# Novel three-phase topology for cascaded multilevel medium-voltage conversion systems in large-scale PV plants

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***Abstract*— Solar photovoltaic renewable energy systems are expanding in the power sector thanks to its increasingly competitive prices. Traditionally, large-scale PV plants have reduced their cost by increasing the power ratings of the inverters and the line-frequency transformers. However, cost-reduction limits of large-scale PV plants are being reached. Cascaded converters have appeared as a solution to continue reducing the cost of large PV plants as they reduce the wiring cost. In this paper, a novel three-phase topology for cascaded conversion structures is proposed. It only has 2 conversion steps, one without switching losses. Hence, it increases the efficiency and reduces the cost of the previously proposed cascaded conversion systems. The topology is patent pending.**

***Keywords—Topology, photovoltaic, cascaded converter, multilevel converter, medium voltage, high-frequency transformer***

## I. INTRODUCTION

Solar photovoltaic (PV) renewable energy systems are expanding in the power sector due to the cost reduction of most of the elements that form its conversion structure [1]. At present, PV plants are configured as shown in Fig. 1 [2]. A group of PV modules is connected to a combiner box, *CB*, whose output is connected to a high-power inverter (in the range of megawatts). Then, the ac output of one or several inverters is connected to a low-frequency high-power transformer, which steps up the voltage from low voltage (grid line voltage in the range of 540-690 Vrms) to medium voltage (grid line voltage in the range of 20-30 kVrms). The power converter, the transformer, the switchgear and the protection equipment are usually grouped in what is called the power station.

During the last years, cost reduction of large-scale PV plants has been achieved by increasing the power ratings of the inverters and low frequency (LF) transformers. Central inverters and transformers with multi-megawatt power ratings are now commercially available [2]. However, an increase of the inverter power rating means a higher copper volume associated to the dc-wiring [3]. Firstly, because its length is increased due to the higher number of PV modules that has to be connected to the same inverter. Secondly, because its cross section is also increased as it delivers a higher power coming from the PV modules. Therefore, the lower cost of the converter and the transformer is compensated by the higher dc-wiring cost, which is becoming more and more relevant in large-scale PV plants. Besides, there is an upper limit in the transformer's power rating (i.e. volume), above which it is not possible to place it in standard shipping containers. If this power-rating limit is exceeded, the transformer is subject to significant additional costs due to transportation. Consequently, a saturation of the large-scale PV plants' cost decrease is expected in the near future.

In order to continue reducing the cost of large-scale PV plants, other alternatives have to be investigated. Medium-voltage cascaded H-bridge conversion systems, MV CHB, and medium voltage modular multilevel conversion systems, MV MMC, [2]–[4] have appeared as potential solutions. They consist of conversion stages whose output is connected in series, generating in medium voltage (MV). The conventional step-up low-frequency transformer is then substituted by a high-frequency transformer in each conversion stage. LF transformers reduce the volume and therefore the cost of the transformer stage [5]. Moreover, the series connection of converters in these conversion systems enables the reduction of the power rating of each individual conversion stage while maintaining the power rating of the conversion structure. Consequently, a reduction of the number of PV modules connected to each conversion stage is achieved. This reduces the dc-wiring length, as the conversion stage is located closer to the PV modules, reducing the dc-wiring cost. In addition, as voltage is stepped up at the output of the conversion stage, current is stepped down, allowing a lower cross section in the ac-wiring than in the dc-wiring. Again, this also reduces the wiring cost. Furthermore, the series connection of conversion stages makes it possible to obtain a multilevel output voltage, reducing the grid current harmonics and therefore the cost of the required output line-filter.

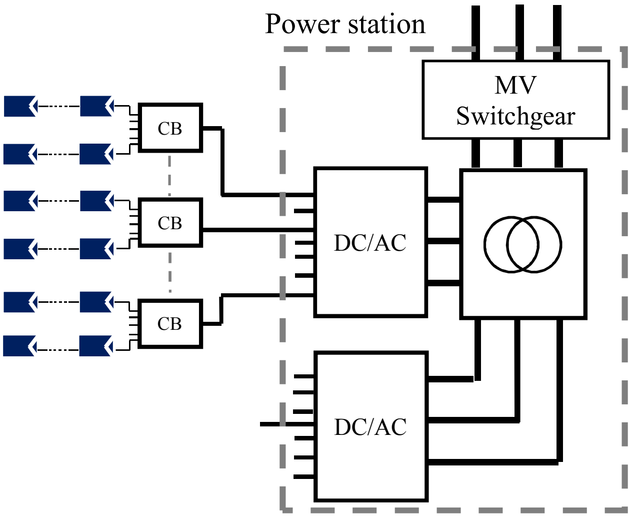

Fig. 1. Traditional large-scale PV plant configuration

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In this paper a novel topology for cascaded medium voltage conversion systems in large-scale PV applications is presented. As shown in Fig. 2, in the proposed conversion system, the $N_s$ conversion stages are connected in series, enabling the substitution of the LF transformer by HF transformers and the wiring cost reduction with respect to the traditional configuration of large-scale PV plants. In the proposed conversion system it is also possible to obtain a multilevel output voltage, reducing the required output line-filter. Furthermore, the proposed topology is a three-phase topology, thus avoiding power imbalances that may appear in single-phase topologies if irradiance or temperature vary between the PV modules of each phase [6]. Besides, even though it is a three-phase topology, it is formed by only 2 conversion steps plus the HF transformer, reducing the number of conversion steps of all the previously investigated three-phase topologies for cascaded medium voltage conversion systems [2]. In addition, thanks to the proposed modulation technique, zero voltage switching, ZVS, and zero current switching, ZCS, are realized in both conversion steps. As a result, the ac/ac conversion step has no switching losses, and in the dc/ac conversion step, only few semiconductors' turn-off generate switching losses. Consequently, the proposed topology maintains the cost-reduction advantages of MV CHB and MV MMC solutions and in comparison with them, it also increases the efficiency and reduces the cost of the conversion system. The following section describes the operation and characteristics of the proposed topology.

