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Design and Application of Hybrid Multilevel Inverter for Voltage Boost

Haiwen Liu

University of Tennessee - Knoxville

To the Graduate Council:

I am submitting herewith a dissertation written by Haiwen Liu entitled "Design and Application of Hybrid Multilevel Inverter for Voltage Boost." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Electrical Engineering.

Leon M. Tolbert, Major Professor

We have read this dissertation and recommend its acceptance:

Fangxing "Fran" Li, Syed Islam, David K. Irick

Accepted for the Council:

Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

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Design and Application of Hybrid Multilevel Inverter for Voltage Boost

A Dissertation
Presented for the
Doctor of Philosophy Degree
The University of Tennessee, Knoxville

Haiwen Liu

December 2009

Dedication

This dissertation is dedicated to my wife as well as a fellow colleague, Hui. Thanks for her sincere love and great patience throughout the years. It is also dedicated to my parents, parents-in-law, who have supported and encouraged me unconditionally all the times, and my little lovely son, Vincent, for the happiness that he brings into my life.

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Abstract

Today many efforts are made to research and use new energy sources because the potential for an energy crisis is increasing. Multilevel converters have gained much attention in the area of energy distribution and control due to its advantages in high power applications with low harmonics. They not only achieve high power ratings, but also enable the use of renewable energy sources. The general function of the multilevel converter is to synthesize a desired high voltage from several levels of dc voltages that can be batteries, fuel cells, etc.

This dissertation presents a new hybrid multilevel inverter for voltage boost. 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. The proposed inverter could be applied in hybrid electric vehicles (HEVs) and fuel cell based hybrid electric vehicles (FCVs). It is of voltage boosting capability and eliminates the magnetics. This feature makes it suitable for the motor running from low to high power mode. In addition to hybrid electric vehicle applications, this paper also presents an application where the hybrid multilevel inverter acts as a renewable energy utility interface.

In this dissertation, the structure, operation principle, and modulation control schemes of the proposed hybrid multilevel inverter are introduced. Simulation models and results are described and analyzed. An experimental 5 kW prototype inverter is built and tested.

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1. INTRODUCTION

1.1 BACKGROUND

In recent years many efforts are made to research and use new energy sources because the potential for an energy crisis is increasing. Multilevel converters have gained much attention in the area of energy distribution and control due to theirs advantages in high power applications with low harmonics. They not only achieve high power ratings, but also enable the use of renewable energy sources. The general function of the multilevel converter is to synthesize a desired high voltage from several levels of dc voltages that can be batteries, fuel cells, etc. [1, 2].

In 1975, the concept of multilevel converters was first introduced [3]. Multilevel means that the inverter can generate more output voltage levels than those of the common three-level converter. Subsequently, several multilevel converter topologies have been developed [2, 4]. The basic principle of a multilevel converter to achieve higher power is to use a series of power semiconductor switches with several lower voltage dc sources to perform the power conversion by synthesizing a staircase voltage waveform. Capacitors, batteries, and renewable energy voltage sources can be used as the multiple dc voltage 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.

Fig. 1.1 shows a multilevel inverter topology example. Each separate dc source (SDCS) is connected to a single-phase full-bridge, or H-bridge, inverter. Each inverter level can generate three different voltage outputs, $+V_{dc}$, 0, and $-V_{dc}$ by connecting the dc source to the ac output by

