A COMPARATIVE STUDY OF FIVE-LEVEL HYBRID MULTILEVEL INVERTERS BASED ON A 3-LEG INVERTER

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ABSTRACT

A hybrid multilevel inverter (HMI) integrates a three-leg voltage source inverters (VSIs) with full-bridge or half-bridge modules, offering advantages such as a reduced number of electronic power switches, DC sources, and DC capacitors compared to traditional multilevel inverters. Despite these advantages, HMIs exhibit distinct characteristics. This study investigates differences in DC power distribution and output voltage quality when operating with a five-level output voltage. Comparative results are obtained through simulation models in MATLAB/Simulink, using consistent parameters for both inverter topologies.

Keywords: Hybrid multilevel inverter, half-bridge, full-bridge, 3-leg voltage source inverter.

1. INTRODUCTION

Multi-level inverters (MLIs) are increasingly gaining attention for their capability of operation at high power levels, with higher efficiency and lower electromagnetic interference [1], [2]. These inverters give adaptability through several applications, from medium- to high-voltage power conversion systems, in which their prowess in managing high voltage and power becomes evident [3], [4]. Moreover, MLIs have made significant strides in different areas, including medium-voltage motor drives in industry [5], the renewable energy systems [6], flexible alternating current transmission systems (FACTS) [7], transmission systems in electric vehicle traction motor [8], and static var compensator (SVC) [9]. Additionally, MLIs have been found properly in low-voltage systems, which can reduce the size of the output passive filters [10].

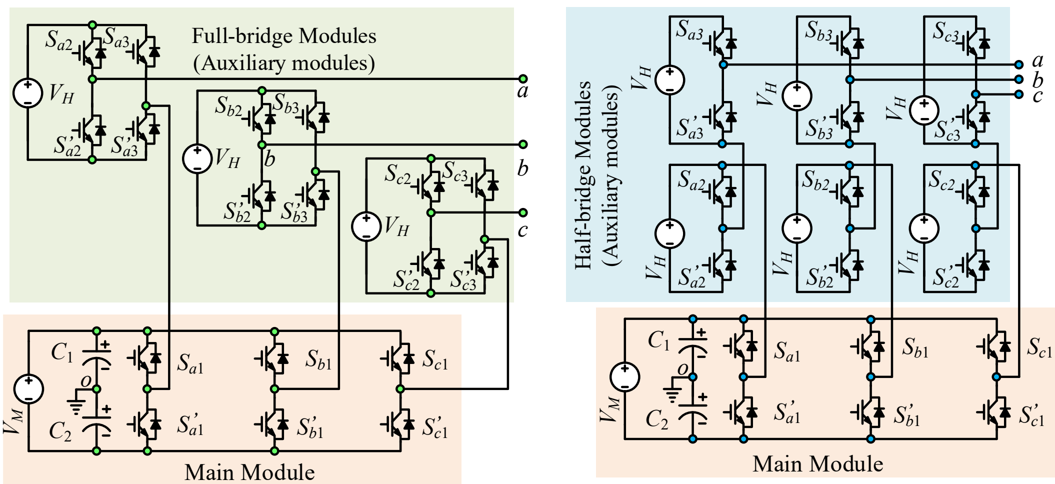
The topologies of the common MLIs are composed of diode neutral-point-clamped (NPC), flying capacitor (FC), and cascaded H-bridge (CHB) configurations [1], [11]. Compared with the two former configurations, CHBs have more advantages of dependability and low cost because of their functionalities and features [13]. Apart from the topologies of the basic multilevel inverter, several hybrid multilevel inverter (HMI) topologies have been suggested by coodinating two of the basic multilevel configurations [11]. The hybrid cascaded H-bridge multilevel inverter (HC-HB) is developed from the basic CHB configuration. In the basic configuration, separate DC voltages are supplied to the H-bridge modules with equal values, whereas in the hybrid configuration, these DC voltages will have different values. This entails the requirement for individual DC sources for each H-bridge module and a significant number of the electronics power switches. These factors escalate expenses and affect reliability.