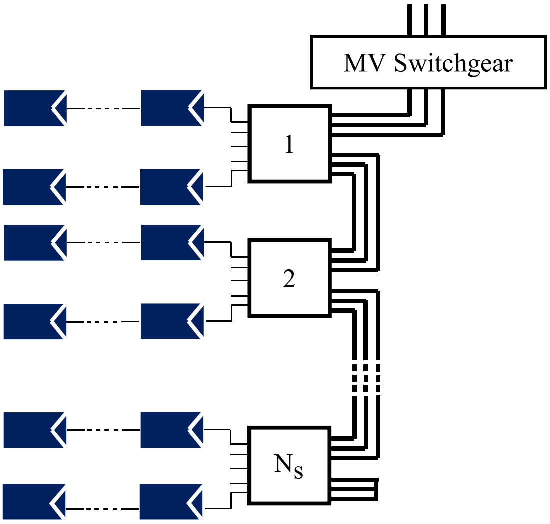


Fig. 2. PV plant configuration of the proposed conversion system.

## II. PROPOSED TOPOLOGY

### A. Topology descripton

The proposed three-phase topology is shown in Fig. 3, where the main conversion steps can be identified. Each one of the $N_s$ conversion stages of Fig. 2 is formed by: an H-bridge as a dc/ac converter, 3 single-phase HF transformers with turns ratio *n2/n1*, and three ac-ac converters (one per phase). Each one of the ac-ac converters is in turn composed by 4 semiconductors. Two of them, T1 and T4, allow to connect the corresponding phase with the output of the high frequency transformer. The other two, T2 and T3, enable to bypass the converter. In addition, each ac-ac converter includes a circuit that protects the ac-ac converter in the event of a semiconductor failure. This circuit, whose operation and design is later explained, is composed of 2 diodes, D1 and D2, and a capacitor, Cp.

### B. Modulation technique

#### 1) Basic operation: sequential control

In the proposed topology, as shown in Fig. 4, the power transfer is carried out sequentially. During a switching period, $t_{sw}$, from $t_0$ to $t_1$ the phase R is fed with power, then from $t_1$ to $t_2$ the phase S and then from $t_2$ to $t_3$ the phase T. Like in a traditional converter, the time during which a phase transfers power (i.e. is active) depends on the comparison between a reference voltage and a carrier wave. In the proposed converter, two reference voltages are needed for each phase: $R_H$ and $R_L$ for phase R, $S_H$ and $S_L$ for phase S, and $T_H$ and $T_L$ for phase T. The suffix H or L indicates whether power has to be transferred with positive or negative voltage when the phase is active (i.e. the voltage that applies the H-bridge when the phase is active). Thus, in a switching period, only one of the two reference voltages of each phase is higher to zero. For example, if power has to be transferred with positive voltage when phase R is active, $R_H$ is higher to zero and $R_L$ is equal to zero. If it has to be with negative voltage, $R_H$ is zero and $R_L$ is higher to zero. The example of Fig. 4 represents the case with power transferred with positive voltage in phase R, and with negative voltage in phases S and T. In addition, adjustments are needed in the reference voltages to perform the sequential control. As can be seen in Fig. 4, the phase R is active when $R_H$, $S_L$ and $T_L$ are higher than the carrier wave, CAR, phase S is active when $R_H$ is lower than the carrier wave and $S_L$ and $T_L$ are higher than the carrier wave, and phase T is active when only $T_L$ is higher than the carrier wave.

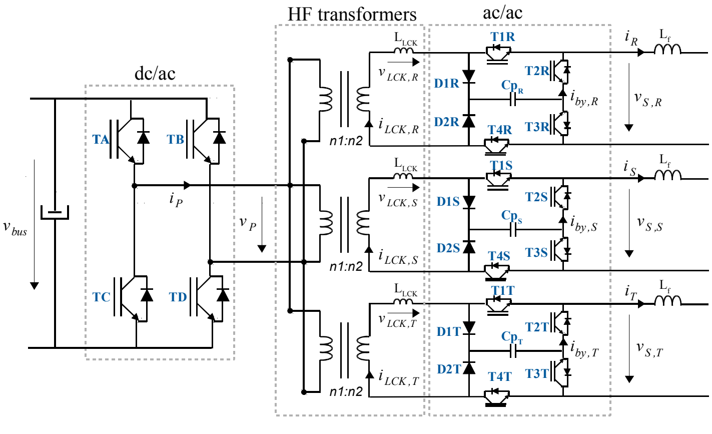


Fig. 3. Proposed novel topology for three-phase dc-ac cascaded conversions structures

