Letters

Phase-Shifting SPWM-Based Modulation for Single-Source Five-Level Current Source Inverter

Ling Xing, Qiang Wei, Yunwei Li, *Fellow, IEEE*, and Yan-Fei Liu, *Fellow, IEEE*

***Abstract*—A single-source five-level current source inverter (CSI) with inherent current balancing and fewer switches was recently proposed. Its modulation scheme that achieves both five-level output and superior harmonic performance with low switching frequency remains a challenge and has not been explored. Phase-shifting sinusoidal pulsewidth modulation (SPWM) is a well-established technique that offers superior harmonic performance at low switching frequencies. Despite these advantages, its application to the single-source five-level CSI is not applicable due to its unique single-source topology. In this work, the challenge associated with applying phase-shifting SPWM to the single-source five-level CSI is identified, and a novel phase-shifting SPWM-based modulation technique retaining all the advantages of phase-shifting SPWM is developed for the single-source five-level CSI. Lab-scale experiments are conducted to verify the performance.**

***Index Terms*—Current source inverter (CSI), five-level, modulation.**

I. Introduction

SINGLE-PHASE current source inverters (CSIs) are a good candidate for applications where continuous input current and voltage boosting are needed, such as solar systems [1] and uninterruptible power supplies [2]. Existing single-phase five-level CSIs can be categorized into two types: those utilizing two isolated current sources [3], [4] and those utilizing a single source [5], [6], [7], [8], [9], [10]. The former employs transformers to realize isolated current sources, resulting in high cost, as well as increased size and weight. In contrast, single-source five-level CSIs [5], [6], [7], [8], [9], [10] are typically implemented using a single voltage source in series with parallel-connected inductors. While this approach reduces cost and size, it presents several challenges, including current imbalance, circulating currents, and the requirement for a large number of switches [11]. To retain the advantages of single-source CSIs while addressing their challenges, a novel single-source CSI was proposed [12]. It features inherent current balancing and fewer switches compared to its peers.

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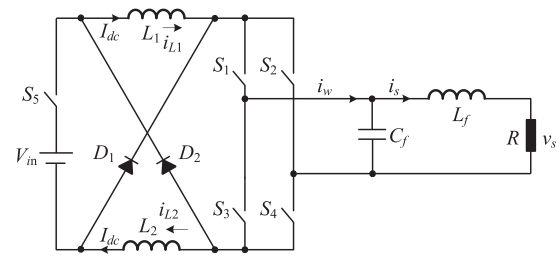

Fig. 1. Single-source five-level CSI [10].

However, for this single-source five-level CSI, developing a modulation scheme that simultaneously achieves a five-level output, superior harmonic performance, and low switching frequency remains a challenge and has not yet been explored. Phase-shifting sinusoidal pulsewidth modulation (SPWM) [13], [14], [15], [16] is a well-established technique that offers several advantages, including simple implementation, superior harmonic performance with a predefined harmonic profile at a given switching frequency, and the absence of low-order harmonics at low switching frequencies. Despite these benefits, it has only been applied to the conventional two-source five-level CSI: a topology that employs two isolated current sources and two H-bridge CSI converters. Its application to a single-source five-level CSI is not feasible due to the inverter's unique single-source topology. In this work, the challenges associated with applying phase-shifting SPWM to the single-source five-level CSI are identified. A phase-shifting SPWM-based modulation that retains all the advantages of conventional phase-shifting SPWM is developed for the single-source CSI.

