Single-phase Multilevel Current Source Inverter with Reduced Device Count and Current Balancing Capability

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***Abstract*—Nowadays power converters play an important role in power system and industrial centers. One of the most important and widely used types of conversion is DC to AC conversion that is also called inverters. Generally inverters are divided to voltage source inverter (VSI) and current source inverter (CSI). From another view the inverters are divided to two-level and multilevel types. The multilevel inverters are attractive because of their good output waveform quality. However, there has been less attention to multilevel current source inverter (MLCSI) when compared with multilevel VSI. In this paper, a new topology for MLCSI is proposed. The proposed topology employs reduced number of switches to generate desired multilevel output current. The proposed MLCSI is capable of balancing the currents of the inductors that are used in the MLCSI structure. A multicarrier PWM based switching strategy is also proposed for the MLCSI. The simulation results using PSCAD/EMTDC as well as the experimental results from a single-phase 5-level CSI laboratory prototype demonstrate its validity.**

***Index Terms*—power electronics, power conversion, pulse width modulation converters, inverters, multilevel current source inverter.**

I. INTRODUCTION

Multilevel converters were developed as a result of requirement for higher power converters [1]. The converters use series/parallel connected semiconductor switches to synthesize switched waveforms at power levels well above the individual device ratings [2]. The multilevel converters have substantial advantages for higher power applications comparing with two level inverters, such as reduced harmonics, and higher power ratings because of reduced switching device voltage and current stresses [3-6]. Voltage Source Inverter (VSI) has been the mostly used multilevel topology up to now. However, as one of multilevel converter types, Current source Inverters (CSIs) have also some advantages such as inherent four-quadrant operation capability, direct control of the output current and easier fault management for higher power applications such as high power drives. Moreover the power circuit of the CSI is simpler and more robust than the VSI due to no freewheeling diodes with unidirectional current flow. Also the CSI can provide a higher reliability related with a dc-link inductor than a capacitor for the VSI [3-4, 7-8]. More comprehensive comparison of VSIs and CSIs can be found in [9-10].

Current source converters (CSCs) are widely used in motor drive applications [7-8, 11]. Also application of CSCs has been developed to high voltage direct current (HVDC) systems [12-13], as grid interface for photovoltaic (PV) [14] and wind energy conversion systems (WECS) [15]. Moreover CSCs has been applied in static synchronous compensators (STATCOM) [16].

There are different topologies available for multilevel current source inverter (MLCSI) in the literature. In [17] an n-level CSI has been presented that uses $2(n-1)$ power electronic switches and $(n-3)$ current-sharing inductors. In [18] a topology for single-phase MLCSI has been presented using $(n+3)$ switches and $(n-3)/2$ current-sharing inductors then extended to three-phase system in [19]. In [3] a three-phase MLCSI using two types of CSI is presented. One is thyristor-based load-commutated converter and the other is a GTO-based converter operating in parallel. In [20] MLCSI topologies using duality principle have been presented in which the MLCSI derived from the multilevel voltage source inverters using duality concept. Another MLCSI topology has been presented in [21] which is based on the concept of H-bridge current cells operating is parallel. In this topology current cells can be both symmetrical and asymmetrical to achieve higher number of current levels. However, the topology considers ideal and non-equal current sources which are not practically available. Other topologies for CSIs concerning dynamic performance and zero current switching can be found in the literature [22-23]. Other topologies of MLCSI have been presented in [24-28].

Different modulation strategies can be used for CSIs. In [29] a six step direct PWM technique has been applied. Space vector modulation of CSI has been investigated in [30]. Selective harmonic elimination PWM of CSI has been investigated in [31-32]. In [33] phase-shifted trapezoidal PWM method has been applied to control an MLCSI. The space vector modulation of the multilevel current source inverter has been investigated in [34]. In [35] implementation of the MLCSI control system in FPGA is addressed. The works presented in [36-37] deal with the DC current balance in the MLCSI.

