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Inverters for photovoltaic systems – comparative analysis

***Abstract**. The paper contains a descriptions of selected topologies of inverters dedicated to work with photovoltaic panels. Also a comparative analysis of the described circuit, including an efficiency. Paper also presents a relatively new solution that has the potential for industrial implementation.*

Streszczenie.** W artykule przedstawiono wybrane topologie falowników dedykowanych do współpracy z panelami fotowoltaicznymi. Dokonano analizy porównawczej opisywanych rozwiązań z uwzględnieniem sprawności falowników. Przedstawiono również stosunkowo nowe rozwiązanie, które ma potencjał do przemysłowego wdrożenia. **Wybrane topologie falowników dedykowanych do współpracy z panelami fotowoltaicznymi

Keywords: photovoltaic, converters, PV Inverters
Słowa kluczowe: fotowoltaika, przekształtniki, falowniki, instalacje fotowoltaiczne

Introduction

Growing number of photovoltaic (PV) installations is a good market for inverters which should have function of tracking the maximum power point (MPP) of PV, high efficiency and generate low level of output voltage/current distortion. There are many different topologies of inverters for photovoltaic systems. To increase the efficiency of converters a SiC or GaN semiconductors can be used [1]. Also a better materials for HF transformer e.g. litz wires instead of single wires or nanocrystalline magnetic materials. In this paper a comparison of different topologies of power converters is done.

Review of PV inverters

There are different groups of PV inverters, which are shown in Fig. 1 [2,3]. The most popular are inverters shown as Type B and C in Fig. 1, where there are one inverter and one or more Maximum Power Point Trackers (MPPT). This type of PV systems can be found in a domestic and small commercial applications. In type C every MPPT (a DC/DC converter) is connected to one string of PV modules so every PV strings can work in different conditions separately (e.g. can have different space orientations).

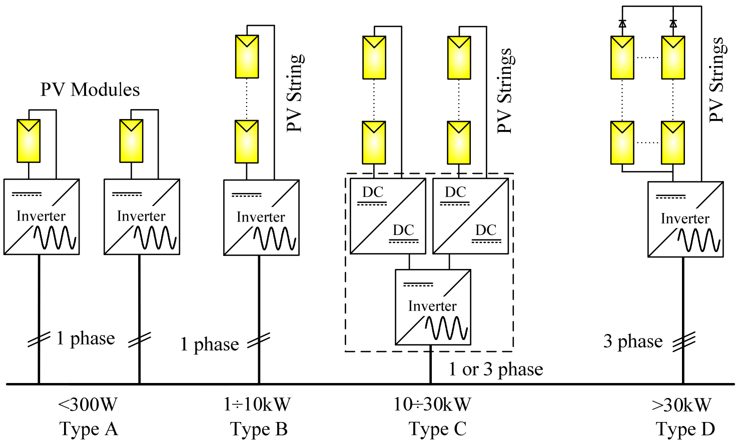

Fig. 1. Grid-connected PV systems: module inverter (Type A), string inverter (Type B), multi-string inverter (Type C) and central inverter (Type D).

Individual inverters for each PV panel (type A in Fig. 1) are used for small installations where PV modules can have different work conditions (different technology of PVs or solar exposure conditions). This solution is very flexible, very easy in expansion and allows to work in MPP for every module in PV system separately. However, it is less popular due to a high installation cost and relatively small efficiency. One central inverter which has connected with more than 2 strings to one input (type D) is used for large scale PV plants where all PV strings has the same parameters and the same solar exposure conditions (in that case every PV module has MPP in the same point). To avoid equalizing currents each PV string should have additional diode connected in series. One central inverter has usual higher efficiency and is usually cheaper than in other solutions.

