Electromagnetic interference-based comparative study between transformerless H5 and optimised H5 grid-connected photovoltaic inverters

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Abstract
In this study, a comparative study between two single-phase transformerless grid-connected photovoltaic (PV) inverters, namely H5 and optimised H5 (oH5), is carried out based on conducted electromagnetic interference (EMI) performance. For this purpose, a high-frequency (HF) model of the grid-connected inverters is proposed and simulated using Simulation Program with Integrated Circuit Emphasis (SPICE)-based circuit simulation software. Moreover, an experimental setup is developed to measure the conducted emissions. The obtained results show an EMI advantage of the oH5 inverter at low frequencies but not at HF frequencies. Therefore, a mitigation method is proposed to optimise the oH5 topology in the HF range. It consists in using only one Resistor–Capacitor (RC) snubber circuit connected in parallel with the inverter’s extra switch. The obtained results show that the oH5 inverter with only one RC snubber circuit provides lower conducted EMI than the H5 in a wider frequency range without worsening the efficiency. The proposed EMI mitigation method can therefore be considered as an adequate and preferred solution for the transformerless grid-connected oH5 PV inverter.

1 | INTRODUCTION

According to the International Energy Agency annual report, the cumulative capacity of installed photovoltaic (PV) panels was about 500 GW in 2018 [1]. Most domestic PV systems are grid-connected; they are classified into two groups: With and without transformers. For safety purposes, it is essential to use transformers in the conception of PV systems since they provide galvanic isolation, which allows breaking ground loops by avoiding undesired current from flowing between units sharing a ground conductor. However, this component is heavy, bulky and expensive. To overcome these limitations, the PV energy injection into the grid without a transformer has been adopted by many manufacturers of solar energy. Hence, the PV energy conversion system becomes lighter, smaller, cheaper and more efficient [2, 3]. Nonetheless, the direct connection of PV panels to the grid may cause the fluctuation of the common-mode voltage (CMV), which in turn causes a leakage current circulating through the parasitic capacitors between the PV cells and the ground. The parasitic capacitances depend on air humidity, the material of cells, and the size of PV array frame. Notice that dangerous leakage current causes multiple problems such as user safety, high system loss and severe electromagnetic interference (EMI). Recently, leakage current reduction methods via galvanic isolation and CMV clamping has been proposed in the literature [4, 5]. New topologies have, therefore, been proposed in the recent decade such as H5 [6], H6 family [7–10], optimised H5 (oH5) [11], and positive-negative neutral point clamping [12] inverters. However, some of these topologies need a considerable number of semiconductors and thus a complicated circuit design.

On the other hand, recent developments in power semiconductor technologies have contributed to the appearance of faster switching devices. Therefore, grid-connected inverters are able to operate at higher switching frequencies and generate a better quality of output voltage and grid current with reduced filters’ size [13, 14]. Nevertheless, characteristics such as the rapid turn-on and turn-off of switching components give rise to high-frequency (HF) common-mode (CM) and differential-mode (DM) emissions also referred to as conducted EMI. CM currents circulate to the ground through parasitic capacitors and stray inductors of the power circuit. These HF disturbances...
may propagate in the neighbourhood of the PV inverter system. Therefore, they may deteriorate the lifetime of PV cells and disturb the nearby electrical equipment [15]. Accordingly, international standards on electromagnetic compatibility such as those of the Federal Communications Commission and the International Special Committee on Radio Interference are more stringent for EMI reduction in switching converters [16]. As a consequence, a thorough evaluation of EMI performance and mitigation of emissions is a fundamental step toward the final realisation of the PV inverter’s circuit. In the literature, many emission reduction methods have been used to reduce CM and DM EMI [17, 18]. The latter has a great contribution to the generation of radiated emissions [19]. Notice that the choice of an optimum EMI mitigation method needs a perfect identification and a knowledge of the inverter’s transient behaviour during commutations.

