High efficiency photovoltaic power conditioning system

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Abstract

A new topology for photovoltaic Power Conditioning System (PCS) with high efficiency under wide input voltage range of the photovoltaic array is introduced. In fact, this redundant topology consists of two new components, one for DC/DC converter and one for inverter. The presented topology of DC/DC converter enhances the efficiency by partial power sharing of DC/DC converters depending on input voltage. Producing a multi-output voltage convenient to the inverter topology. Simulation of a 25-kW PCS in terms of efficiency to verify the proposed topology.

1. Introduction and background

1.1. Introduction

Nowadays, the potential threat of global climate enforced, increasing energy demand and diminishing nonrenewable energy has resulted into the usage of renewable energy as alternative source of energy.

Among renewable energy sources, the solar energy is a clean, efficient and readily available energy. Investment in research and development for solar energy is increasing annually under the support of government to meet CO2 emission regulation [1], so Photovoltaic generated solar power is one of the most promising renewable energy sources in the world. Two main obstacles for using solar energy are the high initial capital costs and the conversion efficiency.

One of the most important types of PV installation is the grid connected power conditioning system (PCS) to increase the energy for many applications.

1.2. Background

Photovoltaic power conditioning grid-connected systems (PCS) convert the available direct current supplied by the PV panels and feed it into the utility grid. There are two main topology groups used in the case of grid-connected PV systems, namely, with and without galvanic isolation [2]. Galvanic isolation can be realized in the dc side in the form of a high-frequency (HF) transformer or on the grid side in the form of a bulky small-frequency (SF) transformer. Unfortunately the efficiency of the whole system is decreased due to power losses in these extra components. In case the transformer is omitted, the efficiency of the whole PV system can be increased by an extra 1%–2% [4]. The most important advantages of transformer-less (TL) PV systems are higher efficiency, lower size, weight and cost compared to the PV systems that have galvanic isolation (either on the dc or ac side) [3].

The European market is dominated by transformer-less types (80%), in Japan approx. 50% of the inverters are transformer-less, while in USA up to now mostly transformer based inverters are used due to national standards[4].

Figure 1 shows a block diagram of conventional photovoltaic power conditioning systems. They consist of an inverter, LP-filter and line transformer. The filter eliminates/attenuates the harmonics on produced by the inverter, the filter output is stepped up at the grid level by a low frequency transformer, e.g. PV-system are coupled to 11kV grid.

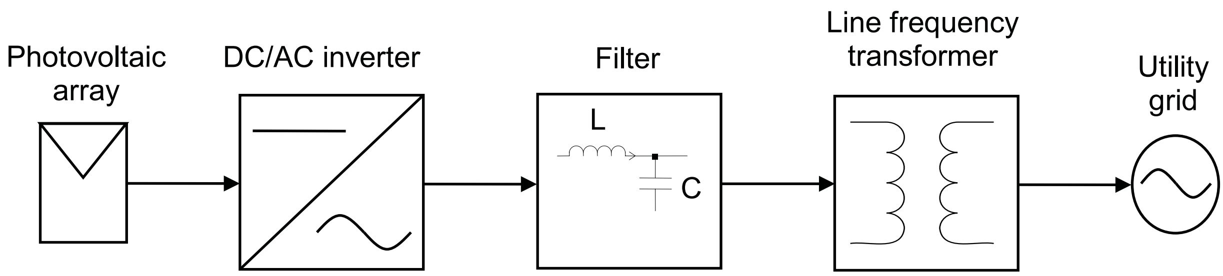

Fig. 1. PV PCS with line frequency transformer

Figure 2 schows a block diagram of a conventional isolated type photovoltaic power conditioning system. In this system, a DC/DC converter using a high frequency transformer converts a DC voltage delivered by the PV into a controlled DC voltage suitable for the inverter.

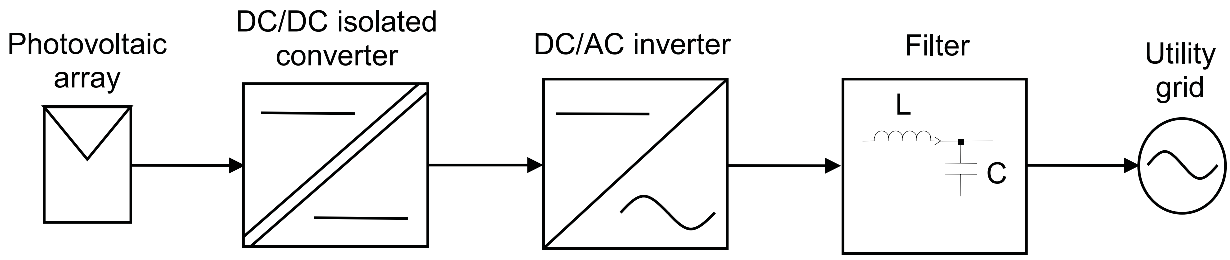

Fig. 2. PV PCS with high frequency transformer

Figure 3 shows a block diagram of a conventional non-isolated type photovoltaic power conditioning system. In this system, a DC/DC non-isolated converter receives the fluctuating DC voltage delivered by the PV and converts it into DC voltage suitable for the inverter.