II. Five-Level CSI With Inherent Current Balancing

A. Single-Source Five-Level CSI

Fig. 1 shows the single-source five-level CSI [12], which consists of an H-bridge CSI (S_1, S_2, S_3, S_4), switch S_5, inductors L_1 and L_2, and diodes D_1 and D_2. Switches (S_1–S_4) should have reverse voltage blocking capabilities. They can be realized using insulated-gate bipolar transistor (IGBT)/MOSFET connected with a diode, bidirectional IGBT/MOSFET, or symmetrical gate

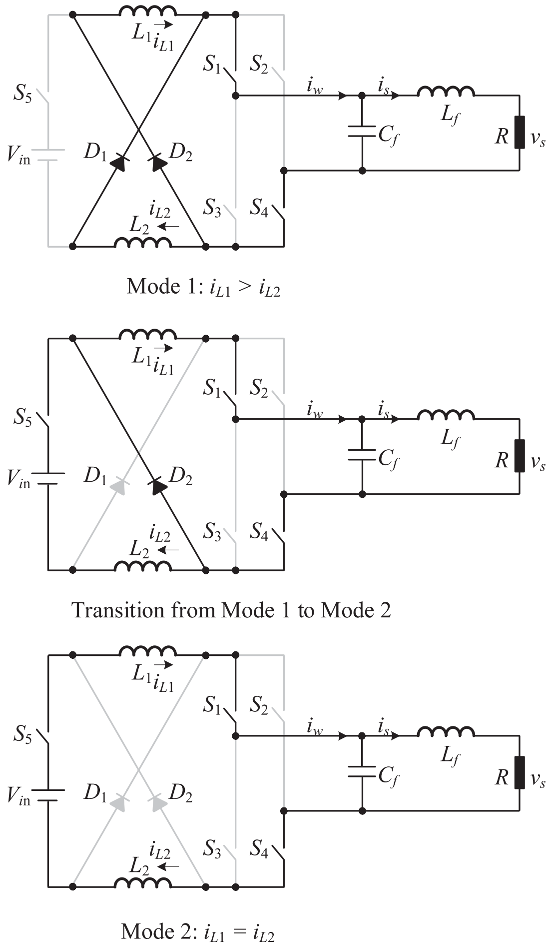

Fig. 2. Equivalent circuits under different modes.

commutated thyristor (GCT) depending on specific applications. The switch S_5 does not need reverse voltage blocking capability and can be any one of those switches used in voltage source converters. In this work, IGBT in series with a diode is used to realize switches (S_1–S_4), and S_5 is realized by IGBT.

It operates in Mode 1 and Mode 2. In Mode 1, S_5 is turned ON, and L_1 and L_2 are connected in series, allowing the generation of I_{dc}, 0, and -I_{dc} at the output i_w. In Mode 2, S_5 is turned OFF, and L_1 and L_2 are connected in parallel, allowing generation of $2I_{\mathrm{dc}}$, 0, and -$2I_{\mathrm{dc}}$ at the output. The series connection of L_1 and L_2 in Mode 1 ensures inductor current balancing ($i_{L1} = i_{L2}$) [12]. For example, as shown in Fig. 2, where the equivalent circuits of Mode 1, Mode 2, and the transient between the two modes are presented. In Mode 1, the two inductors are operating in parallel, resulting in imbalanced inductor currents, e.g., $i_{L1} > i_{L2}$, due to different inductances introduced by manufacturing tolerance in practice. In Mode 2, the two inductors are operating in series, forcing the two unbalanced inductor currents to be the same, that is, $i_{L1} = i_{L2}$. During the transition from Mode 1 to Mode 2, D_2 is turned ON to provide the current path for the different current between i_{L1} and i_{L2}. This inverter therefore offers a natural inductor current balance without additional current balancing schemes.

This converter is a two-stage (two power conversion stages) buck–boost converter. The first stage is composed of S_5, L_1, L_2, D_1, and D_2, and the remaining circuit is the second stage. The two inductors are shared by the two conversion stages. The first stage is a conventional buck converter, whereas the second stage is a conventional current source converter which is a boost converter. Conventional two-source converters as shown in Fig. 3 are single-stage (one power conversion stage) converters. Existing single-source converters are two-stage converters but use more switches than the one presented in this work [5], [6], [7], [8], [9], [10]. Therefore, given the same conditions (power rating, switch, frequency, etc.), this two-stage converter shown in Fig. 1 in this work is expected to have lower efficiency than single-stage converters, whereas it has potential to achieve higher efficiency than existing two-stage converters due to the use of fewer switches.

