

# Grid connected Converters for Photovoltaic, State of the Art, Ideas for Improvement of Transformerless Inverters

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**Abstract**—The paper presents a short overview of the state of the art for grid tied PV inverters at low and medium power level (1..100 kW), mainly intended for rooftop applications. The inverters are categorized according to the configuration of the PV system, the configuration of the conversion stages within the inverter and whether they use transformers or not [1], [3].

After the introduction of the state of the art of inverters for PV systems with and without transformers, the paper focuses on some known problems and challenges for transformerless inverters. Topologies without transformers have big advantages like low weight, volume and cost. In addition they often reach higher efficiencies than topologies with transformers. Therefore they are important for future developments.

## I. INTRODUCTION

Renewable energy sources become a more and more important contribution to the total energy consumed in the world. Because of their independence from limited fossil and nuclear fuels and their low impact on the environment they will become the only crisis-proof and reliable energy supply within the next decades.

Today the contribution from photovoltaic (PV) energy compared to the other renewable energy sources is very low, but due to decreasing system prices the market for PV systems is one of the most stable and fastest growing in the world. If this trend continues, PV will be one of the most important energy sources in the future. To maintain the further spread of PV systems it is important to decrease the cost and at the same time improve the efficiency and reliability of these systems. Valuable improvements can be made on the side of inverters for PV systems. These inverters account for approximately 15..25% of the system cost and are still a bottleneck for system reliability. Therefore it seems to be a well spent effort to have a close look at the inverters, their topologies and control.

## II. OVERVIEW AND STATE OF THE ART

If inverter and PV-generator are treated as a system, basically four different configurations can be identified. They are shown in figure 1.

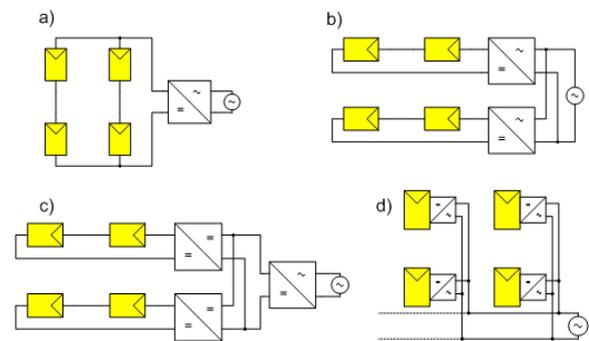


Fig. 1. Configurations for PV-systems

PV-modules are connected in combinations of series and parallel configurations to get a higher power level for the PV-system. Very common is a series connection of modules (the cells inside the modules are connected in series, too). The series connection of modules is called a string. The voltage of such a PV-string can be between 150 V and 1000 V for today's grid connected PV-systems. DC-voltages which are higher than the peak voltage of the grid (325 VDC for 230V-AC-grids) have the advantage, that the inverter does not need to step-up the voltage by a DC/DC-stage or a transformer. In this case often single-stage full-bridge inverters are used, which can have a high efficiency.

The peak current which can be delivered by one string is determined by the size of the solar cells used in the modules. To achieve a higher system power several strings can be connected in parallel, like in the system shown in figure 1a. The resulting large PV-generator is connected to the input of a central inverter. This is why inverters for this configuration are called Central Inverter. In some papers [1] central inverters are described as the past of PV-systems. It is true, that this configuration has disadvantages especially for smaller rooftop applications, like mismatching losses between the modules or strings and missing individual Maximum-Power-Point-Tracking (MPPT) for each string. This leads to relatively

high forfeits in the energy gain from the system, when shading or different orientation of modules occurs. On the other hand this configuration has advantages like high inverter efficiency because of the higher power level in comparison to string-inverters, simplicity and low cost. Therefore central inverters are still the first choice for medium- and large scale PV-applications, where shading or different orientation of modules is avoided already at the planning stage and therefore plays no role (Solar Parks, large rooftop applications). Central inverters are mainly build with three-phase full-bridges (using IGBTs) and low-frequency transformers.