Usually due to a safety reasons and to reduce a leakage capacitance current it is recommended to keep galvanic separation between AC grid and PV panels. Galvanic separation can be done by Low Frequency (LF) transformer (50-60Hz), High Frequency (HF) transformer (with frequency higher than 20 kHz) or so-called: “floating capacitor” or “floating inductance” (where capacitor or inductance works as an energy accumulator and is periodically switched between energy source and a load). The last type of inverters are not popular due to safety reason (galvanic separation is done by resistance of transistors in non-conducting state). Inverters without transformer are usually very simply, has good efficiency and a relatively small volume. They are not very popular due to the safety reason, necessary to use an advanced filters of the output current and occurrence parasitic voltage between the ground and a surface of PV panels (which generate a leakage PE current). The main advantages and disadvantages of PV inverter variants which are on the market are depicted in Fig. 2.

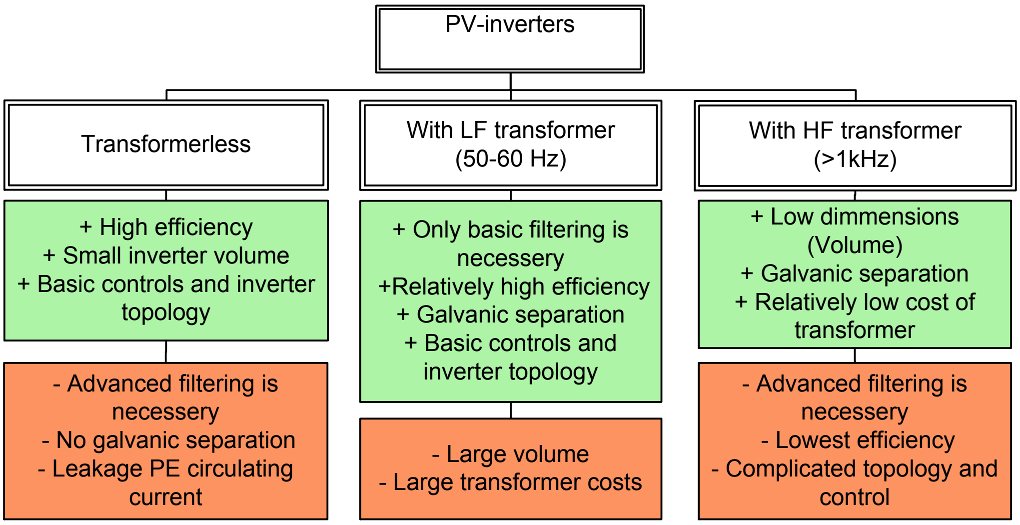

Fig. 2. Main features of different variants of inverters topology for PV installations.

Transformerless or LF transformer converters

PV inverters without galvanic separation and with LF (Low frequency) transformer are usually very simple - they have 50 Hz or 60 Hz inverter (Fig 3 a.) and can have LF transformer on output (Fig. 3 b.). The indicative efficiency which are written on the right side of figures refer to inverters made with standard silicone semiconductors.

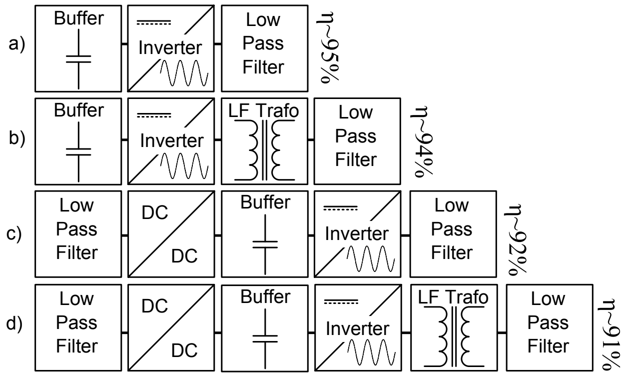

Fig. 3. Different solutions of PV inverters without transformer (a, b) and with LF transformer (c, d).

PV inverters can have an non-isolated DC/DC converter with is used for matching the levels of voltages between PVs and DC bus of a inverter (Fig. 3 c. and d.). An example of commercial PV inverter with non-isolated DC/DC converter is shown in Fig 4. On this topology a simple boost (step-up) converter is used to generate a half-sinusoidal waveforms on DC bus of inverter while inverter (T1 .. T4) is only changing the polarity of output waveform. Thanks to this solution transistors in inverter (T1 .. T4) works with low frequency while only transistor in DC/DC converter works with high frequency. If output voltage is momentary smaller than PV voltage, a DC/DC converter can be bypassed by an additional diode (dotted).