This study is interested in the H5 and optimised H5 (oH5) single-phase transformerless grid-connected PV inverters. The H5 inverter existed in the industrial market several years ago [4]. This topology has been well received in the PV market due to its good performances as regards the galvanic isolation technique. However, its performance is still poor in terms of leakage current mitigation. Hence, an oH5 topology has been developed to eliminate the leakage current by using a simple technique of CMV clamping. Nowadays, the oH5 topology offers better performances than H5 in terms of CM current reduction at a low frequency [11]. Nevertheless, as will be discussed in this study, no noticeable improvement is seen at higher frequencies.

To our knowledge, from the point of view of conducted EMI constraints, the grid-connected H5 and oH5 PV inverters have not been evaluated in the literature in a wide frequency band. In this context, the aim of this work is to perform a comparative study between the H5 and oH5 topologies in terms of conducted EMI over a wide frequency band. The comparative study is based on numerical simulations and experimental tests. Moreover, a mitigation method of HF emissions provided by the oH5 inverter is suggested using only one RC snubber circuit to reduce the HF resonance that occurs across the corresponding switching device during commutation [19, 20].

The remaining of this study is organised as follows: Section 2 is devoted to the presentation of the H5 and oH5 PV inverters topologies and their control technique. Section 3 provides a study of leakage current in both topologies. In Section 4, a conducted EMI-based comparative study is investigated. Moreover, the proposed EMI mitigation method is presented and validated. Section 5 provides experimental results and confirms the effectiveness of the proposed mitigation method of HF EMI in oH5 PV inverter. Finally, Section 6 provides the concluding remarks.

2 | H5 And oH5 GRID-CONNECTED PV Inverters

Recently, there has been a great interest in the use of transformerless grid-connected PV inverters due to their salient advantages. However, limitations associated with the lack of galvanic isolation of PV arrays from the grid during the freewheeling mode have resulted in the need for more complex topologies. The H5 inverter is an industrial topology proposed by SMA solar technology, where an extra switch $S_5$ is used in the dc-bus to avoid the problem of galvanic isolation in the conventional H4 topology (Figure 1(a)). Indeed, this switch disconnects either the positive or the negative terminals of the PV array from the grid during the freewheeling mode so as to maintain the CMV equal to half the dc-link voltage. However, in practice, it is not possible to achieve this objective because of the charging and discharging phenomena of the drain-source junction capacitors $C_{ds}$ [5, 9, 12]. Notice that, keeping the CMV constant is essential to mitigate the leakage current ($i_L$) that circulates between the PV array and the grid through the parasitic capacitors $C_{PV}$ creating a path to ground.

To achieve a better performance in terms of leakage current reduction, an additional controllable switch $S_5$ has been added to the H5 inverter. The obtained topology, referred to as oH5 (see Figure 1(b)), is able to clamp the CMV to half of the dc-bus voltage during the freewheeling mode by turning off $S_5$ and turning on $S_4$ [10].

2.1 | Modulation technique

The unipolar sine pulse width modulation (SPWM) technique is used to achieve a better quality of the modulated output voltage with three output voltage levels ($+v_{dc}$, 0, and $-v_{dc}$). This technique allows the reduction of the grid filter size ($L_1$, $L_2$, and $C_f$). The corresponding gate pulses of transistors are shown in Figures 2(a) and (b) [11–16].

During each switching period, there exists one active operation mode and one freewheeling mode. The active mode of H5 is obtained by switching on $S_5$, $S_1$, and $S_4$, when the modulation signal is positive, and $S_5$, $S_2$, and $S_3$, when the modulation signal is negative. The freewheeling mode is always performed with the switches $S_1$ and $S_3$ turned-on while the switch $S_5$ is turned off. As for the oH5 topology, the only difference is to turn-on switch $S_5$ during the freewheeling operation, that is, the dc-bus voltage becomes equal to $v_{dc}/2$. 