When the focus is on smaller applications, for instance on the roofs of private houses, the drawbacks of central inverters become more eminent. When a PV-generator is installed on an existing roof, in many cases the modules cannot be installed with the same orientation and are subject to different shading conditions during the day. For such applications the string inverter, shown in figure 1b is state of the art. This configuration does not have parallel connections of strings; instead smaller inverters for each string are used. By doing this, each string has its own MPPT, which means that all strings are completely independent from each other. So it is easy to build PV-systems even under constraints like different orientation of parts of the roof, difficult shading conditions or even various types or number of PV-modules. Of course, the modules of each string should be matched and operated under the same conditions because of the series connection within the string. A disadvantage of string-inverters in comparison to central inverters is the higher price per kW because of the rather low power level (1..5 kW) per unit. String inverters are build as single-phase inverters due to the low power level. A very common classic topology is the full-bridge with a low-frequency transformer on the AC-side for galvanic isolation. Newer developments are often build as transformerless inverters using special topologies, which are explained later in this paper.

A variation of the string-inverter is the multistring-inverter shown in figure 1c. Basically it is a string-inverter with two (or three) inputs, which provide independent MPPT. It has the advantage that the inverter can reach a higher power level than a string inverter without having to sacrifice the advantages of the string technology. A disadvantage is that the multistring-inverter always needs two power conversion stages to allow individual tracking at the inputs. This two-stage design leads to a smaller peak efficiency compared to a (single)-string inverter. On the other hand multistring inverters have often a very wide input voltage range (due to the additional DC/DC-stage) which gives the user big freedom in design of his PV-system. This is why multistring-inverters have a good acceptance. An example is the inverter SB5000TL from SMA. It has two input with a voltage range from 125 V to 550 V and a peak power of 5kW [10].

Even if the string- and multistring-inverters give more freedom in the design of a PV-system, the modules of one string still have to be matched and should be installed in the same orientation to achieve a high energy harvest. If the

individual MPPT is extended to the level of one PV-module alone, a logical solution on the inverter side is the module-inverter shown in figure 1d. These inverters are attached to only one PV-module. Because of the low power level, the devices can be small and be integrated into the housing or frame of the PV-module. The result is often called AC-module. As the name implies, these modules can simply be connected to the AC-grid. It is a big advantage that no DC-wiring is needed, because then all wiring of the PV-Generator can be done with normal installation material and the risk of electric arcing and fire within the DC-wiring is minimized. In spite of these advantages the module integrated inverter has still a low acceptance. This is due to several disadvantages: The low power level per unit leads to a low efficiency and high costs, which in most applications cannot be compensated by the better MPPT for each module. In addition the packaging of PV-module and inverter to one device leads to the need for equal lifetimes of module and inverter. Current inverter technology does not reach the lifetime of PV-modules (20 years and more), therefore the bundling of inverter and module often leads to a failure of a valuable PV-module [1], [8]. When the lifetime problem is solved, module integrated inverters could get very interesting because of their straightforwardness in use and installation. If they enter mass production even the higher price due to the small power per device could be compensated.

### III. FUNCTIONAL BLOCKS AND TOPOLOGIES OF PV-INVERTERS

To get a better understanding of the needs, constraints and possibilities of topologies for PV-inverters, it is very helpful to use an analytical approach similar to the one proposed in [1]. When the focus is on the power electronic functions of a PV-inverter and all additional features like communication, monitoring, and safety functions are ignored, five basic functions can be identified for all PV-inverters:

- 1) *MPPT for the DC-input*: The inverter controls the DC-voltage in order to operate the PV-modules at their maximum power point. The MPP varies with the insolation, the module temperature and the shading conditions. Therefore sophisticated tracking algorithms are used. For good efficiency of the MPPT it is important that not only the mean values of voltage and current of the module are tracked to the MPP, but also the behavior at higher frequencies has to be considered. If the power electronic topology of the inverter introduces a voltage ripple at the PV-terminals, that ripple has to be kept small. Otherwise the operating point of the PV-generator would not stay stable in the MPP at all times. Most state of the art string-inverters use a one-stage topology (for example a full-bridge), in which the DC-link is directly connected to the PV-input. By controlling the grid current (and thus the power delivered to the grid) the DC-link voltage can be influenced. But also topologies with a separate DC/DC-stage for MPPT can be found.

