, under new trends and policies, PV plants are integrated as active and smart devices. In this way, PV inverters are able to contribute to the local voltage support, to improve the power quality and to give rise to flexibility and supply reliability. Some of those new demands for inverters are power flow controls [3], voltage level restoration at the Point of Common Coupling (PCC) [3–5], active filtering capabilities [5], integration with energy storage systems [6], and communications compatibilities [7].

These new features of PV inverters require sensors, monitoring and data exchanging between different agents: electrical companies, producers and end-customers to make its integration in the Smart Grid possible. Concurrently, due to the high cost of solar energy (the cost of PV panels is $2.75/W in 2014 [8]), industry and researchers are aiming at cost reductions and enhanced performance of the energy conversion process, with a focus on the inverter topologies.

The first step here is to analyze the enabling technologies that are mainly focused on new advances topologies, to determine the control platform that can be used (in terms of sampling period related to the required switching frequency, number of magnitudes to be measured and number of switches to be controlled) and how many resources will be available for CPS implementation later.

3   Novel Impedance-Source Converters for PV Application

Today different types of the IS converters are available that can be applied to RES. Many papers cover this topic [9] and some authors provide good reviews of the state of the art [10–13]. All these types of converters have a common feature, they use an additional shoot-through (ST) state, which allows boosting the output voltage and enhancing the converter reliability. Hence, IS based inverters can buck-boost the output voltage in a single energy conversion stage, minimizing the number of components, increasing the

efficiency and reducing the cost [15]. IS network provides a second-order filter in their input side, which makes it more effective to suppress input voltage and current ripples. After the first publications of the Z-source inverter [9, 16], many other topologies have been proposed to overcome its drawbacks [15] (limited boost capability, discontinuous input current and high inrush current). The main goal of further research and development regarding IS networks is to reduce the inrush current, improve the input current profile, lower the components stress, and improve the boost capability using modulation techniques variations.

IS inverters can work in two operation modes according to the input current is continuous or discontinuous. They can be associated with transformers in order to boost the output voltage by proper selection of the turns-ratio. Figure 2 presents only three recently proposed IS networks that can be most suitable for PV applications: Trans-qZ-source inverter [17]; LCCT-Z-source Inverters [18]; L-Z-source inverters with two inductors [19].
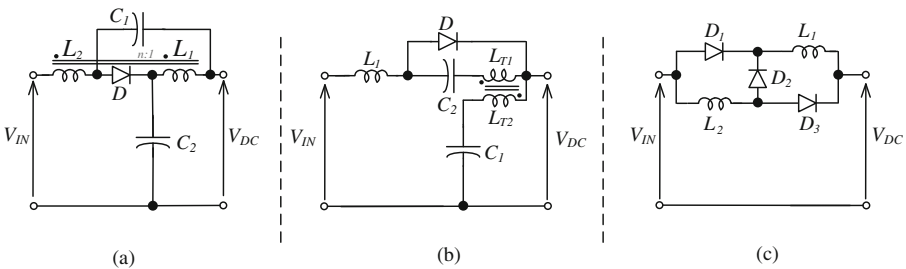

Fig. 2. (a) Trans-qZ-source inverter; (b) LCCT-qZ-source inverters; (c) L-Z-source inverters.

Table 1 summarizes the boost factor and ac voltage amplitude obtained with the discussed topologies. All these topologies operate in continuous mode, improving the Electromagnetic Inteferences (EMI) and allowing reduction of the size of the input filter and the stress of PV modules and an increase in their life-time.

