



OPEN Multi-function multi-level grid tied inverter based on a new combined logic-analog controller with capacitors balancing ability

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In this paper, a modified hysteresis band logic-analog controller with capacitors balancing ability is proposed. A multi-function five-level grid-tied inverter is investigated, which can be used to inject power into the grid and act as an active filter, simultaneously. It is also capable of absorbing active power to act as a storage system using batteries on the DC link and reactive power compensation to some extent. The new hysteresis band controller has been implemented on a conventional 5-level converter, based on the current injection method. In addition, this controller is also capable of balancing the voltage of the capacitors by selecting appropriate switches related the desired voltage vector. The proposed controlling method acts in the time domain and no need for complex transformations; furthermore, it has a high processing speed due to the utilization of logic gates. Moreover, due to the lack of need for a microcontroller or DSP, there is no halt phenomenon or delay in the execution of software loops. In this paper, power injection into the grid and active filtering ability have been investigated. To verify the proper operation, the simulation results as well as the laboratory 350 W prototype results are presented.

Keywords Multi level inverter, Grid-tied, Hysteresis band, Active power injection, Capacitor voltage balancing

An inverter plays a crucial role in transforming DC power to AC power. Multilevel inverters offer advantages such as lower total harmonic distortion (THD), reduced switching voltage stress, and more compact output filters than other types of sine-wave inverters^{1–3}. Consequently, they are frequently used in renewable energy generation, HVDC transmission, active power filtering (APF), high-power motor drives, flexible AC transmission (FACTS), and several other applications^{4–6}. Traditional multilevel inverter (MLI) designs include the cascaded H-bridge (CHB)⁷, neutral-point-clamped (NPC)⁸, and flying-capacitor (FC)⁹ inverters. Among the various multilevel inverter configurations, the cascaded H-bridge (CHB) inverter stands out due to its excellent output performance^{10,11}.

Grid-tied inverters play a vital role in enabling the integration of renewable energy sources. They connect distributed generators (DGs) to the existing grid or a microgrid¹². Generally, grid-connected inverters are divided into two categories: transformer-based and transformerless. While transformer-based inverters offer galvanic isolation, transformerless inverters are preferred due to their smaller size, enhanced efficiency, and affordability^{13,14}. The features of grid-connected inverters (GCIs) closely resemble those of isolated inverters regarding circuit parameters, with the main differences lying in their control and protection mechanisms. As the adoption of renewable energy continues to rise, GCIs have increasingly become a central area of research.

GCIs can be improved by advancements in their topology or control systems. Both aspects of GCI hold high significance. This research contributes to the control field by improving power handling capacity, capacitor voltage balancing, and reducing total harmonic distortion (THD) of the entire system. The control typically performs three main functions: synchronization, current regulation, and harmonic compensation. The synchronization component in some methods captures the grid voltage phase and relays it to the current controller. This captured phase is utilized in the direct-quadrature-zero (DQZ) transformation and the generation of reference signals. The current controller oversees the current and generates a current that corresponds with the grid voltage, thereby enabling active power transfer¹². The controller needs to be designed to produce pure sine-wave currents

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even when harmonics are present in the grid; however, the inverter controller does not successfully mitigate these harmonics, leading to inverter output currents that include low-order harmonics. As a result, harmonic compensators are utilized in conjunction with the current controller to reduce the harmonic contents in the grid current¹².

Numerous control strategies have been examined for single-phase converters, including proportional integral derivative (PID), proportional resonant (PR), and current hysteresis controls, among others^{15–17}. Although these linear controllers have their advantages, they suffer from slow dynamic responses. Consequently, several advanced control techniques, such as model predictive control (MPC), have been investigated and advocated in scholarly literature, particularly due to the advent of high-performance microprocessors, digital signal processors (DSPs), and field-programmable gate array (FPGA) technologies^{18,19}. To manage the variable switching frequency associated with model predictive controllers (MPCs), various approaches, such as optimal switching sequence, have been suggested for single-phase converters^{20,21}.

Low-frequency control methods such as nearest-level controllers (NLC), selective harmonic elimination pulse width modulation (SHEPWM), and selective harmonic mitigation (SHM) are commonly utilized techniques^{22–24}. In the SHE approach, the inverter's optimal switching removes lower-order harmonics by resolving complex non-linear transcendental equations. The primary challenge associated with this control method is that solving these intricate equations is time-intensive and quite complicated. Furthermore, implementing it in a closed-loop operation presents additional difficulties. For NLC, the switching frequency aligns with the power frequency, making it relatively straightforward to implement. However, its main disadvantages include a reduction in voltage levels as the modulation index changes and an increase in the total harmonic distortion (THD) values of the load voltage and current. To merge the benefits of both NLC and SHE, a new control method is introduced in²⁵ which combines these two techniques.

To overcome some of the aforementioned challenges, this paper proposes a novel logic-based hysteresis controller to a grid connected five level inverter which has the following merits:

- *Low-cost and fast operation* No need for high-speed or expensive microprocessors; the controller is implemented using ordinary logic gates, comparators, and analog devices, ensuring high processing speed.
- *Robust and reliable* The control is immune to noise and electromagnetic interference (EMI), with continuous operation and no halting.
- *Simple implementation* Time-domain operation eliminates the need for complex transformations, while a single DC source (solar panels, batteries, or microgrids) is sufficient.
- *Accurate current control* Based on current injection, the hysteresis controller regulates inverter switching to ensure the injected current follows the reference under all operating conditions.
- *DC-link voltage balancing* Proper selection of switching states allows balancing of capacitor voltages, while still producing all output voltage levels even if capacitors are initially unbalanced.
- *Proper switching and reduced losses* Proportional hysteresis band reduces switching frequency at higher voltage and current levels, lowering switching losses and harmonic content.
- *Bidirectional power flow and versatile applications* Suitable for grid-tied inverters, active power filters, active and reactive power injection, and energy storage systems.

The structure of the paper is outlined as follows: "Studied grid-tied five-level inverter" section provide the studied topology. "Proposed logic based modified hysteresis band controller" section presents a comprehensive explanation of the proposed logic-based controller. "Simulation and experimental results" section features the simulation and experimental analysis of the proposed topology. A comparative study with other studied controlling method is conducted in "Comparison study" section. Finally, "Conclusion" section provides the conclusion of the work.

Studied grid-tied five-level inverter

In this section, the five-level active power filter is reviewed. Figure 1 depicts the studied structure which is based on multi-level inverter (MLI). As can be seen from the figure, the topology consists of eight power switches S_1 – S_8 , S_{xa} , S_{xb} , S_{ya} , S_{yb} , and two capacitors C1, C2. Only a brief explanation of the topology studied is provided in this section.

The switching logic of the topology is tabulated in Table 1. The operating modes of the five-level active power filter are explained here.