- 2) *Change of the voltage amplitude*: If the PV-inverter uses a voltage sourced inverter (VSI) as a grid interface, this inverter has a buck-characteristic. This means that its output voltage is always smaller than the input voltage. If the PV-system delivers a voltage that is smaller than the peak value of the grid voltage, a voltage boost is needed. This can be done with use of a transformer or by a DC/DC-stage (e.g. boost converter).
- 3) *Grid interface*: This is the main function block of the inverter. Most common is the use of a VSI. It can be build as a standard full-bridge for inverters with a transformer at the AC-side. For transformerless inverters other topologies (NPC, H5, HERIC, will be explained later) are used.
- 4) *Power decoupling between DC- and AC-side*: The power fluctuations between DC- and AC-side of the inverter (switching frequency and double the grid frequency for single-phase inverters) have to be decoupled by an energy storage. Most common are electrolytic capacitors forming a DC-link. Because the minimization of the DC-link-capacity seems to be essential to achieve higher inverter lifetimes (film-capacitors could be used) a trend to 3-phase-inverters can be expected even for smaller power levels within the 1..5 kW range [8], [4].
- 5) *Galvanic isolation between input and output*: Can be achieved by the use of transformers. Classically transformers operated at grid-frequency are used, which have severe drawbacks like high weight, high cost, additional losses and a non-unity power factor, especially under low load conditions. New developments use high-frequency transformers. A third solution is to leave out the transformer and the isolation between input and output of the inverters. The resulting transformerless inverters have very high efficiencies, a low weight and have lower costs. The commercial inverter SMC8000TL from SMA reaches a peak efficiency of 98% [10]. Transformerless inverters will be discussed in more detail later.

To illustrate that these five basic functions can be identified for every PV-inverter, figure 2 shows block diagrams of two different inverters. The multistring-inverter in figure 2a uses two DC/DC-converters to interface the DC-link to two independent DC-inputs. The grid-interface is a transformerless type. The MPPT and the change of voltage amplitude is done by the DC/DC-converters. The DC-link between the DC/DC- and the DC/AC-stage is used for power decoupling. The inverter does not have galvanic isolation between input and output.

In figure 2b a classic string inverter is shown. It consists of a DC-link, a fullbridge inverter and a transformer operated at grid-frequency. The transformer accomplishes voltage change and isolation, while the MPPT is taken over by the inverter-bridge. By the control of the AC-current the power that is fed into the grid is controlled. When the power fed into the grid is changed at a constant DC-power, the DC-link is charged or discharged, thus changing the voltage at the terminals of the

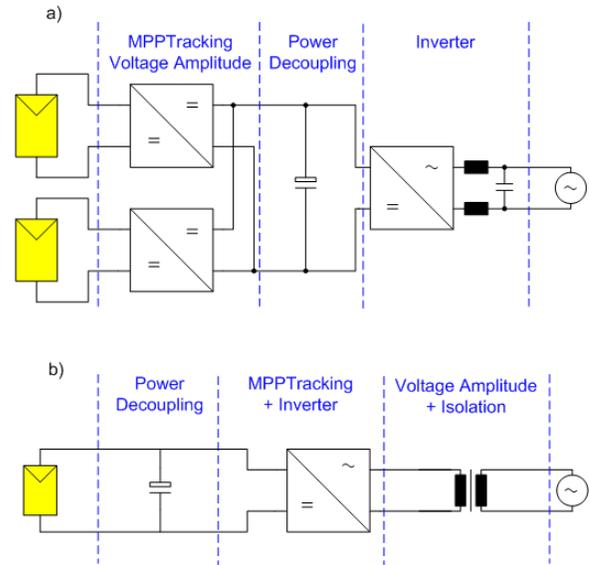


Fig. 2. Examples for Building Blocks of Inverters

PV-generator. The DC-link (power-decoupling) is connected in parallel to the PV-generator. Since the DC-link voltage directly equals the voltage at the PV-generator, the voltage ripple has to be kept small to achieve a good MPPT. This means that the DC-link capacity of this topology has to be high. Values around 0,5 mF/kW are used commonly.

