Study of Grid-Connected Inverter under Modified PWM Control for EMI Mitigation in Photovoltaic Application

S. Kraiem, S. Hedia, J. Ben Hadj Slama, H. Nkwawo, T. Ahmed-Ali

Abstract— **This paper presents an electromagnetic study regarding a real-time implementation of advanced sinusoidal pulse width modulation (SPWM) techniques, applied to a single-phase transformless inverter used in photovoltaic (PV) applications. For experimental investigations, a laboratory prototype of a transformerless H5 grid-connected PV inverter has been developed. Hardware implementations of different control strategies have been carried out using a digital signal processor (DSP) TMS320F28335 platform. Optimization of the equipment configuration has been established through several simulation tools. A co-simulation interface has been created using a circuit type software and a computing environment. The aim of this work is to assess control and modulation methods from an electromagnetic compatibility (EMC) point of view. In particular, conducted EMI can cause a bunch of serious issues while building a grid-tied PV power system. Hence, obtained results have been analyzed considering the ability of delivering a significant reduction in the amplitude of common-mode (CM) voltage.**

I. Introduction

The unprecedented energy crisis has triggered an attention shift in favor of renewable energy. In particular, developments in solar photovoltaic (PV) have received a tremendous concern. Indeed, a lot of it comes also from the fact that PV systems have been already used and successfully grid-tied in order to generate sustainable energy [1]. For instance, nowadays, it is common to install transformlerless PV inverter in residential buildings. It is not costly and it has a good efficiency. Nonetheless, this topology proposes a direct connexion of the PV panel to the grid, which creates several safety and degradation problems. In fact, a major issue in PV applications is common mode (CM) voltage fluctuations. In the one hand, this leads to a high leakage current generation. In the other hand, stray capacitances appears between PV cells and the ground, which stimulates the occurrence of a ground current [2]. Indeed, these are serious issues and can be harmful to the inverter since it affects the electromagnetic compatibility (EMC) compliance of the system.

Indeed, in power converters, radiated and conducted electromagnetic interferences (EMI) occur due to the high-speed switching activity of power semiconductor devices. Hence, in order to reduce high current and voltage changes (di/dt and dv/dt), researchers have attempted to figure out new topologies and control strategies. To confirm EMC requirements, many early stage design considerations have to be made. In particular, a lot of attention is given to the board layout optimization, components selection, EMI filters and shielding efficiency [3]. However, far less work has been conducted to assess control techniques from an EMC point of view.

Hence, with the aim of reducing EMI of power electronic converters, it is also crucial to improve pulse width modulation (PWM) techniques [4]. In the literature, the laters are classified bipolar and unipolar sine pulse width modulations (BSPWM and USPWM). BSPWM generates a two level output voltages varying between $+V_{AN}$ and $-V_{BN}$, which produces a large current ripple and increases the size of the output filter. However, it has been shown that conventional USPWM offers reduced switching losses and a lower total harmonic distortion (THD) compared to BPWM. Nonetheless, most of research works have revealed that due to the constant switching frequency, significant peaks of EMI occur on multiples of this switching frequency. In order to spread these harmonic peaks over a wide frequency band, a variable switching frequency is preferred. Within this context, in the literature, modified unipolar modulation techniques have been established, such as randomized and chaotic USPWM [5 - 7].

In this paper, a detailed conducted EMI mitigation performance study has been carried out based on advanced USPWM control strategies over a frequency range of 10 kHz to 30 MHz. First, a new co-simulation platform has been developed to simulate the behavior of the studied structure under each chosen control technique. Second, a real-time implementation has been investigated using an experimental test stand including a single-phase transformerless inverter connected to photovoltaic panel. The aim of this work is to provide a practical guide to assess the impact of control techniques in EMI mitigation for power systems.

The rest of the paper is organized as follows: Section II presents the proposed studied structure and Section III exhibits the numerical simulation results and a comparative analysis.

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Section IV depicts the experimental test stand and presents EMI measurements results and Section V gives the main conclusions.