Voltage level (0Vin):

Zero voltage level (see Fig. 2a and d) can be achieved either by switches S1 and S3 for positive current flow or switches S2 and S4 for negative current flow.

Voltage level (+1Vin):

This voltage level (see Fig. 2b) can be obtained through Switches S2, S3, S_{ya} and S_{yb} .

Voltage level (+2Vin):

The voltage level is realized (see Fig. 2c) through switches S2, S3, S_{xa} , and S_{ya} .

Voltage level (–1Vin):

As shown in Fig. 2e, the output is generated by S1, S4, S_{xa} , and S_{xb} .

Voltage level (–2Vin):

Finally, this output voltage is achieved (see Fig. 2f) through switches S1, S4, S_{xa} , and S_{ya} .

In Fig. 2, the different operating modes of the topology are presented.

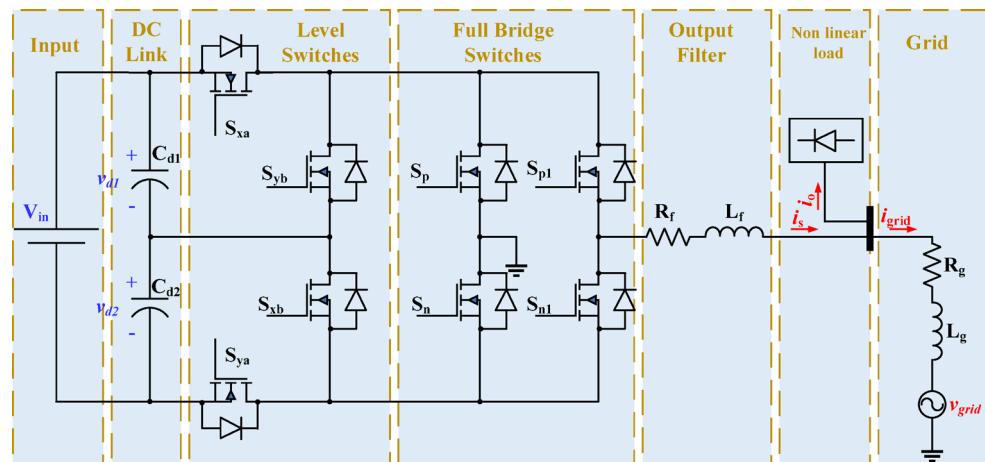


Fig. 1. Studied 5-L grid-connected inverter topology.

Power devices	+1V _{in}	+2V _{in}	+0	-0	-1V _{in}	-2V _{in}
S ₁	0	0	0	1	0	1
S ₂	1	1	1	0	1	0
S ₃	1	1	1	1	0	0
S ₄	0	0	0	0	1	1
S _{xa}	1	0	1	0	0	1
S _{xb}	1	0	0	0	0	1
S _{ya}	0	1	1	0	0	1
S _{yb}	0	1	0	0	0	1

Table 1. Switching states of the proposed 5-L inverter.

Proposed logic based modified hysteresis band controller

In this section, the proposed logic-based controller is discussed. Figure 3 depicts the proposed Controller and controlling method layout. The following assumptions are made:

- Switching controls is done to make $V_{d1} = V_{d2}$.
- To achieve appropriate performance, the controller must $V_{d1} + V_{d2} > V_m$
- To compensate for harmonics caused by the non-linear load, $I_{m,ref} > i_o$

The decision to switch is made at a fixed frequency and at every time instant; first, the operating point is determined by comparing the PCC voltage (or V_s) with the voltage levels V_{d1} and $V_{d1} + V_{d2}$. For this purpose, $|V_s(t)|$ is employed. This is depicted in Fig. 4. M1 and M2 are the two operating regions that are caused in this topology (five-level), and the selection logic is shown in Fig. 5.

If $|V_s(t)|$ is in the M1 region, the switching vectors are chosen from (0 and V_{d1}) or ($-V_{d1}$ and 0). If $|V_s(t)|$ is in the M2 region, the switching vectors are chosen from (V_{d1} and $V_{d1} + V_{d2}$) or ($-V_{d1}$ and $-V_{d1} - V_{d2}$). The reason for these selections of the switching vectors is to create a minimum voltage difference between the inverter output and PCC voltage, which lowers the current ripple. Ka in Fig. 5 is the attenuation coefficient, which is 0.01 here.

At every time instant in which the switching state changes, 2 voltage vectors are selected according to the aforementioned explanations. To determine these voltage vectors, besides M1 and M2, the comparison of the i_s with the reference current is needed, which is carried out by the modified hysteresis band method. In the modified method, which is done by simple circuits, the band limitations are proportional to the magnitude; the higher bandwidth is selected for a higher magnitude and vice versa. While in the conventional hysteresis band method, a fixed band width is employed for different magnitudes. A change in the bandwidth causes changes in the switching frequency. Bandwidth increases for higher magnitude, and hence the switching frequency decreases, which decreases switching losses. In addition, the maximum frequency variation in the switching is controlled by a fixed frequency. These explanations, along with the modified hysteresis band method, are shown in Figs. 6 and 7. In Fig. 7, f_{max} is the maximum variation in switching frequency, which is 100kHz in this case. In Fig. 7, C_b is defined as a coefficient that determines the hysteresis band boundary, which is 5% in this paper.

For the selection of the switching vector, M1 or M2, L, or H and the sign of the PCC voltage is needed. Then, for appropriate switching, the various states and switching vectors in Table 2 are used. Table 2 presents the inverter output voltage with respect to the link voltage and switches S_n , S_{n1} , S_p , and S_{p1} .