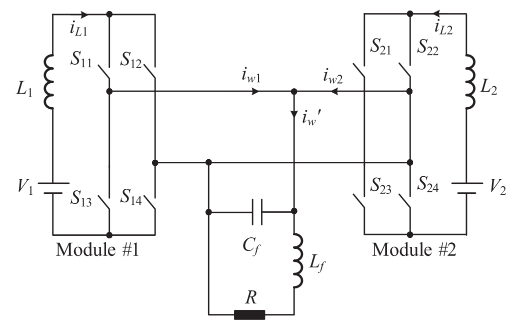

Fig. 3. Two-source five-level CSI.

B. Phase-Shifting SPWM for Two-Source Five-Level CSI

The two-source five-level CSI is shown in Fig. 3, where two H-bridge CSI converters, Module #1 and Module #2, fed by two isolated current sources are used. Conventional phase-shifting SPWM is used to generate five levels at the converter output [16]. For instance, comparing the modulating wave v_m with the carrier wave v_{c1} produces the gating signals for the switches (S_{11}, S_{12}, S_{13}, S_{14}) in Module #1, as shown in Fig. 4. The same SPWM technique is applied to the switches (S_{21}, S_{22}, S_{23}, S_{24}) of Module #2, but with a 180° phase shift applied to the carrier wave v_{c2}. This phase shift ensures that the total pulsewidth modulation current $i_w{}'$ ($i_w{}' = i_{w1} + i_{w2}$) achieves a five-level waveform as shown in Fig. 4. Its harmonics profile is listed in Fig. 4. The phase-shifting SPWM offers simple implementation, superior harmonic performance with a predefined harmonic profile at a given switching frequency, and the absence of low-order harmonics at low switching frequencies.

C. Objective and Challenge

The objective is to develop a phase-shifting SPWM-based modulation for the single-source CSI, capable of generating a five-level output (i_w) identical to that ($i_w{}'$) of the two-source five-level CSI, thereby retaining all the advantages of conventional phase-shifting SPWM. The challenge is that the single-source CSI has only one source and one H-bridge module, preventing the use of the conventional phase-shifting SPWM.