II. PROPBLEM STATEMENT AND SYSTEM DESCRIPTION

In renewable energy systems, inverters are the main devices for power delivery. In particular, for PV systems, electrical inverter isolation generates serious issues. Indeed, galvanic separation between the AC and the DC circuits is the common technique to remove undesired effects of leakage currents and prevent DC disturbances and dangerous harmonics transmission to the public grid. An isolation transformer and a clean wiring can entirely isolate (electrically and physically) the output power circuit from the input circuit. However, it has been shown that this transformer influences notably the system efficiency and weight.

In fact, even with using latest technology, removing the isolation transformer recalls the main concerns about having a direct connection with the grid creating a common-mode (CM) current circulation. It is also possible that the variation of CM voltages electrifies the resonant circuit and provoke even a higher leakage current through the ground (depending on the topology design and control strategies) [2] [8]. Hence, a detailed EMI mitigation study is necessary to deal with transformerless inverters.

In order to carry out CM characteristics investigations of a single-phase grid-connected PV system, a full-bridge (FB) transformerless inverter is an interesting structure to study (Fig 1). Voltages between reference terminal N and mid-points of bridge legs A and B, noted $v_{AN}$and v_{BN} respectively, are depicted in Fig. 1. v_{AB} is the output voltage of the inverter. $C_{dc}$is the DC bus capacitor, L_f and C_f perform low pass filtering. The CM voltage $v_{CM}$is defined as follows:

$$v_{CM} = \frac{v_{AN} + v_{BN}}{2} \tag{1}$$

According to (1), the CM voltage (CMV) is obtained based on bridge-legs voltages, which varies from one inverter topology to another. Therefore, the design topology and the modulation scheme play a crucial role to minimize the leakage current and keep a constant level of CMV. In general, sinusoidal PWM (SPWM) is widely employed in such applications since it allows a direct control of the output voltage and the output frequency [9] [10]. For the scope of this paper, we restrict this study to the use of the conventional unipolar SPWM technique.

Several researchers have addressed the CMV issues with the aim to reduce or eliminate the disturbing leakage current paths by proposing different modified FB topologies. In this work, a H5 inverter topology is proposed. It is a popular commercial transformerless single-phase PV structures. In this topology, an additional power switch is implemented between the positive (or negative) DC pole and the PV array. This additional switch S5 is turned OFF during the freewheeling mode in order to ensure a galvanic isolation. In this section, an EMI mitigation study performed on a H5 transformerless PV inverter based on modified USPWM is established.

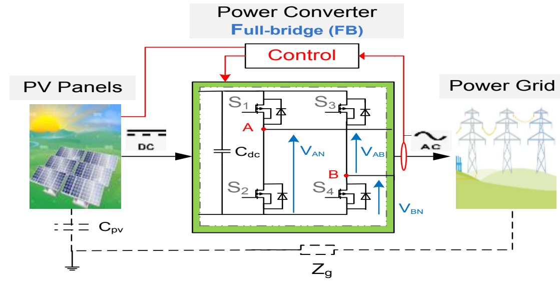


Figure 1. Transformerless FB inverter topology for single-phase grid-tied PV application

III. SIMULATION RESULTS AND COMPARATIVE ANALYSIS

In order to evaluate the impact of control strategies on CM EMI mitigation, simulations have been carried out based on the electrical performance of a simulated model of a grid-tied H5 inverter topology. The employed PV conversion system parameters are shown in Table I. Implementations have been done using MATLAB-Simulink.

TABLE I. CONFIGURATION PARAMETERS OF SIMULATION TESTS

Parameters	***Value***
PV voltage, V_{PV}	400V
Grid voltage/frequency	230V/50Hz
Switching frequency	20 kHz
Bus capacitor C_{dc}	470 uF
Filter's capacitor, C_f	6.6 uF
Filter's inductors, L_f	5 mH
PV parasitic capacitor, C_{PV}	100 nF

A. *Application of the conventional USPWM*

USPWM is a three-level modulation technique, generating three-level output voltages: + V_{PV}, 0, and – V_{PV}. In the conventional strategy, to provide the required gating signals for the switches, USPWM technique is based on making a comparison of two sinusoidal modulating waveforms (with same magnitude and frequency, but are in opposite phases), to a common triangular waveform (with a fixed switching frequency). These reference and carrier signals are depicted in Fig. 2.