The presented topologies for MLCSI available in the literature usually have higher number of switches. In this paper that is extended version of [38], a new topology for MLCSI is proposed that uses reduced number of switches.

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This topology employs $(n+7)/2$ switches and $(n-1)/2$ current-sharing inductors for an *n*-level CSI. At first, the power circuit of the proposed topology along with the comparison with other MLCSI topologies will be presented and then the switching method is described. Two switching methods will be applied, the fundamental frequency modulation and modified multicarrier PWM method. Finally the simulation results in PSCAD/EMTDC software and for 5-level and 7-level CSI and the experimental results from a 5-level laboratory prototype will be presented to validate the proposed topology.

II. Proposed Topology for MLCSI

Fig. 1 shows the proposed MLCSI. As this figure shows, the output current of a current source is divided to several branches using current-sharing inductors. In fact, each of the inductors operates as a current source. For an *n*-level CSI, $(n+7)/2$ power electronic switches and $(n-1)/2$ current-sharing inductors are used. The switches are usually structured by an insulated gate bipolar transistor (IGBT) in series with a diode so that the current can flow unidirectional. The current-sharing inductors are the same, so, applying appropriate control method, the inductors currents are almost the same.

$$L_1 = L_2 = L_3 = \cdots = L_{(n-1)/2}$$
$$I_1 = I_2 = I_3 = \cdots = I_{(n-1)/2} = \frac{2I}{n-1} \quad (1)$$

In (1), I is the source current and $I_1, I_2, I_3, ..., I_{(n-1)/2}$ are the current-sharing inductors currents.

So, each inductor acts as a current source that can be short-circuited by means of the switches $S_5, S_6, \cdots, S_{(n+7)/2}$ or conducted to the load. Therefore the output current can be a multilevel current.

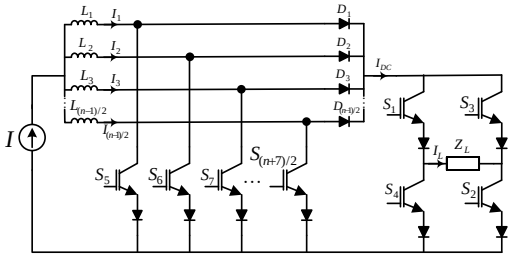


Figure 1. Power circuit of the proposed *n*-level CSI

As shown in Fig. 2, in reality, the current source is made using a voltage source in series with a relatively big-size inductor. However, a chopper can be also used to reduce the size of source inductor [24]. In this case, neglecting the power loss of CSI, the following equation is valid:

$$P_{in} = P_{out} \quad (2)$$

where, P_{in} and P_{out} are the input and output power of the MLCSI. Using (2), the following relation can be obtained:

$$I = \frac{P_{out}}{V} \quad (3)$$

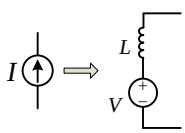


Figure 2. Realization of the DC current source

In the proposed topology, the switches S_1, S_2, S_3 and S_4 are used to change the output current polarity in positive and negative half cycles. So these switches work at output current frequency. Other switches (i.e. $S_5, S_6, \cdots, S_{(n+7)/2}$) are used to generate the desired levels of output current and must be higher frequency switches in the case of carrier phase-shifted SPWM control method. Diodes $D_1, D_2, ..., D_{(n-1)/2}$ are used to separate switches $S_5, S_6, \cdots, S_n$ and without using these diodes it is not possible to achieve the desired levels in the output current.