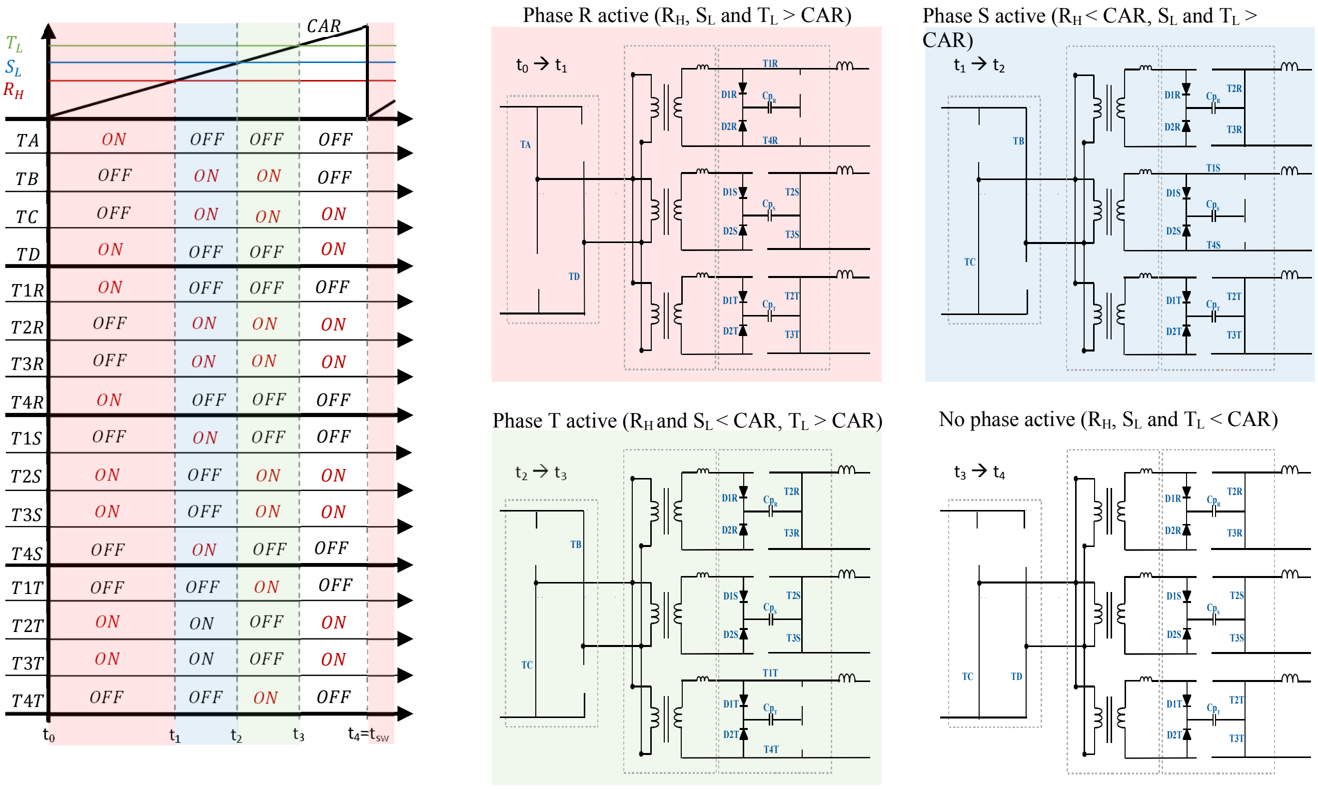


Fig. 4. Basic operation of the topology when $R_H$, $S_L$ and $T_L$ are higher to zero, and $R_L$, $S_H$ and $T_H$ are equal to zero.

One of the main challenges of this new topology is the series connection of the output-filter inductance, $L_f$, and the leakage inductance of the transformer, $L_{LCK}$. Specific turn-on and turn-off transitions to activate and deactivate the phases are needed. They are explained in detail in the next section. In the example of Fig. 4 they take place in $t_0$, $t_1$, $t_2$, $t_3$, $t_4$… For example, in $t_1$, first a turn-off transition of phase R and then a turn-on transition of phase S are carried out.

As can be seen in Fig.4, after a turn-on transition, the active phase is connected to the output of the HF transformer (i.e. T1=T4=ON and T2=T3=OFF), the other phases are only bypassing the current that flows through the rest of the series-connected converter outputs (i.e. T1=T4=OFF and T2=T3=ON in the deactivated phases) and the H-bridge is applying the corresponding voltage (i.e. TA=TD=ON and TB=TC=OFF for positive control voltages or TA=TD=OFF and TB=TC=ON for negative control voltages). This way, only the active phase transfers power. After a turn-off transition all the phases are bypassing the grid current (i.e. T1=T4=OFF and T2=T3=ON) and the H-bridge is applying zero voltage (i.e. TA=TB=OFF and TC=TD=ON), preparing the converter for the next turn-on transiton. The time between $t_3$ and $t_4$ has all the phases deactivated, and its duration depends on the modulation index of the converter. If it is operating with a very high modulation index, the time $t_3$-$t_4$ will be small. If the converter is operating with low modulation index, $t_3$-$t_4$ will increase.

### 2) *Turn-on and turn-off transitions*

As explained in the basic operation of the topology, when a phase has to be activated, a turn-on transition starts. In the same way, when a phase has to be deactivated, a turn-off transition is carried out. A suitable modulation technique for activating and deactivating each phase is proposed. It realizes zero voltage switching, ZVS, and zero current switching, ZCS, in both conversion steps, resulting in an ac/ac conversion step with no switching losses, and a dc/ac conversion step with only few semiconductors' turn-off with switching losses.

Each turn-on and turn-off transition depends on the sign of the voltage that the H-bridge applies when the phase is active, and the sign of the grid current of the corresponding phase. In this paper, two of the four possible combinations are studied. The other two can easily be obtained following the same reasoning. For all cases, before a turn-on transition starts, the grid current of the corresponding phase is circulating through the bypass semiconductors (i.e. $i_r=i_{by,R}$ and $i_{LCK,R}=0$), the H-bridge is applying zero voltage (i.e. TA=TB=OFF and TC=TD=ON), and the ac/ac converters are only permitting the circulation of current to the rest of the cascaded conversion stages (i.e. T1=T4=OFF and T2=T3=ON in the three-phases).

