Fifteen Level Hybrid Cascaded Inverter

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Abstract : *Asingle-phase hybrid cascaded inverter is proposed. It is based on two kinds of power devices - MOSFET and IGBT. The cascaded inverter consists of three H-bridges. The DC voltage of each H-bridge meets the proportional relationship of 1:2:4 and the three modules are connected in series at the AC side. This hybrid cascaded inverter can output at most 15 voltage levels at the AC side with rather low switching frequency. Voltage gradational modulation method is adopted. The proposed topology is compared with the seven level hybrid cascaded topology using carrier cascaded PWM. And THD is found to be less in proposed topology. MATLAB/SIMULINK platform are used to simulate the circuit operation and performance.*

Keywords -*Carrier cascaded PWM Technique, Hybrid Cascaded Multilevel Inverter, Total harmonic distortion (THD), and Voltage gradational method.*

I.   Introduction

Nowadays, the industry requires power equipment increasingly high, in the megawatt range. The rapid evolution of semiconductor devices manufacturing technologies and the designer's orientation has enabled the development of new structures of converters (inverters) with a great performance compared to conventional structures. So, these new technologies of semiconductor are more suited to high power applications and they enable the design of multilevel inverters. A multilevel converter not only achieves as high power ratings. But also enables the use of renewable energy sources. The commutation of the power switches aggregate these multiple dc sources in order to Achieve high voltage at the output; however, the rated voltage of the power semiconductor switches depends only upon the rating of the dc voltage sources to which they are connected. A Multilevel converter has several advantages over a conventional two-level converter. With the requirement of the quality and efficiency in a high power system and the limitation of high power device switching speed, low switching frequency and small THD. In the last few years, the necessity of increasing the power quality enhancement in industry has sustained the continuous development of multilevel inverters due to high efficiency with low switching frequency control method. The multilevel inverters [1]-[5] improve the AC power quality by performing the power conversion in small voltage steps resulted in lower harmonics. The output voltage on the AC side can take several discrete levels of equal magnitude. The harmonic content of this output voltage waveform is greatly reduced, a smaller filter size and a lower EMI, if compared with a two level voltage waveform. Several topologies for multi-level inverters have been proposed over the years the most popular being the diode clamped, flying capacitor and cascaded H-bridge structures. One aspect which sets the cascaded H-bridge apart from other multi-level inverters is the capability of utilizing different DC voltages on the individual H-bridge cells which results in splitting the power conversion amongst higher-voltage lower-frequency and lower-voltage higher frequency Inverters.In this paper, a fifteen-level hybrid cascaded inverter is developed from seven level hybrid cascaded inverter using voltage gradational method. Energy obtained from battery energy sources is converted by the inverter. Compared to the conventional topology, hybrid cascaded multilevel converter improves its output waveform, reduces its harmonic content and the level of EMI generated by the inverters switching operation switching losses that are lower than those of conventional two level inverters, all of which make them cheaper, lighter, and more compact.

II.   Hybrid Cascaded Multilevel Inverter

The hybrid-cascaded multilevel converter is shown in fig. 1, which includes two parts, the cascaded half-bridges with battery cells shown on the left and the H-bridge inverters shown on the right. The output of the cascaded half-bridges is the dc bus which is also connected to the dc input of the H-bridge. Each half- bridge can make the battery cell to be involved into the voltage producing or to be bypassed.Therefore, by control of the cascaded half-bridges, the number of battery cells connected in the circuit will be changed, that leads to a variable voltage to be produced at the dc bus. The H-bridge is just used to alternate the direction of the dc voltage to produce ac waveform. Hence, the switching frequency of devices in the H-bridge equals to the base frequency of the desired ac voltage. The more of the cascaded cells, the more voltage levels at the output side,