Table 1. Boost factor and ac output voltage amplitude

Parameter	Trans-qZS	LCCT-ZSI	L-ZSI
Boost factor	$B = \frac{1}{1-(n+1)D_0}$	$B = \frac{1}{1-(1+\frac{n_{T1}}{n_{T2}})D_0}$	$B = \frac{1}{1-(2+\frac{1}{n_1-1})D_0}$
Ac voltage	$\hat{v}_{ac} = 0.5MV_{dc}$	$\hat{v}_{ac} = 0.5MV_{dc}$	$\hat{v}_{ac} = 0.5MV_{dc}$

Trans-qZ-source inverter can be used to obtain higher boost factors maintaining the voltage stress on the semiconductor devices. To reach better dc-link voltage utilization the higher turns-ratio should be used, which in turns requires higher isolation level between the windings, and producing an increase of the leakage inductance. This leakage inductance is connected in series with the inverter bridge, without any snubber circuit, so *di/dt* caused by the current switching of the windings produces large switch-voltage

spikes. Due to the tight coupling between the primary and secondary inductors, the voltage overshoot has an insignificant value. The effect on *dv/dt* is lower because of parasitic capacitance in the tightly coupled windings.

In LCCT-Z-source inverter topology, the transformer core does not reach the saturation due to the capacitors. They can operate in three different modes during active inverter states: in the first mode, all input currents are continuous; in the second mode, the first inductor current is continuous and that of the second inductor is discontinuous; and in the third mode, all input currents are discontinuous. The first mode is preferable because of better utilization of power devices that will reduce the conduction losses and the input current ripple. There is a higher turn ratio, higher boost factor and voltage stress on the capacitors. Nevertheless, if the turn ratio is more than one, the shoot-through duty cycle can be reduced to obtain the same output voltage. This topology guarantees stable inverter operation even at no load [18].

In the first and second IS networks, there are two capacitors that cause inrush current and voltage overshoot at startup. L-Z-source inverter with two inductors enables avoidance of the inrush current at startup and the resonance of Z-source between capacitors and inductors, providing also a ground path between the dc source and the inverter [19]. The increasing number of inductors raises the boost factor as well as the number of diodes, thus producing more losses. This topology does not suffer from voltage stress on the capacitor (as it has no snubber circuit) but requires that when working in discontinuous mode. 4 Novel soft-switching techniques for PV application. Soft-switching techniques are important in power electronics. These techniques allow reducing the losses in semiconductors and as a result, the switching frequency can be raised or the heat sink may shrink in size. They also help to reduce switching stresses (high voltage and current spikes) on the semiconductors during the turn-on and turn-off, increasing the Safe Operating Area (SOA) and reducing *di/dt* and *dv/dt* values responsible for EMI.

There are several ways to achieve soft-switching, such as a resonant circuit and active-clamping circuit. The converter should maintain the soft-switching capability in a wide range of input and output voltages. Also in IS converters where the shoot-through states are included, the soft-switching algorithm can be implemented as it is shown in paper [20].

3.1   Novel Naturally Clamped Topologies

Different types of topologies with naturally clamped commutated algorithm were proposed in the literature [21–24]. Several examples are shown in Fig. 3. Such topologies can be used as intermediate step-up dc-dc converters.

These novel naturally clamped topologies have the following features: Zero-Current Switching (ZCS) and Natural Voltage Clamping (NVC) that eliminate the need for active-clamping circuits or passive snubbers required to absorb surge voltage in conventional current-fed topologies. Switching losses are reduced significantly due to the ZCS of primary-side devices and the zero-voltage switching (ZVS) of secondary-side devices. Turn-on switching losses are also negligible in primary devices. Soft-switching and NVC are inherent and load independent. The voltage across primary-side devices is independent of duty cycle with varying input voltage and output power and clamped

