Hysteresis current control for single-phase transformerless inverter

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ABSTRACT

The total harmonic distortion (THD) of grid current and leakage current are significant for transformerless inverters, as they impact power quality, efficiency, and compliance with grid codes. Monitoring and minimizing these currents ensure safe and reliable grid integration of photovoltaic (PV) systems while reducing electromagnetic interference. Therefore, in this paper, the analysis THD of grid current and leakage current is described. The bipolar pulse width modulation (BPWM) technology provides a stable common-mode voltage (200 V), fewer leakage currents (< 30 mA), and better system efficiency, compared to the unipolar pulse width modulation (UPWM) technique. To ensure the inverter complies with the IEC 61000-3-2 class C (THDi < 5%), the current control strategy should be considered during the design of the transformerless inverter. Therefore, this paper presents an implementation and evaluation of the bipolar hysteresis current control (BHCC) technique. In comparison to the BPWM technique, the BHCC technique delivers lower leakage current (0.007274 A), reduced grid current harmonic distortion (1.81%), and increased efficiency.

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1. INTRODUCTION

There is no denying that the usage of photovoltaic (PV) systems in business and residential settings helps to minimize the usage of fossil fuels. PV systems connected to the grid are frequently connected through a transformer. Although a transformer provides galvanic isolation between the DC and AC parts, its disadvantages include decreased efficiency, increased bulk, and weight [1], [2]. Thus, many researchers have recently introduced the PV grid transformerless inverter technology [3], [4]. When the transformer is removed, a galvanic connection is made between the PV module and the electrical grid, and the common mode (CM) leakage current is generated [5]. In [6], the maximum common mode leakage current allowed by the VDE 0126-1-1 standard is 300 mA (ICM < 300 mArms). High common mode leakage current in transformerless inverter grid-connected systems can lead to electrical safety hazards, electromagnetic interference, and ground loop issues. It may cause device malfunctions, equipment damage, and pose risks to personnel. Effective mitigation strategies are necessary to ensure safe and reliable operation of the system [7].

To mitigate high common mode leakage current in transformerless inverter grid-connected systems, several strategies can be employed. The first one uses bipolar sinusoidal pulse width modulation (SPWM) modulation, which prevents changes in the common mode voltage and consequently lowers leakage current [8],

[9]. The second strategy is to disconnect PV modules from the grid when the common mode voltage fluctuates. Therefore in [2], [10], [11] the various topologies for single-phase transformerless inverters, including HERIC, H5, HBZVR-D, and H6 are introduced. Each topology employs different circuit arrangements and control strategies to minimize common mode leakage current and ensure safe and efficient grid-connected operation. The third strategy is proposed the filter design. The grid connection through a modified LCL filter is a promising alternative for the reduction of the common mode leakage current [12], [13].

A low total harmonic distortion (THD) current in transformerless inverters is crucial for ensuring the stable and efficient operation of electrical systems. By regulating the output current, it ensures optimal power delivery to the grid while minimizing harmonic distortion and reducing electromagnetic interference. This enables reliable grid-connected applications with improved power quality and performance. Certainly, some common techniques are used for current control in transformerless inverters such as hysteresis current control, predictive control, and proportional integral derivative (PID) control. Predictive control in transformerless inverters anticipates future system behavior to adjust switching signals, ensuring precise current regulation, and minimizing distortion [14]. Hysteresis control compares actual current with predefined thresholds, swiftly switching to maintain regulation within a set band [15], [16]. PID control adjusts inverter output based on error, incorporating proportional, integral, and derivative terms for precise regulation [17]. Hysteresis control in transformerless inverters offers rapid response and simplicity, swiftly adjusting switching signals based on current deviations within a preset band. Unlike predictive and PID control. It requires minimal computational resources and is less sensitive to parameter variations, making it suitable for real-time applications with stringent response requirements.