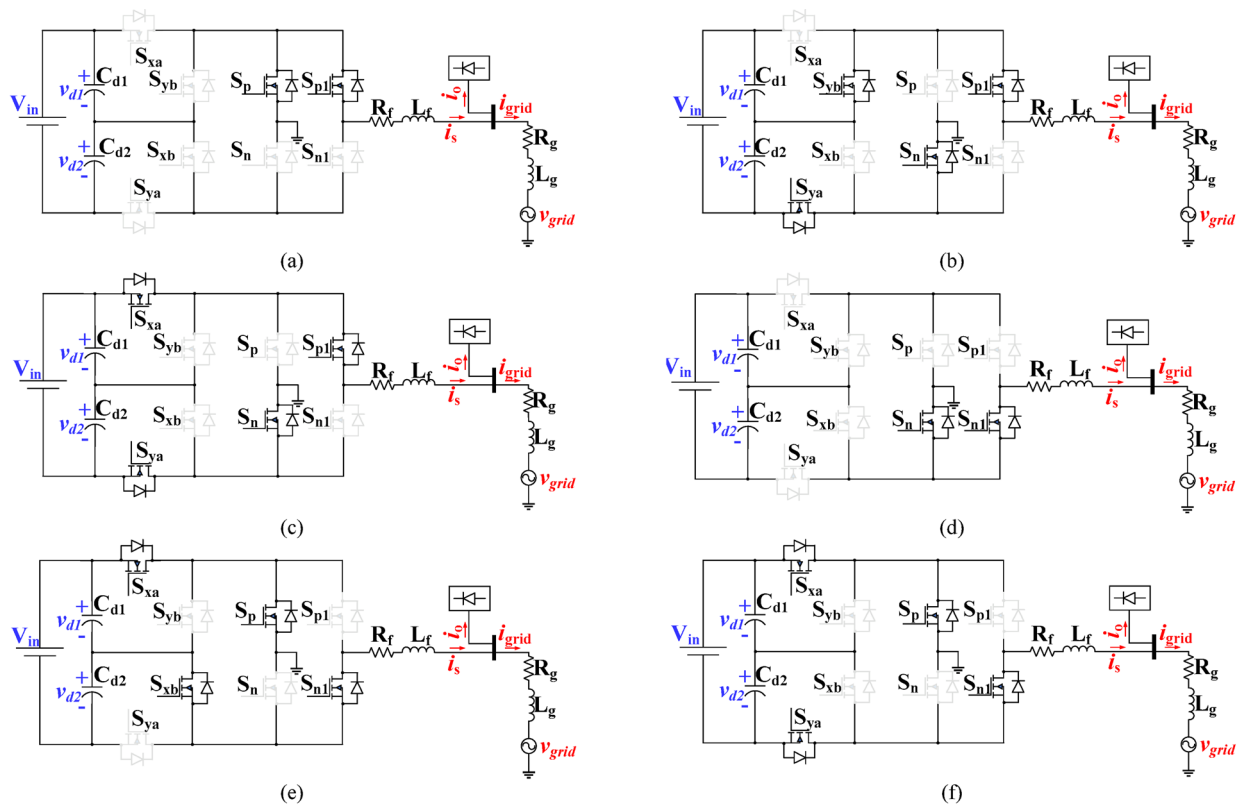


Fig. 2. Operating modes of the proposed five-level inverter. (a) zero state (positive flow), (b) +1V_{in}, (c) +2V_{in}, (d) zero state (negative flow), (e) -1V_{in}, (f) -2V_{in} state.

Fig. 2. Operating modes of the proposed five-level inverter. (a) zero state (positive flow), (b) +1 Vin, (c) +2Vin, (d) zero state (negative flow), (e) -1 Vin, (f) -2Vin state.

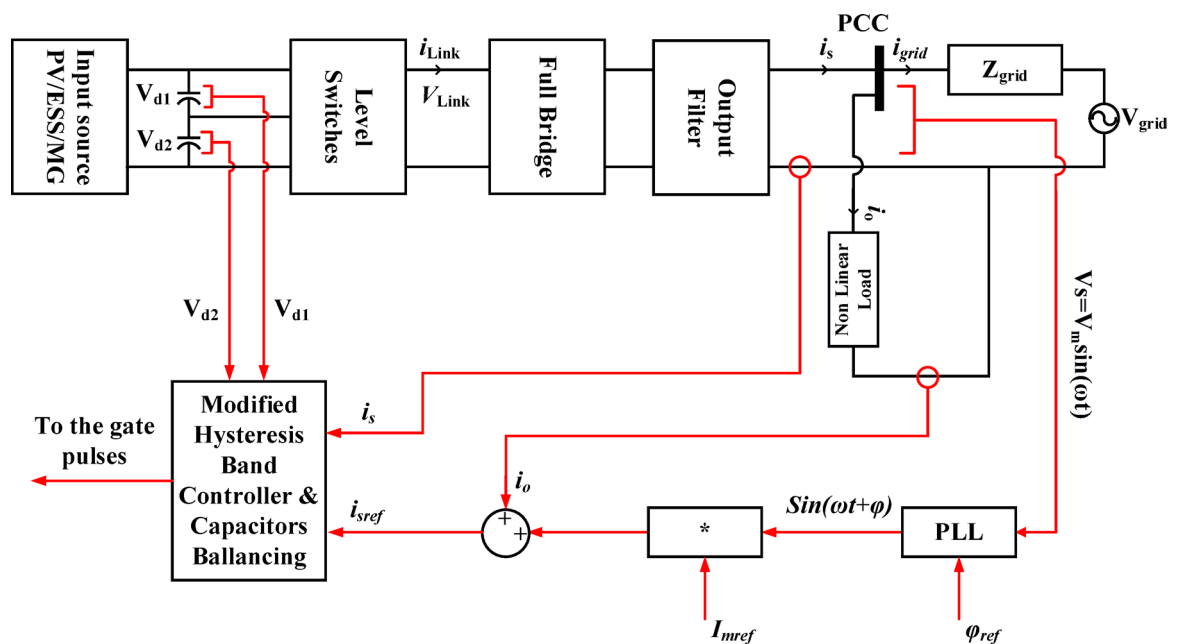


Fig. 3. The proposed controlling method layout.

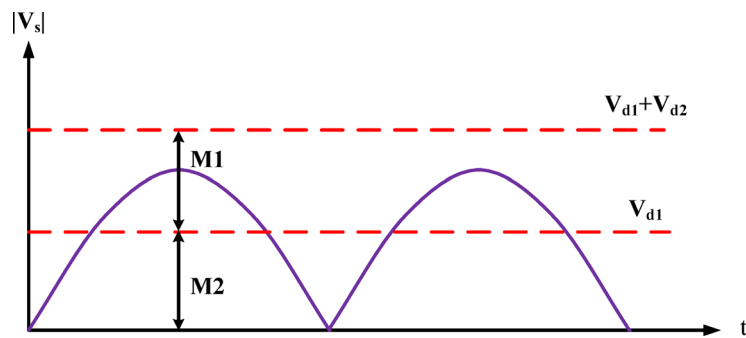


Fig. 4. The selection logic of switching vectors.

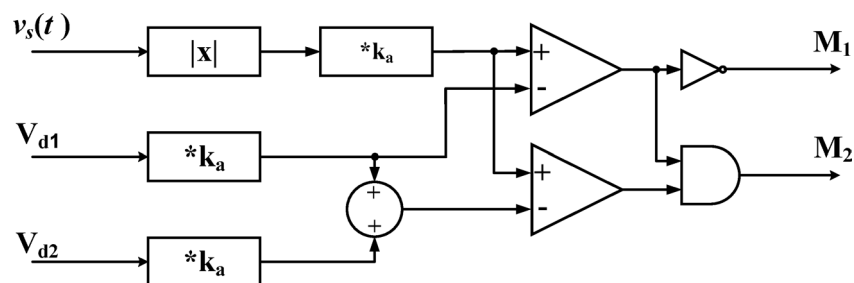


Fig. 5. The selection logic of M1 and M2 region.