at rather low reflected output voltage, enabling the use of semiconductor devices of low voltage rating [23]. They use a secondary-modulation technique that naturally clamps the voltage across the primary-side devices with zero-current commutation, avoiding the necessity of an active-clamping circuit or passive snubbers (as mentioned above). All of these topologies have a HF transformer with a high step-up ratio that also provides galvanic isolation.
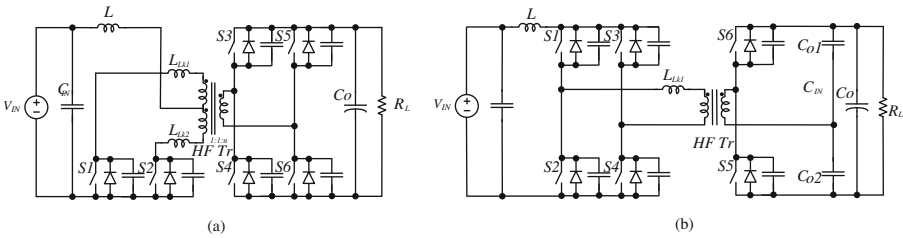

Fig. 3. (a) ZCS current-fed push-pull dc-dc converter [22]; (b) Soft-switching snubberless naturally clamped current-fed full-bridge front-end converter [23].

It should be mentioned that hard-switching of secondary switches leads to higher switching losses, which, however, are not so significant because this hard-switching occurs only four times by period. The losses are mainly due to the HF transformer, boost inductor, secondary diodes and switches [23]. These topologies were tested under different situations and the results showed that the stresses on the devices are increasing proportionally with the increasing output power [22–24]. All of these topologies exhibit high efficiency [21], but the value of the first one differs significantly from that of others, because the voltage across the primary switches is twice the value in other topologies. It can be concluded that naturally clamped topologies may be a suitable solution for use as part of a PV microinverter or a string single-phase PV inverter. At the same time, full soft-switching operation is not the case in these topologies, since the transistors on the secondary side have hard turn-on and off.

3.2   qZS dc-dc Converter with a Novel ZVS and ZCS Technique

Recently isolated qZS dc-dc converter with a novel ZVS and ZCS switching technique has been presented in [20]. Figure 4 shows this solution. The idea lies in the boundary conduction mode in the qZS network along with the snubber capacitors in the two out of four transistors and a special control algorithm implementation.

As a result, full soft-switching of the FB transistors without any auxiliary circuits is achieved. The main aim of the proposed idea lies in the elimination of the switching losses and resulting rise of the switching frequency, which turns in higher switching frequency with decreased value of the passive components and, consequently, also in a more compact design of the converter.
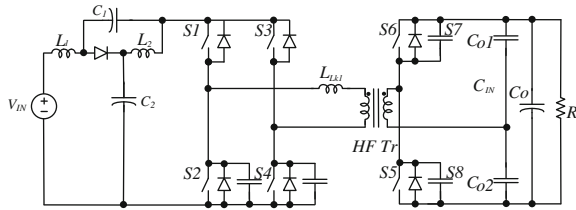
Fig. 4. Isolated dc-dc converter with full soft-switching based on the qZS network.

4   Conclusions and Further Work

This paper has reviewed novel topologies suitable for PV applications that have appeared recently. The main benefits of the discussed converters lie in the improved input voltage range regulation, possible decrease in the cost and size due to their benefits. The IS inverters possess several qualities that are also very interesting for PV applications, such as single-stage buck-boost operation capable of operation with a wide range of input voltage. In advance, the soft-switching algorithm can be implemented in the IS converters. Naturally clamped commutated converters have an ability to decrease switching losses, maintaining soft-switching in a wide range of the input and output voltage. Also, the topologies discussed are suitable for the Smart-Grid concept due to the possibility of the implementation of the advanced functions that can be controlled by using ICT. As a result, such kinds of converters are integrated to the CPS. Regarding the resources required for the control platform (and hence the free resources left for integrating these CPS functions), the advantage of the IS networks is that they need no dead-time control in one inverter branch as far as they can operate in ST states. The soft-switching topologies require a more complex modulation that consumes large amounts of control resources.

At the same time, it should be emphasized that none of the discussed topologies have been commercialized yet and they are under research and development. In the future work, these solutions should be tested to provide data for a comparative analysis between the topologies under development and those on the market.

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