

# Comparison of Fundamental Frequency and PWM Methods Applied on a Hybrid Cascaded Multilevel Inverter

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**Abstract**-This paper presents a hybrid cascaded multilevel inverter for electric vehicles (EV) / hybrid electric vehicles (HEV) and utility interface applications. The inverter consists of a standard 3-leg inverter (one leg for each phase) and H-bridge in series with each inverter leg. It can use only a single DC power source to supply a standard 3-leg inverter along with three full H-bridges supplied by capacitors or batteries. Both fundamental frequency and multilevel carrier-based PWM methods are used for the hybrid multilevel inverter. An experimental 5 kW prototype inverter is built and tested. The above two switching control methods are validated and compared experimentally.

## I. INTRODUCTION

In recent years many efforts are made to research and use new energy source because the potential for an energy crisis is increasing. Multilevel inverter has gained much attention in the area of energy distribution and control due to its advantages in high power possibility with low harmonics. The general function of the multilevel inverter is to synthesize a desired high voltage from several levels of dc voltages that can be batteries, fuel cells, etc. Several kinds of modulation control schemes can be used for multilevel inverter, which are

mainly divided into two categories, fundamental switching frequency and high switching frequency PWM.

In this paper, both fundamental frequency and multilevel carrier-based PWM methods are applied on the proposed hybrid cascaded multilevel inverter. This inverter includes a standard full bridge 3-leg inverter (one leg for each phase) and an H-bridge in series with each inverter leg. It can use only a single DC power source to supply a standard 3-leg inverter along with three full H-bridges supplied by capacitors or batteries. Traditionally, each H-bridge requires a DC power source [1-5]. The inverter can be used in electric vehicles (EV) / hybrid electric vehicles (HEV) and utility interface. A 5 kW prototype inverter has been built and tested. The fundamental frequency and PWM modulation control methods are experimentally validated and compared with the prototype inverter.

## II. TOPOLOGY AND OPERATION PRINCIPLE

The topology of the proposed hybrid multilevel inverter is shown in Fig. 1, which includes a complete and a simplified single-phase topology. The bottom is one leg of a standard 3-leg inverter with a dc power source. The top is an H-bridge in series with each standard inverter leg. The H-bridge can use a capacitor, battery or other dc power source [6-8].