- *Transitions to transfer power with positive voltage and positive grid current*

Fig. 5 and Fig. 6 represent the turn-on and turn-off transitions for the phase R, when power is transferred with positive voltage and the grid current is positive.

The turn-on transition starts in $t_0$, when the phase connects to the output of the HF transformer (i.e. T1R=T4R=ON, both ZCS as $i_{LCK,R}=0$). Then, in $t_1$, T2R is turned off so that $i_{by,R}$ cannot later become negative (ZVS because the current is passing through its freewheeling diode). Then, in $t_2$, the H-bridge applies a positive voltage, $v_P$, (i.e. TA=ON and TC=OFF, both ZCS as no current is passing through them). This causes that a positive voltage is also applied to $L_{LCK}$, $v_{LCK,R}$, and consequently, $i_{LCK,R}$ starts increasing. Once this current reaches the value of the grid current, $i_R$, a positive voltage appears in the output of the phase, $v_{S,R}$, and power starts to be transferred from the input to the output of the converter. The turn-on transition finishes in $t_3$ when T3R is turned off (also ZCS as $i_{by,R}=0$).

The turn-off transiton begins in $t_0$ when the H-bridge starts applying zero voltage. Thus, TA=OFF (in this case with current and therefore with losses) and TC=ON (ZVS since current is passing through its freewheeling diode). Then, in $t_1$, the bypass semiconductors are turned on (i.e. T2R=T3R=ON, both ZCS as $i_{by,R}=0$), and, in $t_2$, T4R is turned off to avoid $i_{LCK,R}$ to later become negative (ZVS as the current is passing through its freewheeling diode). In order to extinguish the current in $L_{LCK}$, the H-bridge applies in $t_3$ a negative voltage. Thus, TD=OFF (with current and therefore with losses) and TB=ON (ZVS because the current is passing through its freewheeling diode). This causes that a negative voltage is applied to $L_{LCK}$, $v_{LCK,R}$, and therefore $i_{LCK,R}$ starts decreasing, being finally extinguished. The turn-off transition finishes applying the H-bridge zero voltage (TD=ON and TB=OFF, both ZCS as there is no current flowing through the H-bridge) and turning T1R off (also ZCS as $i_{LCK,R}=0$).

In these transitions, from a total of 8 IGBT's turn-on and 8 IGBT's turn-off, only 2 IGBT's turn-off generate losses, neither of them in the ac/ac converter.

- *Transitions to transfer power with positive voltage and negative grid current*

Fig. 7 and Fig. 8 represent the turn-on and turn-off transitions for the phase R, when power is transferred with positive voltage and the grid current is negative.

The turn-on transition starts in $t_0$ when the ac-ac converter connects to the output of the HF-transformer (i.e. T1R=T4R=ON, both ZCS as $i_{LCK,R}=0$). Then, in $t_1$, T3R is turned off so that $i_{by,R}$ cannot later become positive (ZVS because the current is passing through its freewheeling diode). Then, in $t_2$, a negative voltage is applied in the H-bridge (i.e. TB=ON and TD=OFF, both ZCS as no current was passing through them). This causes that a negative voltage is applied to $L_{LCK}$, $v_{LCK,R}$, and consequently, $i_{LCK,R}$ starts decreasing. Once this current reaches the value of the grid current, $i_R$, a negative voltage appears in the output of the phase, $v_{S,R}$. However, as the power has to be transferred with positive voltage, the turn-on transition is not finished. After a waiting a minimum time to ensure that at any operation point of the converter the grid current will be flowing through the transformer (i.e. $i_R=i_{LCK,R}$), in $t_3$, the H-bridge applies zero voltage. Thus, TB=OFF (with current and therefore with losses) and TD=ON (ZVS because the current is passing through its freewheeling diode). Then, in $t_4$, T2 is turned off (ZCS as $i_{by,R}=0$). Finally, in $t_5$, TA=ON (ZVS because the current is passing through its freewheeling diode) and TC=OFF (with current and therefore with losses). This way, power is transferred from the input to the output of the converter with positive voltage, finishing with the turn-on transition.

The turn-off transition begins in $t_0$, when the H-bridge starts applying zero voltage. Thus, TA=OFF (in this case with current and therefore with losses) and TC=ON (ZVS since current is passing through its freewheeling diode). Then, in $t_1$, the bypass semiconductors are turned on (i.e. T2R=T3R=ON, both ZCS as $i_{by,R}=0$), and in $t_2$, T1R is turned off to avoid $i_{LCK,R}$ to later become negative (ZVS as the current is passing through its freewheeling diode). In order to extinguish the current in $L_{LCK}$, the H-bridge applies a positive voltage. Thus, in $t_3$, TC=OFF (with current and therefore with losses) and TA=ON (ZVS because the current is passing through its freewheeling diode). This causes that a positive voltage is applied to $L_{LCK}$, and after a certain time, $i_{LCK,R}$ is extinguished. The turn-off transition finishes with the H-bridge applying zero voltage (TA=OFF and TC=ON, both ZCS as no current is flowing through the H-bridge) and turning T4R off (also ZCS as $i_{LCK,R}=0$).

In these transitions, from a total of 10 IGBT's turn-on and 10 IGBT's turn-off, only 4 IGBT's turn-off generate losses. Again they are located in the semiconductors of the H-bridge and not in the ones of the ac/ac converter.