A replacement topology for HC-HB by combining a three-leg voltage source inverter (VSI) with H-bridge modules (HMI-VSI-FB) is presented in [14]. The H-bridge topology is also called as a full-bridge. Another hybrid topology using a VSI connected to pairs of half-bridge modules (HMI-VSI-HB) has been suggested in [15]. These half-bridge modules are fed by individual DC power supplies such as AC/DC rectifiers, photovoltaic cells, or batteries. As we know that the number of output voltage levels relate to the DC voltage ratio which is supplied to the VSI and to the H-bridge or half-bridge modules [15].

Compared to similar topologies of the same type, both topologies share the advantage of reducing the switch count. Table 1 presents a comparison of component count for typical MLIs, both giving a 5-level output. Meanwhile, the three-leg VSI with full-bridge and 3-leg VSI with half-bridge employ fewer components, resulting in cost savings. Regarding the number of separate DC sources, the VSI with half-bridge requires more than one compared to the HC-HB. However, relatively little attention has been paid to comparisons between these two topologies. This paper presents a comparison between the HMI-VSI-FB and the HMI-VSI-HB in their five-level version. The output of these inverters is connected to a three-phase 8 kW- RL load. The proposed control technique for five-level output voltage depends on the multi-carrier pulse width modulation method. This study aims to investigate differences in DC power and total harmonic distortion (THD) of load voltage and current. The simulation using MATLAB/Simulink has been done to verify the superiority of the investigated topology.

2. HYBRID MULTILEVEL INVERTER BASED ON A 3-LEG INVERTER

The hybrid multilevel inverter, which utilizes a 3-leg voltage source inverter (VSI) in combination with full-bridge and half-bridge modules, is depicted in Figures 1a and 1b, respectively. The VSI serves as the main module, with its input connected to a DC voltage supply denoted as V_M. The output of the main module is then linked in series with either an full-bridge module or two half-bridge modules (referred to as auxiliary modules) for each phase. Each auxiliary module is associated with separate DC voltage sources, all having equal values denoted as V_H. Additionally, C_1 and C_2 represent DC capacitors connected in parallel with the DC source V_M. The midpoint between these two DC capacitors establishes the neutral point 'o' on the DC source side.



a) 3-leg VSI with full-bridge modules *b) 3-leg VSI with half-bridge modules*

Figure 1. Topology of HMI based on 3-leg VSI

The single-phase equivalent circuit of the two topologies used in this research is expressed in Figure 2. As can be seen clearly, the output of one phase of the 3-leg VSI will connect to either one full-bridge module or two half-bridge modules.

The single phase output voltage with the DC neutral point 'o' of the HMI-VSI-FB and HMI-VSI-HB is given by equations (1) and (2), respectively

$$v_{xo1} = v_{xM} + v_{xH} \tag{1}$$

$$v_{xo2} = v_{x1} + v_{x2} + v_{x3} \tag{2}$$

where x represents phase a, b, or c.

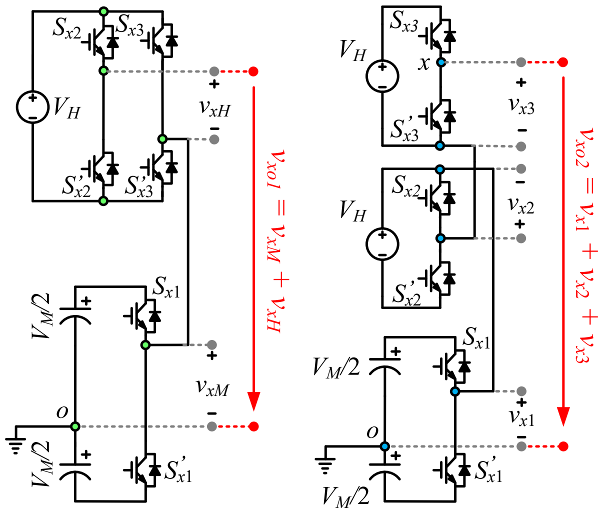


Figure 2. Single-phase equivalent circuit

Since the voltages across both DC capacitors are balanced, the switches on a single leg, known as S_{xj} and S'_{xj}, where $x = a, b, c,$ and $j = 1, 2, 3,$ are turned in a complementary way.