![FIGURE 1 Transformerless grid-connected single-phase photovoltaic (PV) inverters, (a) H5 topology, (b) optimised H5 (oH5) topology](image-url)
3 | PRELIMINARY STUDY BASED ON LEAKAGE CURRENT

The leakage current is a part of the CM current (CMC) that circulates in the PV system through the PV parasitic capacitor \( C_{PV} \) creating a path to ground. When the converter operates at the constant switching frequency, the leakage current is mainly caused by the variation in the amplitude of CMV \( v_{CM} \). Indeed, due to the use of the unipolar SPWM technique, the CMV of H5 inverter fluctuates around \( v_{dc}/2 \) [2, 3]. Notice that the total CM voltage is a function of \( v_{AN}, v_{BN}, \) the filter inductance, grid voltage and stray capacitances. According to CM and DM foundations, \( v_{CM} \) and the DM voltage \( v_{DM} \) are defined as follows [21]:

\[
\begin{align*}
    v_{CM} &= \frac{v_{AN} + v_{BN}}{2} \\
    v_{DM} &= v_{AN} - v_{BN} = v_{AB}
\end{align*}
\]

The total CM voltage \( v_{TCM} \) can be expressed as follows:

\[
v_{TCM} = v_{CM} + \frac{v_{DM}}{2} \frac{L_2 - L_1}{(L_2 + L_1)}
\]

Single-phase transformerless inverters are constructed with symmetrical filter inductances, that is, \( L_1 = L_2 \) that yields

\[
v_{CM} = v_{TCM}
\]

The generated leakage current \( i_L \) is expressed in terms of CMV and the equivalent PV parasitic capacitor \( C_{PV} \) such that

\[
i_L = C_{PV} \frac{dv_{CM}}{dt}
\]

Therefore, the leakage current can be mitigated by maintaining the CMV constant during the grid fundamental period.

\[
v_{CM} = \frac{v_{AN} + v_{BN}}{2} = \frac{v_{dc}}{2} = \text{const}
\]

In order to verify the correct operation of both topologies and compare their performances in terms of leakage current mitigation, numerical simulations are carried out with a step time equal to 1 µs. Figures 4(a) and (b) show the waveforms of the modulated output voltage, grid voltage, grid current, CMV and the leakage current obtained with the H5 and oH5 inverters, respectively. The specifications of the power conversion system are listed in Table 1. Both topologies provide a three-level output voltage and a high quality of grid current with near-unity displacement factor confirming the correct operation of the control and modulation algorithms. Furthermore, the oH5 topology provides a constant CM voltage (equals to \( v_{dc}/2 = 200 \) V) during the whole grid fundamental period and consequently a reduced leakage current that confirms its superiority to the H5 inverter.

2.2 | Grid connection and PI-based control scheme

A control block diagram that can be used for either the H5 or oH5 grid-connected inverters is depicted in Figure 3. The maximum power point tracking algorithm is not included in this control strategy. The grid voltage measurement is fed to a phase-locked loop (PLL) block to determine the instantaneous grid phase and build the reference grid current. A proportional integral (PI) controller generates the control law so that the grid current can track its target reference, that is, the inverter can inject a sinuosoidal current with unity displacement factor. The PI output is multiplied by \( L_1 + L_2 \) and added to the grid voltage. The obtained value is divided by the dc-bus voltage and used as a modulation signal fed to the SPWM block that operates as explained in Section 2.1.
FIGURE 4 Simulation results: $v_{AB}$, $i_g$, $v_{CM}$, and $i_L$ obtained with (a) H5 inverter, (b) oH5 inverter

TABLE 1 Parameters of grid-connected inverter

| Parameter                  | Value |
|----------------------------|-------|
| DC voltage ($v_{dc}$)      | 400 V |
| Grid voltage/frequency     | 230 V/50 Hz |
| Rated power                | 1000 W |
| Switching frequency        | 20 kHz |
| Bus capacitor ($C_b$)      | 470 µF |
| Filter capacitance ($C_f$) | 6.6 µF |
| Filter inductance ($L_1$, $L_2$) | 5 mH |
| Parasitic capacitance ($C_{ps1}$, $C_{ps2}$) | 100 nF |
| Ground resistance ($R_g$)   | 2 Ω   |

4 | THEORETICAL STUDY OF CONDUCTED EMI

4.1 | HF modelling of the PV inverter

Conducted EMI in the PV installation are the HF components in the CM and DM currents. They are coupled to the inter-ferred system through parasitic resistors, capacitors, inductors and metal wires. The fast switching behaviour of power semiconductors is the main source of EMI. Indeed, high $dv/dt$ and transient voltage oscillations provided by the switching devices during commutation excite the parasitic inductors and capacitors of the power circuit and provide HF resonant currents. CM emissions leave the PV inverter through the parasitic capacitors ($C_p$) of the power circuit creating a path to ground. They may also circulate through the parasitic capacitors ($C_{ps}$) of the PV frame.