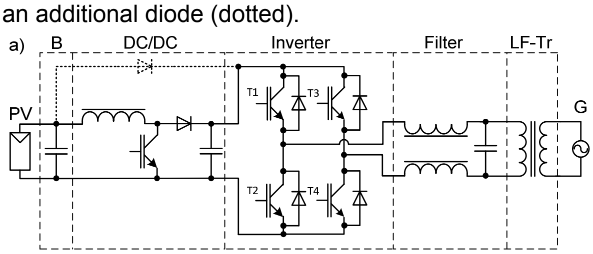

Fig. 4. An example of topologies with LF transformer that are on the market, where: B - Buffer, G - power grid, LF-Tr Low frequency transformer, PV - photovoltaic panels

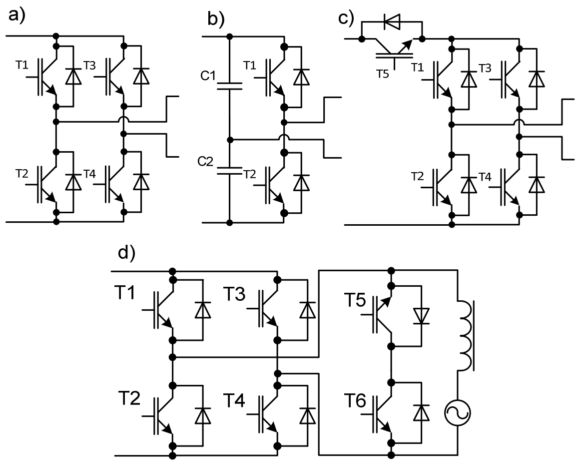

Fig. 5. Example of popular inverters: full-bridge (a), half-bridge (b), 5T bridge (c) and HERIC inverter (d)

Typical topology for inverters which are used in PV system are shown in Fig. 5 and Fig. 7 a. Full bridge or so call "H-bridge" (Fig 5 a.) is the most popular DC/AC converter – it can work as an voltage or current inverter with or without transformer. Half bridge (Fig. 5 b.) has usually higher efficiency than full bridge due to a lower number of semiconductors, but transistors works with two times higher current than in full bridge at the same output power, output voltage is twice times smaller and generated output voltage has to be symmetric to keep symmetric voltages on capacitors (C1 and C2). 5T bridge (Fig. 5 c.) can be used to decrease cost of inverter. Transistor T5 should have small switching loses because it is used to generate in PWM mode a half-sinusoidal waveforms. The others transistors (T1 .. T4) works as a switch to change the polarization of output voltage. This four transistors are switching with very low frequency (50 or 60 Hz) without voltage (0 voltage switching). HERIC topology of inverters (Fig. 5 d.) [4] is used mainly with inductive load. By switching on transistors T5 and T6 it is possible to force zero voltage on output and to reduce a reactive power exchange. All this circuits can be a part of a DC/DC converter with a HF transformer and rectifier or can be an output inverter to generate 50 Hz (60 Hz) sinusoidal waveforms.

Converters with HF transformer

They are numerous variants of PV inverters with HF (high frequency) transformer [5,6]. Fig. 6 presents an example of PV inverter which are on the market. This topology contain two inverters: first transfers energy by high frequency transformer and keeps PV in MPP, second inverter generates 50 Hz (60 Hz) sinusoid waveform of output current. The disadvantage of this family of PV inverters is a triple transformations of voltage waveforms (from DC to HF AC, from HF AC back to a DC and from DC to a LF AC) with result a relatively low efficiency (Fig 8 c.).