#### IV. TRANSFORMERLESS TOPOLOGIES

##### A. Introduction

As mentioned above, transformerless topologies for PV-inverters are an upcoming technology. This is due to the fact that transformers operated at grid frequency are bulky and expensive and produce losses. In addition the transformer limits the freedom to control the grid current of the inverter. Especially at low load the reactive power used for the magnetization of the transformer leads to a lower power factor.

One way to omit the bulky transformer is to operate at higher frequencies. Topologies with HF-transformers are a good solution when galvanic isolation is necessary. At the moment this is the case in countries where the safety standards for PV-systems do not yet cover transformerless topologies. One example is the UL-standard UL1741 [11] which is valid in the USA. HF-inverters are often realized as resonant topologies with zero-voltage- or zero-current-switching to achieve low losses.

Whenever galvanic isolation is not important, transformerless PV-inverters get more interesting: They use simpler topologies, have higher efficiencies and are cheaper. That is why my main focus is on these topologies.

##### B. Transformerless Topologies, Constraints due to System Grounding, Ground leakage Currents

One of the most important aspects when considering topologies for transformerless inverters is, that a single-phase inverter is system grounded at the AC-side. This is due to the fact that

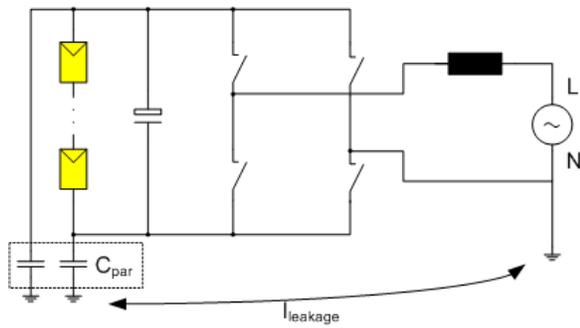


Fig. 3. Full-bridge with one inductor

the N-conductor of the grid is connected to earth at some point (potential equalization) in all TN- and TT-grids.

In addition to the grounding at the AC-side a grounding of the DC-side can also occur. One possibility is system grounding of the positive or the negative terminal. The other possibility which has to be taken into account is, that a PV-generator without system grounding forms a parasitic capacity against earth. This capacity can reach considerable values, because of the big area of the generator, the grounded frames (equipment grounding) and conducting water or dirt layers on top of the modules. So even an ungrounded PV-generator has some parasitic connection to ground, which can be a path for undesired HF-currents.

The result is, that the earth-ground has to be considered as a current path. Due to safety and EMC aspects the currents flowing through earth have to be limited.

Another aspect of the ground-leakage currents is an effect observed for thin-film-PV-modules. It is reported, that when thin-film-modules are exposed to high ground leakage currents, they suffer an excessive degradation, thus losing their efficiency irreversibly. It is difficult to find information or publications on this topic, but since thin-film-technology is upcoming and promising a cheaper and more energy efficient production of solar modules, this effect should be kept in mind. If a well working combination of thin-film-modules and transformerless inverters can be found, this could be important for the future PV-market.

For explanation of the leakage current problem figure 3 shows a single-phase full-bridge converter with one inductor in the L-conductor. When switching, this topology connects in turns the positive and the negative DC-terminal with the N-conductor, which is grounded. That means that the potential of the generator terminals is jumping with respect to ground at the switching frequency. This leads to excessive leakage currents flowing through the parasitic capacity of the PV-generator. The leakage currents exceed the limits given in the standards already at small system power for this topology. Due to the high ground currents (which are common mode) the common mode chokes in the EMI-filters are easily saturated, leading to big troubles with EMC.