and the output voltage is closer to the ideal sinusoidal. The dv/dt and the harmonics are very little. So it is a suitable topology for medium and high voltage applications.Circuit configuration of seven level hybrid cascaded inverter is shown in fig. 1. For obtaining seven level output, three cascaded half bridges and one H-bridge are required.The switching states of hybrid cascaded inverter for obtaining seven level output waveform is shown in Table 1.
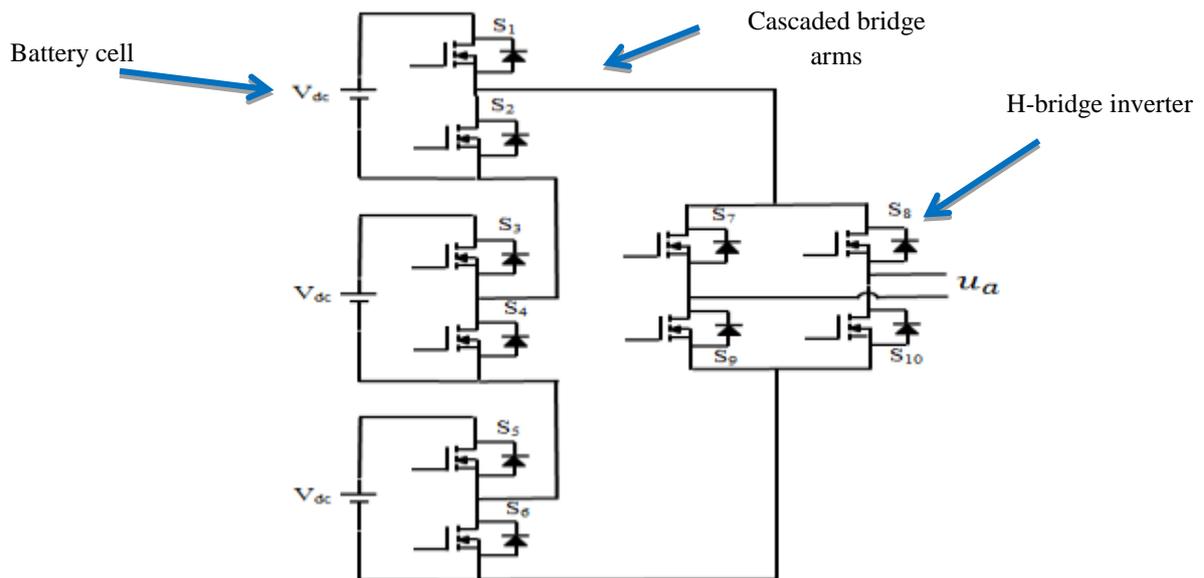

Fig. 1: General configuration of hybrid cascaded multilevel converter [5]

For the cascade half-bridge converter, define the switching state as follows:

$S_x = 1$: Upper switch is conducted, lower switch is OFF.

$S_x = 0$: Lower switch is conducted, upper switch is OFF.

When $S_x = 1$, the battery is connected in the circuit. When $S_x = 0$, the battery cell is bypassed from the circuit. In the suggested converter, the H-bridge is just used to alternate the direction of the dc bus voltage, so the reference voltage of the dc bus is the absolute value of the ac reference voltage, just like a half sinusoidal wave at a steady state. It means that not all the battery cells are needed to supply the load at the same time.

Table 1: Switching states of seven level hybrid cascaded inverter

S9	S7	S10	S8	S6	S5	S4	S3	S2	S1	Output voltage
1	0	1	0	1	0	1	0	0	1	0
0	1	1	0	1	0	1	0	0	1	V_{dc}
0	1	1	0	1	0	0	1	0	1	$2V_{dc}$
0	1	1	0	0	1	0	1	0	1	$3V_{dc}$
0	1	1	0	1	0	0	1	0	1	$2V_{dc}$
0	1	1	0	1	0	1	0	0	1	V_{dc}
1	0	1	0	1	0	1	0	0	1	0
1	0	0	1	1	0	1	0	0	1	$-V_{dc}$
1	0	0	1	1	0	0	1	0	1	$-2V_{dc}$
1	0	0	1	0	1	0	1	0	1	$-3V_{dc}$
1	0	0	1	1	0	0	1	0	1	$-2V_{dc}$
1	0	0	1	1	0	1	0	0	1	$-V_{dc}$
1	0	1	0	1	0	1	0	0	1	0