Accordingly, the strategy impact on common mode leakage current and current control technique for regulating output current was found in the literature. Therefore, this paper presents a methodology for designing a transformerless H-bridge inverter with a bipolar PWM technique. In section 3, the performance between bipolar pulse width modulation (BPWM) and unipolar pulse width modulation (UPWM), bipolar pulse width modulation without hysteresis current control (BPWM), and bipolar hysteresis current control (BHCC) in terms of THD load current, THD leakage current and power conversion efficiency are presented. To validate the theoretical approach, simulation data for a 1 kW model are presented.

2. SINGLE PHASE TRANSFORMERLESS INVERTER

Figure 1 shows the configuration of a single-phase transformerless inverter, which includes a PV model, an H-bridge inverter, and an AC LCL filter. The mechanical structure of the PV modules and their installation is defined as parasitic capacitance (CPV). The parasitic capacitance (CPV) due to grounded support PV modules frame is modeled in Figure 1 where i is actual current and i^* is the reference current. Parasitic capacitance creates a pathway for common mode leakage currents, potentially causing safety concerns and affecting transformerless inverter performance. The maximum leakage current allowed by the VDE 0126-1-1 standard is 300 mA (ICM < 300 mArms) [18]. The surface of the PV array and the grounded frame affect the parasitic capacitance value, in [19], the parasitic capacitance changes between 50 nF and 150 nF per kW of installed PV panels.

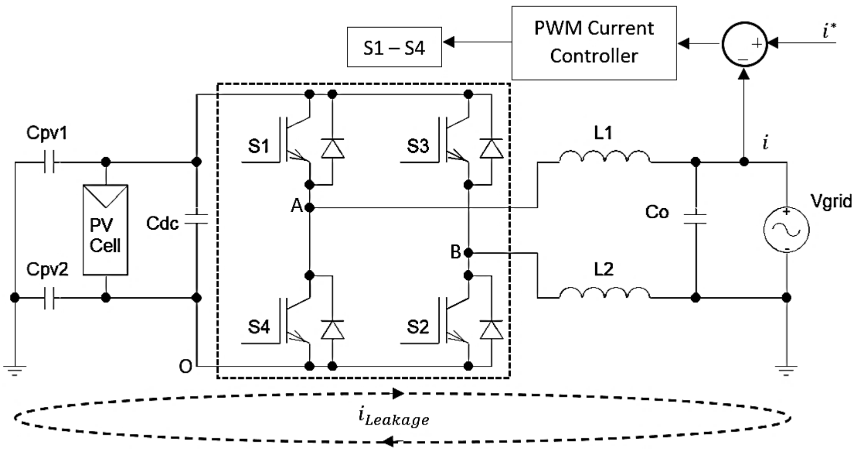

Figure 1. Leakage current path of single-phase transformerless inverter

The path of the generated leakage current is also affected by the value of parasitic capacitance (CPV) is estimated by (1).

$$ICM = \mathrm{CPV}\frac{dVCM}{\mathrm{dt}} \quad (1)$$

The conduction path of the leakage current in typical transformerless inverters is illustrated. in Figure 1 is caused by the instantaneous common-mode voltage (VCM). The VCM can be found. using (2) [20], [21] on the voltage potential respectively at points A and B to the neutral point.

$$VCM = \frac{\mathrm{V_{AO}+V_{BO}}}{2} \quad (2)$$

2.1. Design parameters

A nominal output voltage (VO) of 230 Vrms is required from the inverter due to grid-connected applications. The (3) is thus used to calculate the required input voltage (VPV) value.

$$VO = (ma)(VPV) \quad (3)$$

Since m_a is 0.8.

$$(230\, Vrms)(\sqrt{2}) = (0.8)(VDC)$$
$$VDC = 406\, V \approx 400\, V$$

H-bridge circuit employs insulated-gate bipolar transistors (IGBT) in parallel with diode switches. The LCL filter in transformerless inverters is significant for mitigating leakage current by providing effective filtering of common mode voltage [22]. The value of LCL is calculated using the (4) and (5) [23].