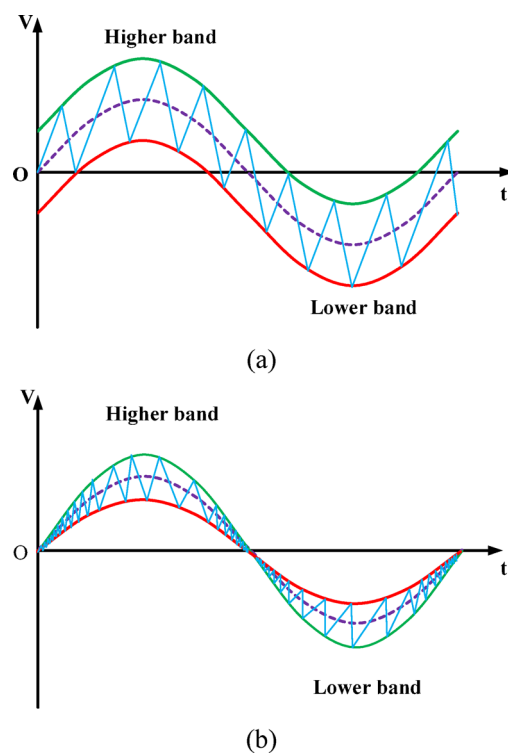


Fig. 6. The modified hysteresis band method.

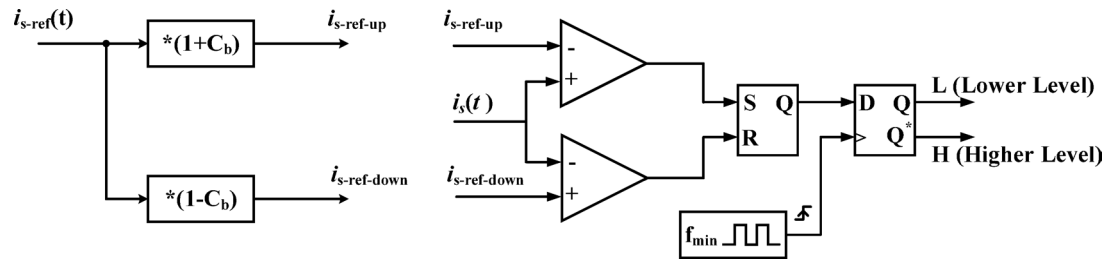


Fig. 7. The logic block diagram of the modified hysteresis band realization.

V_o	S_n	S_p	S_{n1}	S_{p1}
V_{Link}	0	1	1	0
$-V_{Link}$	1	0	0	1
Positive zero	0	1	0	1
Negative zero	0	0	1	1

Table 2. Switching states of the full bridge section.

S_{xa}	S_{xb}	S_{ya}	S_{yb}	V_{Link}	Capacitors status	
1	1	0	0	V_{d1}	$P_s > 0: C_{d1} \downarrow$	$P_s < 0: C_{d1} \uparrow$
0	0	1	1	V_{d2}	$P_s > 0: C_{d2} \downarrow$	$P_s < 0: C_{d2} \uparrow$
1	0	1	0	$V_{d1} + V_{d2}$		

Table 3. Switching states of the level switches and capacitors status.

Where, V_{Link} is obtained from the previous stage, which is called level switches here. From P_s (average injected power to the grid), which is calculated by φ , the capacitors' charging and discharging states can be determined, and are tabulated in Table 3.

Assuming that the proposed control system could balance the capacitors C_{d1} and C_{d2} Voltage, therefore: $V_{d1} \simeq V_{d2} \simeq V_d$. Hence, there are five voltage vectors, including the zero voltage vector. V_d or $-V_d$ could be chosen by V_{d1} or V_{d2} , and this selection depended on the charge levels of capacitors C_{d1} and C_{d2} and current flow direction, i_s , in order to keep the capacitors' voltage balanced. The voltage vectors are: $V_1 = V_d$, $V_2 = 2V_d$, $V_3 = -V_d$, $V_4 = -2V_d$, $V_5 = 0$. The logic diagram of voltage vectors and gate signals is shown in Fig. 8. In Fig. 8, B_x and B_y are related to the capacitors' voltage balance and controlled by that logic.

Simulation and experimental results

The proposed topology's performance is evaluated through simulation results carried out in PSCAD/EMTDC software and experimental results. A 350 W prototype of the 5-level active power filter is built in the laboratory.

Simulation results

In this section, the simulation results of the 5-level active power filter with the proposed control method are provided. The components values and their ratings are listed in Table 4.

In Fig. 9, the flowchart of the controlling method is presented. The whole process is held true if the input supply like, PV panel's power is higher than the nonlinear/linear load absorbing power.

The non-linear load current is shown in Fig. 10. The proposed method is tested under a laboratory prototype of about 350 W. The amplitude of the non-linear load current is about 2.5 A. As can be seen from the figure, the rectifier loads absorb non-sinusoidal (needle type) current from the grid.

In Fig. 11, the waveforms of the voltage and current of the grid before employing the proposed controlling method of the active power filter are presented. As can be seen, the current waveform of the grid is non-sinusoidal, although the voltage waveform is sinusoidal. Also, in Fig. 11c, the current waveform of the grid with the proposed controlling method for the 5-level active power filter is shown. It is obvious from the figure that the current waveform of the grid is close to the sinusoidal waveform, although the load absorbs non-sinusoidal current from the grid.

In Fig. 12, the output voltage waveform of the 5-level active power filter studied is depicted. Also, the voltage waveforms of the inverter and the grid is shown in this figure.

In order to facilitate the comprehension of the benefits provided by the proposed control method, Table 5 presents a comparison between the RMS, THD and PF of the load and grid currents with the proposed control method compensation for both the non-linear loads scenarios. As it can be seen, the THD values decreases. It