The prediction of conducted EMI is based on measurements carried out on an HF model of the PV inverter [24]. Prior to HF model development, it is essential to identify and estimate parasitic parameters of the overall circuit elements [22, 23]. Figure 5 depicts a simplified schema of the HF model of the PV installation. The blue dotted lines show the DM current path, and the red dotted lines show the CMC path. $R_p$ and $L_p$ are parasitic resistors and inductors of the printed circuit board (PCB) traces. Their values are estimated with Equations (7) and (8), respectively [25]. Where $l$ is the length, $e$ is the thickness $= 0.035 \text{ mm}$, $d$ is the width, and $\rho$ is the resistivity of the track $= 1.7 \times 10^{-8} \Omega \text{ m}$.

$$R_p = \rho \frac{l}{d \times e}$$  \hspace{1cm} (7)

$$L_p = 0.2 \times 10^{-6} \times \frac{e}{l} \times \left[ \ln \left( \frac{2l}{d + e} \right) + 0.5 + 0.22 \times \left( \frac{d + e}{l} \right) \right]$$  \hspace{1cm} (8)

Furthermore, parasitic capacitors ($C_p$) between MOSFETs and the grounded heatsink are also considered. Their values are estimated using Equation (9) [26]. Where $\varepsilon_0$ is the free space permittivity and equal to $8.85 \times 10^{-12} \text{ F m}^{-1}$, $\varepsilon_r$ is the relative permittivity, $Y$ is the width of the heatsink, $H$ is the distance between the heatsink and the conducting drain plate; $A$ is the area of the bottom side of the heatsink and $d$ is the distance between the bottom side of the heatsink and the bottom side of

FIGURE 5 Simplified schema of the HF model of the PV system including the line impedance stabilising network (LISN)
the PCB board:

\[ C_p = \frac{4\varepsilon_r\varepsilon_0}{\pi} \frac{Y}{H} + \frac{A}{d} \varepsilon_0 + 0.88\varepsilon_0 \]  

(9)

Moreover, the parasitic inductances of the drain and the source of MOSFET are obtained from its corresponding datasheet. Parasitic inductance and capacitance of the grid filter and the dc-bus capacitor are measured with an impedance analyzer [27, 28]. On the other hand, a line impedance stabilising network (LISN) is connected between the inverter's ac terminals and the grid to measure the HF conducted emissions. The latter is an image of the voltage across the two 50 Ohm resistors \( R_1 \) and \( R_2 \). The CM and DM emissions are deduced from the voltages across \( R_1 \) and \( R_2 \) resistors as follows [3]:

\[ CMV_{LISN} = \frac{v_{R1} + v_{R2}}{2} \]  

(10)

\[ DMV_{LISN} = v_{R1} - v_{R2} \]  

(11)

### 4.2 | Numerical simulations

In order to compare H5 and oH5 topologies in terms of conducted EMI, numerical simulations are performed using circuit software running with a simulation step equal to 7 ns. The three-level PSPICE MOSFET model is used for each commutation cell. The same HF model presented in Figure 5 is used for both topologies since the PCB of oH5 is extended from one of H5 by simply adding the switch \( S_6 \). The values of all parasitic elements are depicted in Figure 6.

The time-domain waveforms of CMV and DMV are first obtained by measuring the voltages \( v_{R1} \) and \( v_{R2} \) across the LISN. Thereafter, their frequency spectra are deduced as shown in Figures 7(a) and (b). The obtained conducted emission spectra show that both topologies provide important HF interferences magnitudes. For instance, both topologies have a significant peak in the CMV at 10 MHz. Moreover, the amplitude of the peak is a little bit more important with the oH5, which is supposed to reduce the leakage current. This outcome is justified by the presence of the additional switch \( S_6 \) in the oH5 topology.