In order to compare the proposed topology with the other topologies presented in the literature, the number of switches in different topologies is illustrated in Fig. 3. As this figure shows, in the proposed MLCSI the number of switches is reduced considerably. For example, for a 5-level CSI, the topologies presented in [17] and [18] use 8 switches while the proposed topology in this paper uses only 6 switches. For the 7-level CSI the topologies presented in [17] and [18] use 12 and 10 switches respectively where the proposed MLCSI uses 7 switches. According to Fig. 3, as level number increases the difference between number of switches in the topologies grows up considerably while the switches number of the proposed MLCSI has the least increasing rate against level number. When compared from the view point of the number of current-sharing inductors, in the proposed topology, the number of current-sharing inductors decreases comparing with the topology presented in [17] but, comparing with the topology presented in [18], only one additional current-sharing inductor is used for each output current level number.

Figs. 4 and 5 show the power circuit of the proposed 5-level and 7-level CSI, respectively. Table I and II show the switching combinations to achieve the desired levels in the output current for the proposed 5-level and 7-level CSI, respectively.

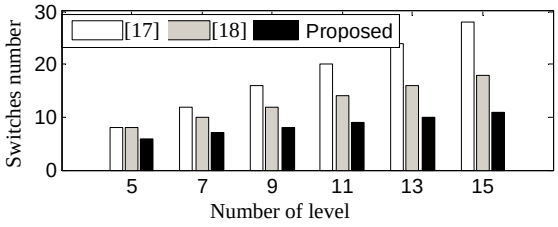


Figure 3. The number of switches against level number in different topologies

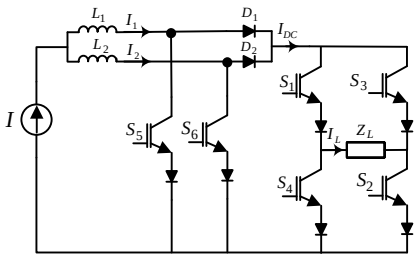


Figure 4. Power circuit of the proposed 5-level CSI

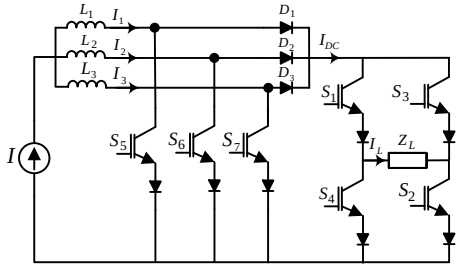


Figure 5. Power circuit of the proposed 7-level CSI

TABLE I. SWITCHING COMBINATIONS OF THE 5-LEVEL CSI

Level	Redundant switching combinations	DC bus Current (I_{DC})	Output Current
1	S_5, S_6	0	0
2	S_1, S_2, S_6 or S_1, S_2, S_5	$I/2$	$I/2$
3	S_1, S_2	I	I
4	S_3, S_4, S_5 or S_3, S_4, S_6	$I/2$	$-I/2$
5	S_3, S_4	I	$-I$

TABLE II. SWITCHING COMBINATIONS OF THE 7-LEVEL CSI

Level	Redundant switching combinations	DC bus current (I_{DC})	Output current
1	S_5, S_6, S_7	0	0
2	S_1, S_2, S_5, S_6 or S_1, S_2, S_5, S_7 or S_1, S_2, S_6, S_7	$I/3$	$I/3$
3	S_1, S_2, S_5 or S_1, S_2, S_6 or S_1, S_2, S_7	$2I/3$	$2I/3$
4	S_1, S_2	I	I
5	S_3, S_4, S_5, S_6 or S_3, S_4, S_5, S_7 or S_3, S_4, S_6, S_7	$I/3$	$-I/3$
6	S_3, S_4, S_5 or S_3, S_4, S_6 or S_3, S_4, S_7	$2I/3$	$-2I/3$
7	S_3, S_4	I	$-I$

III. SWITCHING STRATEGY

A. Fundamental frequency switching

The switching strategy should ensure two main requirements; (1) generation of the desired levels of the output current and (2) current balance between current-sharing inductors. To satisfy these requirements we should use all the redundant switching combinations that are presented in Table I and II for 5-level and 7-level CSI respectively. In other words, if we have more than one possible combination for an output current level, all of them should be used to ensure the current balance between current-sharing inductors. For example, for the 5-level CSI two different combinations are available to achieve the output current level of $I/2$ and both should be used in each output current cycle. For the 5-level CSI we can use all of the switching combinations in a cycle of output current. So, the switching states will be as Fig. 6. The figure indicates a typical output current for the 5-level CSI and the states of the switches in each time interval.