$$\mathrm{L} = \frac{1}{8}\frac{\mathrm{VDC}}{\Delta_{\mathrm{ripple,max}}\mathrm{f_{sw}}} \quad (4)$$

$$\mathrm{C} = \left(\frac{10}{2\pi \mathrm{f_{sw}}}\right)^2\left(\frac{1}{\mathrm{L}}\right) \quad (5)$$

2.2. Bipolar PWM and unipolar PWM technique

The bipolar and unipolar PWM techniques are applied in the H-bridge and the common mode voltage is analyzed. The bipolar PWM output voltage and common mode voltage are shown in Table 1. It concludes that bipolar switching generates two output voltage levels with a steady common mode voltage [24]. Maintaining a constant common mode voltage is essential for minimizing leakage current in transformerless inverters [25], [26].

The unipolar PWM output voltage and common mode voltage are shown in Table 2. The three output voltage levels and fluctuating common mode voltage levels resulting from the unipolar PWM technique are identified. Bipolar and unipolar PWM techniques reveal distinct impacts on leakage current in PV transformerless inverter systems. Unipolar PWM, with three-level output voltage (VDC, 0 V, -VDC), may lead to higher leakage currents due to its wider voltage swings. Conversely, bipolar PWM, with two-level output voltage (VDC, -VDC), tends to exhibit lower leakage currents, enhancing system efficiency, and reliability. Through detailed analysis, this paper optimizes modulation techniques to mitigate leakage currents and improve the overall performance of the proposed transformerless inverter for PV grid-connected applications.

Table 1. Bipolar PWM mode

S1	S2	S3	S4	VO	V_{AO}	V_{BO}	VCM
On	On	Off	Off	$+VDC$	VDC	0	$\frac{VDC}{2}$
Off	Off	On	On	$-VDC$	0	VDC	$\frac{VDC}{2}$

Table 2. Unipolar PWM mode

S1	S2	S3	S4	VO	V_{AO}	V_{BO}	VCM
On	Off	On	Off	0	VDC	VDC	VDC
On	On	Off	Off	$+VDC$	VDC	0	$\frac{VDC}{2}$
Off	On	Off	On	0	0	0	0
Off	Off	On	On	$-VDC$	0	VDC	$\frac{VDC}{2}$

2.3. Bipolar hysteresis current control technique

Bipolar hysteresis PWM in transformerless inverters offers enhanced performance by reducing harmonic distortion and electromagnetic interference. Its bidirectional control improves efficiency and power quality, making it suitable for various grid-connected applications with stringent performance requirements. Bipolar hysteresis current control as shown in Figure 2 regulates the inverter current output by comparing the actual current (i) with upper (n) and lower (m) thresholds. When the current exceeds the thresholds, the inverter switches direction, maintaining the current within the hysteresis band [27].

Hysteresis bipolar current control in transformerless inverters ensures precise regulation by swiftly adjusting switching signals within a preset band. This approach effectively reduces total harmonic distortion (THD) of the current output, enhancing power quality and efficiency in grid-connected applications. The THD of current is calculated by (6) [28].

$$THD(m),\% = \frac{\sqrt{\sum_{n\neq 1}^{\infty} {I_n}^2}}{I_1} \times 100 \quad (6)$$