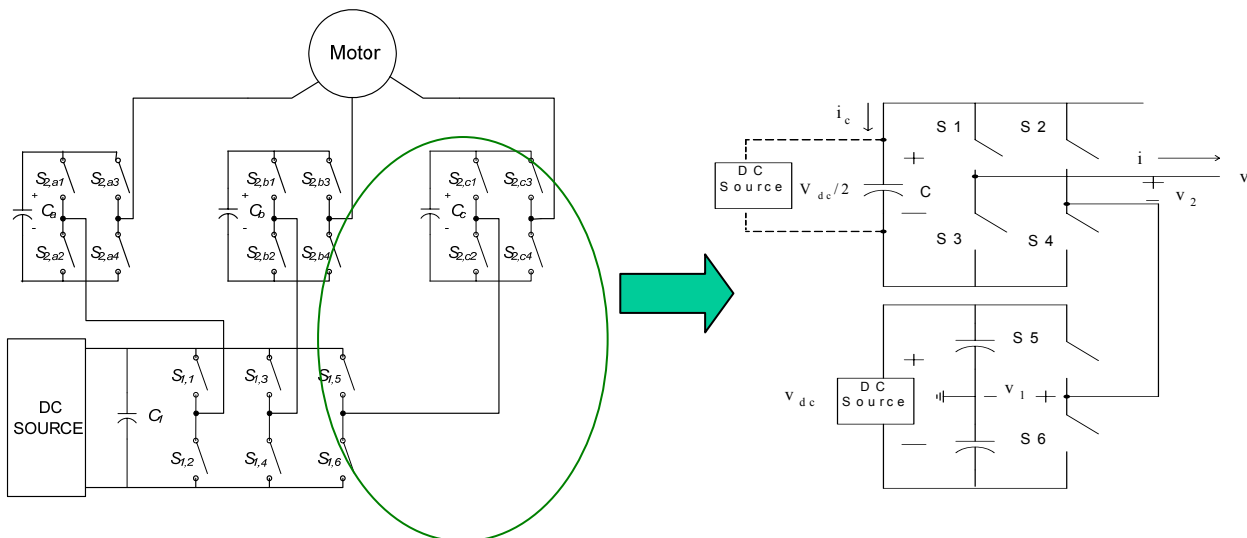


Fig. 1. Topology of the hybrid cascaded multilevel inverter and its Simplified single-phase structure.

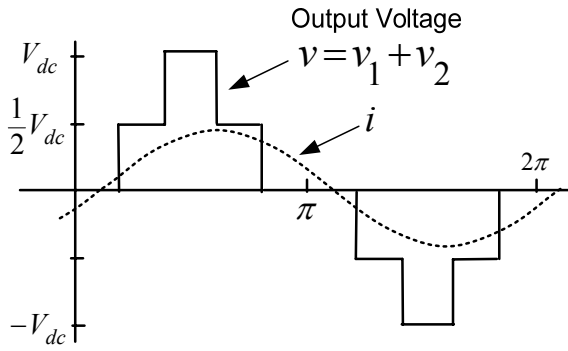


Fig. 2. Five level output waveform.

The output voltage  $v_1$  of this leg (with respect to the ground) is either  $+V_{dc}/2$  ( $S_5$  closed) or  $-V_{dc}/2$  ( $S_6$  closed). This leg is connected in series with a full H-bridge, which in turn is supplied by a capacitor voltage. If the capacitor is used and kept charged to  $V_{dc}/2$ , then the output voltage of the H-bridge can take on the values  $+V_{dc}/2$  ( $S_1, S_4$  closed),  $0$  ( $S_1, S_2$  closed or  $S_3, S_4$  closed), or  $-V_{dc}/2$  ( $S_2, S_3$  closed). Fig. 2 shows an output voltage example.

The capacitor's voltage regulation control method consists of monitoring the output current and the capacitor voltage so that during periods of zero voltage output, either the switches  $S_1, S_4$ , and  $S_6$  are closed or the switches  $S_2, S_3, S_5$  are closed depending on whether it is necessary to charge or discharge the capacitor. This method depends on the voltage and current not being in phase. That means one needs positive (or negative) current when the voltage is passing through zero in order to charge or discharge the capacitor. Consequently, the amount of capacitor voltage the scheme can regulate depends on the phase angle difference of output voltage and current.

### III. MODULATION CONTROL SCHEMES OF HYBRID CASCADED MULTILEVEL INVERTER

The modulation control schemes for the multilevel inverter can be divided into two categories, fundamental switching frequency [3][4-7] and high switching frequency PWM [9-13] such as multilevel carrier-based PWM, selective harmonic elimination and multilevel space vector PWM. Both PWM and fundamental frequency switching methods can be used for the hybrid multilevel inverter.

#### A. Fundamental Frequency Control Method

The key issue of the fundamental frequency modulation control is to choose two switching angles  $\theta_1$  and  $\theta_2$ . In this paper, the goal is to output the desired fundamental frequency voltage and to eliminate the 5<sup>th</sup> harmonic. Mathematically, this can be formulated as the solution to the following equations:

$$\begin{aligned} \cos(\theta_1) + \cos(\theta_2) &= m_a \\ \cos(5\theta_1) + \cos(5\theta_2) &= 0 \end{aligned} \quad (1)$$

Where,  $m_a$  is the output voltage amplitude modulation index. Traditionally, the modulation index is defined as