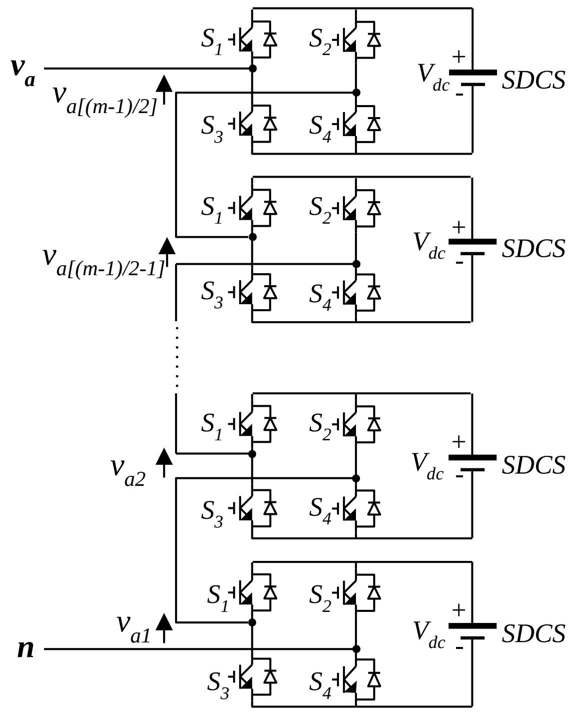

Fig. 1.1. Single-phase topology of a multilevel cascaded H-bridges inverter.

different combinations of the four switches, S_1, S_2, S_3, and S_4.

To obtain $+V_{dc}$, switches S_1 and S_4 are turned on, whereas $-V_{dc}$ can be obtained by turning on switches S_2 and S_3. By turning on S_1 and S_2 or S_3 and S_4, the output voltage is 0. The number of output phase voltage levels m in a cascade inverter is defined by $m = 2s+1$, where s is the number of separate dc sources. The AC outputs of each of the different full-bridge inverter levels are connected in series such that the synthesized voltage waveform is the sum of the inverter outputs. The phase voltage $v_{an} = v_{a1} + \ldots + v_{a\,[(m-1)/2]}$.

Multilevel converters have developed quickly based on theirs several attractive features as follows.

1. Industry has begun to demand higher power equipment, which reaches the megawatt level now. Inverter drives in the megawatt power level are usually connected to the medium-voltage network. Today, a single power semiconductor switch does not have the voltage blocking capability to connect it directly to medium voltage grids. As a result, multilevel inverter drives (MLIDs) have become a solution for high power drive applications.

2. Multilevel converters can solve problems with conventional inverter drives (CIDs) consisting of six power switches with two-level sinusoidal pulse width modulation (SPWM). Motor damage and failure have been reported by industry as a result of some CIDs' high-voltage change rates (*dv*/*dt*), which produce a common-mode voltage across the motor windings. High frequency switching can exacerbate the problem because of the numerous times this common mode voltage is impressed upon the motor each cycle. The main problems are reported as "motor bearing failure" and "motor winding insulation breakdown" because of circulating currents, dielectric stresses, voltage surge, and corona discharge [1].

Multilevel converters inherently tend to have a smaller *dv*/*dt* due to the fact that switching involves several smaller voltages. Therefore it can reduce *dv*/*dt* to conquer the motor failure problem and EMI problem.

3. Multilevel converters can generate a staircase output voltage waveform as the number of DC voltages increases. It can result in a better approximation to a sinusoidal waveform. Furthermore, the increased number of DC voltages provides the opportunity to eliminate more harmonic contents. Eliminating harmonic contents will make it easier to filter the remaining harmonic content. As a result, filters will be smaller and less expensive.

4. Multilevel converters can operate at both fundamental switching frequency and high frequency switching PWM. It should be noted that lower switching frequency usually means

lower switching loss and higher efficiency. Also, switching at the fundamental frequency will result in decreasing the number of voltage changes that occur per fundamental cycle, which is helpful to reduce the number of *dv/dt* changes.

5. Since multilevel converters usually utilize a large number of dc voltages, several switches are required to block smaller voltages. Since switch stresses are reduced, required switch ratings are lowered.

6. Multilevel converters are of high system reliability. They tend to have switching redundancies. In other words, there might be more than one way to produce the desired voltage. When a component fails on a multilevel converter, most of the time the converter will still be usable at a reduced power level.

Multilevel converters do have some disadvantages. One particular disadvantage is they require more power semiconductor switches than conventional converters. The system cost may increase (part of the increased cost may be offset by the fact switches with lower ratings are being used). Using more devices also means the probability of a device failure will increase. Additionally, although lower voltage rated switches can be utilized in a multilevel converter, each switch requires a related gate drive circuit. This causes the overall system to be more expensive and complex.