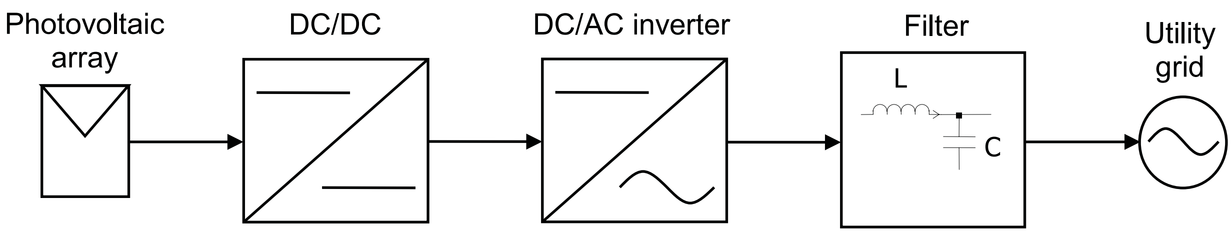

Fig. 3. Conventional non-isolated type PV PCS

All previous topologies[7] have a common problem: since the total capacity of the system they suffer of reduced efficiency. Due to the power ratings of the DC/DC converts (isolated and non-isolated) must be equal to the system power, these topologies can't be applied to a large power system.

2. Proposed solution

In this contribution a new PCS topology is presented in Fig. 4, to overcome the problem of the conventional PCS.

The proposed topology makes best use of photovoltaic characteristics exposed to a large of thermal conditions which has a wide voltage range according to the climatic circumstances, although this is a disadvantage, the proposed system can utilize this disadvantage and transforms it into a partially advantage. There is no need for DC/DC converter operation in case of sufficient voltage generated by the PV array for inverter, but the DC/DC converter is operated to compensate the lack of the input voltage for the inverter in case of the PV array generates insufficient voltage. Therefore the DC/DC converter is worked only for a small part of output power, where the dominant part will be delivered directly from the PV array to the inverter [7]. Also, a new topology of 5-level DC/AC inverter is proposed to enhance the decreasing of the power capacity of DC/DC converter and enhance the decreasing of the semiconductor power modules conduction and switching losses, therefore increasing the overall system efficiency.

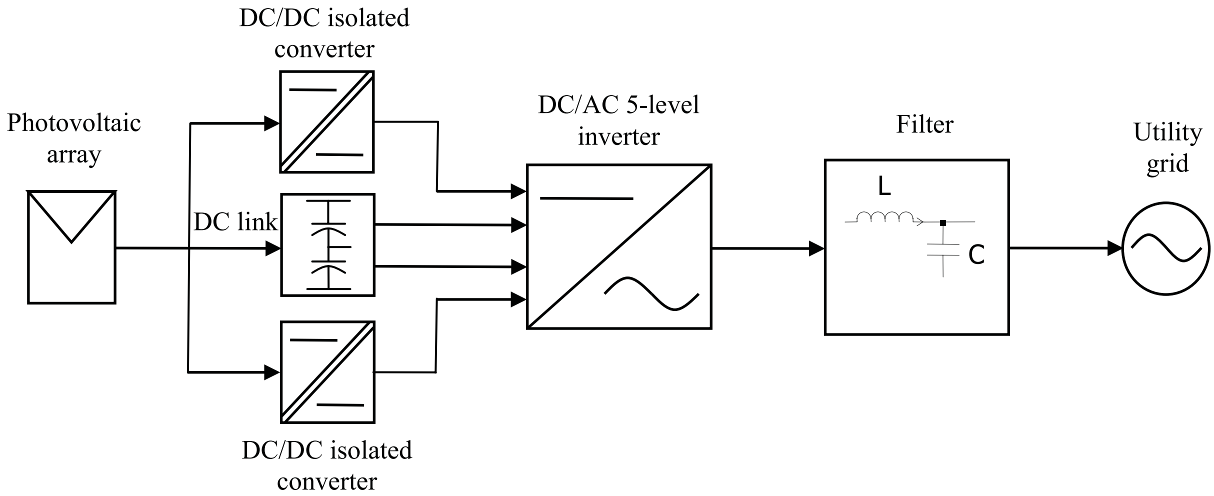

Fig. 4. Block diagram of the proposed grid-connected PCS

2.1. Photovoltaic characteristic

The output characteristic of a PV cell is largely affected by climatic circumstances, such as irradiation (G, W/m²) and the operating temperature (T, °C). Figure 5 shows the output characteristics of a PV array. On the one hand constant temperature, an increasing irradiation increased output power as well as slight increase of output voltage. On the other hand, at constant irradiation conditions, a decreased in temperature generates an output power increased as well as an increasing in output voltage. Fig. 5 shows that the output voltage of a PV array should be controlled to obtain maximum power from the PV module; we call it maximum power point tracking (MPPT) [5]. In order to connect the output of a PV PCS to the grid, the latter must generate a dc-voltage higher than the amplitude of the grid. To supply the 400V three phase grid, a minimum DC input voltage of 650V is required. A problem appears, if the input voltage range is 470-650V. Then a DC/DC converter with boast capability must compensate the lack of DC input voltage of the PV array.