Taking Table II into consideration, there are 6 possible switching combinations to achieve each DC bus current levels of $I/3$ and $2I/3$ in the proposed 7-level CSI. So, we have 36 different switching combinations. To ensure current balance between the current-sharing inductors, all of these possible switching combinations should be used. But, this is available in three cycles of the output current. So, the switching states for the 7-level CSI will be as Fig. 7. This figure shows a typical output current for the 7-level CSI and states of the switches in each time interval.

B. Carrier phase-shifted PWM

One of the PWM strategies that are widely used in the multilevel inverters is the phase-shifted PWM (PS-PWM) method. In this method several carriers depending on the structure of the inverter are used. The carriers have certain phase shift from each other. The reference wave in this method is a sine wave which is compared with the carriers to provide proper pulses for switches in a multilevel inverter.

The multicarrier PS-PWM method can be applied for the proposed MLCSI with some modifications. As mentioned before, the multilevel current created on the dc bus (I_{DC}) is unidirectional and the same for positive and negative half cycles. The polarity of the output current in every half cycle is changed using switches $S_1 - S_4$. So, the PS-PWM method is only applied for other switches (i.e. $S_5, S_6, \cdots, S_{(n+7)/2}$). As a result, variation of carrier waveforms is between 0 and 1. Also absolute value of reference waveform is compared with carrier waveforms.

Fig. 8 shows the application of the PS-PWM method for the *n*-level MLCSI. In this figure, *m*, ϕ and ω_o are modulation index, output current initial phase angle and angular frequency of the output current, respectively. In this method, to extract the switching pattern, $(n-1)/2$ triangular carrier waveforms which have a phase shift $4\pi/(n-1)$ radians from each other, are compared with the absolute value of the reference waveform. The output signal of each comparator is applied for a switch to create a multilevel current.

Two carrier waveforms phase shifted from each other by π radians are required for the 5-level CSI and three carrier waveforms phase shifted from each other by $2\pi/3$ radians are required for the 7-level CSI. Carrier and reference waves of the 7-level CSI are illustrated in Fig. 9.

It is worth noting that by the PS-PWM method the current balance between current-sharing inductors is provided naturally. The reason is that firstly due to the relatively higher frequency modulation the time duration that each inductor is shorted by the switch is very small so that it has not enough time to increase its current. Secondly, by this method all of the redundant switching combinations are used resulting is a good current balance between the inductors.

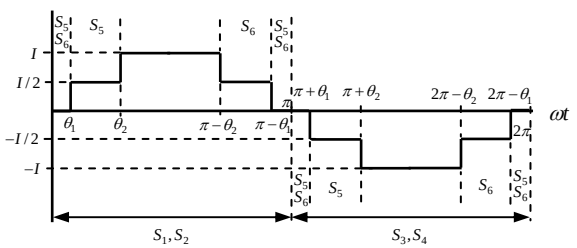


Figure 6. Typical output current for 5-level CSI and states of the switches using all redundant switching combinations to balance the inductors currents