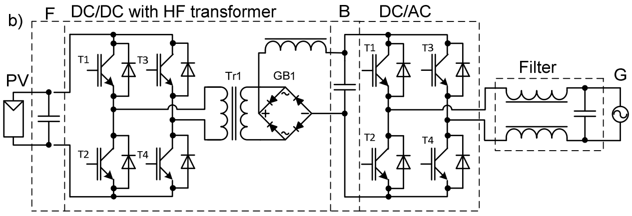

Fig. 6. An example of topology with HF transformer that is on the market, where: F - Low Pass Filter, B - Buffer, G - power grid, PV - photovoltaic panels, HF - high frequency

In order to decrease number of semiconductors an isolated single-transistor DC/DC converter can be used (Fig. 8 a.). An example of a Flyback or Forward converter with a HF transformer are showed in Fig. 7 a. and 7 b., respectively. Transistor T1 is used for generating 100/120 Hz half-sinusoidal voltage waveform while transistors T2 and T3 are used to choosing output voltage polarity. Switching frequency of T2 and T3 transistors is only 50/60 Hz.

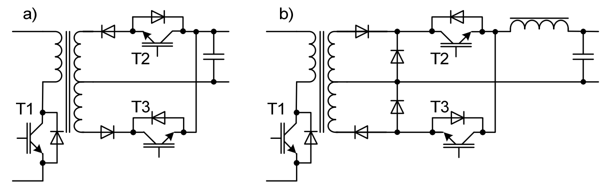

Fig. 7. a) Example of inverters based on Flyback (a), and Forward converter (b).

Other family of PV inverters with HF transformers is based on cycloconverters (Fig. 8 b. and 8 d.). In this type of PV inverters there is no voltage conversion back to DC.

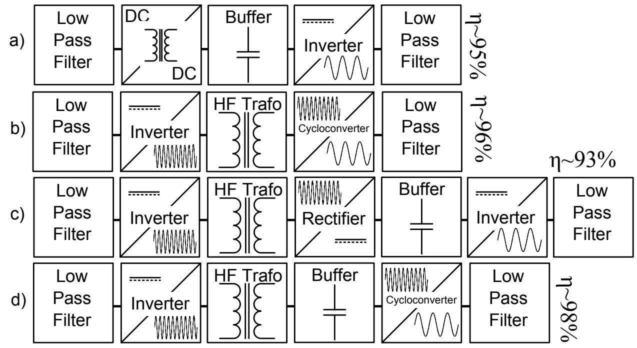

Fig. 8. Different variants of inverters topology for PV installations with HF transformers

The efficiency of PV inverters with HF transformers can be increased by a resonance circuit connected in series with a transformer. Resonance circuit in a natural way allow to switch off the transistors in zero-current moments which reduce the switching losses. Fig. 9 a. and b. are showed an example of resonant circuit in series with a primary and a secondary windings of a transformer, respectively.

Buffer

A common element of all PV inverter is a buffer which is necessary to keep PV power on constant level (1) while output power is periodically changing from zero to $2 \cdot P_{AV}$ (2) with double of the grid frequency [1]. To have constant flow of power in this family of inverters it is necessary to use an energy buffer (usually a capacitor). In that reason most popular topologies have a DC bus (e.g. Fig. 4, 6). Capacity of buffer should be enough big to storage a different of input and output energy, while power is changing according to (3).