The resultant output voltage on one side of the main module is expressed as

$$v_{xM} = \begin{cases} -\dfrac{V_M}{2} & \text{when } S_{x1} = 0 \\ \dfrac{V_M}{2} & \text{when } S_{x1} = 1 \end{cases} \tag{3}$$

$$v_{x1} = \begin{cases} -\dfrac{V_M}{2} & \text{when } S_{x1} = 0 \\ \dfrac{V_M}{2} & \text{when } S_{x1} = 1 \end{cases} \tag{4}$$

The output voltage of full-bridge module is described as

$$v_{xH} = \begin{cases} -V_H & \text{when } S_{x2} = 0,\ S_{x3} = 1 \\ 0 & \text{when } S_{x2} = S_{x3} = 1 \text{ or } S_{x2} = S_{x3} = 0 \\ V_H & \text{when } S_{x2} = 1,\ S_{x3} = 0 \end{cases} \tag{5}$$

The output voltage of half-bridge modules is obtained as

$$v_{x2} = \begin{cases} -V_H & \text{when } S_{x2} = 0 \\ 0 & \text{when } S_{x2} = 1 \end{cases} \tag{6}$$

$$v_{x3} = \begin{cases} V_H & \text{when } S_{x3} = 1 \\ 0 & \text{when } S_{x3} = 0 \end{cases} \tag{7}$$

where "0" and "1" values represent the open and closed states of the switches, respectively.

Combining (1), (3), and (5), the output voltage equation of the HMI-VSI-FB can be rewritten as follows:

$$v_{xo1} = \left(S_{x1} - \frac{1}{2}\right) \times V_M + \left(S_{x2} - S_{x3}\right) \times V_H \tag{8}$$

Similarly, the output voltage equation of the HMI-VSI-HB can be rewritten from (2), (4), (6), and (7) as follows:

$$v_{xo2} = \left(S_{x1} - \frac{1}{2}\right) \times V_M + \left(S_{x3} - S_{x2}\right) \times V_H \quad (9)$$

With the combination of the eight open-circuit states of the switches, as illustrated in (8) and (9), the corresponding output voltage values are obtained, as shown in Table 2. These values are surveyed, based on the ratio of the DC voltage fed to the main module and the DC voltage fed to the auxiliary modules. With this survey, the number of levels for these two inverters have been determined as:

$$n_{level} = \begin{cases} 4 & \text{if } V_H = V_M \\ 5 & \text{if } V_H = \dfrac{V_M}{2} \\ 6 & \text{if } V_M \neq V_H \neq \dfrac{V_M}{2} \end{cases} \quad (10)$$

3. MODULATION SCHEME

The common modulation techniques for multilevel inverters such as multi-carrier sinusoidal pulse-width modulation (MCPWM), space vector pulse-width modulation (SVPWM), and selective harmonic elimination (SHE) and so on have been investigated in this research. Among these, MCPWM is considered to be traditional and more accessible. Depending on MCPWM technique, $(n - 1)$ carrier with similar frequency and amplitude has been applied. The modulated waveform, v_{mod} is continuously compared with each of the carrier waveforms to generate the pulse for switches.