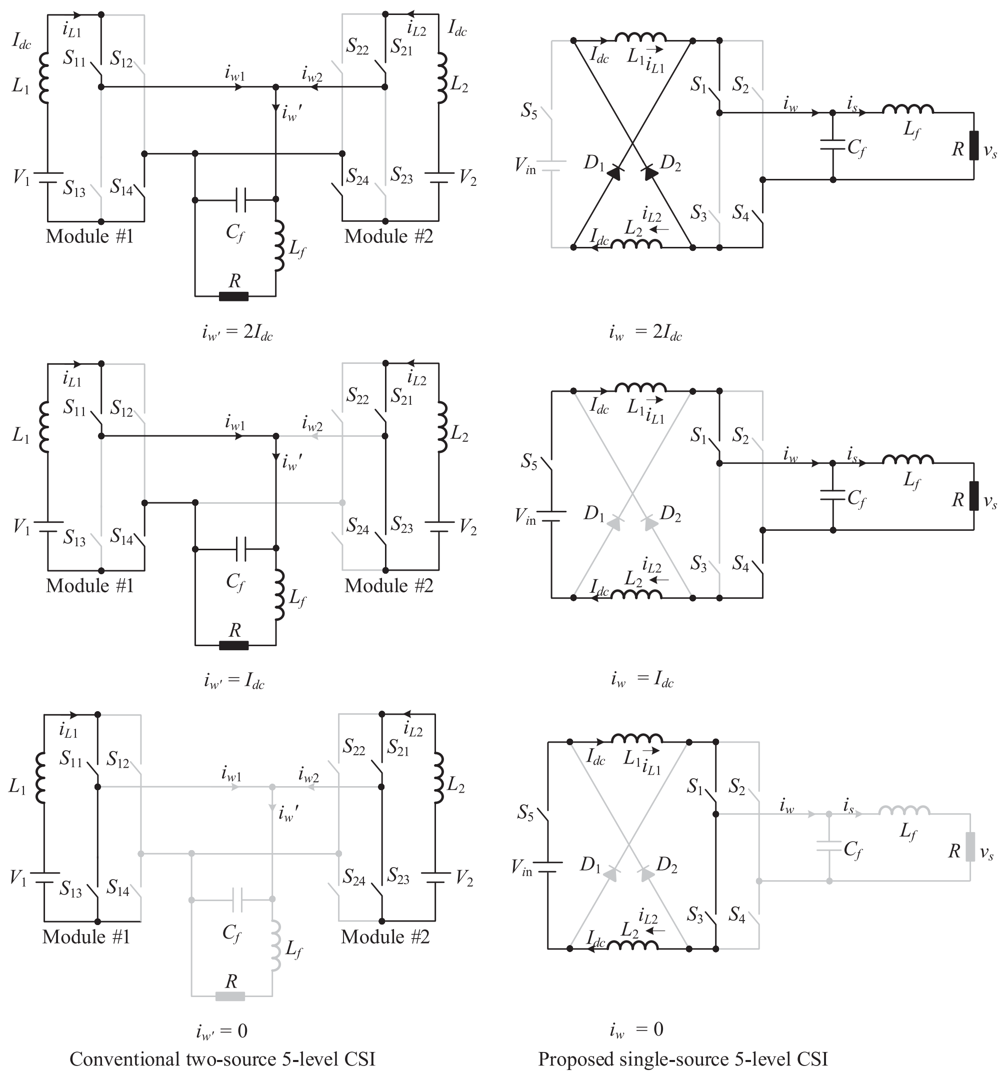

Fig. 4. Equivalent circuits of the conventional and proposed five-level CSIs under different switching states in the positive cycle of i_w (or $i_w{}'$).

D. Proposed Phase-Shifting SPWM-Based Modulation for Single-Source Five-Level CSI

The methodology is to switch the corresponding switches of the single-source CSI to ensure its output current is identical to the two-source CSI, that is, $i_w = i_w{}'$. In other words, the output current $i_w{}'$ of the two-source five-level CSI, generated using the phase-shifting SPWM, serves as the reference waveform for the single-source CSI. The relationship between the respective switching states of the two-source and single-source CSIs is listed in Table I. The equivalent circuits of the conventional two-source five-level CSI and the proposed single-source five-level CSI under different switching states in the positive half cycle of i_w (or $i_w{}'$) are shown in Fig. 4. Note that the two inverters share the same criteria of switching pattern design, that is to minimize switching frequency [16]. For example, in the transition from $i_w{}' = 2I_{\text{dc}}$ to $i_w{}' = I_{\text{dc}}$, S_{23} is turned ON, while S_{24} is turned OFF to minimize switchings, and the same for the transition from $i_w{}' = I_{\text{dc}}$ to $i_w{}' = 0$, where S_{13} is turned ON, while S_{14} is turned OFF while the other switches remain the prior switching state. The same criteria also apply to the proposed single-source five-level CSI as shown in Fig. 4.