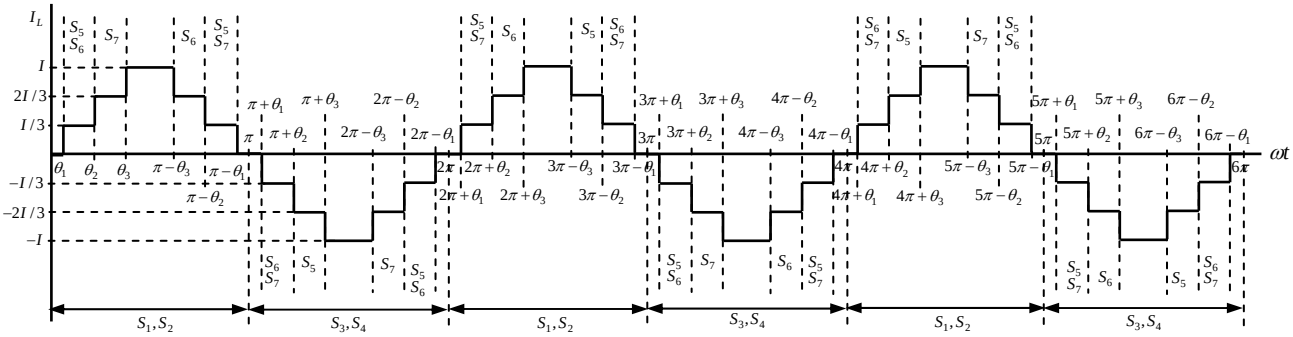


Figure 7. Typical output current for 7-level CSI and states of the switches using all redundant switching combinations to balance the inductors currents

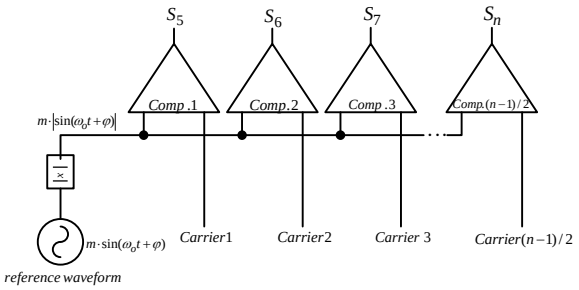


Figure 8. Carrier phase-shifted PWM control of the proposed MLCSI

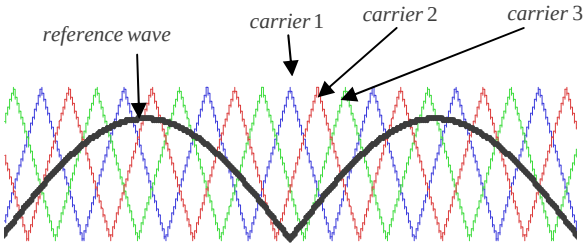


Figure 9. Carrier and reference waves of the 7-level CSI

IV. Simulation and Experimental Results

In this section, the simulation results of the 5-level (Fig. 10) and 7-level proposed CSI (Fig. 11) carried out by PSCAD/EMTDC are presented to verify the capabilities of the proposed topology in generating the desired output current and providing current balance of the current-sharing inductors. For the proposed 5-level CSI, the experimental results are also presented. For simulations and experimental studies the PS-PWM method is used. As shown in Fig. 10 and Fig. 11, in order to realize the current source the AC voltage source is rectified so that the DC voltage is generated, then, a large inductor is used to have a current source.

A parallel *R-C* load with $R = 60\Omega$ and $C = 4.7\mu F$ is connected to MLCSI output. The frequency of the output current and carrier waveforms is $50Hz$ and $1250Hz$, respectively. The inductance of each current-sharing inductor is $60mH$.

Fig. 12 shows the operation of the proposed 5-level CSI using carrier phase-shifted PWM control method. Figs. 12(a), 12(b), and 12(c) show the output current, output voltage, and current-sharing inductors current, respectively.