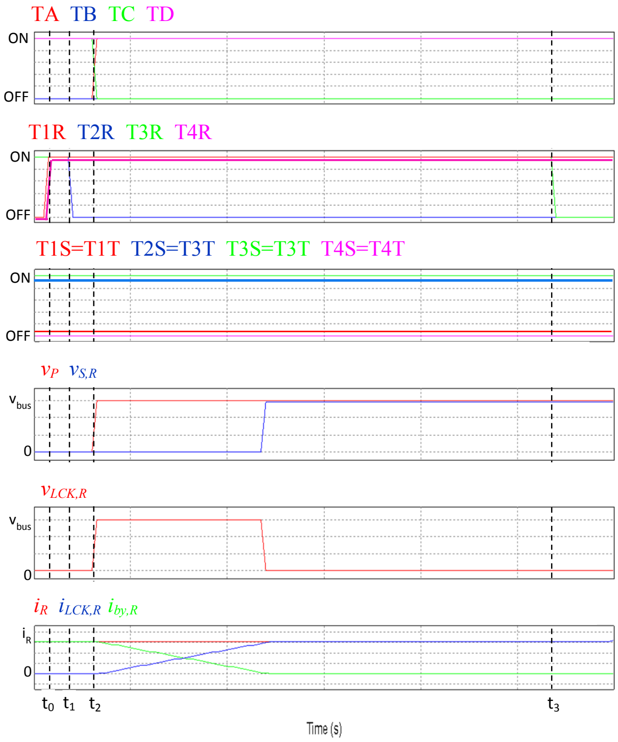


Fig. 5. Turn-on transition to transfer power with positive voltage and positive grid current

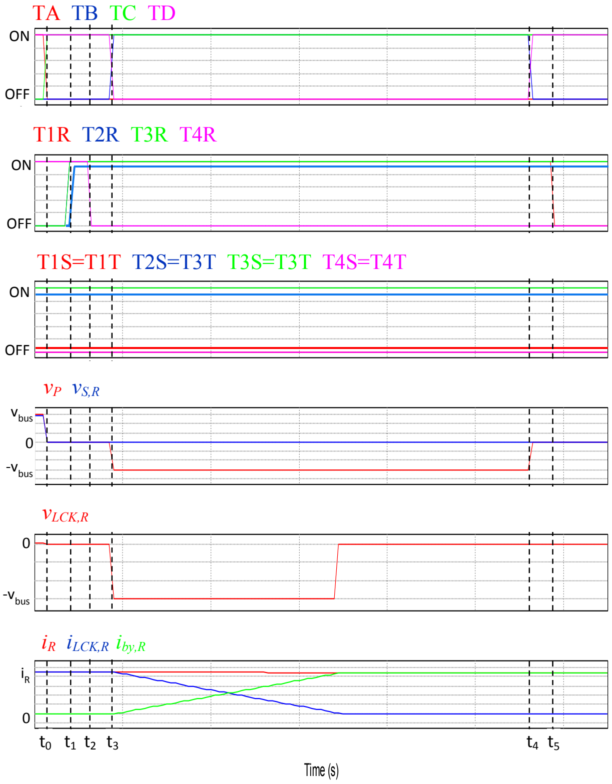


Fig. 6. Turn-off transition to transfer power with positive voltage and positive grid current

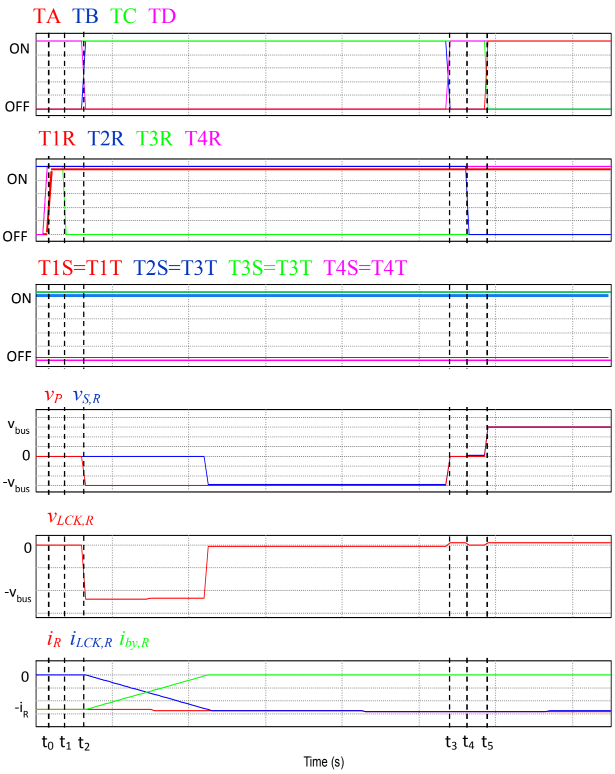


Fig. 7. Turn-on transition to transfer power with positive voltage and negative grid current