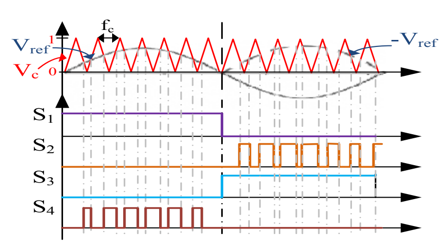


Figure 2. Conventional USPWM control signals for FB.

During the switching activity, diagonal pairs of switches S_1-S_4 (or S_2- S_3) are commuting at positive (or negative) half cycles with a fixed switching frequency, Fig. 3. In the positive half cycle, when S1 and S4 are turned on: $v_{AN} = V_{PV}$ and $v_{BN} = 0$, then $v_{CM}= V_{PV}/2$, and when S1 and S4 are turned off: $v_{CM} \neq V_{pv}/2$. Similarly, for the negative half cycle. Hence, it is clear that USPWM creates variable CMV.

For a H5 PV inverter under USPWM, the control signal of its five switches (S1-S5) is generated by comparing two low-frequencies sinusoidal modulated signals with the high-frequency carrier signal [11] [12]. The switching frequency is defined by the carrier frequency, Fig. 3.

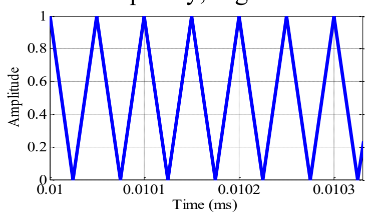


Figure 3. Carrier waveform for USPWM.

Fig. 4 and 5 present the simulation results of the USPWM control strategy. The inverter output voltage and the grid voltage/current waveforms are shown in Fig. 4(a–b), while the CM current is depicted in Fig. 4(c). A constant CM voltage results in zero CM current, whereas high-frequency CM voltage variations generate CM current. The FFT spectra and THD of the output voltage and current are illustrated in Fig. 5(a–b), showing harmonic components over several tens of kilohertz. Lower THD indicates reduced EMI and noise.

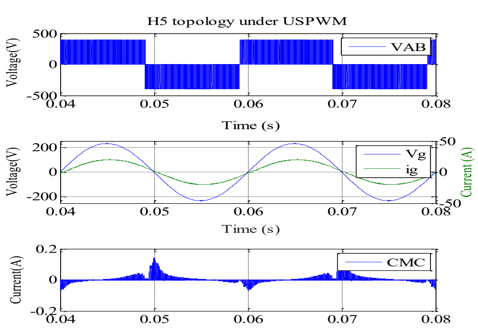
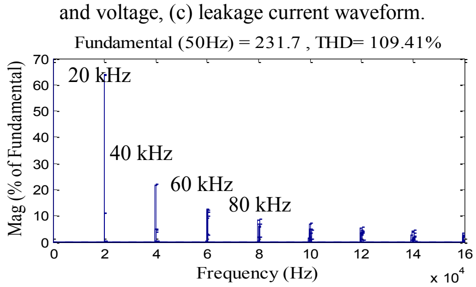
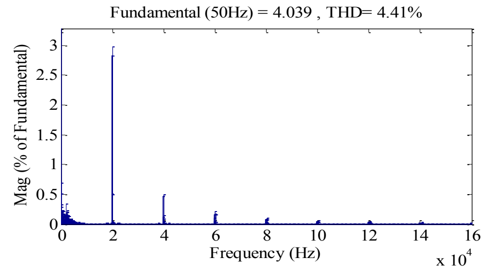


Figure 4. Obtained results for unipolar modulation: (a) v_{AB}, (b) grid current and voltage, (c) leakage current waveform.