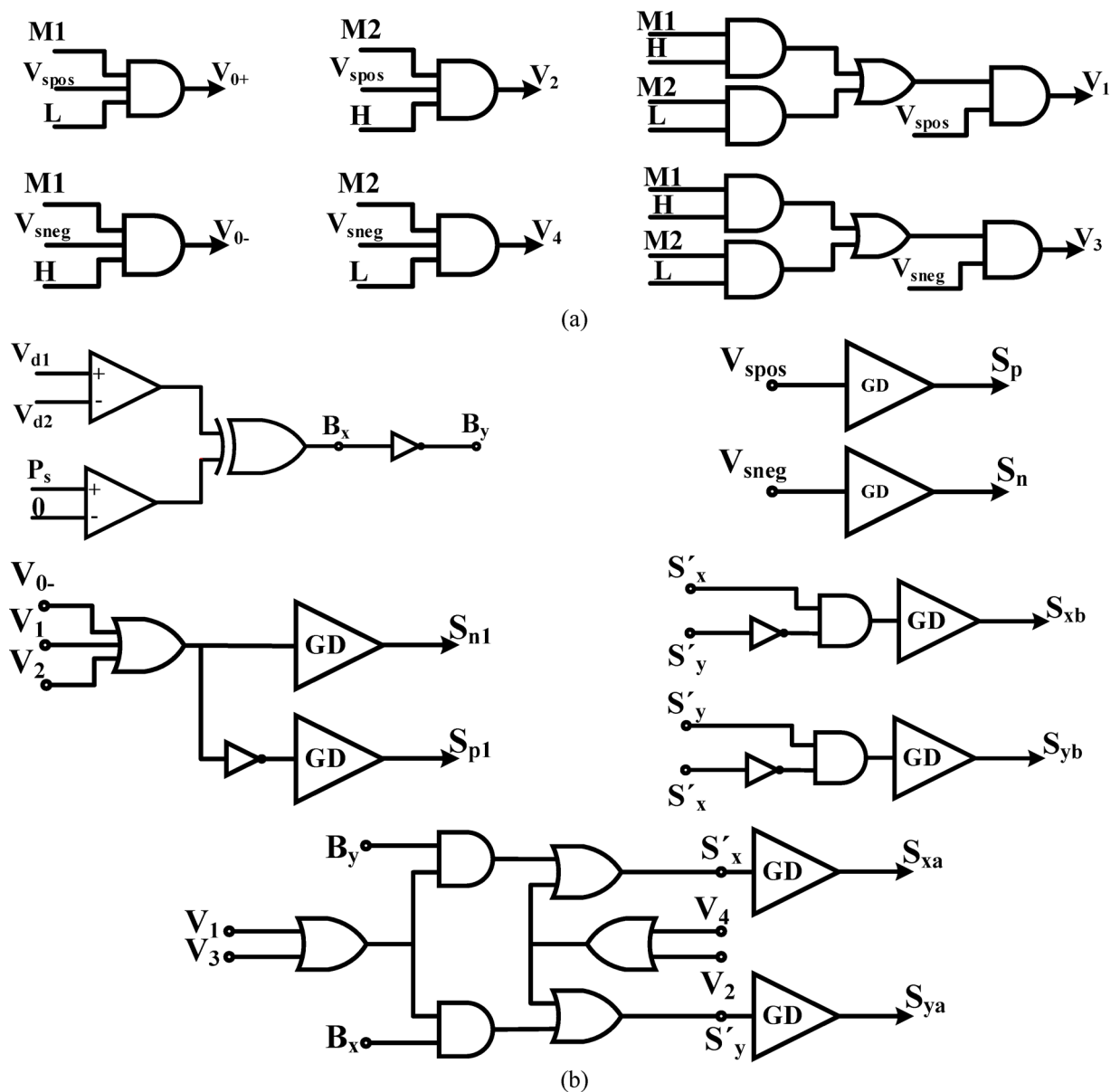


Fig. 8. The logic diagram of voltage vectors and gate signals. (a) voltage vectors, (b) gate signals.

Parameter	Value
C_{d1}	2200 μ F
C_{d2}	2200 μ F
L_f	5 mH
R_f	0.5 Ω
L_g	200 μ H
R_g	0.01 Ω
C_{Load}	470 μ F
R_{Load}	200 Ω
L_{Load}	1 mH

Table 4. Parameters used in the studied topology.

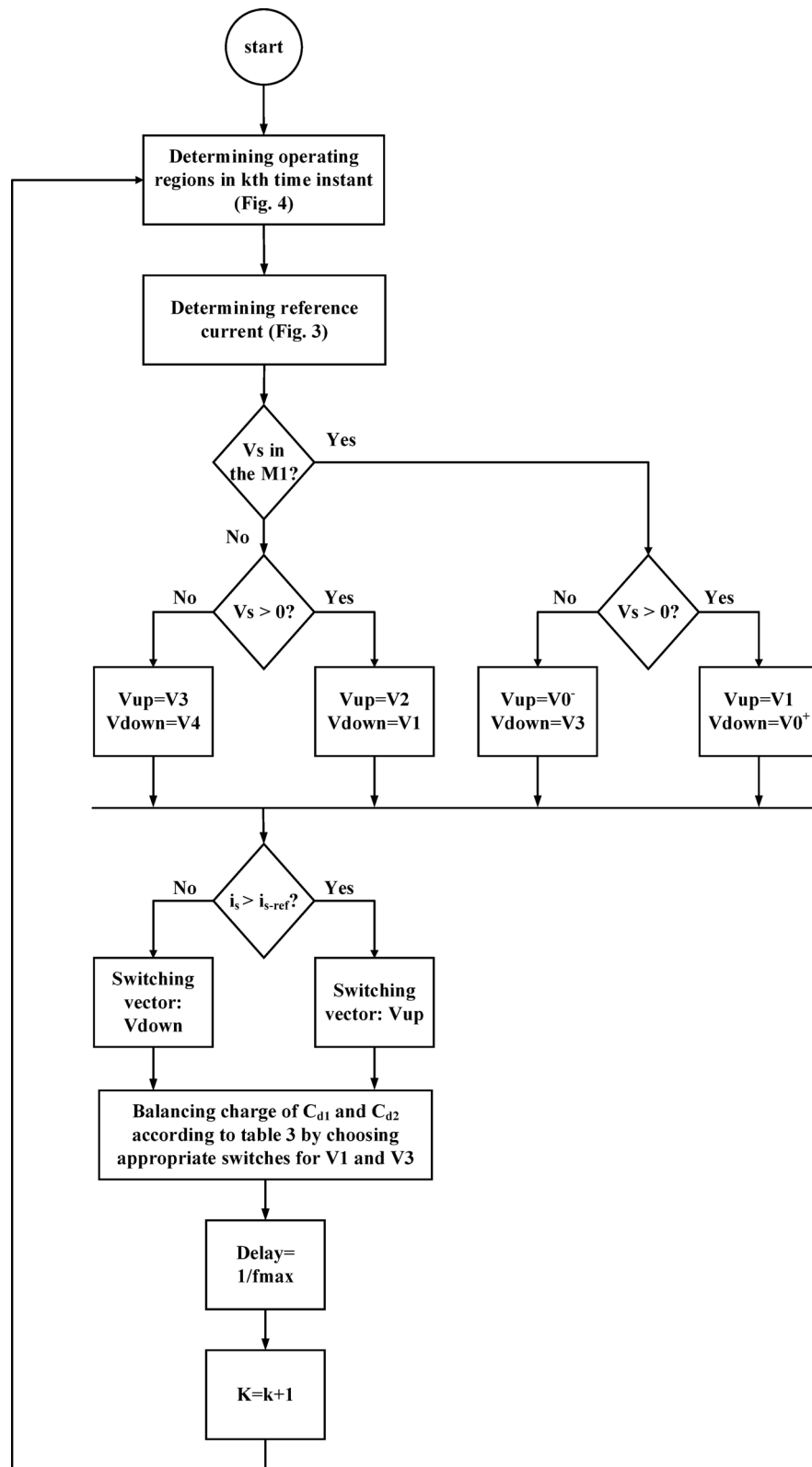


Fig. 9. The flowchart of the proposed controlling method.

is obvious from Table 6 that the current THD of the grid reduced from 140 to 5.3% with the proposed modified logic-based method.