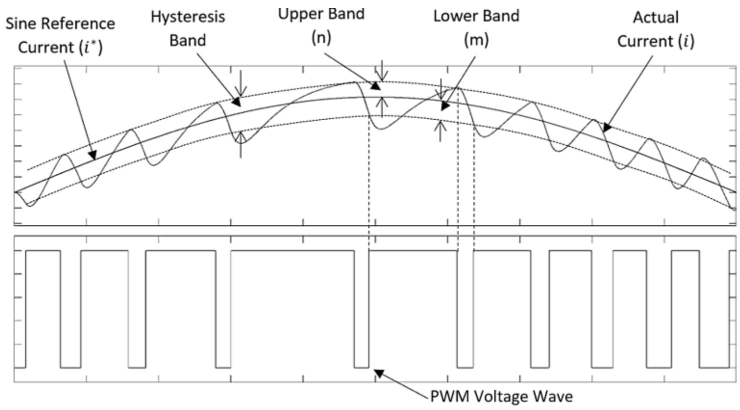

Figure 2. Bipolar hysteresis current control

3. SIMULATION RESULTS AND DISCUSSION

The circuit of single-phase transformerless inverter with bipolar SPWM, unipolar PWM, and bipolar hysteresis current control are simulated using MATLAB/Simulink tool. The simulation parameter of the proposed single-phase transformerless inverter is illustrated in Table 3. Unipolar PWM offers half of the bipolar PWM switching frequency while maintaining the value of the inductor, L. The parasitic capacitance value, denoted as CPV, is specified at 150 nF.

Table 3. Single-phase transformerless inverter parameters

No.	Parameters	Values
1.	Switching frequency	8 kHz (BPWM) and 4 kHz (UPWM)
2.	Inductance L1 and L2	19.79 mH
3.	Capacitance	2 μF
4.	Parasitic capacitance	150 nF
5.	Output power	1 kW

Figures 3 and 4 demonstrate the output voltage (V_{AB}) of an inverter when bipolar and unipolar PWM are utilized. The unipolar PWM generates three-level output voltages while bipolar PWM produces two-level output voltage. As highlighted in 2.2, the observation of common mode leakage current (ICM) is investigated further in this section. In Figures 5 and 6, the common mode voltage (VCM) is constant when using the bipolar PWM technique rather than the unipolar PWM technique.

Figure 7 illustrates how stabilizing the common mode voltage (VCM) mitigates oscillations that could lead to higher leakage current. Variations in common-mode voltage, as seen in Figure 8, can cause higher common-mode leakage currents. Figures 9 and 10 show the total harmonic distortion (THD) simulation results of output current and leakage current for bipolar (BPWM) and unipolar PWM (UPWM) switching techniques. As shown in Figure 10, the higher output current total harmonic distortion (THD) which is 29.58% and is corresponds with a higher common-mode leakage current.