TABLE I
SWITCHING STATES OF TWO-SOURCE AND SINGLE-SOURCE CSIS

Switching states									Output PWM Current i_w and $i_w{}'$
Upper switches		Lower switches							
		Two-source 5-level CSI				Singel-source 5-level CSI			
S_{11} S_{21} S_1	S_{12} S_{22} S_2	S_{13}	S_{14}	S_{23}	S_{24}	S_3	S_4	S_5	
1	0	1	0	1	0	1	0	0	0
0	1	0	1	0	1	0	1	0	0
1	0	0	1	1	0	0	1	1	I_{dc}
1	0	1	0	0	1				
1	0	0	1	0	1	0	1	0	$2I_{dc}$
0	1	1	0	0	1	1	0	1	$-I_{dc}$
0	1	0	1	1	0				
0	1	1	0	1	0	1	0	0	$-2I_{dc}$

The proposed modulation is shown in Fig. 5, and its implementation is shown in Fig. 6. Note the sawtooth wave in Fig. 6 is

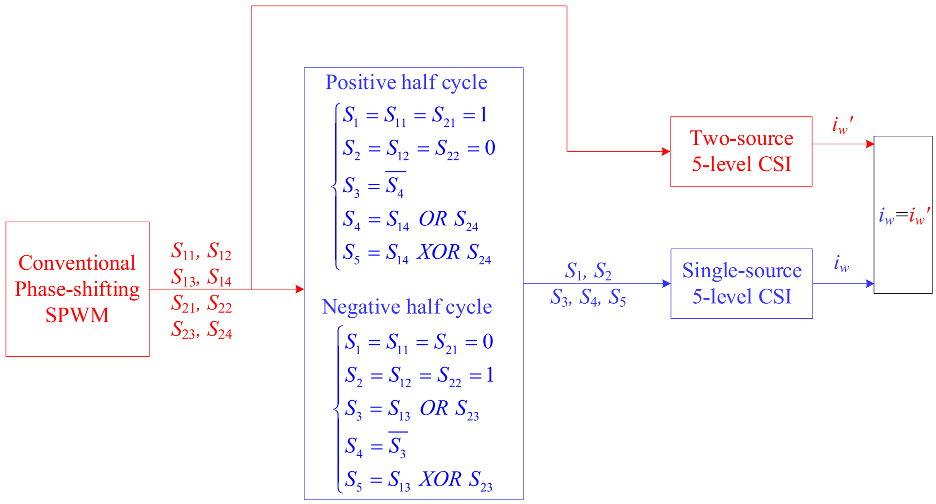

Fig. 5. Proposed phase-shifting SPWM-based modulation for single-source five-level CSI.