(a)



(b)

Figure 5. Obtained outputs frequency spectrum for unipolar modulation: (a) voltage, (b) current.

B. *Application of Randomized USPWM*

Authors in [13] has proposed the use of a random PWM. It had been demonstrated that if a carrier sequence has a very high random degree, harmonic peaks would be scattered to other frequency points. It is worth noting that the increase of harmonic dispersion in the frequency domain depends on improving random PWM by changing strategies and random variables. Yet, there has not been an established standard to judge how the stochastic degree is depending on each of the random strategies. There is no doubt that a proper variable frequency PWM can affect the switching-related energy attenuation in some particular frequency spectrum parts, achieving EMI and acoustic noise reduction [6]. Indeed, RUSPWM distributes harmonics spectrum of the output voltage of the inverter in a random manner without affecting the fundamental frequency component. Random switching schemes are based on the comparison of a randomly generated signal with the reference waveform.

Assuming that v_c is the carrier sequence, T_c is a fixed carrier period and T_i is the variable carrier period (corresponding to the carrier frequency f_i). The random carrier sequence can be expressed as $\{T_1, T_2, .., T_n\}$, where n is the number of the random carriers. The average value of this sequence is given in (2). An example of generated random carrier signal for RUSPWM is illustrated in Fig. 6 and is used for the control of the proposed structure.

$$T_c = \frac{1}{n}(T_1 + T_2 + \ldots + T_n) \qquad (2)$$

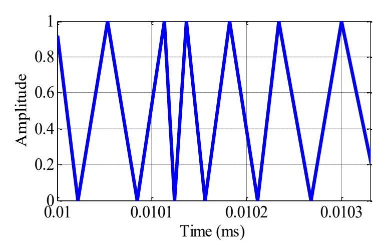
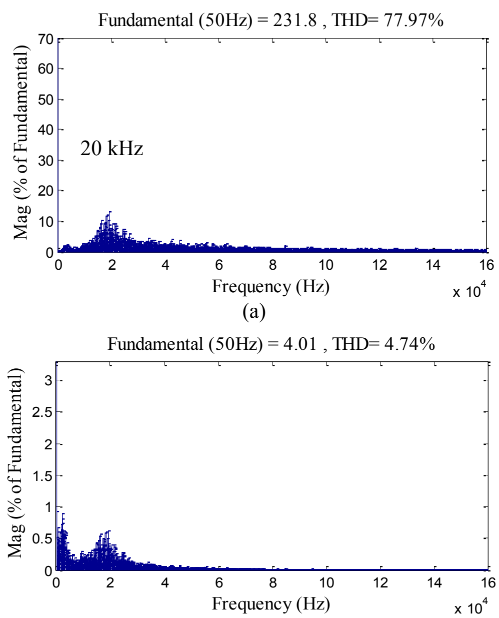


Figure 6. Random carrier signal for RUSPWM.

Applying a random switching signal to the H5 inverter instead of a conventional cyclic switching frequency produces acceptable output signals. Compared to classical modulation, RUSPWM reduces harmonic distortion by spreading harmonics over a wider frequency range rather than eliminating them (Fig.7). As shown by the THD values in Table 2, the harmonic performance depends on the applied random control signal. For example, the THD of the grid current varies significantly between tests, decreasing from about 109% with conventional USPWM to values such as 78% or 55.6% under random modulation. However, the results remain inconsistent, as repeated tests with the same random strategy do not guarantee stable or optimal THD reduction due to variations in pulse positions.

TABLE II. OBTAINED THD USING RUSWPM CONTROL SIGNALS

THD (%)	Test1	Test2	Test3	Test4	Test5	Test6
$V_{AB}(t)$	77.97	55.6	77.22	75.77	76.51	70.99
$i_g(t)$	4.74	3.11	4.94	4.57	4.69	4.00



(b)

Figure 7. Outputs spectra under RUSPWM: (a) v_{AB} (b) current

C. Application of a Chaotic USPWM

The main concern when dealing with power inverters is reducing harmonics and improving the frequency spectrum distribution. In the literature, it has been established that the chaotic modulated signal does not decrease performance, but even better, it offers lower costs. Therefore, although the fact that chaotic behavior studies can be complex while the engineering design process, chaotic PWM is worthy for further researches and being used in practice.