In figures 4 and 5 two more promising topologies with system grounding on the DC-side are presented. Both of them

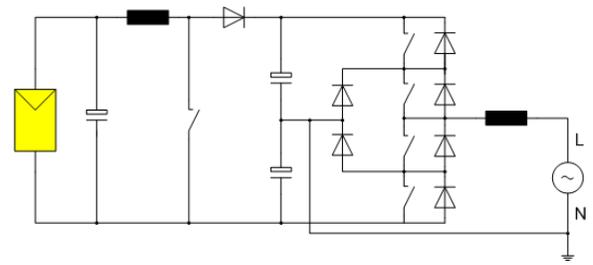


Fig. 4. Grounded three-level-bridge

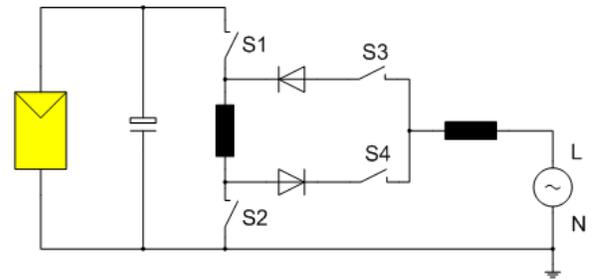


Fig. 5. Karschny-topology

are commercially available. The hard grounding of the DC-side prevents the flow of leakage currents.

One of them is the grounded three-level-bridge. The circuit shown in the figure also contains a boost converter for voltage change. Because the middle of the DC-link is connected to ground, the potential of the PV-generator is fixed independently of the switching state of the bridge.

In the Karschny topology in figure 5 the minus terminal of the PV-generator is grounded. Switches S1 and S2 are operated with HF, S3 and S4 are switched with the grid frequency.

Another possibility to prevent a fluctuating potential of the PV-generator is to disconnect to DC-side from the AC-side during the freewheeling periods of the inverter. Two patented topologies use this idea: HERIC (Highly Efficient and Reliable Inverter Concept) [6] and the H5-topology [5]. Both base on the standard full-bridge. The HERIC-topology, shown in figure 6 introduces a combination of two switches and diodes in parallel to the grid. They are operated at grid-frequency and form a new free-wheeling path. During free-wheeling the switches of the full-bridge can be open, thus disconnecting DC- and AC-side.

The H5-Topology [5] shown in figure 7 only needs one more switch compared to the normal full bridge. The switches S5, S2 and S4 are operated at high frequency, S1 and S3 at grid frequency. During free-wheeling S5 is open, disconnecting DC- and AC-side. The free-wheeling-path is closed via S1 and the inverse diode of S3 for positive and S3 and the Diode of S1 for negative current. Compared to HERIC, H5 has the advantage of using less components while HERIC uses less switches in series on the other hand. A closer explanation of the topologies is given in [4].