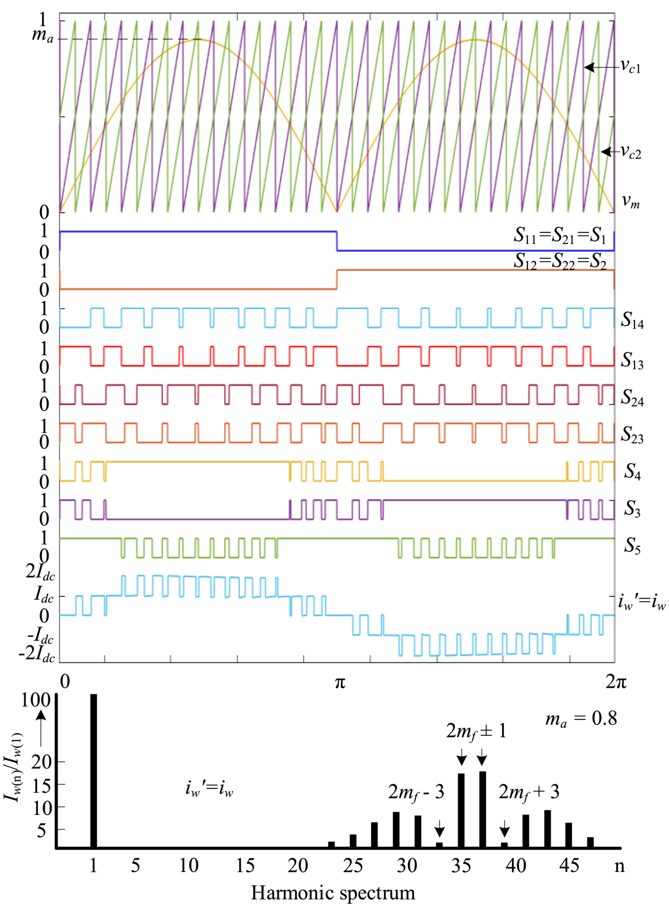

Fig. 6. Proposed phase-shifting SPWM-based modulation, where (S_1, S_2, S_3, S_4, S_5) are switches of the single-source CSI, and (S_{11}, S_{12}, S_{13}, S_{14} and S_{21}, S_{22}, S_{23}, S_{24}) are switches of the two-source CSI.

an example and it can be replaced with a triangular wave. Please refer to [17] for details of different modulation implementations.

The upper two switches S_1 and S_2 operate at the same fundamental switching frequency as the upper switches of the conventional two-source CSI, specifically, $S_1 = S_{11} = S_{21}$ and $S_2 = S_{12} = S_{22}$, where S_{11} and S_{12} are the upper switches of Module #1 of the two-source CSI, and S_{21} and S_{22} are the upper two switches of Module #2. In the positive cycle of the output current i_w, $S_1 = 1$, and $S_2 = 0$.

Switching patterns of S_3 and S_4 of the single-source CSI are obtained based on the states of S_{13}, S_{23}, S_{14}, and S_{24} of the two-source CSI. Taking S_4 in the positive half cycle of i_w as an example, it is switched ON whenever the output current i_w is not zero, and it is switched OFF when a zero-output current i_w is required. In the two-source CSI, the corresponding switching states to a zero output are ($S_{14} = 0$, $S_{24} = 0$), whereas the corresponding states to a nonzero output are ($S_{14} = 0$, $S_{24} = 1$; $S_{14} = 1$, $S_{24} = 0$; $S_{14} = 1$, $S_{24} = 1$). S_4 can be obtained by S_{14} OR S_{24}.

The switching state of S_5 is derived based on i_w. As shown in Fig. 1, when $i_w = I_{\mathrm{dc}}$, S_5 is switched ON, whereas when $i_w = 2I_{\mathrm{dc}}$, S_5 is switched OFF. The state of S_5 remains the same as its previous state when $i_w = 0$ to minimize switching frequency. In other words, in the two-source CSI, only ($S_{14} = 0$, $S_{24} = 1$) and ($S_{14} = 1$, $S_{24} = 0$) enable an ON state for S_5. An XOR logic can be applied to obtain the switching state of S_5. The switching states in the negative cycle are obtained in the same manner.

The same as conventional phase-shifting SPWM, the upper switches (S_1 and S_2) operate with a fundamental frequency, and the lower switches (S_3 and S_4) have a switching frequency of $m_f f$, where m_f is the frequency modulation index, f is the fundamental frequency, and the product of m_f and f is the switching frequency of S_3 and S_4. The switching frequency of the switch S_5 is $2m_f f$. Different switching frequencies result in uneven power loss distribution, which is an issue for most multilevel converters and requires attention for thermal and cooling system design [16]. Switches S_1–S_4 share the same voltage rating due to their same maximum voltage stress ($V_{c-\mathrm{peak}}$, the peak value of the output capacitor voltage), whereas the maximum voltage stress of S_5 is $V_{\mathrm{in}} + V_{c-\mathrm{peak}}$. The current rating of S_5 is two times the average of switches (S_1–S_4). The modulation index m_a determines the number of levels of output current i_w. Under

TABLE II
EXPERIMENT PARAMETERS

Currents	Passive components	Switching frequency
I_{dc}=5 A	L_1=40 mH, L_2 = 50 mH	f_{s1}=f_{s2}=50 Hz
I_{L1}=5 A	L_f =5 mH	f_{s3}=f_{s4}=900 Hz
I_{L2}=5 A	C_f =100 μF	f_{s5}=1800 Hz

m_a>0.5, the output i_w achieves five levels, whereas under $m_a <= 0.5$, i_w has three levels, at which the single-phase five-level CSI becomes a conventional three-level H-bridge CSI. This is because under $m_a <= 0.5$, the single-source CSI only operates under Mode 1.