### 4.3 | Proposed EMI mitigation solution

To reduce the HF CM emissions of the transformerless oH5 inverter topology, we propose to add an RC snubber circuit in parallel with the additional \( S_6 \) switch as illustrated in Figure 6. This allows to damp the noise provided by this switch in its birth source. This solution is simple, not expensive, and allows reducing the size of the EMI filter. Certainly, the use of RC snubber circuits with all switching cells will reduce the EMI generated by the inverter but at the cost of higher design complexity and lower efficiency of the PV inverter. The suggested approach is, therefore, to opt for a trade-off between EMI and efficiency by adding only one snubber circuit to the additional switch \( S_6 \). To justify this choice, let us first examine the gates pulses of the oH5 over a grid fundamental period as depicted in Figure 2. The four transistors \( S_1, S_2, S_3, \) and \( S_4 \) are not commutating.
during an overall half cycle of the output voltage $v_{AB}$. Only $S_5$ and $S_6$ remain in commutation at any switching period whatever the polarity of $v_{AB}$. This implies that they commutate twice over a grid fundamental period as compared to the remaining switches. Therefore, the idea is to damp the resonance of the most disturbing source among $S_5$ and $S_6$.

Figures 8(a) and (b) illustrate the drain-source voltages across the MOSFETs of $S_6$ and $S_5$ when they are turned off. As can be seen, the most important resonance (ringing) occurs across $S_6$. The amplitude and duration of transient oscillation generated by $S_5$ are less important. Therefore, it is more judicious to add the snubber circuit with $S_6$.

The design of the RC snubber circuit needs knowledge of the exact resonant frequency ($f_r$). The minimum value of the snubber resistor ($R_{snub}$) is obtained by dividing the voltage across the switch by the maximum current rating. As for the capacitance, its value is deduced as given in Equation (12):

$$C_{snub} = \frac{1}{2 \pi f_r R_{snub}}$$  \hspace{1cm} (12)

Figure 8(c) illustrates the transient voltage across $S_6$ with a snubber circuit. As can be seen, a very important mitigation of the noise in its birth source is achieved. Furthermore, Figures 9(a) and (b) illustrate the frequency spectra of the CMV and DMV provided by the H5 inverter and oH5 inverter with snubber circuit. It is clear that the magnitude of the conducted EMI provided by the oH5 with snubber circuit at the resonant frequency of 10 MHz has become much lower than that provided by the H5 inverter. Therefore, the proposed oH5 topology with RC snubber circuit in parallel with $S_6$ provides better EMI performances than the H5 topology at both low and high frequencies.

5  | EXPERIMENTAL INVESTIGATION OF CONDUCTED EMI

A universal prototype of single-phase grid-connected PV inverter has been developed in the laboratory as illustrated in

![Figure 9](image_url)  \hspace{1cm} (a)

![Figure 10](image_url)  \hspace{1cm} (b)

Figure 10. It can operate as H5 or oH5 inverter. In order to have the same test conditions and perform a better conducted EMI-based comparative study, we used the same PCB for both power circuits of H5 and oH5. All switching cells consist of the Silicon MOS transistors (N-channel TK20N60W). The control algorithm and unipolar SPWM are implemented in real time on the DSP TMS320F28335. The optical isolation between the controller and the power circuit is ensured using the opto-drivers.
HCPL3120. For a better quantification of the CM and DM EMI, a LISN is connected between the PV inverter and the grid. The CM and DM emissions are obtained from the voltage measurement across the LISN resistors ($v_{R1}$ and $v_{R2}$) using an oscilloscope operating with a sampling rate equal to 2GS/s. The frequency-domain results are obtained by applying the fast Fourier Transform (FFT) to the measured time-domain conducted EMI. For experimental tests, the power conversion system characteristics are listed in Table 1. However, due to some equipment limitations, the dc-bus and grid voltage values are set to 120 and 50 V/50 Hz, respectively.