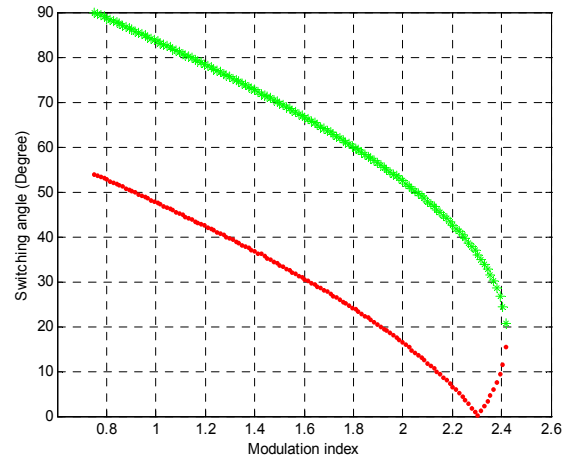


Fig. 3. Switching angles  $\theta_1$  (lower) and  $\theta_2$  (upper) vs. Modulation index.

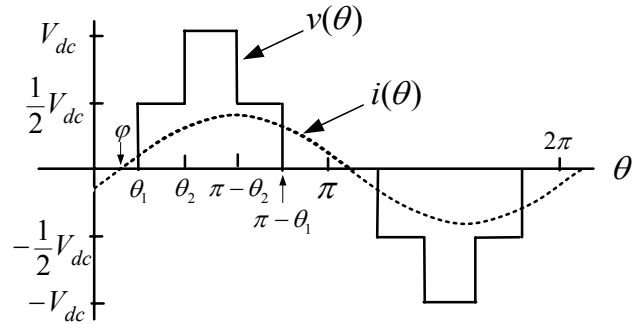


Fig. 4. Five level output waveform.

$$m = \frac{V_1}{V_{dc}/2} \quad (2)$$

Therefore, the relationship between the modulation index  $m$  and the output voltage index  $m_a$  is

$$m = \frac{4}{\pi} m_a \quad (3)$$

A practical solution set is shown in Fig. 3, which is continuous from modulation index 0.75 to 2.42. However, the maximum modulation index 2.42 depends on displacement power factor as shown below.

It is assumed that the load current displacement angle is  $\varphi$  as shown in Fig. 4.

To balance the capacitor voltage, the capacitor charging amount needs to be greater than the discharging amount. That is, to regulate the capacitor's voltage with fundamental frequency switching scheme, the following equation must be satisfied,

$$\int i_{charging} d\theta - \int i_{discharging} d\theta > 0 \quad (4)$$

In detail, we have the following equations

$$i = I \sin(\omega t - \varphi) \quad (5)$$

and the displacement power factor

$$pf = \cos(\varphi) \quad (6)$$

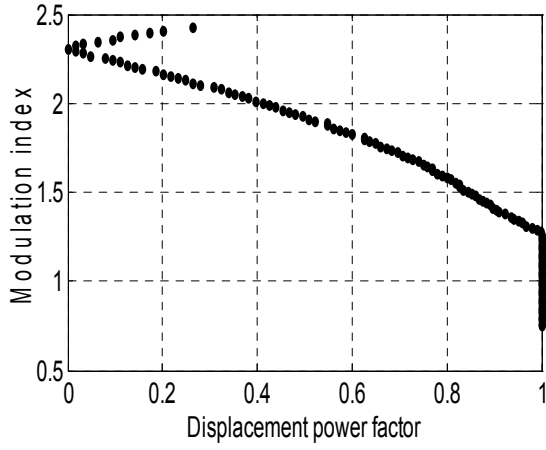


Fig. 5. Displacement power factor and output voltage modulation index.