Many kinds of converter topology have been proposed during the last two decades. Contemporary research has engaged novel converter topologies and unique modulation schemes. Three different major multilevel converter structures have been reported: cascaded H-bridges converter with separate dc sources, diode clamped (neutral-clamped), and flying capacitors (capacitor clamped). In addition, many multilevel converter applications focus on industrial medium-voltage motor drives [1], utility interface for renewable energy systems [5, 6], flexible AC transmission system (FACTS) [7], and traction drive systems [8].

1.2 POWER CONVERTERS FOR TRACTION MOTOR DRIVE

The traction motor drive is a key part of a hybrid electric vehicle (HEV) and fuel cell based vehicle (FCV). A HEV typically combines a smaller internal combustion engine of a conventional vehicle with a battery pack and an electric motor to drive the vehicle. The combination offers lower emissions but with the power range and convenient fueling of conventional (gasoline and diesel) vehicles. A FCV is one type of HEV. Both HEV and FCV need a traction motor and a power inverter to drive the traction motor [9]. The requirements of the power inverter include high peak power and low continuous power rating.

Currently available power inverter systems for traction motor drives use a dc-dc boost converter to boost the battery voltage for a traditional 3-phase inverter. If the motor is running on low to medium power, the dc-dc boost converter is not needed, and the battery voltage will be directly applied to the inverter to drive the traction motor. If the motor is running in high power mode, the dc-dc boost converter will boost the battery voltage to a higher voltage so that the inverter can provide higher power to the motor. The present traction motor drive inverters have medium power density, are expensive, and have low efficiency because they need bulky inductors for the dc-dc boost converters.

Therefore, a multilevel inverter with combined converter and inverter functions and that can eliminate the magnetics is an interesting research topic.

1.3 POWER CONVERTERS FOR RENEWABLE ENERGY UTILITY INTERFACE

Distributed and renewable power sources (solar panels, fuel cell, wind turbines, etc.) have receive significant interest recently. The connection between distributed power sources and utility grid and/or load generally needs a power converter for processing the locally generated power and injecting current into the system. When the power source produces a dc voltage, the power converter must be able to produce a low-distortion ac current.

Traditionally available power converter systems for renewable energy applications use a dc-dc boost converter, or connect a custom-built transformer to a traditional 3-phase inverter to boost the renewable energy source voltage. Not only the bulky inductors for the dc-dc boost converters lower the system efficiency, but also the transformers are the most expensive equipment in the system and produce about 50% of the total losses of the system [6].

Multilevel converters can generate high voltages with low harmonics without inductors and transformers. Furthermore, the structure of cascaded multilevel inverter makes it a perfect fit for renewable energy utility interface.

1.4 ORGANIZATION OF THE DISSERTATION

This dissertation is to develop a new hybrid multilevel inverter for voltage boost. Simulation models and results are described and analyzed. An experimental 5 kW prototype inverter has been built and tested. Experiment results based on fuel cell and renewable energy utility interface applications are presented.

The dissertation is arranged as follows:

Chapter 2 summarizes the previous works on multilevel inverter structures and modulation strategies, available power converters in HEVs and FCVs, renewable energy system, and cascaded multilevel inverter with fewer dc power sources.

Chapter 3 introduces the structure, operation principle, and two kinds of modulation control schemes of the hybrid multilevel inverter. Simulation models with PSIM and MATLAB/SIMULINK are provided.

Chapter 4 presents the simulation results with fundamental frequency and PWM modulation methods. Experiment implementation and validation of the prototype inverter are illustrated. Experiment results are given and explained.

Chapter 5 presents the experiment results and analysis based on the fuel cell system and solar grid applications.

Finally, summaries and future work are discussed in chapter 6.

2. LITERATURE SURVEY

2.1 INTRODUCTION

In this chapter, an overview of previous research on multilevel inverter topologies and modulation control schemes are reviewed firstly. Secondly, some information on power converters used in HEV/FCV propulsion and renewable energy systems are introduced. Finally, cascaded multilevel inverters with fewer dc power sources are presented.