III.   Fifteen Level Hybrid Cascaded Inverter

Based on the conventional structure of cascaded H-bridge inverter, a new kind of hybrid cascaded inverter (HCI) is accomplished in this paper. This inverter is derived from the seven level hybrid cascaded inverter explained in the previous section. The circuit configuration of the fifteen level hybrid cascaded inverter is shown in fig. 2. This includes two parts, the cascaded half-bridges with battery cells shown on the left and the H-bridge inverters shown on the right.
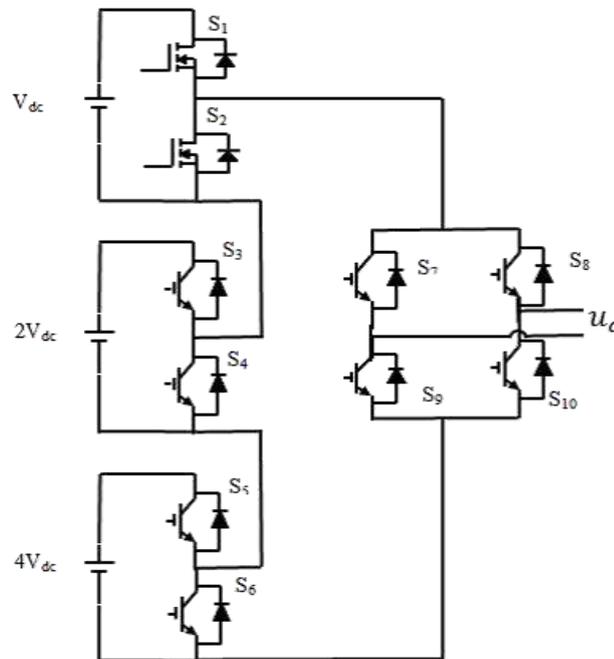

Fig. 2: Circuit configuration of fifteen level hybrid cascaded converter

The output of the cascaded half-bridges is the dc bus which is also connected to the dc input of the H-bridge. Each half-bridge can make the battery cell to be involved into the voltage producing or to be bypassed. Therefore, by control of the cascaded half-bridges, the number of battery cells connected in the circuit will be changed, that leads to a variable voltage to be produced at the dc bus. The H-bridge is just used to alternate the direction of the dc voltage to produce ac waveforms. Hence, the switching frequency of devices in the H-bridge equals to the base frequency of the desired ac voltage. The more of the cascaded cells, the more voltage levels at the output side, and the output voltage is closer to the ideal sinusoidal.The hybrid structure is shown in two aspects. Firstly, the DC buses have hybrid voltages. They are V0, 2V0 and 4V0 respectively. Secondly, hybrid power devices are adopted. For DC buses with different voltages are employed, more voltage levels can be reached at the AC side, with rather lower switching frequency. As a result, the output harmonic loss and the switching loss are lower down. At the same time, for different kinds of power switches are employed, the performance of the inverter system can be further improved. According to the selected modulation method, the switching frequency in the three H-bridges are different. In V_0 H-bridge, the DC bus voltage is lower and the switching frequency is higher, so power MOSFET is adopted. On the other hand, in $2V_0$ and $4V_0$ H-bridges, the DC bus voltage is higher and the switching frequency is lower, so IGBT is adopted. With the above combination of power switches, the advantages of different devices can be shown and the system loss is further lowered down. The high efficiency operation of the inverter system can be reached.

In the paper, two types of modulation methods are used. They are voltage gradational modulation method and PWM carrier method [6]. In voltage gradational method, V is supposed to be the required voltage at the AC side. It is the superposition result of V0, 2V0 and 4V0, as shown in (3.1).

$$V = [x *(V0)] + [y *(2V0)] + [z *(4V0)] \qquad (3.1)$$

Here, coefficients x, y and z equal to 1, or 0 according to the required voltage V. The coefficients 1 and 0 mean the cascaded half bridge outputs positive and zero DC bus voltage, respectively. For example, V0 is obtained as V=[1*(V0)]+[0*(2V0)]+[0*(4V0)] .

Table 2 Switching states of fifteen level hybrid cascaded inverter

S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	Output voltage
0	1	0	1	0	1	1	1	0	0	0
1	0	0	1	0	1	1	0	0	1	V_{dc}
0	1	1	0	0	1	1	0	0	1	$2V_{dc}$
1	0	1	0	0	1	1	0	0	1	$3V_{dc}$
0	1	0	1	1	0	1	0	0	1	$4V_{dc}$
1	0	0	1	1	0	1	0	0	1	$5V_{dc}$
0	1	1	0	1	0	1	0	0	1	$6V_{dc}$
1	0	1	0	1	0	1	0	0	1	$7V_{dc}$
1	0	0	1	0	1	0	1	0	0	$-V_{dc}$
0	1	1	0	0	1	0	1	1	0	$-2V_{dc}$
1	0	1	0	0	1	0	1	1	0	$-3V_{dc}$
0	1	0	1	1	0	0	1	1	0	$-4V_{dc}$
1	0	0	1	1	0	0	1	1	0	$-5V_{dc}$
0	1	1	0	1	0	0	1	1	0	$-6V_{dc}$
1	0	1	0	1	0	0	1	1	0	$-7V_{dc}$