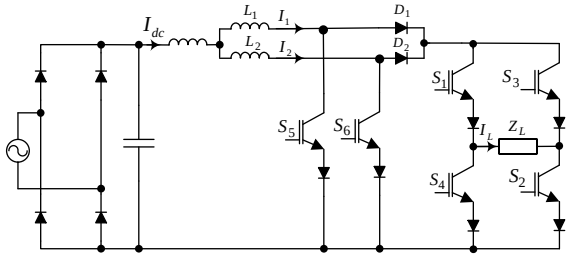


Figure 10. Implementation of the proposed 5-level CSI

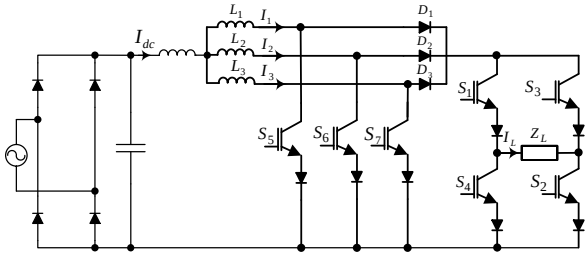
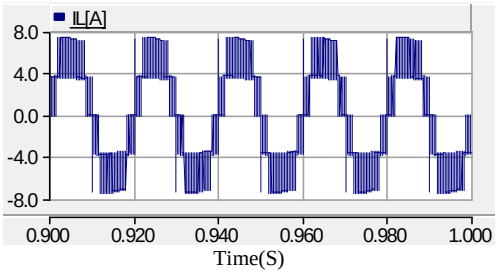
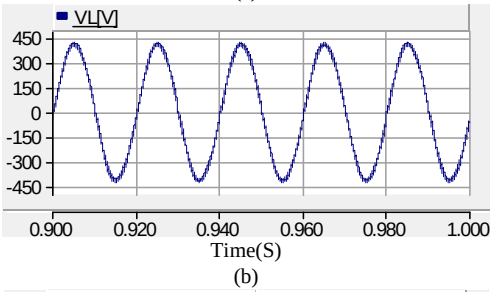


Figure 11. Implementation of the proposed 7-level CSI



(a)



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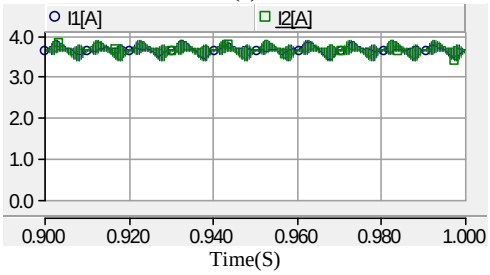

(c)

Figure 12. Operation of 5-level CSI using carrier phase-shifted PWM control (a) output current, (b) output voltage, (c) current through current-sharing inductors

As Fig. 12 shows, the multilevel output current is generated successfully. Also, the control method can be successfully applied for the proposed CSI topology. Applying this control method, the current balance between current-sharing inductors improves considerably compared with the latter control method and the current through current-sharing inductors are almost the same and equal to one half of the output current. Moreover, output current magnitude can be linearly controlled by controlling the modulation index *m*, and also there are no low order harmonic components in the output current. The harmonic components of the output current are around the switching frequency which can be easily canceled out using a small LC filter. So this method is a suitable option to control the proposed MLCSI.

Fig. 13 shows the simulation results of the 7-level CSI using carrier phase-shifted PWM control. Figs. 13(a) and 13(b) show the output current and output voltage, respectively. Fig. 13(c) shows the current of the current-sharing inductors that have the same values equal to one third of the total output current.