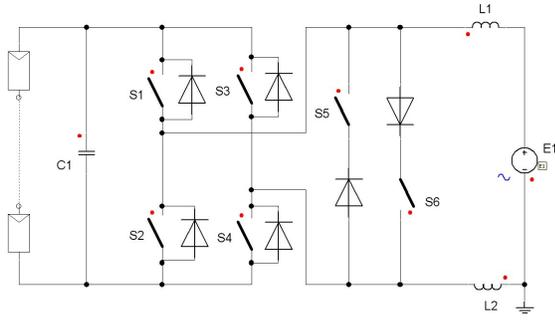


Fig. 6. HERIC-topology

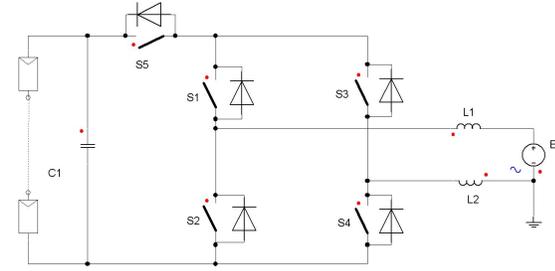


Fig. 7. H5-topology

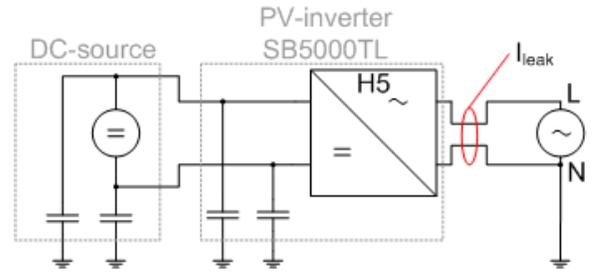


Fig. 8. Setup for measurement of leakage current

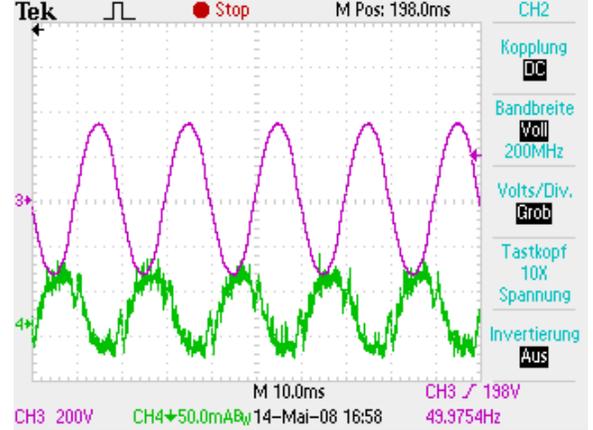


Fig. 9. Leakage currents H5-topology

### C. Safety

Because the PV-generator is not isolated from the grid when using a transformerless inverter, isolation faults at the PV-generator or the DC-wiring can get a safety hazard for persons touching the equipment.

For this reason transformerless inverters are equipped with Residual Current Devices (RCD), which monitor the ground leakage current during operation. When a dangerous leakage current is recognized, the inverter is disconnected from the AC-grid immediately. In addition most inverters measure the insulation resistance of the PV-generator before connecting to the grid and go into operation only, when sufficient isolation resistance is detected. The electromechanical relays, which are used to connect the AC-side of the inverter to the grid are designed fault tolerant, i.e. the inverter can still be disconnected safely, even if one relay does not disconnect due to a failure. (The standard solution is to connect two relays in series for both, the L- and the N-conductor.)

RCD, measurement of isolation resistance and the failure safe design of the grid connection unit incorporate a high safety level for transformerless inverters. Relevant standards are [11], [13] and [12], which is currently a draft.

### D. Measurement

As a first experiment to get some knowledge about the leakage currents of modern transformerless topologies, the leakage currents of an inverter using the H5 technology is measured. The setup is shown in figure 8. Instead of a PV-generator a switch-mode-DC-supply is used for simplicity. The leakage current in this setup is determined by the capacity

between the DC-terminals and earth. The main contribution to this capacity are the EMI-Y-capacitors in the EMI-filters of both, the DC-supply and the inverter. Together, the capacity of the DC-part of the setup against earth is approximately 500 nF. In an actual system this capacity would be determined by the PV-generator. The leakage current is measured with a current probe, which is put around the AC-connections of the inverter, as shown in figure 8.

The result for 180 V and 15 A in each of the two strings is shown in figure 9. Channel 3 shows the grid voltage and Channel 4 the leakage current. It can be seen, that it has a small HF-component, the main part is a 50 Hz current.

## V. CONCLUSION

PV-systems offer a wide range of possibilities and configurations for the use of power electronic converters. An overview over technologies and transformerless topologies is given and the technology is presented as promising for the future. In addition some problems from the application side are given. Future work will be to compare the transformerless topologies with special respect to the induced ground-leakage currents by simulation and measurements on an experimental setup. Experimental measurements are important, because parasitic effects, which are difficult to understand only by simulation, play a role for the paths of the leakage currents at higher frequencies.

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