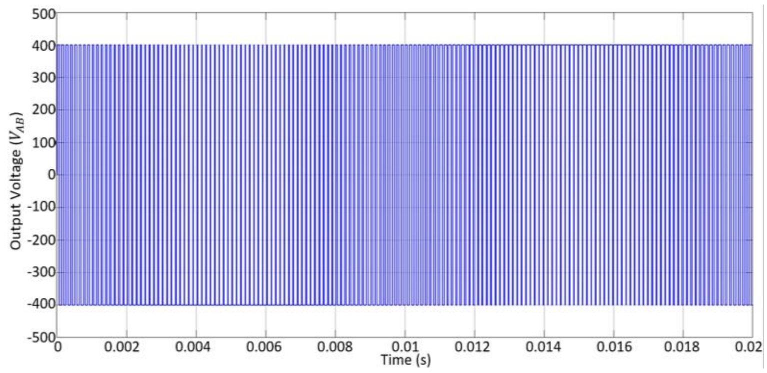

Figure 3. Output voltage (V_{AB}) of BPWM

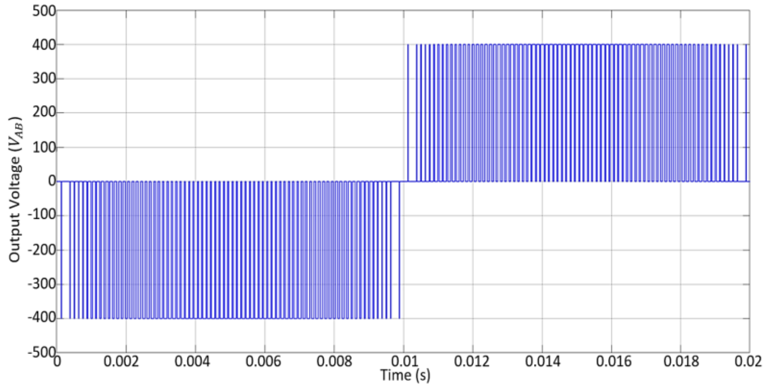

Figure 4. Output voltage (V_{AB}) of UPWM

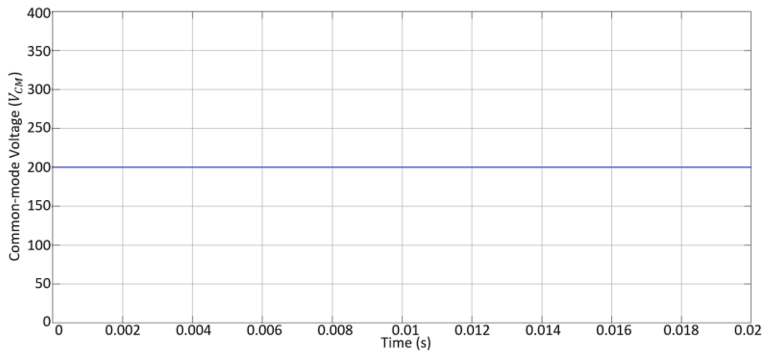

Figure 5. Common mode voltage (VCM) of BPWM

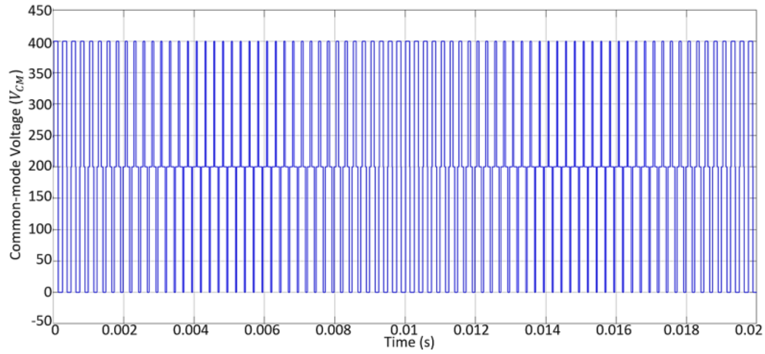

Figure 6. Common mode voltage (VCM) of UPWM

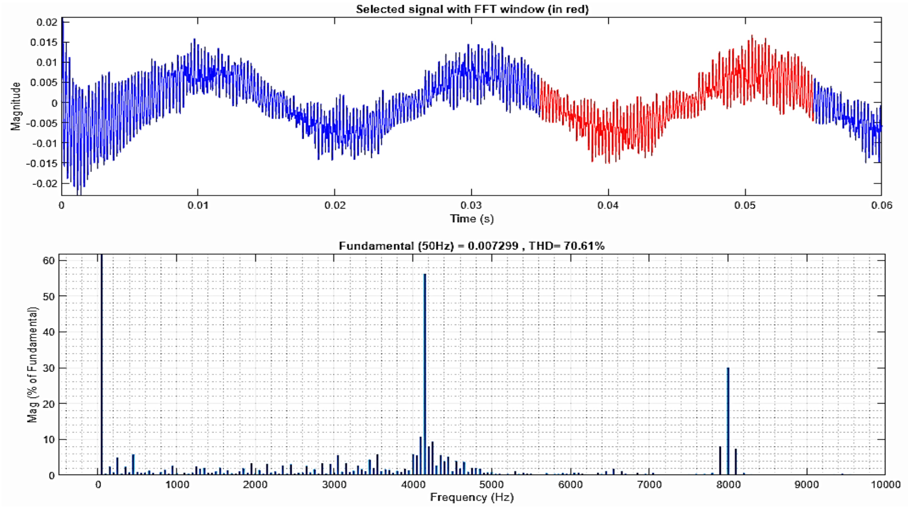

Figure 7. Leakage current with BPWM technique

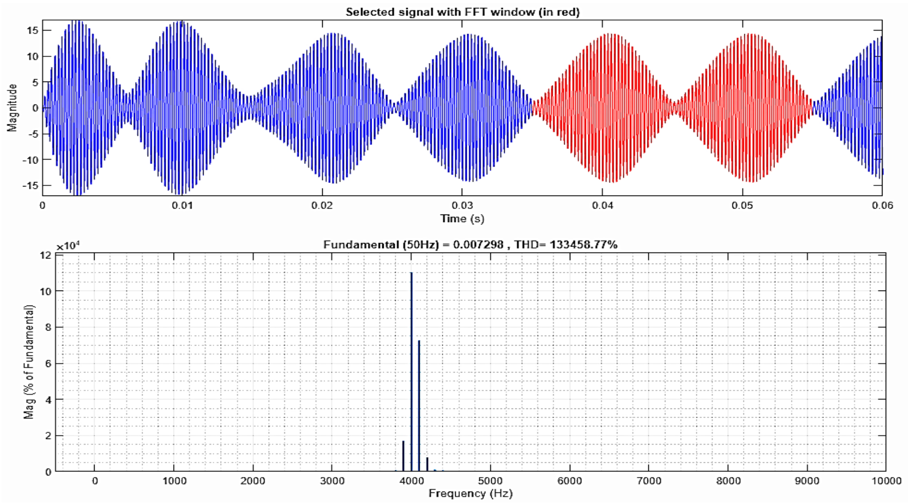

Figure 8. Leakage current with UPWM technique

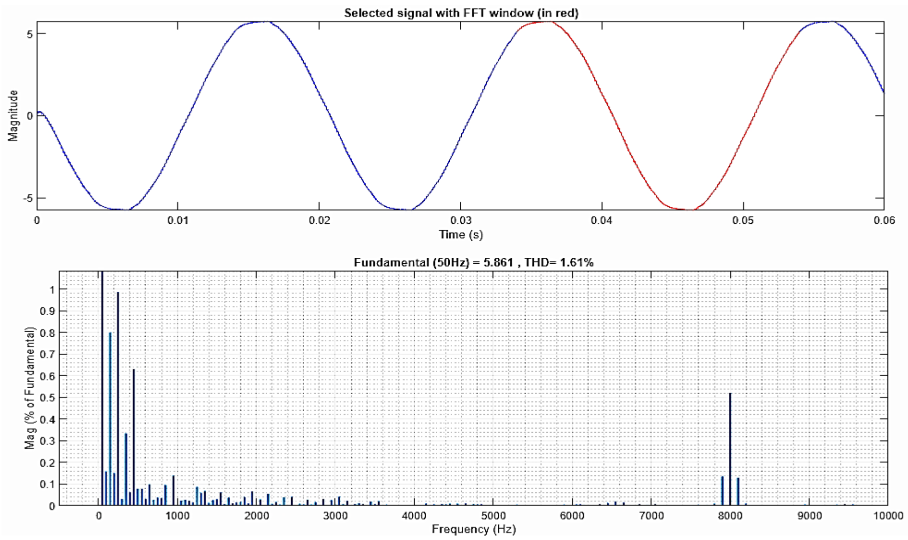

Figure 9. Load current with BPWM technique

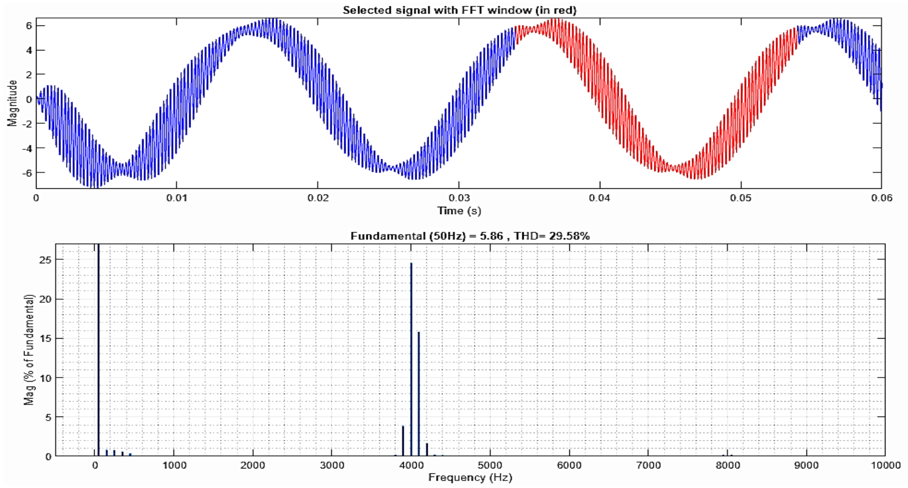

Figure 10. Load current with UPWM technique

Based on the simulation findings, the comparison of leakage current generated, the power conversion efficiency, and the value of THD load current in relation to the IEC 61000-3-2 