The three cases are:

$$0 \leq \varphi \leq \theta_1$$

$$\int_0^{\varphi} |i| d\theta + \int_{\varphi}^{\theta_1} id\theta + \int_{\pi-\theta_1}^{\pi} id\theta - \int_{\theta_2}^{\pi-\theta_2} id\theta > 0 \quad (7)$$

$$\theta_1 < \varphi \leq \theta_2$$

$$\int_0^{\theta_1} |i| d\theta + \int_{\pi-\theta_1}^{\pi} id\theta - \int_{\theta_2}^{\pi-\theta_2} id\theta > 0 \quad (8)$$

$$\theta_2 < \varphi \leq \pi/2$$

$$\int_0^{\theta_1} |i| d\theta + \int_{\pi-\theta_1}^{\pi} id\theta - \int_{\theta_2}^{\pi-\theta_2} id\theta > 0 \quad (9)$$

Combining (5), (6), (7), (8) and (9), it can be concluded that

$$\text{for } 0 \leq \varphi \leq \theta_1,$$

$$pf \leq \frac{\pi}{4m} \quad (10)$$

$$\text{and for } \theta_1 < \varphi \leq \pi/2,$$

$$pf \leq \cos \left[ \tan^{-1} \left( \frac{\cos(\theta_2)}{\sin(\theta_1)} \right) \right] \quad (11)$$

Furthermore, to use minimum phase displacement angles is a more convenient way to use equations (10) and (11). It means if the phase displacement angle is greater than the minimum angle, the voltage can be regulated anyway. Fig. 5 is derived from equations (4)-(11). It can be seen in Fig. 5 that the highest output voltage modulation index depends on the displacement power factor. For practical applications, the highest output voltage is determined when the load is determined.

### B. Multilevel PWM Control Method

Multilevel carrier-based PWM strategies are the most popular methods because they are easily implemented. Three major carrier-based techniques used in a conventional

inverter that can be applied in a multilevel inverter: sinusoidal PWM (SPWM), third harmonic injection PWM (THPWM), and space vector PWM (SVM). SPWM is a very popular method in industrial applications. It uses several triangle carrier signals, one carrier for each level and one reference, or modulation, signal per phase. In the proposed inverter, the top H-bridge inverter is operated under the SPWM mode and the bottom standard 3-leg inverter is operated under square-wave mode in order to reduce switching loss.

Traditionally, the maximum modulation index for linear operation of a traditional full-bridge bi-level inverter using SPWM control method is 1 (without third harmonic compensation) and 1.15 (with third harmonic compensation, and the inverter output voltage waveform is SPWM waveform, not square waveform).

With the cascaded H-bridge multilevel inverter, the maximum modulation index for linear operation can be as high as 2.42 under fundamental frequency mode. This means it can output a boosted AC voltage to increase the output power, and the output voltage depends on the displacement power factor of the load. The highest voltage is determined when the load is determined. This feature makes the inverter suitable for EV/HEV applications. Moreover, in consideration of the implementation of modulation control methods, the fundamental frequency and PWM methods can be chosen for high power and low power stage in practical application.

When the hybrid cascaded multilevel inverter is used for utility interface, one example is that the bottom is one leg of a standard 3-leg inverter with a DC power source such as solar panel, and the top H-bridge use a battery separately as dc power source, which is charged by the solar panel, the PWM method is a better choice due to the need of battery charging for the inverter.

## IV. EXPERIMENT RESULTS AND COMPARISON

A 5 kW prototype using power MOSFETs (100V, 180A) as shown in Fig. 6 has been built. The load is a 15 hp three-phase induction motor, which is loaded less than 5kW. An Altera FLEX 10K field programmable gate array (FPGA) controller is used to implement the control algorithm

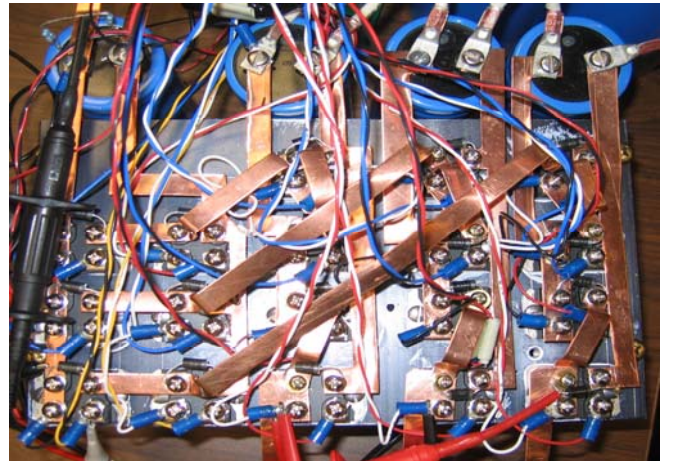


Fig. 6. Hybrid cascaded multilevel inverter prototype.