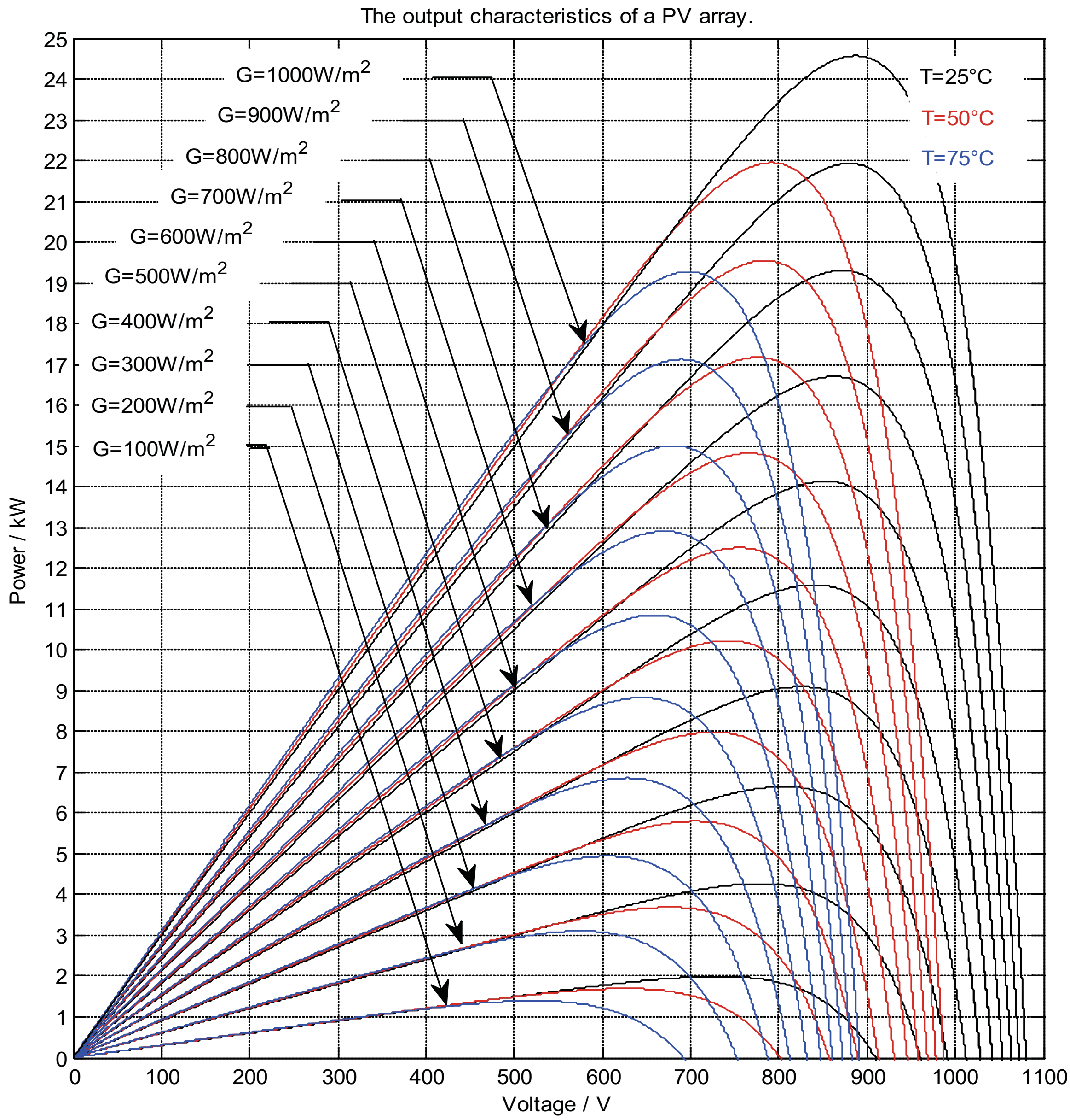

Fig. 5. The output characteristics of a PV array

2.2. The proposed grid-connected PCS

Figure 4 shows a block diagram of the proposed grid-connected PCS. It includes the two isolated DC/DC converter rated for partial load, an inverter, and a filter. The isolated DC/DC converter is operated only, if the input voltage is less than 650V. The main DC converter is a non-isolated converter producing four values of DC output voltages; two of them are produced by DC/DC isolated converters and the others are produced by DC link using capacitive voltage divider of PV voltage. The inverter operates as five level inverter, if the input voltage is less than 650V, and as three level inverter, if it is more than 650V. The LCL filter performs LP-filtering.