The same as the two-source CSI under the conventional phase-shifting SPWM, the output current i_w of the single-source CSI with the proposed modulation does not contain any low-order harmonics and the dominant harmonics are also located at around $2m_f \pm 1$. The dc current utilization $I_{w,\max}/I_{\rm dc}$ is also linearly related to m_a:$I_{w,\max}/I_{\rm dc} = 2m_a/\sqrt{2}$.

E. Experimental Verification

The parameters used for lab-scale experiments are listed in Table II. Fig. 7 shows the experimental waveform under a steady state with different modulation indexes. Under $m_a = 0.5$, the boundary modulation index, the output current i_w becomes three levels, which agrees with the previous analysis that the proposed SPWM-based modulation generates three-level output under $m_a <= 0.5$. Under $m_a = 0.6$ and $m_a = 0.8$, as shown in Fig. 8, the output current i_w achieves five levels. Also, as shown in the harmonics profile in Fig. 7, the dominant harmonics are located at $2m_f \pm 1$, and the dc current utilization is $2m_a/\sqrt{2}$, which agrees with the previous analysis. As presented in [12], the inherent current balancing of the single-source five-level CSI is well maintained under different dc inductors, which are purposely set to verify the natural current balancing. For example, as shown in Fig. 7, the two inductor currents are well balanced ($i_{L1} = i_{L2} = I_{\rm dc} = 5$ A) without balancing control in all cases of $m_a = 0.5$, $m_a = 0.6$, and $m_a = 0.8$. Fig. 8 shows current balancing when inductor currents ($i_{L1} = i_{L2} = I_{\rm dc}$) are changed from 2 to 5 A under $m_a = 0.8$.

In experimental results, there are spikes at zero crossings, and they are caused by the switching overlap. For CSI, an overlap is added during switching transitions to ensure there is a guaranteed path for the current flow. This is analogous to voltage source inverters, where a dead time is applied.

Fig. 9 shows the gating signals of the single-source five-level CSI using the proposed SPWM-based modulation under $m_a = 0.8$. As shown in the figure, the top switches (S_1 and S_2) are operating with a fundamental frequency of 50 Hz, whereas the bottom switches (S_3 and S_4) are switched with a modulating frequency of 900 Hz. The switching frequency of the switch (S_5) is switching with a switching frequency of 1800 Hz, which is double the modulating frequency.