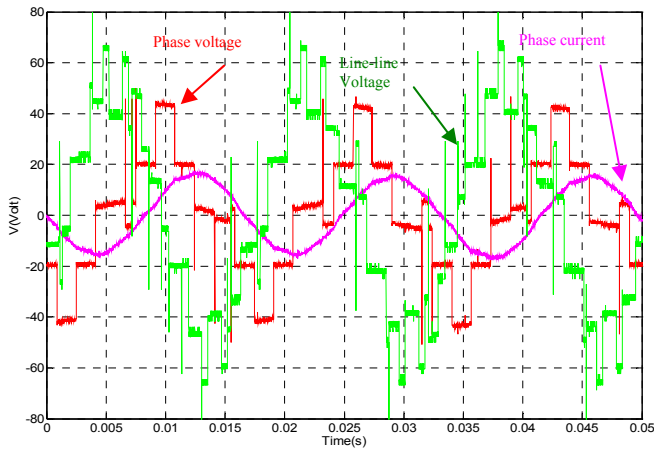


Fig. 7. Output line-line and phase voltage, phase current of the hybrid cascaded multilevel inverter ( $m=2.03$ ).

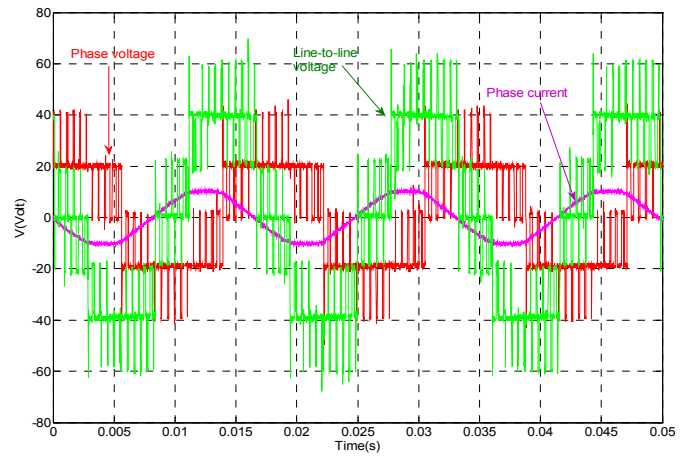


Fig. 9. Output line-line and phase voltage, phase current of the hybrid cascaded multilevel inverter ( $m=1$ ).

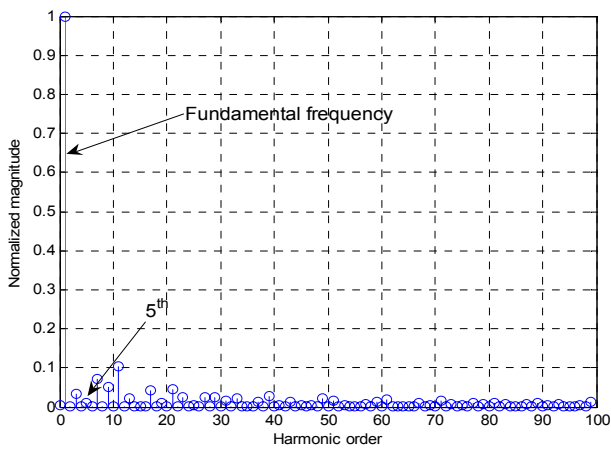


Fig. 8. Normalized FFT analysis of phase voltage.