The proposed DC/DC isolated converter

In order to set down expenses and obtain a high efficient comparison for the perfectly method dc/dc isolated converter a simple LC Series Resonance Converter (SRC) was selected. The circuit diagram of a half bridge Series Resonant Converter is shown in Fig. 6. The DC characteristic of SRC is shown in Fig. 7. The resonant inductor L_r and resonant capacitor C_r are in series. They form with the resonant tank being in series with the load, the resonant tank and the load acts as a voltage divider. By changing the frequency of input voltage V_a, the impedance of the resonant tank varies accordingly. Due to this voltage divider structure, the DC gain of the SRC is always lower than 1. So for the SRC, the maximum gain occurs at resonant frequency.

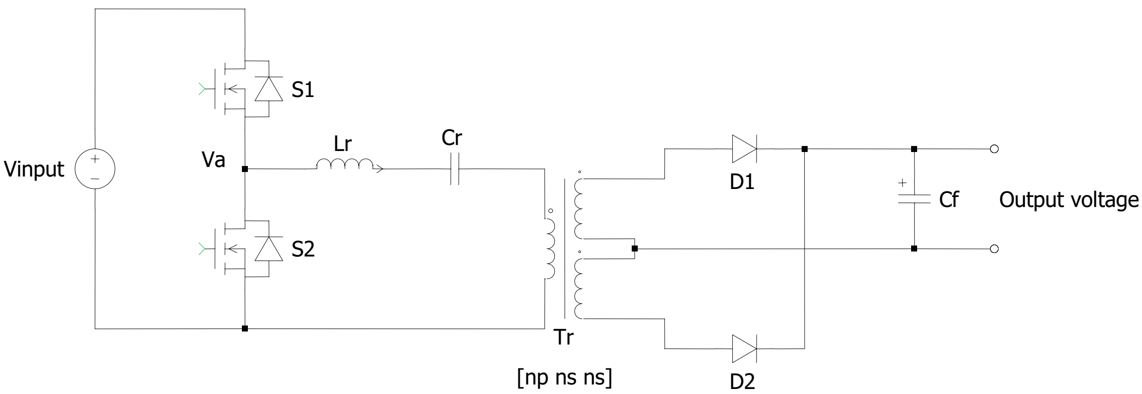

Fig. 6. Circuit diagram of a half bridge Series Resonant Converter

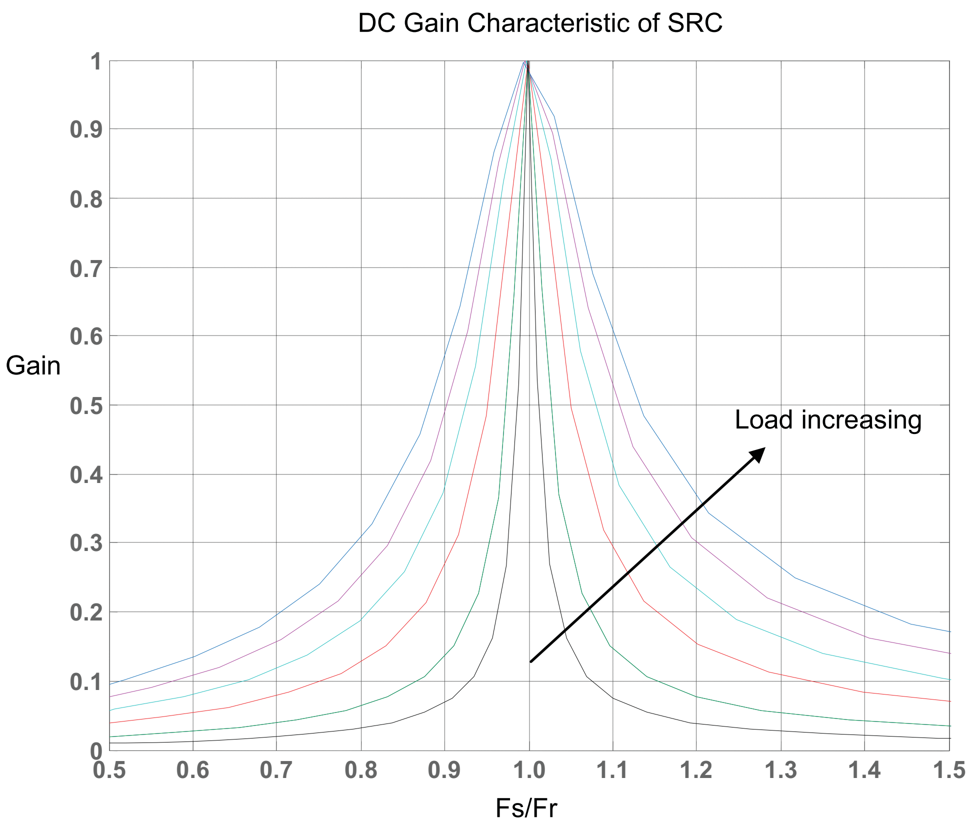

Fig. 7. The DC characteristic of Series Resonant Converter

The operating region shall be on the right side of the gain characteristic in order to obtain zero voltage switching (ZVS) for the converter. When switching frequency is lower than resonant frequency, the converter is operated under zero current switching (ZCS) condition.
Note, from the DC characteristic of SRC shown in Fig.7, that at operating point, $F_s = F_r$ the converter is operated at unity gain. It works as DC/DC transformer without any switching losses of the semiconductor switches, because it works under ZCS and ZVS at the same time. Hence, its efficiency should be highest.

It operates as DC/DC step down transformer with a turns ratio of 90/470. There are two modes of operation:

1- Turn on mode, with $470 \leq V_{PH} < 650$:

The output voltage range will be $90 \leq V_{out} < 125$, therefore the DC link voltages will be 90V, 235V,235V, and 90V respectively, if the photovoltaic voltage is V_{PH}=470V. And 125V, 325V, 325V, and 125V respectively, if the photovoltaic voltage is V_{PH}=650V; this means the total DC link voltage range will be 650V≤V_{DC}<900V, which is sufficient for the inverter to be connected to the 400V grid.

2- Turn off mode, with 650V≤ V_{PH}<900V:

In this range, no need for DC/DC isolated converter, the photovoltaic voltage V_{PH} is already sufficient to be connected to the 400V grid.

The proposed inverter

The neutral point clamped NPC topology was introduced by Nabae, Takahashi and Akagi in 1981 [6] showing great improvements in terms of lower switching efforts, in comparison with the classical 2-level inverter. It is one of the inverter topologies connecting to the grid without using any transformer to improve the efficiency; the transformer is usually used for providing personal protection and avoiding leakage currents between the PV system and the ground. Compared with the traditional 2-level PWM inverters, the NPC topology produces lower switching losses, harmonics and common mode currents, which significantly improve the efficiency of the inverters.