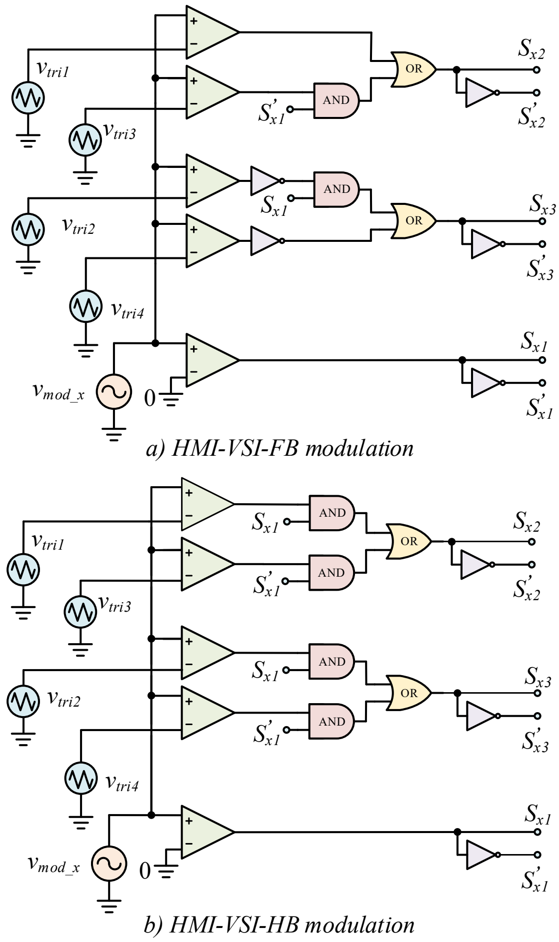


Figure 3. Modulation scheme for HMIs based on a 3-leg VSI

To obtain an output waveform with five levels ($n = 5$), choose $V_M = 2V_H = V_{DC}$, which necessitates the use of four carrier signals. The control signals for the switches in a 3-leg VSI are not directly derived from the comparison of modulation and carrier signals. During the positive half-cycle of the modulated waveform, the output voltage on one leg of the 3-leg VSI is held at $V_{DC}/2$, while during the negative half-cycle, it is held at $-V_{DC}/2$. Therefore, the control signals for the VSI switches are generated by comparing the modulated waveform with the zero level. On the other hand, the control signals for the auxiliary modules are produced by comparing the sinusoidal modulating waveforms with four synchronized triangular carriers, as illustrated in Figure 3. This arrangement allows the VSI switches to operate at a lower frequency, while the switches on the auxiliary modules operate at a higher frequency. This enables the use of low-speed switches in the three-phase inverter, thus decreasing the conduction losses in the VSI [10].

4. SIMULATION AND RESULTS

The simulation has been done to verify the five-level control scheme for HMIs based on 3-leg VSI. The HMIs are connected to a three-phase load RL, while the main module and auxiliary modules are supplied with DC source with values of $V_M = 350$ V and $V_H = 175$ V, respectively. At the input of the main module, both capacitors are connected in series with the same value and connected in parallel with the DC source V_M, the middle point of the two capacitors is called a neutral point on the DC side. The system parameters used in simulation are listed in Table 3.

Table 3. Simulation parameters

Parameters	Value
Rated power (P)	8 kW
Load resistance (R)	15 Ω
Load inductance (L)	20 mH
DC Capacitor ($C_1 = C_2$)	4700 µF
Fundamental frequency (f_0)	50 Hz
Carrier frequency (f_{tri})	5 kHz

A survey of the THD (Total Harmonic Distortion) of the voltage and current on the load was conducted with modulation index varying from 0.1 to 0.86. This result is shown in Table 4. The voltage on the load in both cases exhibited the same level of harmonic distortion, with a value of approximately 18% at the $m_a = 0.86$. The current on the load had lower distortion due to the effect of the inductive component on the load. Figure 4 provides a clearer comparison of the THD of the voltage on the load.