2.2 MULTILEVEL INVERTER STRUCTURES

There are three major multilevel inverter structures in industrial applications: diode-clamped, capacitor-clamped and cascaded H-bridge inverter with separate dc sources [2, 4].

The neutral point converter (NPC) proposed by Nabae *et al.* in 1981 is the simplest diode-clamped inverter [10]. An m-level diode-clamped inverter has an m-level output phase voltage and a ($2m$-1)-level output line voltage. The multilevel diode-clamped inverter can be applied as an interface between a high-voltage dc transmission line and an ac transmission line, as a variable speed drive for high-power medium-voltage motors, and for static var compensation [2, 11].

The structure of the capacitor-clamped inverter is similar to that of the diode-clamped inverter except that instead of using clamping diodes, the inverter uses capacitors in their place, which is introduced by Meynard *et al.* in 1992 [12]. The capacitor-clamped multilevel inverter allows more flexibility in waveform synthesis and balancing voltage across the clamped capacitors. Unlike the diode-clamped inverter, the flying-capacitor inverter does not require all of the switches that are on (conducting) be in a consecutive series. Moreover, the capacitor-clamped inverter has phase redundancies, whereas the diode-clamped inverter has only line-line redundancies [1, 2, 13]. These redundancies allow a choice of charging/discharging specific capacitors and can be incorporated in the control system for balancing the voltages across the various levels.

A cascaded H-bridge inverter as shown in Fig. 1.1 is several H-bridges in a series configuration [1, 2, 4]. Each separate dc source is connected to a single-phase H-bridge inverter. Besides the above three basic topologies, other plentiful multilevel topologies have been proposed. Most of them are some circuit modification or combination of the basic multilevel inverters developed for some specific application fields.

2.2.1 Cascaded H-bridge Inverters

Fig. 2.1 shows a single H-bridge. The four switches S_1, S_2 , S_3 and S_4 in a single H-bridge are controlled to generated three discrete output V_{out} with levels V_{dc}, 0 and $-V_{dc}$. When S_1 and S_4 are on, the output is V_{dc}, when S_2 and $S_3$are on, the output is $-V_{dc}$, when either pair S_1 and S_2 or S_3 and S_4 are on, the output is 0.

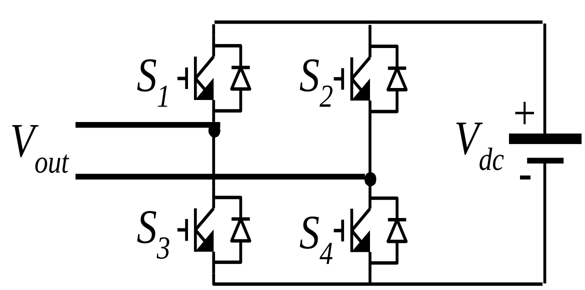

Fig. 2.1. Single H-Bridge inverter.

Figure 2.2 shows an example phase voltage waveform for an 11-level cascaded H-bridge inverter with 5 separate dc sources and 5 full bridges. The phase voltage $v_{an} = v_{a1} + v_{a2} + v_{a3} + v_{a4} + v_{a5}$. For a stepped waveform such as the one depicted in Fig. 2.2 with s steps, the Fourier Transform for this waveform follows [1, 8]:

$$V(\omega t) = \frac{4V_{dc}}{\pi}\sum_{n}\left[\cos(n\theta_1) + \cos(n\theta_2) + \ldots + \cos(n\theta_s)\right]\frac{\sin(n\omega t)}{n}, \quad \text{where } n = 1, 3, 5, 7, \ldots \tag{2.1}$$

From (2.1), the magnitudes of the Fourier coefficients when normalized with respect to V_{dc} are as follows:

$$H(n) = \frac{4}{\pi n}\left[\cos(n\theta_1) + \cos(n\theta_2) + \ldots + \cos(n\theta_s)\right], \quad \text{where } n = 1, 3, 5, 7, \ldots \tag{2.2}$$