The chaotic triangular carrier signal corresponding to chaotic PWM is generated using the simulated chaotic carrier scheme described in [12]. The waveform of the chaotic carrier applied to the studied structure is shown in Fig. 8.

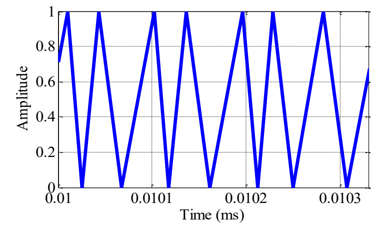
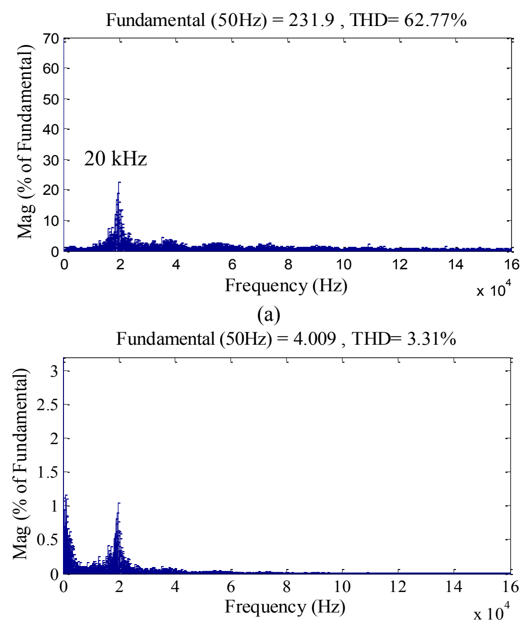


Figure 8. Chaotic carrier signal for CUSPWM

Compared to a conventional modulation, we observe a considerable reduction in harmonics magnitude, as shown in Fig.12. In addition, compared to the frequency spectrum in Fig. 8 (a) where peaks are concentrated at multiples of the switching frequency (around 40 kHz, 60 kHz, 80 kHz, etc.), under a CUPWM control harmonics around the aforementioned frequencies are distributed all over the frequency band. Moreover, a significant decrease in THD values is noticed for both voltage and current outputs.



(b)

Figure 9. Outputs spectra with CUSPWM: (a) v_{AB}, (b) i_g current.

D. Comparative EMI study based on HF modeling

In order to evaluate the impact of previous USPWM control strategies on CM disturbances over a wide frequency band, a high frequency (HF) model of the studied H5 transformerless inverter has been carried out. All stray elements of the circuit tracks have been considered along with the layout. As depicted in Fig. 10, in addition to parasitic capacitances between transistors and the grounded heatsink, the parasitic inductances of the drain and the source of the five MOSFETs have to be taken into account. Their corresponding values can be found in components datasheets. Furthermore, in order to measure CM voltage, a line impedance stabilized network (LISN) is placed between AC terminals of the studied H5 and the grid.

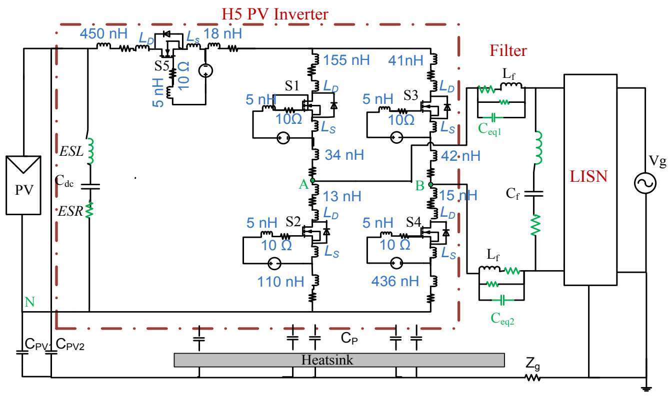


Figure 10. HF model of transformerless H5 topology.