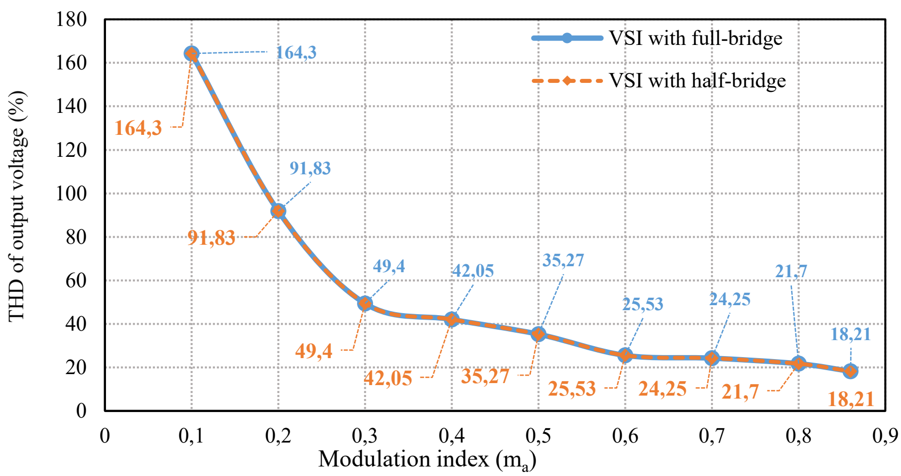
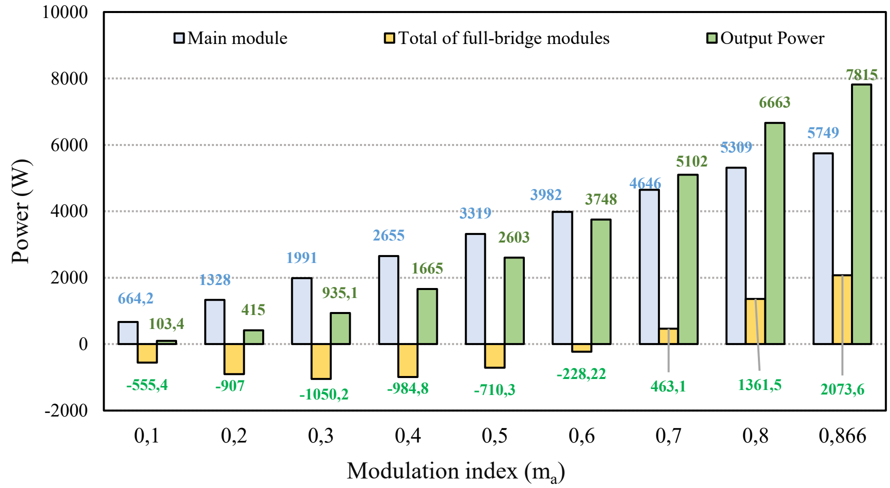
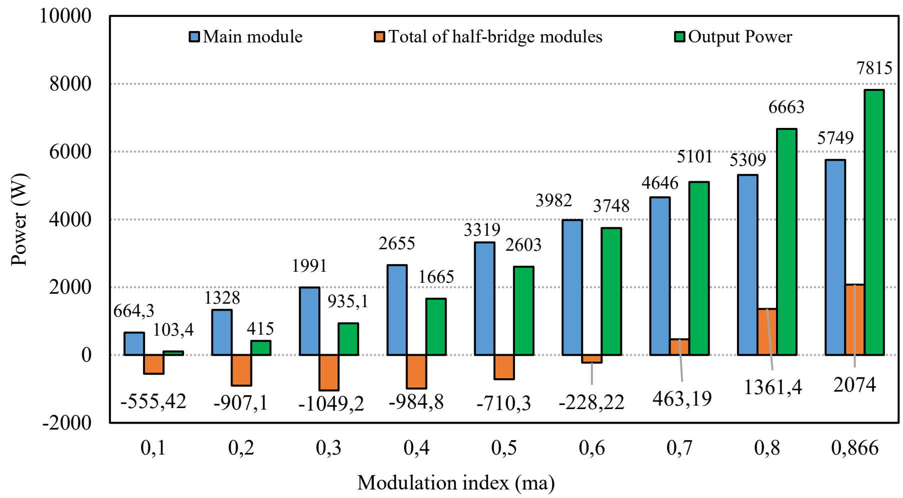


Figure 4. Comparison of the THD of the two topologies



a) HMI-VSI-FB



b) HMI-VSI-HB

Figure 5. Distribution of DC sources power

Table 4. Effect of modulation index on THD (%)

m_a	*HMI-VSI-FB*				*HMI-VSI-HB*			
	v_{la} (V_{rms})	THD_v (%)	i_a (A)	THD_i (%)	v_{la} (V_{rms})	THD_v (%)	i_a (A)	THD_i (%)
0.1	47.33	164.3	1.513	2.206	47.33	164.3	1.513	2.206
0.2	67.05	91.83	3.037	1.415	67.05	91.83	3.037	1.415
0.3	82.72	49.4	4.561	0.8088	82.72	49.4	4.561	0.8088
0.4	107.3	42.05	6.085	0.5808	107.3	42.05	6.085	0.5808
0.5	131.2	35.27	7.607	0.6115	131.2	35.27	7.607	0.6115
0.6	153.2	25.53	9.127	0.319	153.2	25.53	9.127	0.319
0.7	178.2	24.25	10.65	0.3744	178.2	24.25	10.65	0.3744
0.8	202.5	21.7	12.17	0.374	202.5	21.7	12.17	0.347
0.866	217.8	18.21	13.18	0.2778	217.8	18.21	13.18	0.2778