Switching states of fifteen level hybrid cascaded inverter is shown in Table 2 .Switches of cascaded bridge arms are operated to obtain dc bus voltage. H-bridge is just used to alternate the direction of output voltage of the cascaded half bridge arms. Hence we get fifteen level ac voltage waveforms at the output terminal. The realization process of voltage gradational modulation method can be shown as follow. Firstly, according to the actual required amplitude and frequency, confirm the ideal instantaneous voltage value. Secondly, divide the ideal instantaneous voltage by the reference voltage V0. Round the result and get the voltage level to the instantaneous voltage. Finally, confirm the concrete output voltage of each cascaded half bridge and the concrete state of each power switch. Then H-bridge is used to just alternate the direction of the output voltage obtained from the cascaded half bridges. In this way fifteen level output ac voltage waveform can be obtained from the hybrid cascaded structure using voltage gradational modulation method. In order to lower down the contents of low frequency harmonic components, PWM carrier modulation method is employed. In this method, the outputs of 2V0and 4V0 H-bridges are kept same as voltage gradational method. The sum of the above two output voltage waveform has seven level staircases. The ideal sinusoidal waveform minus the seven level staircases waveform reaches the modulation wave inV0 H-bridge. So, PWM method is employed and the sum of the output waveforms in three H-bridges approximates to the ideal sinusoidal wave.

IV.   Simulation Studies

The Simulink block diagram of fifteen level inverter derived from the seven level hybrid cascaded inverter is shown in fig. 3.
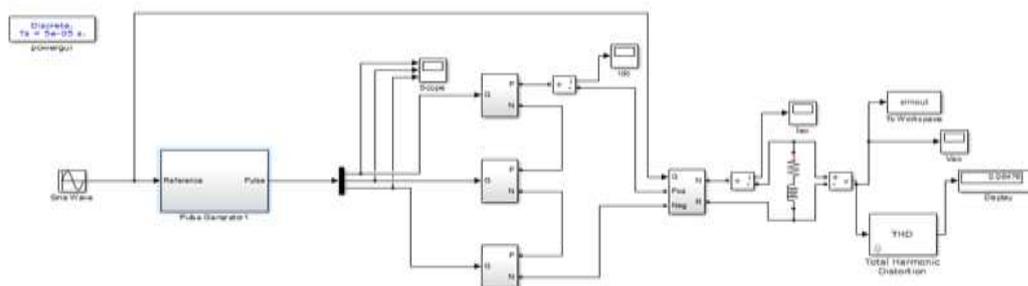

Fig. 3: Simulink block diagram of fifteen level hybrid cascaded inverter using voltage gradational modulation method

Output voltage waveform of fifteen level hybrid cascaded inverter is shown in fig. 4. Three battery sources of voltage 10V, 20V and 40V are used to obtain fifteen level output ac voltage. Hence the peak value of output ac voltage is found to be 70V. The output voltage waveform of fifteen level hybrid cascaded inverter more approaches to sine wave as compared to conventional topologies. FFT analysis of the fifteen level hybrid cascaded inverter is shown in fig. 5. And the percentage THD is found to be 6.46.
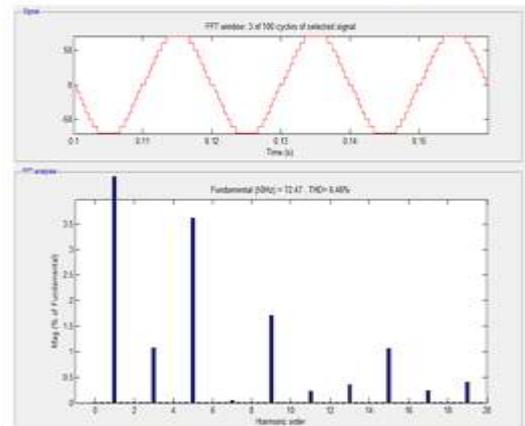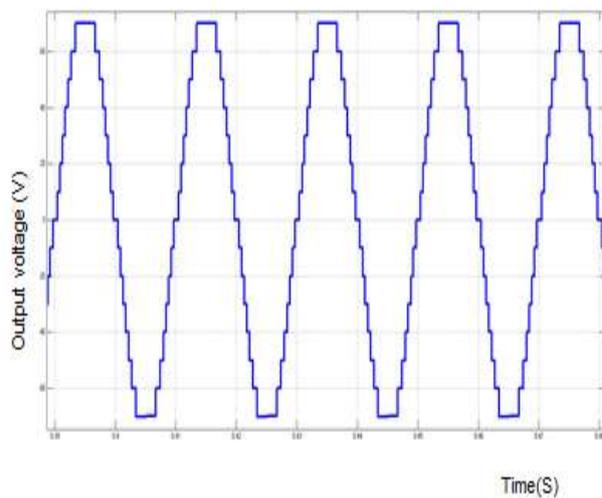
Fig. 4: Output voltage waveform of fifteen level hybrid cascaded inverter   Fig. 5: FFT analysis of fifteen level hybrid cascaded inverter