In Fig. 13, the FFT of the non-linear load current and the grid current with the proposed controller is provided.

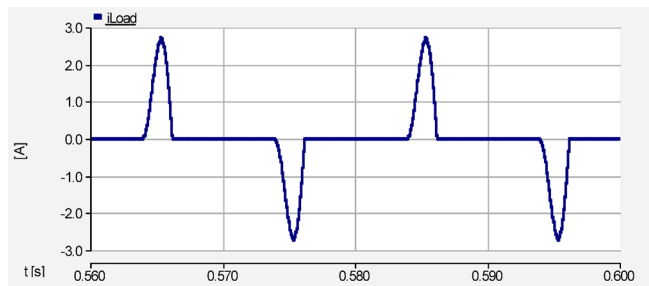


Fig. 10. The non-linear load current waveform.

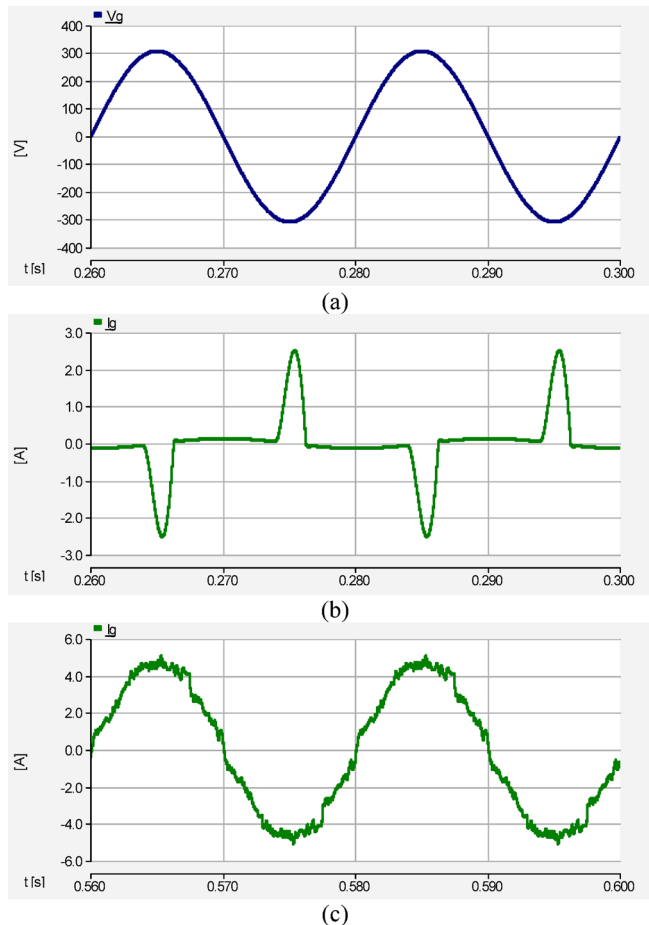


Fig. 11. The grid voltage and current waveform. (a) the grid voltage, (b) the grid current without and (c) with the proposed controller.

In the Fig. 14, the current waveforms of the MLI, the grid, and the load with respect to each other is shown. As can be seen from the figure, the multi-level inverter can also inject the load and the grid current to compensate for the current that the nonlinear load absorbs from the grid.

Experimental results

In this section, the experimental results are provided to confirm the accuracy of the claims provided in the previous sections. Thus, the results of the laboratory prototype are included here. The experimental setup of the prototype is shown in Fig. 15.

In Fig. 16, the experimental results of the voltage of the grid and the multi-level inverter, the current of the grid without the proposed controller, are presented. As it is obvious, without the controller, the grid current is not sinusoidal and is the same as the load current.

In order to demonstrate the performance of the proposed control method and compensator role, the waveforms of the grid current, inverter current, and the load current experimental results with respect to each

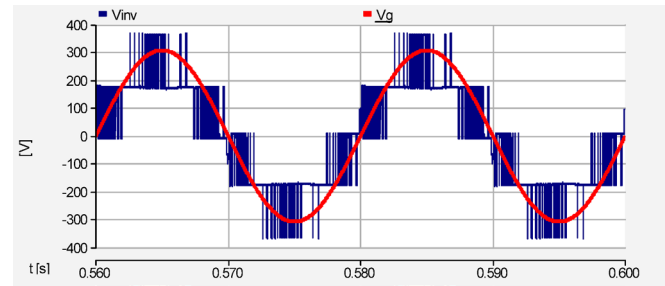


Fig. 12. The voltage waveform of the 5-level active power filter.

Parameters	Non-linear load 1		Non-linear load 2	
	Grid	Load	Grid	Load
Current (RMS)	3.35	0.47	3.39	0.44
Current THD (%f)	5.3	140	4.75	71

Table 5. Comparison of simulation results of the root mean square (RMS) and total harmonic distortion (THD) of the load current and grid current with proposed control method compensation, for operation with the two non-linear loads.

References	Topology	Controller	Weighting factor	No. of weighting factors	No. of sensors	Components	Additional controller for dc capacitors voltage	Reference filter current generation method
26	1ph NPC	FCS-MPC	Not needed	N/A	6	2 DC capacitors, 1 inductor, 8 switches and 4 diodes	Needed	5 multiplications, 2 additions, and 2 low pass filter
27	1ph CHB	Model-based controller	N/A	N/A	5	2 DC capacitors, 1 inductor, 8 switches	Needed	RMS calculation, current tracking loop and harmonic oscillators
28	1ph 5Level	Predictive current controller	Not needed	N/A	5	2 DC capacitors, 1 inductor, 6 switches and 2 diodes	Needed	Transformation to $\alpha\beta$ frame, pq theory and predictive current controller
29	1ph CHB	Direct current controller	N/A	N/A	5	2 DC capacitors, 1 inductor, 8 switches	Needed	Transformation to dq frame, Transformation to ab frame, 1 high pass filter and 3 PI controllers
30	1ph MPUC5	FCS-MPC	needed	1	6	2 DC capacitors, 1 inductor, 6 switches	Not needed	1 subtraction
31	1ph T-type	Energy-MPC	Not needed	N/A	5	2 DC capacitors, 1 inductor, 8 switches	Not needed	1 subtraction
[P]	1ph 5Level	Logic-based Hysteresis band	Not needed	N/A	5	2 DC capacitors, 1 inductor, 8 switches	Not needed	1 subtraction

Table 6. Comparison study of the proposed controlling with respect to the other studied methods.

other are shown in Fig. 17. As it is obvious, the current of the grid with the proposed controller more resembles the sinusoidal waveform. In Fig. 17a, the inverter injecting current with respect to the grid compensated current is shown, which is near a sine wave. In Fig. 17b, the grid compensated current with respect to the load current is shown. And finally, in Fig. 17c shows the inverter injecting current with respect to the load current.