class C standard is indicated in Table 4. Bipolar PWM complies with the THD load current standard, which is less than 5%, but unipolar PWM does not comply with the standard, which is more than 20%. Additionally, bipolar PWM exhibits a 12.8% increase in power conversion efficiency over unipolar PWM.

This paper examines bipolar PWM and bipolar hysteresis PWM to maximize the proposed inverter performance. Figure 11 displays the simulation results of load current for bipolar PWM hysteresis current control (BHCC). As demonstrated in Figure 11, the BHCC technique results in a THD current output that satisfies the IEC standard (THDi < 5%) and a considerable rise in the output current peak. Furthermore, the results demonstrate that the distribution of the load current's spectrum contents is significantly affected by the random hysteresis current control based on bipolar hysteresis PWM modulation.

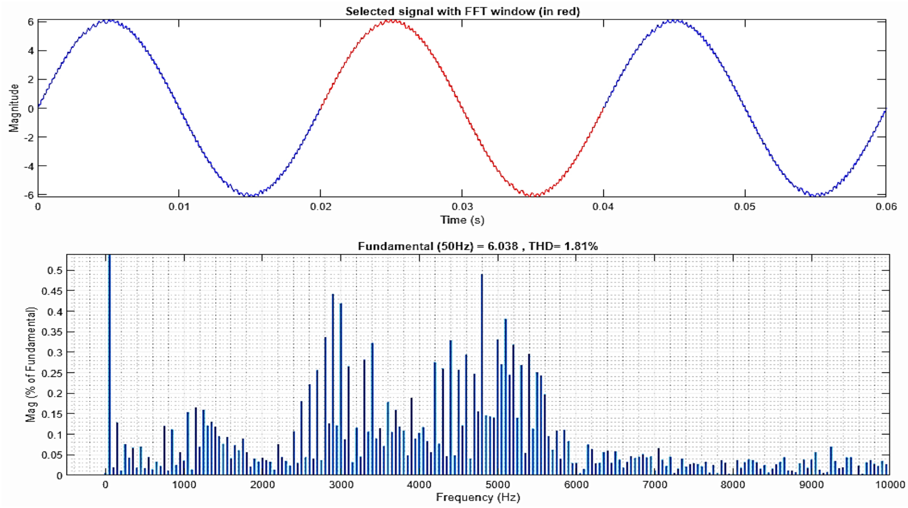

Figure 11. Load current with BHCC

The simulation results of leakage current when applying bipolar hysteresis PWM modulation are shown in Figure 12. Hysteresis bipolar PWM in transformerless inverters demonstrates improved performance in reducing leakage currents and complies with the VDE standard, which is 7.274 mA. Table 5 presents a comparison of THD load current, amplitude leakage current, and power conversion efficiency between bipolar PWM with and without hysteresis current control. In contrast to bipolar PWM without hysteresis current control, which is an open loop circuit without a feedback loop, bipolar PWM with hysteresis current control is a closed loop circuit with a feedback loop. Therefore, a feedback loop is required to enable the output current to meet the desired current.