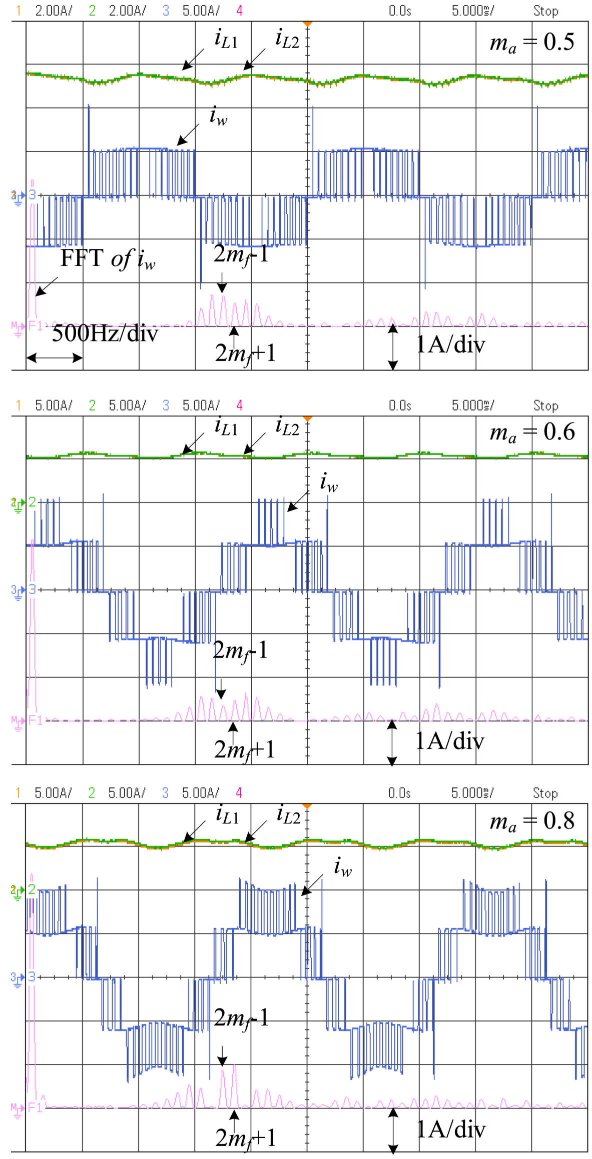

Fig. 7. Experimental waveforms under $m_a = 0.5$, $m_a = 0.6$, and $m_a = 0.8$.

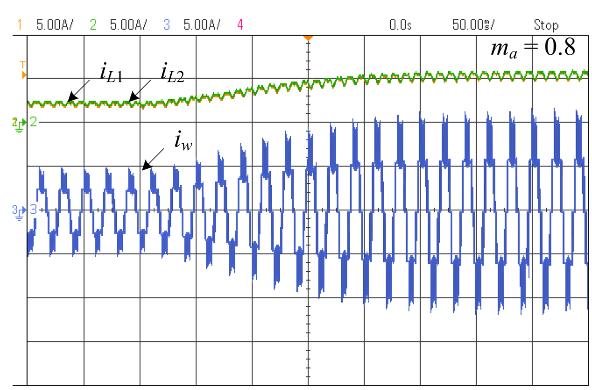

Fig. 8. Experimental waveforms under dynamic state.

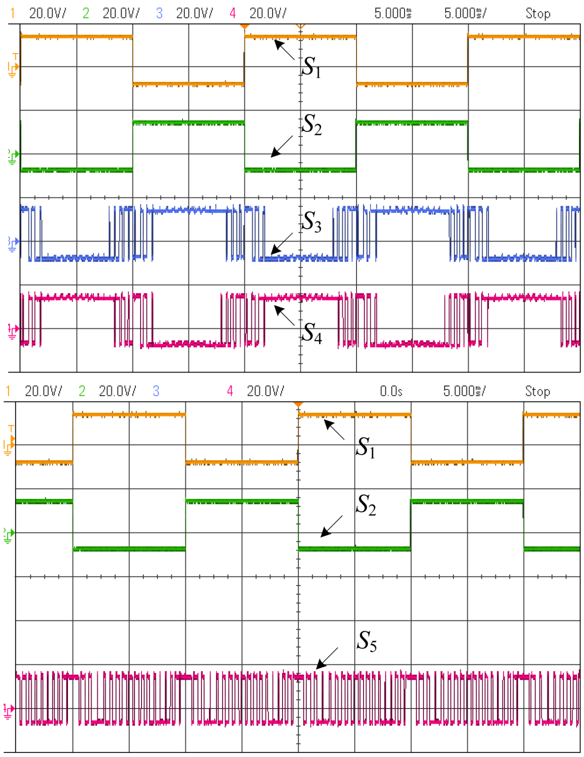

Fig. 9. Gating signals under $m_a = 0.8$.

III. Conclusion

A phase-shifting SPWM-based modulation is developed for the single-source five-level CSI. It retains all the advantages of conventional phase-shifting SPWM, including simple implementation, superior harmonic performance with a predefined harmonic profile at a given switching frequency, and the absence of low-order harmonics at low switching frequencies. It also retains all the benefits of the single-source five-level CSI, including the inherent inductor current balancing.

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