In Fig. 18, the capacitors C_{d1} and C_{d2} voltage is shown. The capacitors voltage is almost same and equal to about 180 V.

Comparison study

The suggested logic-based hysteresis band method is also evaluated against six control methods discussed in^{26–31}. This evaluation considers the type of controller, the necessity of weighting factors, the number of weighting factors required, the number of sensors needed, the requirement for an additional controller to manage DC capacitor voltages, and the method used for generating reference filter currents, as detailed in Table 6. It is clear that the proposed logic-based hysteresis band method offers advantages such as a structure that does not require weighting factors, decreased controller complexity, as it does not necessitate an additional control loop for regulating the DC capacitor voltage or generating reference filter currents, and it also eliminates the need for a microprocessor like STM. Unlike the methods in^{26–29}, the method proposed in this study and those in^{30,31} do

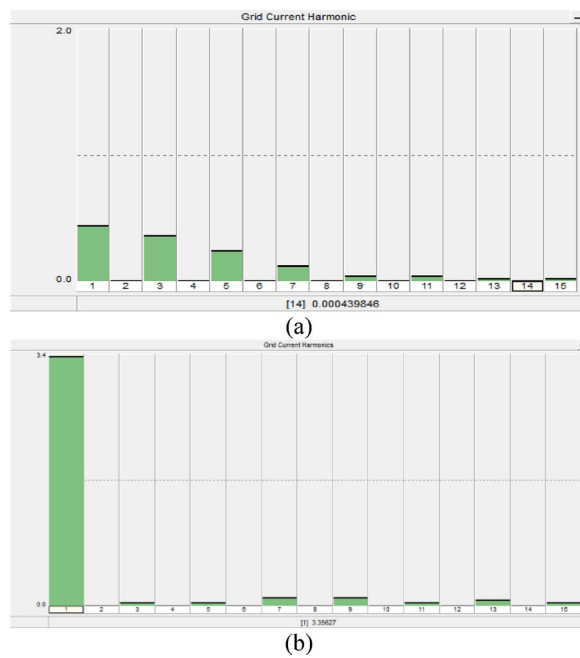


Fig. 13. FFT of the grid current (a) without and (b) with the proposed controller.

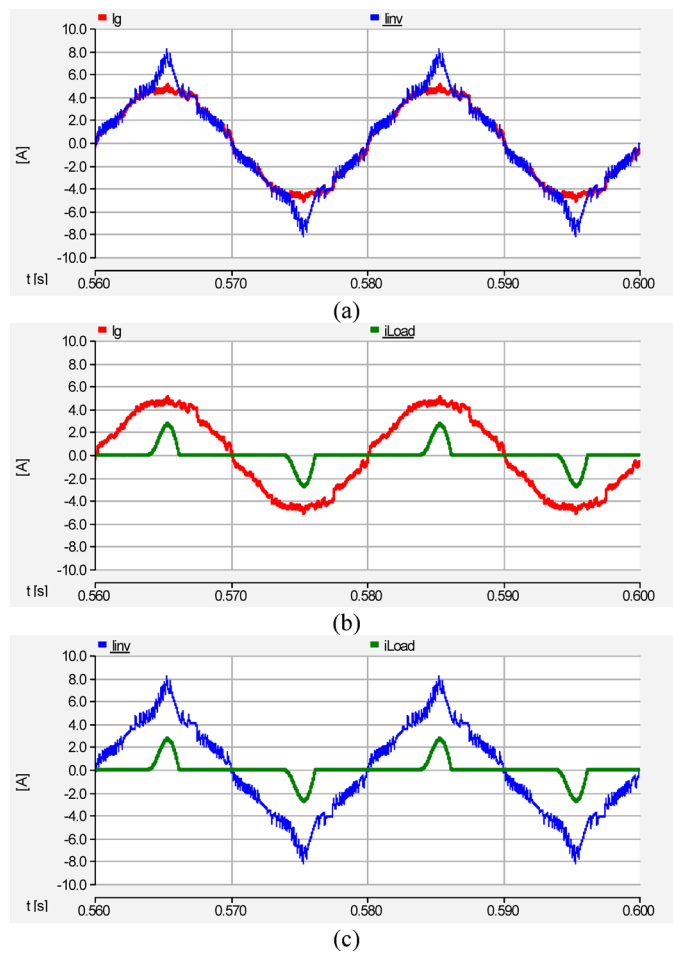


Fig. 14. The current waveforms. (a) the grid and the inverter, (b) the grid and the load (c) the inverter and the load.

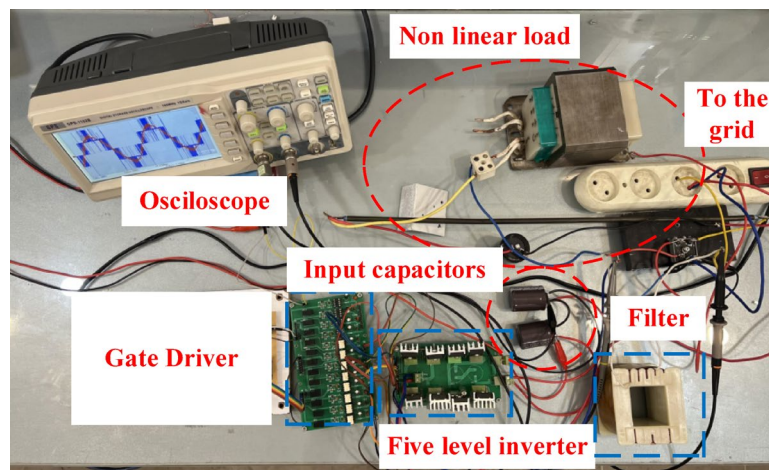


Fig. 15. The experimental of the prototype built in laboratory.