Bipolar hysteresis current control has a 0.33% lower value in terms of amplitude leakage current than bipolar PWM without hysteresis. The bipolar PWM without hysteresis has a 2.93% lower amplitude load current than bipolar hysteresis current control. Furthermore, the power conversion efficiency of bipolar hysteresis current control is 2.7% greater than bipolar PWM without hysteresis control. The analysis demonstrates that incorporating hysteresis current control lowers leakage current slightly and improves the power conversion efficiency.

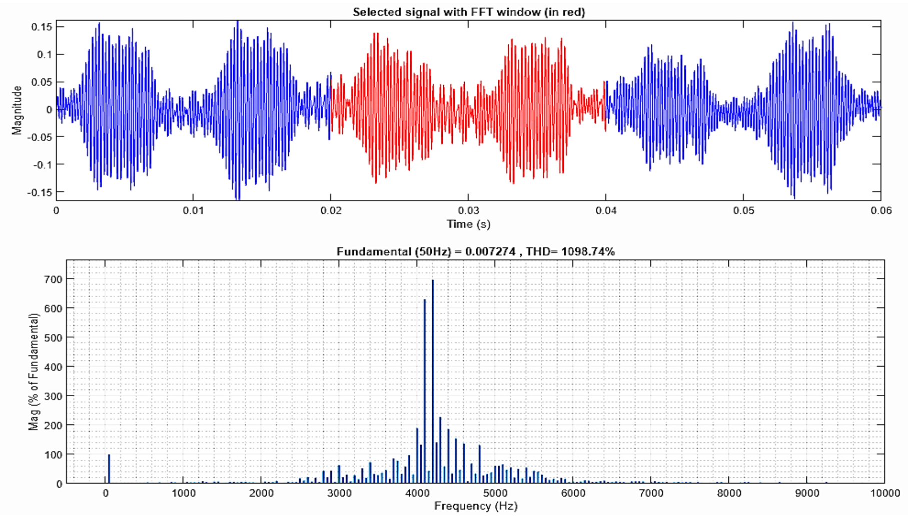

Figure 12. Leakage current with BHCC

Table 4. Comparison between bipolar PWM switching technique and unipolar PWM switching techniques

Parameter	BPWM	UPWM
Amplitude load current (A)	5.861	5.859
Percentage THDi load (%)	1.61	29.58
Amplitude leakage current (mA)	7.299	7.298
Efficiency (%)	77.30	64.50

Table 5. Comparison between bipolar PWM and bipolar hysteresis current control

Parameter	BPWM	BHCC
Amplitude load current (A)	5.861	6.038
Amplitude leakage current (mA)	7.299	7.274
Efficiency (%)	77.30	80

4. CONCLUSION

In conclusion, the comparison between bipolar and unipolar PWM techniques in transformerless inverters highlights the crucial role of leakage current, THD load current standards, and power conversion efficiency in system performance. Bipolar PWM demonstrates compliance with the THD standard of less than 5%, while unipolar PWM falls short, exceeding it by over 20%. The bipolar PWM exhibits a substantial increase in power conversion efficiency, outperforming unipolar PWM by 12.8%. Additionally, the analysis delves into the impact of hysteresis current control on leakage current and system efficiency. Bipolar hysteresis current control showcases a slight reduction in leakage current compared to bipolar PWM without hysteresis, enhancing system integrity, and reliability. However, the trade-off between leakage current reduction and THD load current must be carefully considered, as bipolar PWM without hysteresis demonstrates a lower THD load current by 0.2%. Notably, bipolar hysteresis current control exhibits superior power conversion efficiency, surpassing bipolar PWM without hysteresis by 2.7%. Overall, these findings contribute to advancing the understanding and optimization of transformerless inverter systems for diverse applications in renewable energy and power electronics.

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