Numerical HF model of a grid-connected H5 inverter and a LISN filter has been implemented using a circuit-type software running with a 10 ns simulation time step. Thereafter, control signals generation using the aforementioned USPWM techniques has been performed through Simulink environment. Hence, a co-simulation of circuit-type based software and Matlab/simulink has been achieved. On the one hand, this approach offers options from an electromagnetic field solver with a precise physics-based modeling environment. On the other hand, it provides the ease of control algorithms implementation. Indeed, this new co-simulation platform perfectly serves the needs for the present EMI study with offering powerful tools of both time and frequency domain analysis for power electronics systems.

Using the proposed co-simulation platform, we have simulated the whole behavior of the studied structure under the control of the three aforementioned strategies. CMV has been also obtained at the terminals of the LISN. Fig. 11 shows a comparison between the spectrum of the output CM voltage using conventional USPWM, RUSPWM and CUSPWM. As it can be noticed, when comparing to obtained standard USPWM method results, both RUSPWM and CUSPWM ensure a significant reduction in the amplitude of harmonic peaks at the carrier frequency and its multiples. Therefore, for grid-connected PV inverters, these modulation techniques can be good alternatives to reduce EMI without adding any additional bulky and heavy devices or components especially in low frequencies.

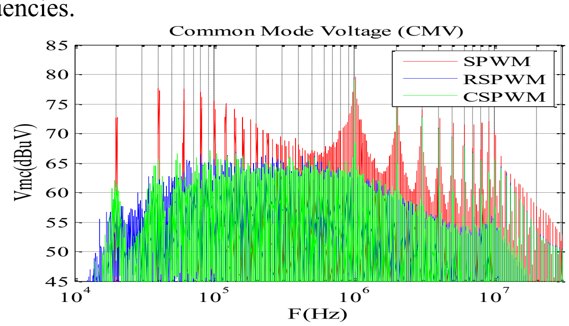


Figure 11. Spectrum of CM voltage in HF model of H5 inverter.

IV. EXPERIMENTAL TEST STAND AND REAL-TIME MEASUREMENTS

In the previous section, the proposed EMI study demonstrated that CUSPWM is more advantageous than RUSPWM at low frequencies when used as a control strategy for the H5 topology. To validate these results, a DSP-based real-time implementation of CUSPWM is presented in this section, followed by a comparative analysis.

With the aim to validate previous simulation results, DSP real time implementations of conventional and chaotic unipolar SPWM techniques are performed. Then, they are applied to a laboratory prototype of a transformerless H5 grid-connected PV inverter. The developed test stand is illustrated in Fig.12.

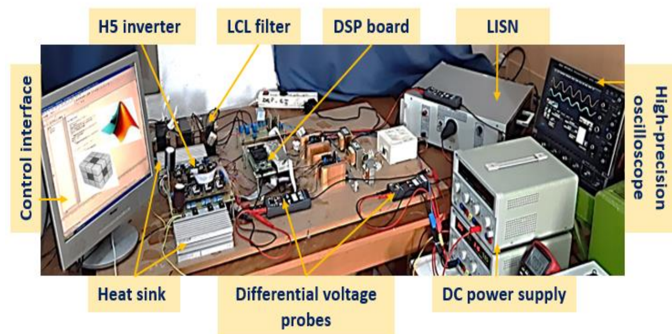


Figure 12. In-lab test stand of a single-phase transformerless grid-connected PV inverter.

Time domain Conducted emissions are measured using a high precision oscilloscope. Whereas, the frequency spectrum is obtained by simply applying a fast Fourier transform. Obtained spectrum is depicted in Fig.13. Frequency-domain signals are distributed in a band strating from 150 kHz to 30 MHz. It is clear from Fig. 13 that in case of a conventional USPWM, harmonic peaks are located exactly at multiples of the switching frequency (20 kHz, 40 kHz, 60 kHz, etc.). For CUSPWM, the energy at each of harmonic is distributed over the defined bandwidth with reduced peak amplitudes (of about 10 dBuV compared to classical USPWM). This clearly reveals the spread spectrum effect of the studied chaotic modulation technique, which reduces the impact of interferences, noise, etc.