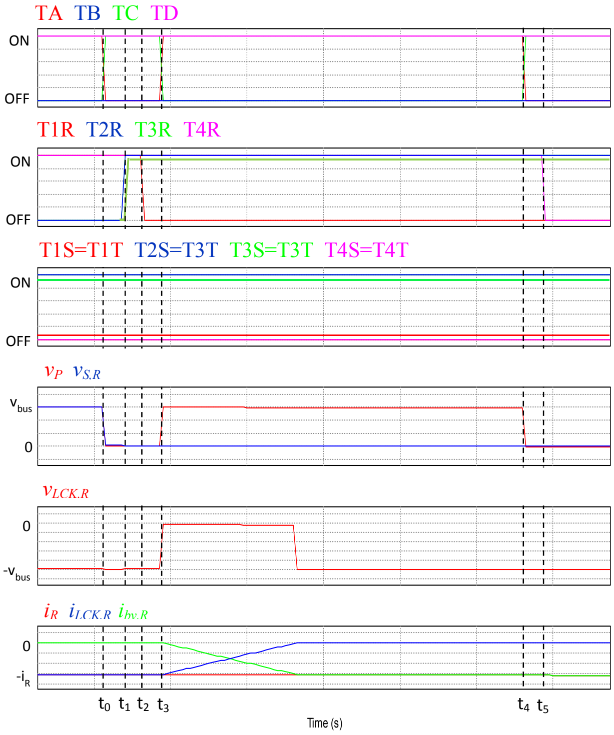


Fig. 8. Turn-off transition to transfer power with positive voltage and negative grid current

### C. High-frequency transformer

The result of the sequential control of the example in Fig. 4, including the transitions between phases, is shown in Fig. 9. The waveforms of the voltage applied by the H-bridge, $v_P$, and the voltage at the output of each phase, $v_{S,R}$, $v_{S,S}$, $v_{S,T}$, are depicted.

In the proposed topology, a positive, negative, or zero voltage can be obtained in each phase. However, as the three phases are sequentially activated in a switching period, $t_{sw}$, only a maximum of 50% of the switching period can be dedicated to transfer power to a phase.

A dead time, $t_d$, is needed for the turn-off transition before the next phase is activated. During the dead time, the H-bridge applies a voltage of opposite sign to the one of the grid current. This way, the current in $L_{LCK}$ is extinguished and the phase is correctly deactivated. The minimum value of the dead time $t_{d,min}$ can be calculated as:

$$t_{d,min} = L_{LCK} \cdot \frac{i_{max}}{v_{bus,min} \cdot \frac{n2}{n1}} + t_{semi} \tag{1}$$

As (1) shows, the minimum dead time value depends on the minimum dc bus voltage, $v_{bus,min}$, the transformer turns ratio $n2/n1$, the leakage inductance of the transformer, $L_{LCK}$, and the maximum current that has to be extinguished in $L_{LCK}$, $i_{max}$, which can be in turn determined by the maximum grid current (i.e maximum value of $i_R$, $i_S$ or $i_T$). The time needed to switch the semiconductors, $t_{semi}$, also increases the minimum dead time.

The three dead times of a switching period reduce the effective time that can be used to transfer power by a factor of:

$$f_{red} = \frac{t_{sw} - 3 \cdot t_{die}}{t_{sw}} \tag{2}$$

Regarding the magnetization of the transformer, in a switching period, as the addition of the modulation indexes of the three phases is equal to zero, $v_p$ has an average value of zero (i.e. the same positive and negative volts-seconds is applied). This way, the magnetization of the transformer is done at switching frequency, obtaining a HF transformer.

However, the voltage that is applied during the dead times to extinguish the current in $L_{LCK}$ also affects the magnetization of the transformer. In a switching period, as there is a total of 3 dead times, depending on the signs of the grid currents (i.e. $i_R$, $i_S$ or $i_T$), a small positive or negative dc voltage is in fact applied to the transformer, which can cause its saturation. In addition, other different phenomena such as unmatched turn-on/turn-off times, semiconductor forward voltage mismatches, gate driving delays, etc., can also contribute to saturate the transformer [7].

The saturation of a HF transformer can easily happen even if the volt-seconds imbalance is very small [7]. The flux-balancing of the HF transformers of the proposed topology is studied in detail in [8].

### D. Protection circuit

As can be seen in Fig. 3, each ac/ac converter includes a protection circuit formed by two diodes, D1 and D2, and one capacitor, Cp. The aim of this circuit is to always give an alternative path for the grid current flow in the event of a semiconductor failure. During normal operation (i.e. without failures) the protection circuit does not alter the current flow, since Cp is charged at a voltage equal to $v_{bus} \cdot n2/n1$ (i.e. the value of $v_{sec,R}$ when the phase is active).