The Simulink block diagram of the fifteen level hybrid cascaded inverter using PWM carrier modulation method is shown in fig. 6. Output voltage waveform of fifteen level hybrid cascaded inverter is shown in fig. 7. Three battery sources of voltage 10V, 20V and 40V are used to obtain fifteen level output ac voltage. Hence the peak value of output ac voltage is found to be 70V. The output voltage waveform of fifteen level hybrid cascaded inverter more approaches to sine wave as compared to conventional topologies.
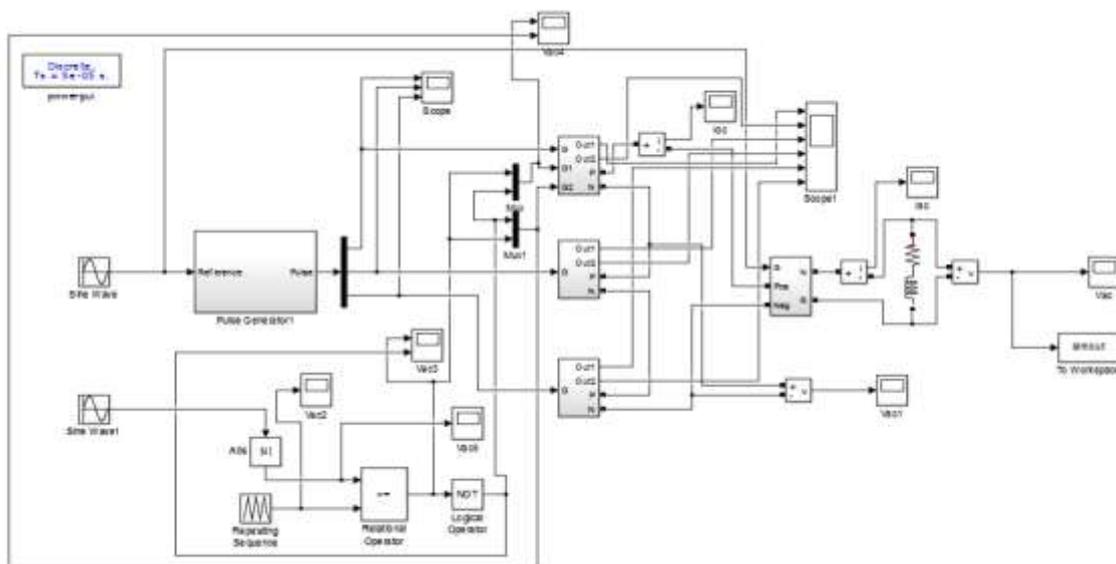

Fig. 6: Simulink block diagram of fifteen level hybrid cascaded inverter using PWM carrier method