5.1 Experimental results

Figures 11(a) and 12(a) show the modulated output voltage $v_{AB}$ and interference voltages ($v_{R1}$ and $v_{R2}$) across the LISN resistors of H5 and oH5 topologies, respectively. As can be seen, $v_{AB}$ consists of three levels that appear because of the unipolar modulation method. The voltage $v_{AB}$ also involves an HF noise with an important amplitude caused by the switching operation of the power semiconductors. As for the voltages $v_{R1}$ and $v_{R2}$, only an HF noise can be observed implying that only HF current is circuiting through the LISN resistors. On the other hand, Figures 11(b) and 12(b) show the waveforms of the grid voltage and current obtained with the H5 and oH5 topologies. It is clear that the grid current is almost sinusoidal and in phase with the grid voltage implying that both converters can inject high-quality current with near-unity displacement factor.

Figure 13 depicts the corresponding spectra of CM and DM emissions of H5 and oH5 topologies. These obtained results show that from 20 kHz to few hundreds of kHz, the harmonic peaks are located at multiples of the switching frequency (20, 40, 60 kHz etc). However, some main peaks appear at HFs of the spectra. Moreover, the oH5 topology produces lower amplitude peaks than the H5 topology at low frequencies. Particularly, in the CM conducted EMI, the superiority of the oH5 topology is explained by the elimination of leakage current. Nevertheless, at HFs, the oH5 topology provides important conducted EMI magnitude, which is also obtained using the H5 topology. Hence, the performances of both topologies look similar at HFs, such as at 9/10 MHz. Therefore, the oH5 inverter provides less conducted emission than the H5 only at low frequencies of the EMI spectra. Moreover, it is clear that simulation and experimental results have the same tendency despite the little difference. This is due to several causes such as the accuracy of estimated PCB parasitic elements and disregarding of measurement probes’ effect, as well as the opto-drivers’ on-off delays.

5.2 Application of proposed mitigation method

The obtained results in Sections 4.2 and 4.3 showed that the switch $S_6$ produces significant conducted EMI in HF range and then limits the performances of oH5 topology. Consequently, an experimental test is carried out on the oH5 inverter with an RC snubber circuit connected in parallel with $S_6$. 
Figure 14 shows the frequency spectra of CMV and DMV of H5 and oH5 with RC snubber circuit. Notice that these spectra are obtained by applying the FFT to the time domain of CMV and DMV deduced from $v_{R1}$ and $v_{R2}$ across the LISN resistors. The obtained results show that the added RC snubber circuit provides an important reduction of the peak’s amplitude of the CM emission by approximately 10 dB at 10 MHz. Hence, these results confirm that the design of oH5 topology with only one RC snubber circuit in parallel with $S_6$ provides lower conducted emissions in the entire frequency band.

Figure 15 shows the efficiency versus the output power of H5, oH5, and oH5 with RC snubber circuit. As can be seen, despite the addition of the RC snubber circuit, the efficiency of oH5 inverter with the proposed resonance mitigation across $S_6$ remains very close to that of H5 for an output power varying from 300 W to 1 kW. This is due to the fact that we used only one snubber circuit connected in parallel with the extra switch $S_6$. Therefore, a considerable reduction in the EMI amplitude is achieved without worsening the inverter’s efficiency. The proposed EMI mitigation method can, therefore, be considered as an adequate and preferred solution for the transformerless grid-connected oH5 PV inverter.

6 | CONCLUSION

The connection of PV inverters to the grid without transformers leads to serious EMI problems that may affect the electric systems in the neighbourhood of the PV installation. In this study, a conducted EMI-based comparative study was carried out between two single-phase transformerless grid-connected PV inverters, namely, H5 and oH5. The obtained results showed that the oH5 inverter has provided better EMI performances than the H5 at low frequencies. However, in the HF range, both
H5 and oH5 inverters provide significant interference magnitudes in the frequency spectra of CMV and DMV. Moreover, an EMI mitigation method of oH5 inverter has been proposed using only one RC snubber circuit in parallel with the extra switch \( S_p \). Consequently, the oH5 inverter with the RC snubber circuit provided lower conducted EMI than the H5 in a wider frequency band. This very important enhancement of EMI performance was achieved without worsening the PV inverter’s efficiency.

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