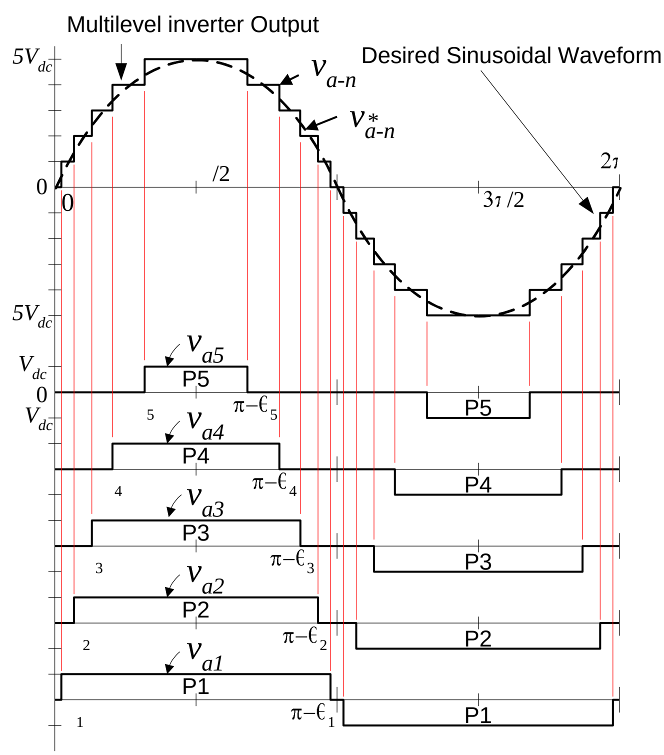

Fig. 2.2. Output phase voltage waveform of an 11-level cascade inverter with 5 separate dc sources.

θ_1, θ_2, ..., θ_s are the conducting angles, which can be chosen in order to acquire a minimum voltage total harmonic distortion is. Generally, they are chosen so that predominant lower frequency harmonics, 5^{th}, 7^{th}, 11^{th}, and 13^{th} harmonics, are eliminated [14].

Multilevel cascaded H-bridge inverters have been proposed for use as the main traction drive in electric vehicles, where several batteries, fuel, or ultracapacitors are well suited to serve as separate dc sources [8, 15]. The cascaded inverter could also serve as a rectifier/charger for the batteries of an electric vehicle while the vehicle was connected to an AC supply. Additionally, the cascade inverter can act as a rectifier in a vehicle that uses regenerative braking.

The inverters have also been proposed for an interface with renewable energy sources, static var generation, and battery-based applications. The inverters are ideal for connecting renewable energy sources with an ac grid, because of the need for separate dc sources, which is the case in applications such as photovoltaics or fuel cells. Peng has demonstrated a prototype multilevel cascaded static var generator connected in parallel with the electrical system that could supply or draw reactive current from an electrical system [16-18]. The inverter could be controlled to either regulate the power factor of the current drawn from the source or the bus voltage of the electrical system where the inverter was connected. Peng [16] and Joos [19] have also shown that a cascade inverter can be directly connected in series with the electrical system for static var compensation.

The main advantages and disadvantages of cascaded H-bridge multilevel converters are as follows [2, 4].

Advantages:

- The number of possible output voltage levels is more than twice the number of dc sources

($m = 2s + 1$).

- The series of H-bridges allows for modularized layout and packaging. This will enable the manufacturing process to be done more quickly and cheaply.
- No extra clamped diodes and voltage balancing capacitors are necessary.

Disadvantages:

- Separate dc sources are required for each of the H-bridges. This will limit its application to products that already have multiple separate dc sources readily available.
- Need to balance dc sources among different levels.
- Need several connectors/cables to connect dc sources.

Another kind of cascaded multilevel converter with transformers using standard three-phase bi-level converters has been proposed [20]. The circuit is shown in Fig. 2.3. The converter uses output transformers to add different voltages. In order for the converter output voltages to be added up, the outputs of the three converters need to be synchronized with a separation of 120° between each phase. For example, obtaining a three-level voltage between outputs *a* and *b*, the output voltage can be synthesized by $V_{ab} = V_{a1\text{-}b1}+V_{b1\text{-}a2}+V_{a2\text{-}b2}$. An isolated transformer is used to provide voltage boost. The phase between b_1 and a_2 is provided by a_3 and b_3 through the isolated transformer. With three converters synchronized, the voltages $V_{a1\text{-}b1}$, $V_{b1\text{-}a2}$, $V_{a2\text{-}b2}$, are all in phase; thus, the output level can be tripled [4].