The circuit diagram of the proposed inverter is shown in Fig. 8. This topology of 5-level NPC inverter, is operated as 5-level inverter, if the input voltage is less than 650V, and as 3-level inverter, if it is more than 650V. This topology decreases the switching losses due to lower switching voltage, it also decreases the conduction losses due to the fact that only one switch is conducting during some active states.

The proposed topology uses standard configuration of IGBT modules produced by many suppliers: it composed by 3 pieces of 3-level one phase IGBT Module 600V (red), 1 piece of sixpack IGBT module 1200V (blue), 6 pieces of single IGBT with anti-parallel diode 600V (green) and 6 mechanical switches.
There are two modes of operation:

1- 5-level mode, with $470 \leq V_{PH} < 650$:

In this mode, all semiconductor switches are used to produce a 5 level AC waveform at 50Hz fundamental frequency. Three of these 5 voltage levels are produced by capacitive voltage dividers of the photovoltaic voltage V_{PH} ($\frac{V_{PH}}{2}$, 0, and $-\frac{V_{PH}}{2}$), the two levels ($V_{PH}\left(\frac{325}{470}\right)$ and $-V_{PH}\left(\frac{325}{470}\right)$) are produced by the isolated DC/DC converters. The switching states for 5-level and 3-level operation are summarized by Table I. It is clear from this table that only one semiconductor switch is required to produce the DC levels of $V_{PH}\left(\frac{325}{470}\right)$ and $-V_{PH}\left(\frac{325}{470}\right)$. Thus, the conduction losses will be significantly lower compared to the conventional 5-level NPC inverter. This topology still has the advantage of lower switching voltage which enhances efficiency improvement too.

2- 3-level mode, with 650V≤ V_{PH}<900V:

This mode is similar to the conventional 3-level NPC inverter, producing three voltage level ($\frac{V_{PH}}{2}$, 0, and $-\frac{V_{PH}}{2}$) at 50Hz fundamental frequency. By using the mechanical switches to form a single piece of 3-level three phase IGBT module, there isn't any need to use high speed semiconductor switches instead of mechanical switches, because they are switched on and off with low speed at zero voltage thanks of its parallel IGBT. In this mode, the sixpack IGBT module and 6 pieces of single IGBT are out of operation as well as DC/DC isolated converters, this means the DC power from PV array is transferred to the inverter with a very high efficiency which enhances the overall efficiency of the system.