Table 5. Comparison between HMIs based on a 3-leg VSI combine full-bridge modules and half-bridge modules

Parameter	VSI combine full-bridge modules	VSI combine half-bridge modules
Number of switch	18	18
Number of DC sources	4	**7**
Number of capacitors	5	**8**
Number of levels at output voltage	4, 5, and 6	4, 5, and 6
THD of load voltage at $m_a = 0.86$	18.21%	18.21%
Average power of DC sources at $m_a = 0.86$ (except 3-leg VSI)	4.4% of output power	**8.8%** of output power
Switching frequency at (except 3-leg VSI)	High	High
Switching frequency at 3-leg VSI	Low	Low

Figures 5a and 5b show the power distribution of the DC voltage sources for HMI-VSI-FB and HMI-VSI-HB at different modulation index values. For the case where $m_a = 0.86$, the output power of the two topologies is equivalent at 7815 W. The DC power supplied to the main module is 5749 W. The DC power supplied to the full-bridges is nearly equal at 691.2 W, and the DC power supplied to the half-bridges is also nearly equal at 345.7 W.

At modulation index ranging from 0.1 to 0.6, the power delivered by the DC sources to the auxiliary modules can be negative. The sign of the power (positive or negative) for these DC sources is influenced by the direction of the phase current. Since the main module's output voltage remains constant each half-cycle, the auxiliary modules are required to absorb more power and convert it back when the modulation index is low. Consequently, at lower modulation index, the power handled by all DC sources is significantly higher compared to the total power supplied to the load. This suggests that the control method may not ensure a consistent DC power flow in the supplies feeding the auxiliary modules throughout the entire range of modulation index.

Table 5 summarizes the comparisons for the two configurations. Several surveys indicate that the two configurations have similar operating parameters. The difference is that the DC power supplied to the half-bridge modules is less than the DC power supplied to the full-bridge modules. This also provides a basis for selecting appropriate semiconductor switch power for the experiment.

5. CONCLUSION

This study provides a comparative analysis of two hybrid multilevel inverter (HMI) topologies: HMI-VSI-FB and HMI-VSI-HB, focusing on their performance in a five-level output configuration. Simulation results indicate that both topologies exhibit similar operating parameters, particularly in terms of total harmonic distortion (THD) of load voltage and current. However, the DC power distribution differs, with the half-bridge modules requiring less power than the full-bridge modules. This finding is critical for the selection of semiconductor switches for the experiment. While both topologies effectively reduce the number of components, further research is needed to optimize their control methods to ensure consistent DC power flow across all modulation indices.

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TÓM TẮT

NGHIÊN CỨU SO SÁNH BỘ NGHỊCH LƯU NĂM BẬC LAI DỰA VÀO BỘ NGHỊCH LƯU BA CHÂN

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Bộ nghịch lưu đa bậc lai (HMI) tích hợp bộ nghịch lưu nguồn điện áp 3 chân (VSI) với các mô-đun cầu toàn phần hoặc cầu bán phần, mang lại những lợi ích như giảm số lượng khóa nguồn, nguồn DC và tụ điện DC so với bộ nghịch lưu đa bậc truyền thống. Mặc dù có những ưu điểm này, HMI vẫn có những đặc điểm riêng biệt. Nghiên cứu này điều tra sự khác biệt về chất lượng điện áp DC và điện áp đầu ra khi vận hành với điện áp ngõ ra năm bậc. Kết quả so sánh thu được thông qua các mô hình mô phỏng trong MATLAB/Simulink, sử dụng các tham số đồng nhất cho cả hai cấu trúc bộ nghịch lưu.

Từ khóa: Bộ nghịch lưu đa bậc lai, bán cầu, toàn cầu, bộ nghịch lưu nguồn điện áp 3 chân.