FFT analysis of the fifteen level hybrid cascaded inverter is shown in fig. 8. And the percentage THD is found to be 5.65. Percentage THD of fifteen level hybrid cascaded inverter using voltage gradational modulation method is found to be 6.46 and that of fifteen level hybrid cascaded inverter using PWM carrier method is found to be 5.65. Hence fifteen level hybrid cascaded inverter using PWM carrier method is found to be with better harmonic performance. And is verified using MATLAB/SIMULINK.The hardware setup of fifteen level hybrid cascaded inverter is shown in fig. 9. Three battery sources 3V,6V and 12v are used. Hence the output is fifteen level ac voltage waveform with peak value 21V.
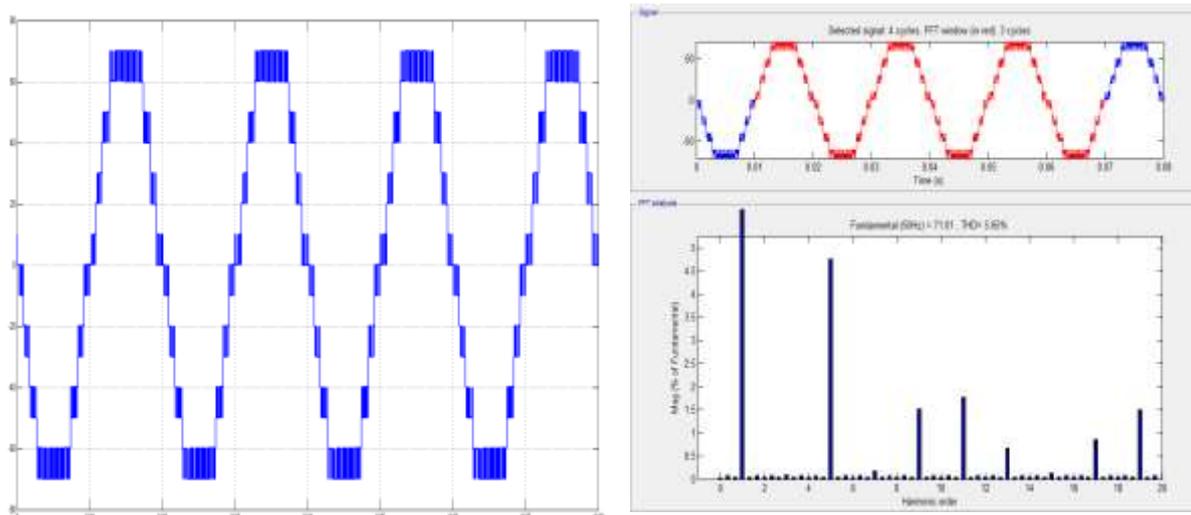
Fig. 7: Output voltage of 15 levelHCI using PWM carrier methodFig. 8: FFT analysis of 15 level HCI using PWM carrier method
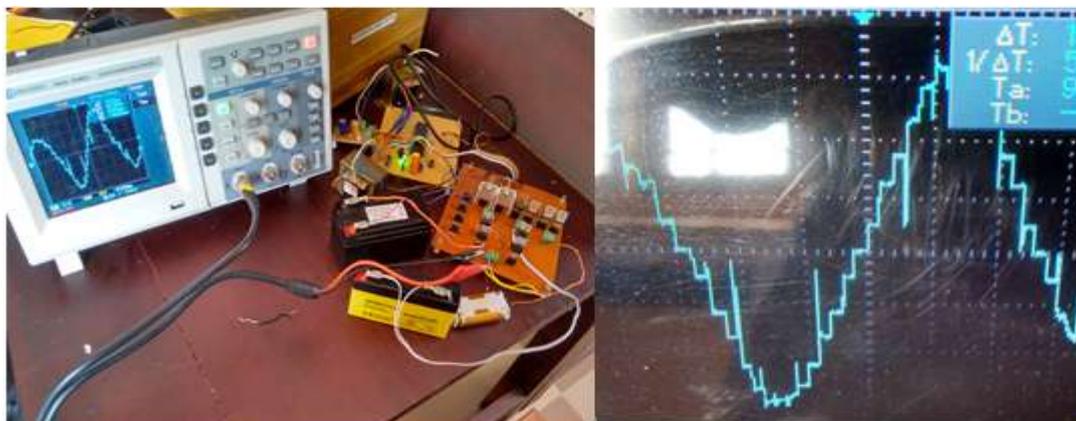
Fig. 9: Hardware prototype and output waveform of fifteen level hybrid cascaded converter

V. Conclusion

In order to improve the performance of the systems using multilevel inverters, HCI is employed. In this project, the topology and modulation method of a single phase HCI are discussed. Concretely, hybrid power devices are involved. The HCI is composed of three H-bridges. The DC voltage of each H-bridge meets the proportional relationship of 1:2:4 and their AC sides are connected in series. As a result, it can output more voltage levels at the AC side with lower switching frequency. Voltage gradational modulation method and PWM carrier method is used to obtain fifteen level output ac voltage. Fifteen level hybrid cascaded inverter is found to be with better harmonic performance. Percentage THD of fifteen level hybrid cascaded inverter using voltage gradational method is found to be 6.46. And that of fifteen level hybrid cascaded inverter using PWM carrier method is found to be 5.65. And this is verified using MATLAB/SIMULINK. And a hardware prototype of fifteen level hybrid cascaded inverter is developed to test operation of the circuit.

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