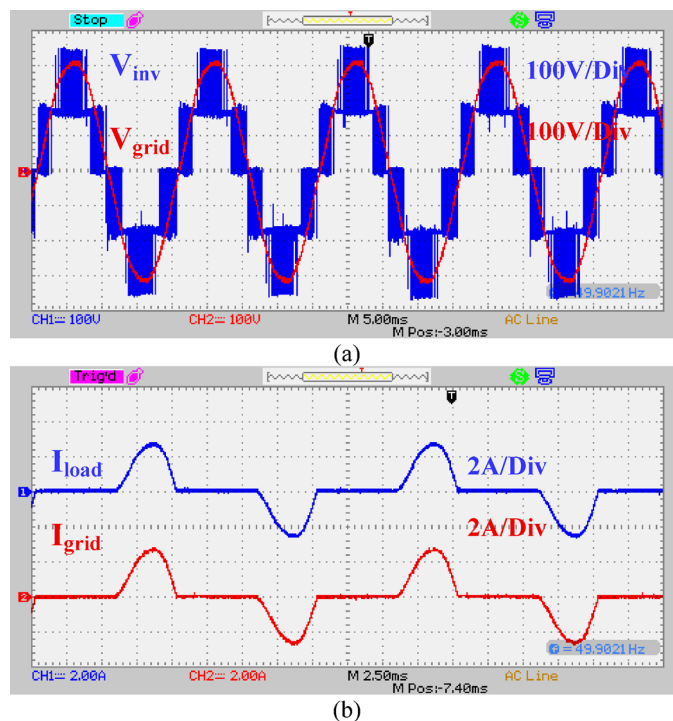


Fig. 16. The experimental results of the grid voltage and current waveform. (a) the grid voltage, (b) the grid and the load current without the proposed controller.

not require an additional controller for DC capacitor voltage regulation. However, the control approach in³⁰ does require a weighting factor and an extra sensor compared to the method being proposed here. In contrast to the reference filter current generation in the proposed method, the approaches presented in^{26–29} involve substantial computations, additional transformations, and the use of low-pass and high-pass filters.

The proposed hysteresis method determines the reference current, proportional to the reference current magnitude and real current magnitude, with increasing the current, the hysteresis band increases. The output voltage level is created by four regions explained above and the voltage balancing condition. Therefore, preventing unstable switching due to rapid voltage or load current variations. In the proposed method, the frequency variations are somehow less.

Conclusion

This paper introduced a multifunctional five-level grid-tied inverter capable of power injection, active filtering, reactive power compensation, and energy storage support through DC-link batteries. A novel logic-based

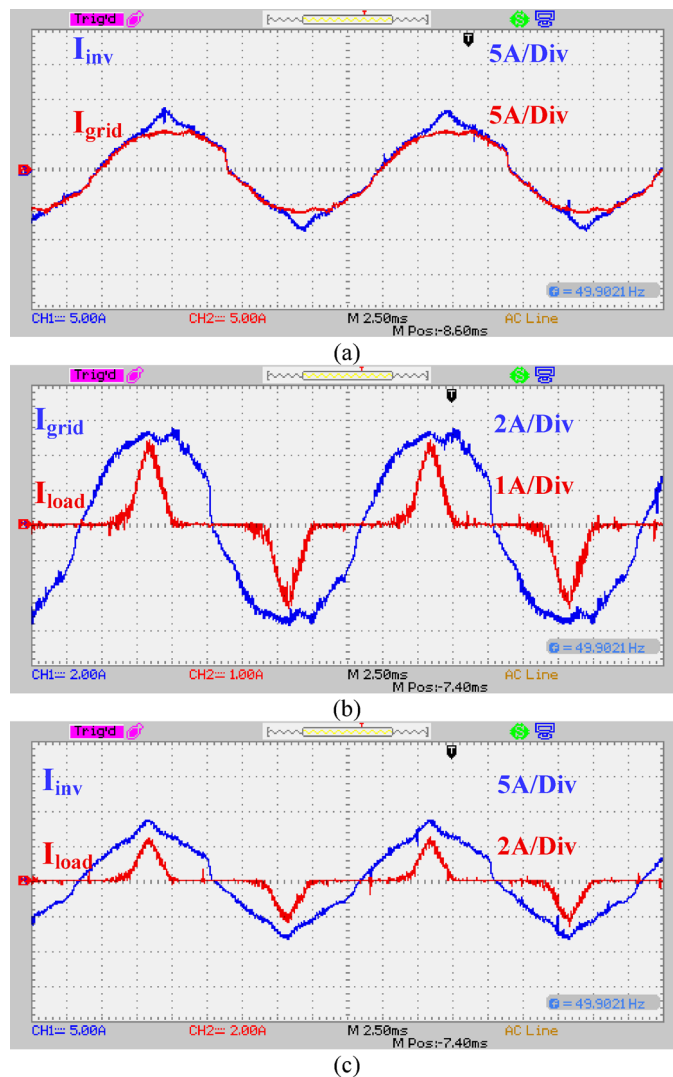


Fig. 17. The current waveforms experimental results. (a) the grid and the inverter, (b) the grid and the load (c) the inverter and the load.

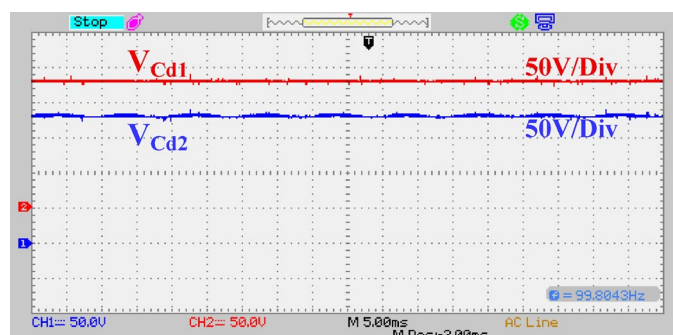


Fig. 18. The current waveforms experimental results. (a) the grid and the inverter, (b) the grid and the load (c) the inverter and the load.

hysteresis band controller was proposed to achieve precise current injection, capacitor voltage balancing, and reduced switching losses without relying on digital processors. The method effectively injected a near-sinusoidal current into the grid even under non-linear load conditions, ensuring power quality improvement while tolerating capacitor voltage imbalance. Furthermore, the adaptive switching strategy minimized losses by

varying the switching frequency across voltage levels. Both simulation and 350 W prototype results verified the accuracy and practicality of the proposed system. The main merits of the proposed controlling method are: no need for expensive microprocessor; using logic gates, comparators, and analog devices; no halt and robust to noise and EMI; capability to balance the voltage of dc link capacitors; ability to produce output voltage levels even if the capacitors voltages are not balanced; modifies hysteresis band method that can enhance performance and decrease switching losses; reduction in harmonic contents; bidirectional power flow. These findings highlight the inverter's potential as a cost-effective and scalable solution for smart grid applications and renewable energy integration, with future work directed toward exploring its full multifunctional capabilities. However, some aspects remain open for future investigation. The present study focuses on single-phase operation; extending the control strategy to three-phase systems and unbalanced grid conditions would be an important next step.

Data availability

The datasets used and/or analyzed during the current study available from the corresponding author on reasonable request.

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Declarations

Competing interests

The authors declare no competing interests.

Additional information

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