Figs. 14 and 15 show THD values of the output voltage v_{AB} and output current i_g under the control of USWPM and CUSPWM, respectively. Obtained results are quite similar to those expected by previous numerical simulations, which validates the efficiency of the real-time implementation and highlights the pertinence of the chaotic modulation control. In addition, experimental results confirm the usefulness of developed co-simulation platforms when carrying out a detailed EMI investigation, in particular for the control strategies assessment.

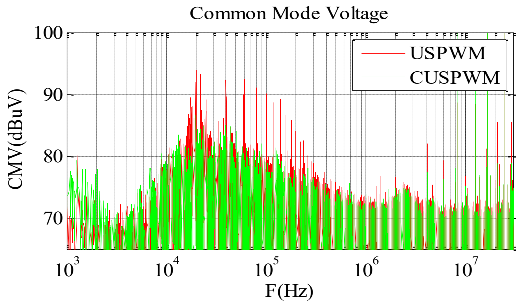
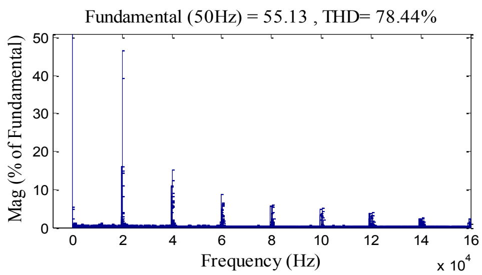
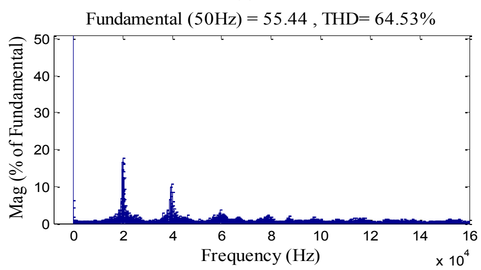


Figure 13. Frequency spectrum of conducted emissions under strategies: USPWM and CUSPWM

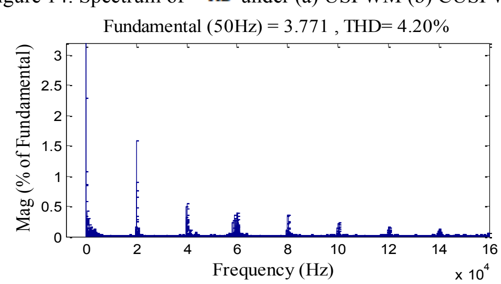


(a)



(b)

Figure 14. Spectrum of v_{AB} under (a) USPWM (b) CUSPWM.



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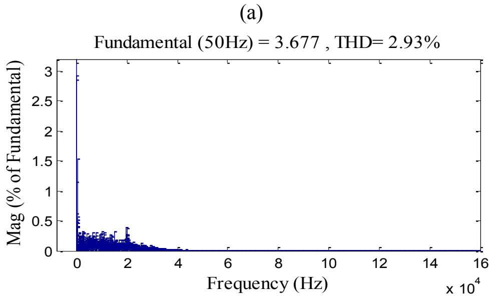

(b)

Figure 15. FFT of current i_g under (a) USPWM (b) CUSPWM.

V. CONCLUSIONS

This paper evaluates the impact of modulation strategies on inverter EMC performance. Conventional, randomized, and chaotic unipolar SPWM are compared on a transformerless single-phase H5 PV inverter. Results show that chaotic modulation provides the best EMI reduction by spreading harmonics over the frequency spectrum, achieving up to 10 dB lower conducted emissions at low frequencies without additional filtering. The study highlights the trade-off between modulation technique and inverter topology for effective EMI mitigation.

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