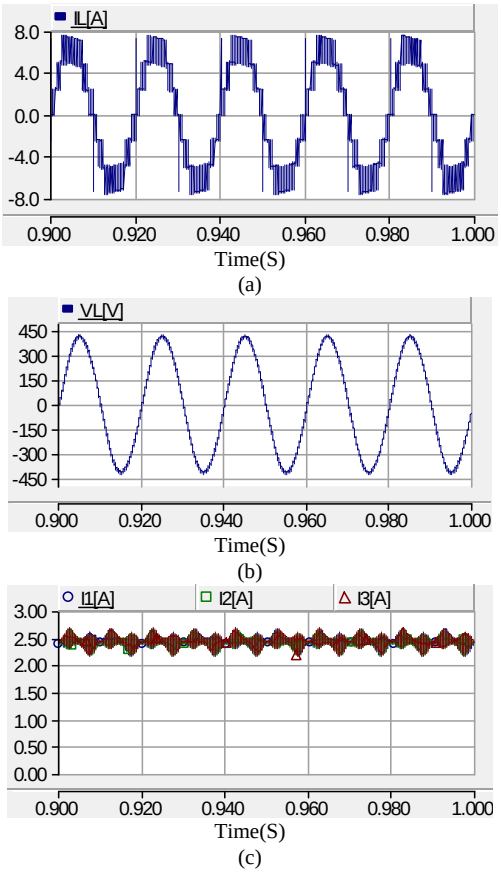

Figure 13. Operation of 7-level CSI using carrier phase-shifted PWM control (a) output current (b) output voltage, (c) current through current-sharing inductors

A laboratory prototype of the proposed 5-level CSI has been implemented. The photo of the prototype is shown in Fig. 14. The control of the experimental setup is based on a microcontroller. The switching states are stored in the microcontroller as look-up tables so that the controller generates the switching pulses according to the stored look-up tables. The TLP250 switch drivers have been used in the setup. The STGW30NC60VD type IGBTs are used in the experimental setup.

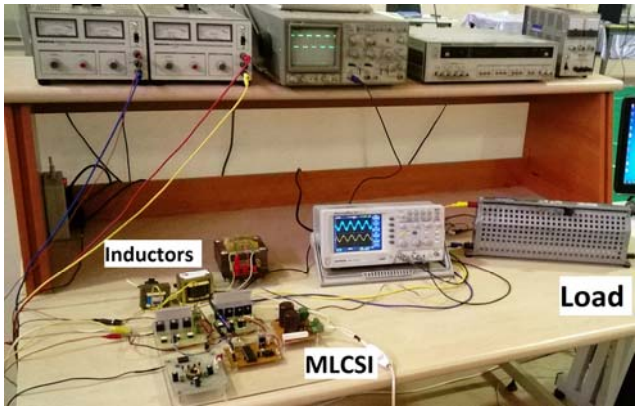

Figure 14. Photo of the experimental setup

Fig. 15 shows the experimental results of the proposed 5-level CSI. The upper waveform in the figure indicates the output current and the lower waveform shows the output voltage. As the figure shows, the output current of the inverter is a 5-level waveform. The voltage waveform is similar to a sinusoidal waveform because of the fact that the output capacitor acts as a filter and removes high-order harmonics of the output voltage.

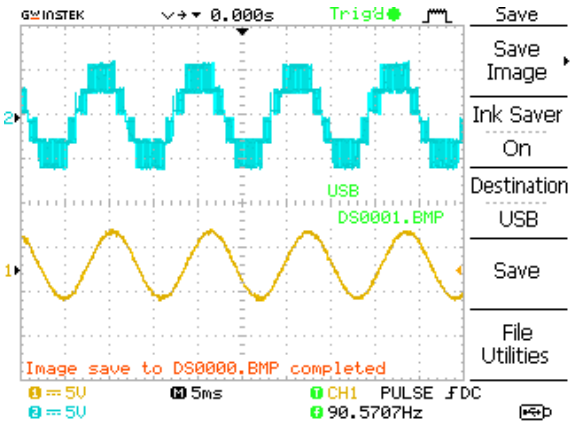

Figure 15. Output current and voltage of the 5-level CSI (experimental)

V. Conclusion

A new general *n*-level current source inverter has been proposed. The proposed topology uses reduced number of switching devices and is able to produce the desired output current while the current balance between current-sharing inductors is guaranteed using appropriate control method. For a 5-level and 7-level CSI the proposed topology uses six and seven switching devices, respectively, which is lower than the switches that the already existing topologies use. A multicarrier phase shifted PWM technique has also been proposed for the proposed MLCSI. The simulation results carried out using PSCAD/EMTDC as well as the experimental results from an implemented 5-level CSI prototype validate the capabilities of the proposed topology and the modulation scheme.

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