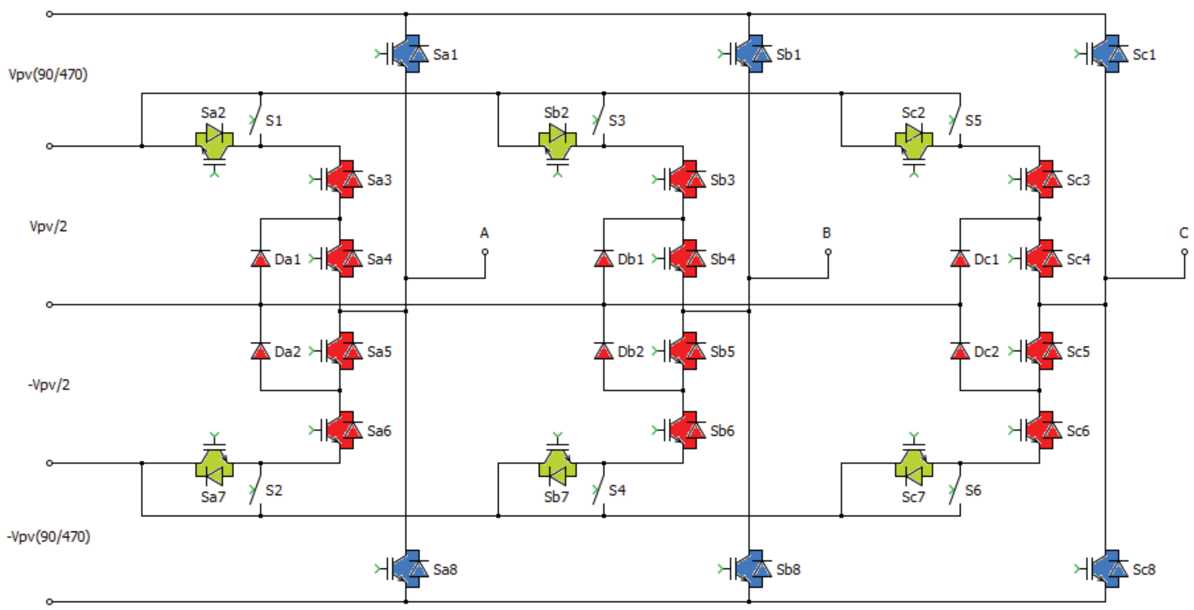

Fig. 8. The circuit diagram of the proposed inverter

Table I: Switches States for 5-level and 3-level modes.

Operating mode	V_{AO}	Sa1	Sa2	Sa3	Sa4	Sa5	Sa6	Sa7	Sa8	S1 and S2
5-level	$V_{PH}\left(\frac{325}{470}\right)$	1	0	0	0	0	0	0	0	0
	$\frac{V_{PH}}{2}$	0	0	1	1	0	0	0	0	
	0	0	0	0	1	1	0	0	0	
	$-\frac{V_{PH}}{2}$	0	0	0	0	1	1	0	0	
	$-V_{PH}\left(\frac{325}{470}\right)$	0	0	0	0	0	0	0	1	
3-level	$\frac{V_{PH}}{2}$	0	0	1	1	0	0	0	0	1
	0	0	0	0	1	1	0	0	0	
	$-\frac{V_{PH}}{2}$	0	0	0	0	1	1	0	0	

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The proposed full system

Figure 9 shows a circuit diagram of the proposed grid-connected PCS including DC/DC converters and DC/AC 5-level inverter.

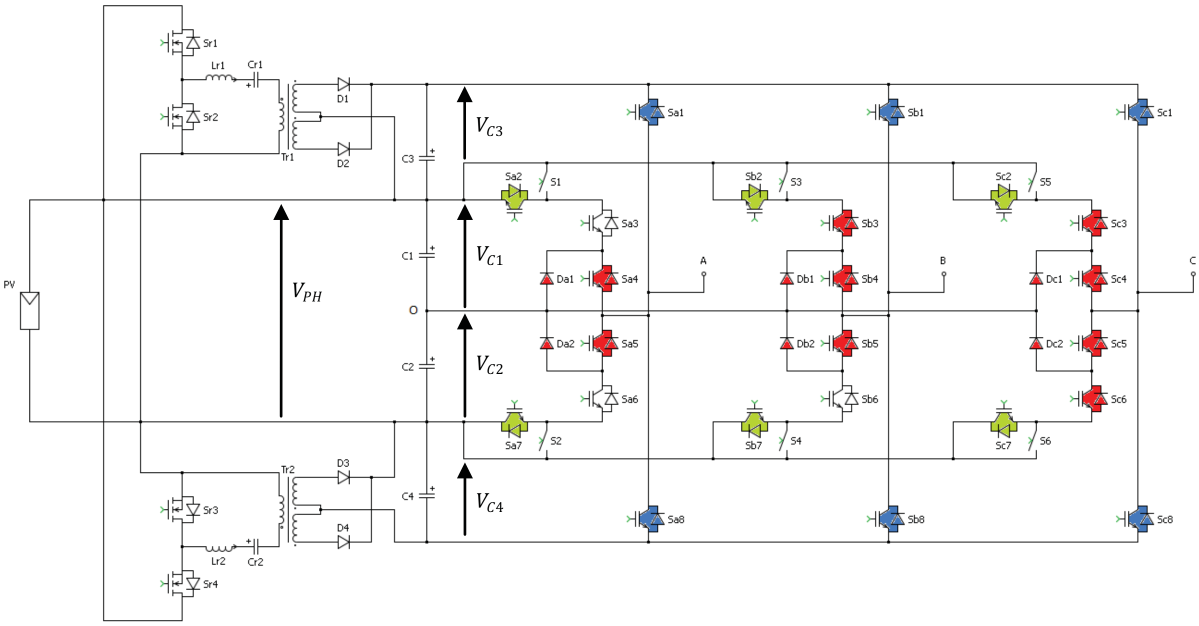

Fig. 9. The circuit diagram of the proposed grid-connected PCS

The output voltages of the DC/DC isolated converters are expressed as follows:

$$V_{C3} = V_{C4} = V_{PH}\left(\frac{90}{470}\right) \quad \text{(eq. 1)}$$

Where V_{PH} is the photovoltaic voltage, the DC link voltages are expressed as follows:

$$V_{C1} = V_{C2} = \frac{V_{PH}}{2} \quad \text{(eq. 2)}$$

$$V_{DC1} = V_{DC2} = V_{C1} + V_{C3} = V_{C2} + V_{C4} = \frac{V_{PH}}{2} + V_{PH}\left(\frac{90}{470}\right) = V_{PH}\left(\frac{325}{470}\right) \quad \text{(eq. 3)}$$

2.3. Power flow diagram

Figure 10 shows a power flow diagram of the proposed PCS to illustrate the efficiency flow of each block of the system. In the present work, the DC/DC converter is responsible for a small part of the DC inverter power and the rest of the DC power is supplied without any power converter structure so that the remaining DC power is transferred through the capacitive voltage divider at an efficiency of 100%. The total system efficiency η_s is obtained from the product of efficiency of the DC/DC converter $\eta_{DC/DC}$ and that of the inverter η_i, the system efficiency can be calculated as follows:

$$P_{DC/DC} = \eta_c(p/2)P_{PH} + (1-p)P_{PH} + \eta_c(p/2)P_{PH} \quad \text{(eq. 4)}$$

$$P_{DC/DC} = \eta_c p P_{PH} + (1-p)P_{PH} \quad \text{(eq. 5)}$$

$$P_{DC/DC} = (1 - p + \eta_c p)P_{PH} = \eta_{DC/DC} P_{PH} \quad \text{(eq. 6)}$$

$$\eta_{DC/DC} = 1 - p + \eta_c p \quad \text{(eq. 7)}$$

$$P_{output} = \eta_i P_{DC/DC} = \eta_i \eta_{DC/DC} P_{PH} \quad \text{(eq. 8)}$$

$$P_{output} = \eta_i(1 - p + \eta_c p)P_{PH} = \eta_s P_{PH} \quad \text{(eq. 9)}$$

$$\eta_s = \eta_i(1 - p + \eta_c p) = \eta_i\left(1 - p(1 - \eta_c)\right) \quad \text{(eq. 10)}$$

Where:

p : The power ratio of DC/DC isolated converters to the total power,

$P_{DC/DC}$: Output power of DC/DC converter,

η_c : Efficiency of DC/DC isolated converter,

$\eta_{DC/DC}$: Efficiency of DC/DC converter,
P_{output} : Output system power,
η_i : Efficiency of DC/AC inverter,
η_s : Total system efficiency.

It is clear from the above equation that the total system efficiency η_s is directly proportional to the efficiency of DC/DC isolated converter η_c and the efficiency of the inverter η_i , it is also inversely proportional to the power ratio of DC/DC isolated converters p . So, to improve the system efficiency we have to increase η_c, η_i, and decrease p. This is implemented by increasing η_c (operate resonant converter at resonance frequency), by increasing η_i (using a new topology of 5-level inverter), and by decreasing p (using this DC link configuration).

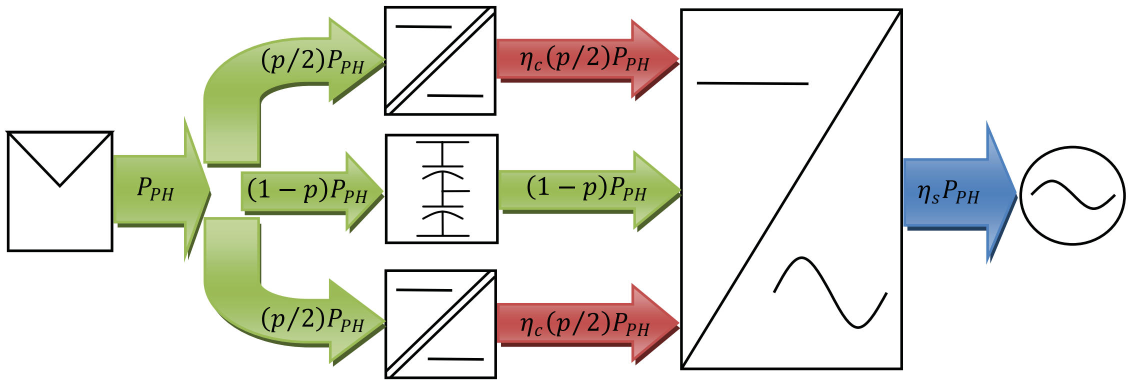

Fig. 10. Power flow diagram of the proposed PCS

2.4. Simulation results

Figure 11 shows the simulated efficiency curves of the overall system η_s. Note, the system efficiency is significantly increased with a wide range of photovoltaic voltage.