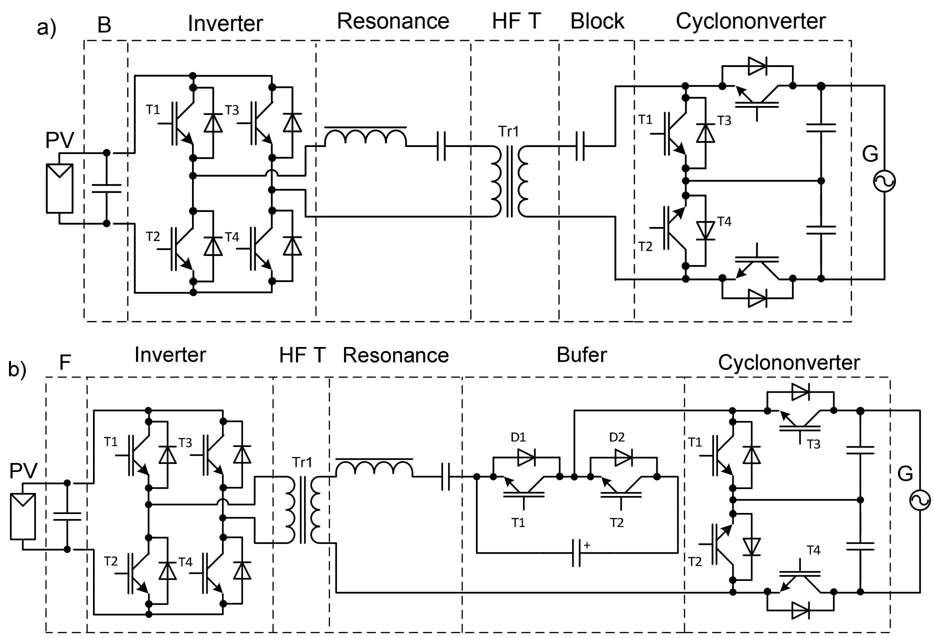

Fig. 9. An example of topologies with cycloconverter instead of AC/DC and DC/AC converters: without buffer (a) [7] and with a buffer (b) [1], where: F - Low Pass Filter, G - power grid, PV - photovoltaic panels, HF T - high frequency transformer, B – Buffer

(1) $P_{PV} = P_{AV}$

(2) $P_{Line} = P_{AV}\left(1-\cos(2\varpi t)\right)$

(3) $P_B = P_{PV} - P_{Line} = -P_{AV}\cos(2\varpi t)$

where: P_{AV} - average power on output of PV converter, P_B - power on buffer, P_{Line} - power developed to AC grid

Losses of energy conversion are neglected. If the buffer capacitor is connected in parallel to a converter its voltage is changing due to the following equation:

(4) $V_{BH}^2 - V_{BL}^2 = \frac{2P_B}{C_B f}$

where: V_{BH} *and* V_{BL} - upper and lower voltage on the buffer, respectively, P_B - power supplied to the buffer, C_B – capacitance of the buffer, f – grid frequency (50/60 Hz)

If a buffer is connected in parallel to a PV its capacitance C_B should be relatively big to reduce the level of voltage ripple on PV. If a buffer is connected between a DC/DC and DC/AC converters (like in Fig. 6.) its capacity can be smaller, because the voltage on capacitor can be changed in wide range - usually the only limitation is to keep a buffer voltage over the peak of output voltage V_{AC} and below withstand voltage of transistors.

A brand new idea is to connect buffer capacity in series as it is shown in Fig 9 b. [1]. in this case voltage of the buffer capacity can change in very wide range: from 0 to its maximum value. Thanks that a relatively small capacitor can be used. In this example a buffer capacitor *C* together with an inductance of series resonant circuit and semiconductors T1, D2 or T2, D1 form a step-up or a step-down converter, respectively.

Filters

All types of PV converters should have a low pass filter on input which is used to limit voltage and current deviations from MPP point. In simple converters role of a filter can be played by a buffer (e.g. Fig 4). If the first step of converter is working with higher frequency, a smaller filters is necessary.

To reduce level of higher harmonics in output currents and to reduce a current stress for semiconductor switch there are commonly used a low pass filters on the output of PV inverters. In many cases a leakage inductance and capacitance of low frequency transformer is enough to decrease a level of current higher harmonics by itself.

Conclusions

Inverters that have the highest efficiency have usually basic construction (like in Fig. 3 a.) or quite complicated topology with resonant circuit as are shown in Fig 8 b., d. Resonance converters are more complicated to control but on the other hand they allow to operate transistors in zero-current- or zero-voltage-switching mode what minimize a switching loses. Selection of the best converter topology should depend on maximum costs, requirements of galvanic separation, power of PV installation, input voltage, desired efficiency and maximum volume of PV converter.

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