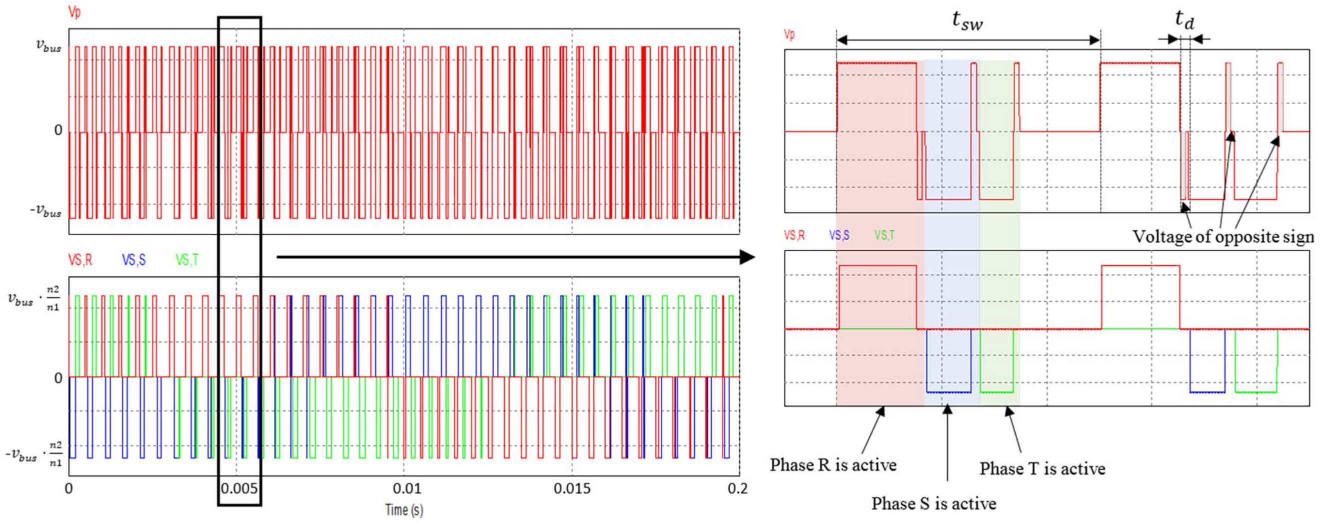


Fig. 9. Main voltage waveforms of the proposed topology

Fig. 10 considers as an example the case in which power is being transferred from the H-bridge to the phase R with positive voltage, and a failure in T1R occurs, suddenly turning it off. This can happen due to different reasons such as a failure in the supply voltage of its gate driver, or an electromagnetic noise in the input signal of the driver.

As explained in the basic operation of the conversion stage, when a phase is active, the grid current is passing through the secondary of the HF transformer (i.e. $i_R = i_{LKC,R}$), and the output of the activated phase is connected to the HF transformer (i.e. T1R=T4R=ON and T2R=T3R=OFF). When the failure in T1R occurs, if there is no protection circuit in the ac/ac converter, the current $i_{LKC,R}$ does not have a path to flow. This causes an interruption in the current flow of $L_f$, originating an overvoltage that will break the semiconductors.

If the ac/ac converter includes the protection circuit, when the failure in T1R occurs, as shown in Fig. 10 (b), D1R, $Cp_R$, and the freewheeling diode of T2R create an alternative path for the current flow, avoiding an overvoltage in $L_f$. In addition, as a consequence of the alternative current path, $v_{S,R}$ suddenly falls to a value of $v_{sec,R} - v_{cp}$. As before the failure $v_{cp}$ is approximately equal to $v_{sec,R}$, when the failure occurs, $v_{S,R}$ suddenly drops to a value close to zero. This sudden change of $v_{S,R}$ is used to detect that a failure has happened in the converter and needs to stop.

All possible failures in any of the semiconductors of the ac/ac converter have been analyzed, always offering the protection circuit an alternative path to avoid interrupting the current flow in $L_f$. Furthermore, with just monitoring the voltage $v_{S,R}$ it is possible to detect any semiconductor malfunctioning failure and stop the conversion system in a safe way.

The fastest method to extinguish the grid currents and stop the $N_s$ conversion stages is to turn off all their semiconductors, both in the H-bridge and the ac/ac converters. Until the grid current of each phase is extinguished, as shown in Fig. 10, Cp is charged. A minimum capacitance value is therefore required so that while the current is being extinguished, the capacitor voltage does not increase above the rated voltage of the semiconductors of the ac/ac converter. This capacitance value can be calculated as:

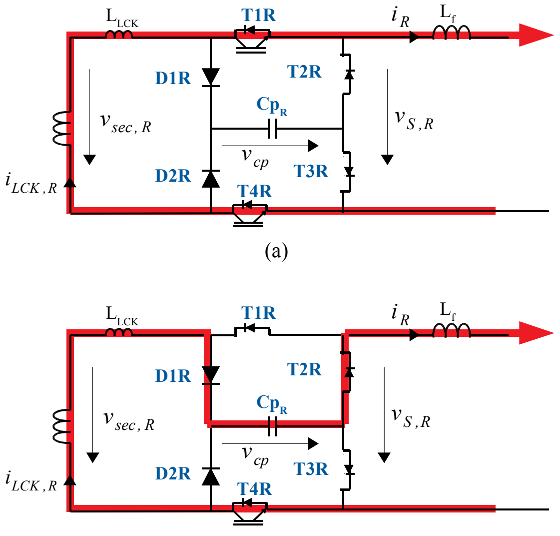
$$Cp \ge \frac{i_{max}\cdot t_{st}}{2}\cdot\frac{1}{V_{rated}-V_{cp,max}} \ , \qquad (3)$$

where $i_{max}$ is the maximum grid current that has to be extinguished, $V_{rated}$ is the rated voltage of the semiconductors T1, T2, T3 and T4, $V_{cp,max}$ is the maximum voltage at which it is possible to have nominal power, but referred to the secondary of the HF transformer, and $t_{st}$ is the time needed to extinguish the grid currents, which in turn can be obtained as:

$$t_{st} = \frac{i_{,max}}{V_{cp,max}}\cdot L_f + \Delta t \ , \qquad (4)$$

where $\Delta t$ is the time between the failure occurs and all the semiconductors are ordered to turn off. In addition, the minimum rated voltage of Cp must also be $V_{rated}$, the rated voltage of T1, T2, T3 and T4.

Regarding the design of the protection circuit diodes, they also have to be of the same rated voltage as the T1, T2, T3 and T4. However, they can be of a much lower rated current, since current is only going to pass through them during very short periods of time.



(a)

(b)

Fig. 10. (a) Current flow when phase R is active and there are no failures, (b) if a failure in T1R occurs and the ac/ac converter includes protection circuit.