$$\eta_{euro} = 0.03\eta_{5\%} + 0.06\eta_{10\%} + 0.13\eta_{20\%} + 0.1\eta_{30\%} + 0.48\eta_{50\%} + 0.2\eta_{100\%}$$

Where:

η_{euro} : is the Euro efficiency,

$\eta_{x\%}$: is the conversion efficiency at x % of the system output rated power.

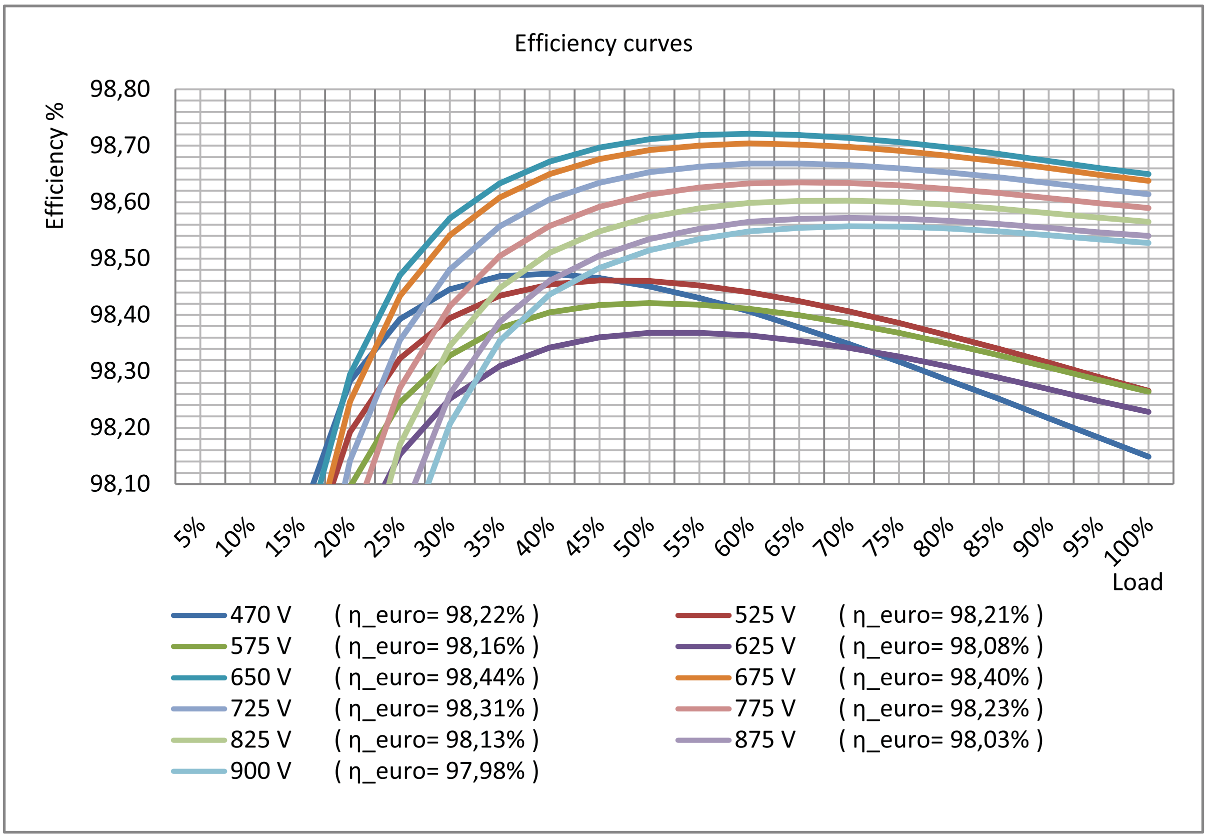

Fig. 11. The simulated efficiency curves of the overall system

3. Conclusion and future work

This contribution introduces a new topology of photovoltaic power conditioning system to enhance the system efficiency. It consists of DC/DC converter that is charged only by a small part of the output power. Using a series resonant converter operated at resonance frequency which leads to decrease the switching losses to enhance the efficiency improvement, the proposed DC/DC converter is not cost effective because we need only 16% of the rated system power. The proposed work has also a new topology of 5-level inverter which has a lower conduction and switching losses, which increases the efficiency too. Briefly, the overall efficiency of the system will be significantly increased.
The future work will be a prototype building of this system.

4. Literature

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