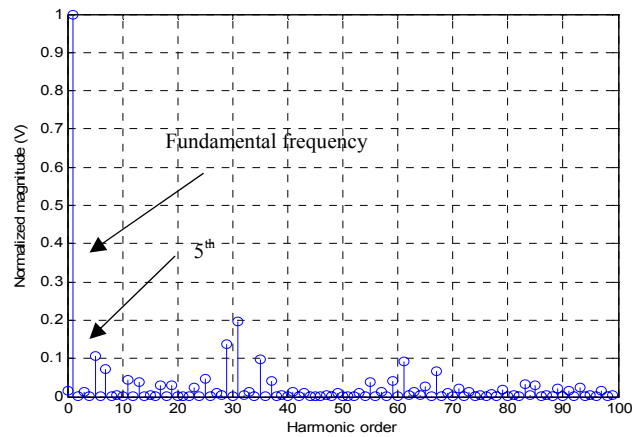


Fig. 10. Normalized FFT analysis of phase voltage.

to drive the motor with the real-time variable output voltage and variable frequency. The H-bridge DC power source (capacitor or battery) voltage is detected by a voltage sensor and fed into the FPGA controller to realize its voltage regulation.

#### A. EV/HEV Application

The experiment results with fundamental frequency method including phase voltage, line-line voltage, and phase current are shown in Fig. 7. Fig. 8 shows the normalized FFT analysis result of phase voltage.

The experiment results and normalized FFT analysis with PWM method are shown in Fig. 9 and Fig. 10.

Both methods produce a five-level output phase voltage. The same load is used to test the output voltage and current based on the different two control methods. DC bus is the same 40V. Fig. 7 shows that the load current with the fundamental frequency method is higher than with the PWM method in Fig. 9. This means that DC link utilization of the fundamental frequency method is better for the hybrid cascaded multilevel inverter. Its wide modulation index range makes it possible to output a boosted AC output voltage. Both methods are of low harmonic and their phase currents are close to sinusoidal.

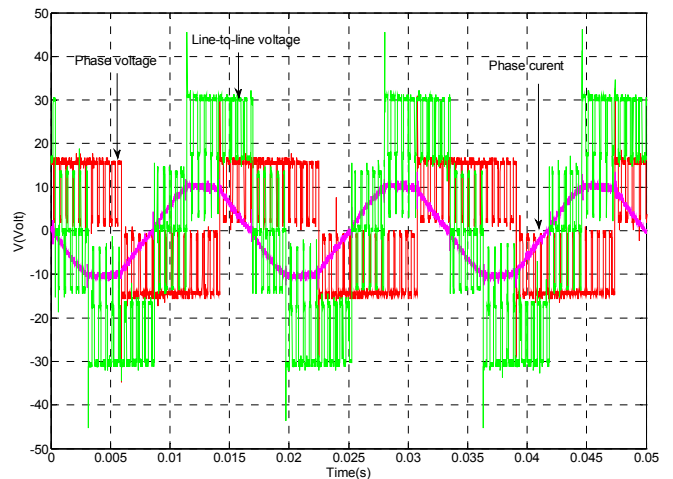


Fig. 11. Output line-line and phase voltage, phase current of the hybrid cascaded multilevel inverter when battery charging ( $m=0.9$ ).

#### B. Utility Interface Application

Multilevel inverter is ideal for utility interface applications with renewable energy source due to its functions and features [14-16]. When the hybrid cascaded multilevel inverter is adaptively used for solar grid application, the

bottom standard 3-leg inverter connects with a solar panel and the top three H-bridges use a battery separately as an energy storage device. In consideration of the charging and discharging condition of the batteries, the PWM method is chosen to do modulation control. The battery voltage can follow the voltage command. Based on the voltage command value and the actual voltage value, the battery is decided in charging or discharging condition.

The experimental output phase voltage, line-line voltage, and phase current under battery charging condition are shown in Fig. 11.

## V. CONCLUSION

A hybrid cascaded multilevel inverter with fundamental frequency and multilevel carrier-based PWM methods has been developed. The paper presents and compares the experiment results for the EV/HEV and utility interface applications with the above two modulation control methods.

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