### E. *Converter gain and minimum number of cascaded conversion stages*

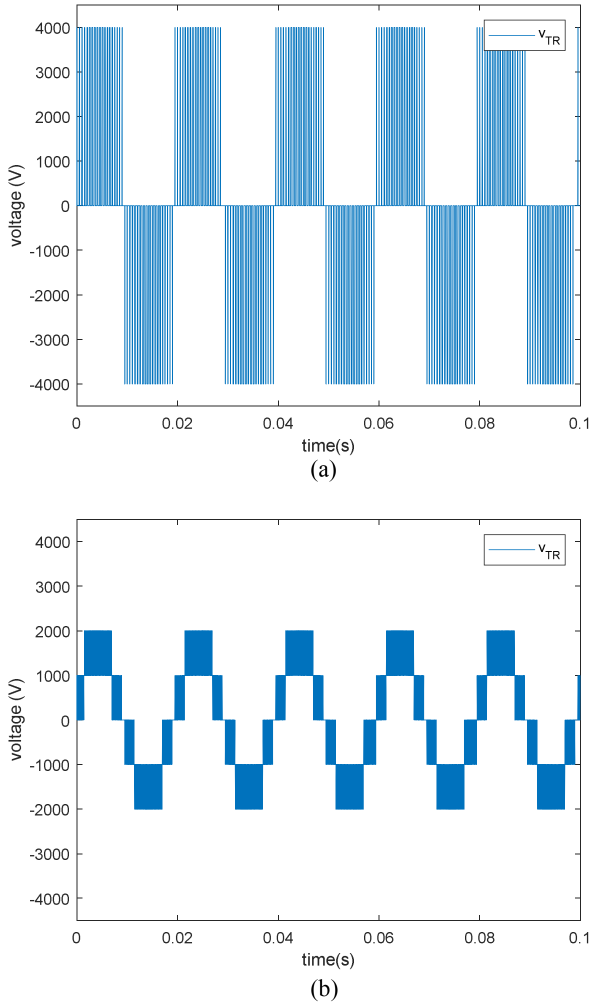
In the proposed topology, the rms output voltage per phase, $V_{ac,rms}$, can be calculated as:

$$V_{ac,rms}=\frac{v_{bus}}{\sqrt{2}}\cdot\frac{n2}{n1}\cdot 0.5\cdot f_{red}\cdot m_i\ , \tag{5}$$

where $v_{bus}$ is the dc voltage of the converter, *n2/n1* is the transformer turns ratio, $f_{red}$ the reduction factor calculated with (2) due to the dead time needed for the turn-off transition to deactivate a phase, and $m_i$ is the modulation index of the corresponding phase. The factor 0.5 is due to the sequential control, of the phases. Thus, the maximum achievable output voltage per phase is the one obtained with (5) for a modulation index equal to one

One of the most important design values of the proposed conversion structure is the minimum number of cascaded conversion stages to connect the conversion structure to a certain grid, $N_{s,min}$. It can be determined by the grid line-to-line rms voltage, $U_{grid}$, and the maximum output voltage of the converter with minimum bus voltage, $v_{bus,min}$, as:

$$N_{s,min}\geq\frac{U_{grid}/\sqrt{3}}{\frac{v_{bus,min}}{\sqrt{2}}\cdot\frac{n2}{n1}\cdot 0.5\cdot f_{red}} \tag{6}$$



(a)

(b)

Fig. 11. Total output voltage of phase R in a conversion structure with $N_s$=4 when (a) the carrier waves of each conversion stage are not shifted, (b) the carrier waves are phase shifted *360º/N*$_s$.

For example, for a 24 kV grid voltage, a minimum bus voltage of 900 V, a transformer turns ratio of 1/1 and a reduction factor of $f_{red}$=0.9, at least 49 cascaded conversion stages are needed.

The design of $N_{s,min}$ has to be carried out for $v_{bus,min}$ as a worst case scenario. In all other cases, the result will be that the cascaded conversion stages will be operating with a modulation index lower to 1.

### F. *Mutilevel output voltage*

The series connection of the $N_s$ conversion stages makes it possible to obtain a multilevel output voltage. Fig. 5 shows the total output voltage of phase R, $v_{TR}$, (i.e. the addition of $v_{S,R}$ of each conversion stage), in a conversion structure with $N_s=4$, and $v_{bus}$=1000 V in all of them. Fig. 5 (a) corresponds to the case in which the carrier waves of all the conversion structures are in phase, and Fig. 5 (b) when the carrier waves of the $N_s$ conversion stages are phase-shifted a value of *360º/N*$_s$.

When the carrier waves of the conversion stages are phase-shifted, the number of voltage levels in the phase output voltage increases, creating a staircase waveform. If $N_s$ is increased, the number of voltage levels also increases, obtaining an output voltage similar to a sinusoidal voltage.

This multilevel output voltage reduces the grid current harmonics and therefore the required output line-filter. In consequence, it helps to increase the efficiency of the conversion stage and also reduce its cost.

## III. CONCLUSION

In this paper, a novel three-phase topology for medium voltage cascaded conversion systems in large-scale photovoltaic applications is presented. The topology is applied to a conversion system formed by cascaded conversion stages, which allows reducing the wiring cost of the PV plant. Its main advantage compared to previously investigated cascaded structures is that it is a three-phase topology and it is formed by only 2 conversion steps, increasing the efficiency and reducing the cost of previously investigated topologies. Special attention is paid in this paper to the modulation technique of the topology as the leakage inductance of the high-frequency transformer and the filter inductance of the conversion stage are connected in series. With the proposed turn-on and turn-off transitions of the phases, the high frequency ac voltage of the transformer is transformed to low frequency ac voltage in one single step, and without switching losses in the ac/ac converter.

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