The advantage of the cascaded multilevel converters with transformers using standard three-phase bi-level converters is the three converters are identical and thus control is simpler. However, the three converters need separate DC sources and a transformer is needed to add up the output voltages.

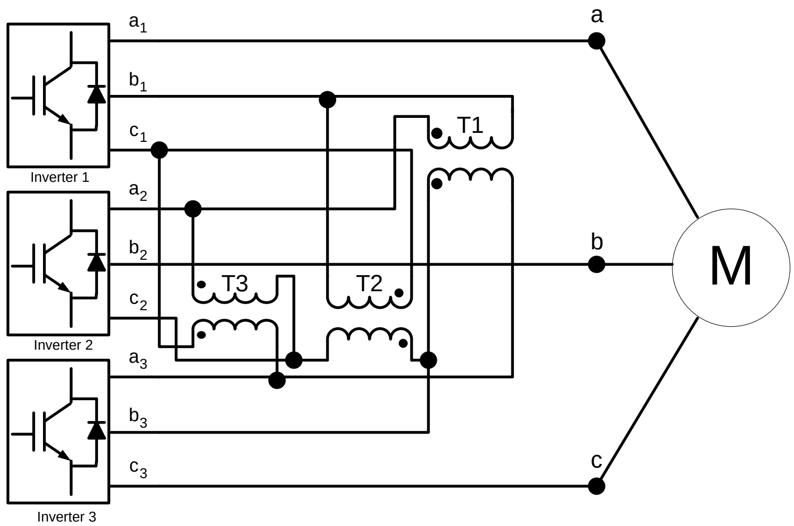

Fig. 2.3. Cascaded multilevel converter with transformers using standard three-phase bi-level converters.

2.2.2. Other Multilevel Inverters Based on H-bridges

Many kinds of multilevel inverter structures have been derived from the above three basic topologies. Some of them are introduced here.

A. Mixed-Level Hybrid Cascaded Multilevel Inverter

To reduce the number of separate dc sources for high-voltage, high-power applications with multilevel converters, diode-clamped or capacitor-clamped converters could be used to replace the full-bridge cell in a cascaded inverter [21]. An example is shown in Fig. 2.4. The nine-level cascaded inverter incorporates a three-level diode-clamped inverter as the cell. The original cascaded H-bridge multilevel inverter requires four separate dc sources for one phase leg and twelve for a three-phase converter. If a five-level inverter replaces the full-bridge cell, the voltage level is effectively doubled for each cell. Thus, to achieve the same nine voltage levels

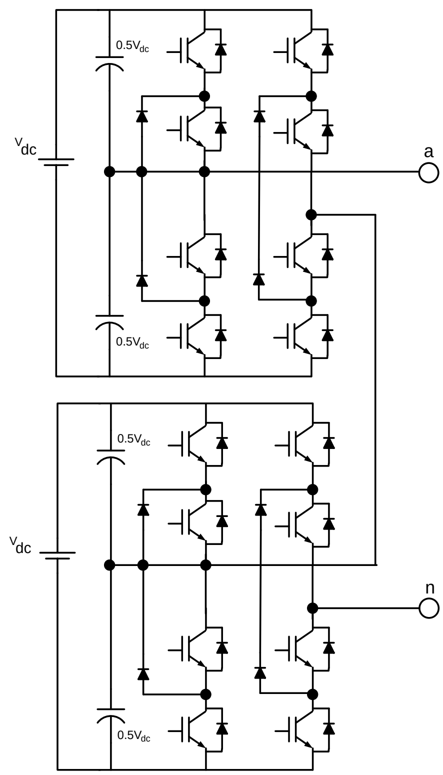

Fig. 2.4. Mixed-level hybrid unit configuration using the three-level diode-clamped inverter as the cascaded inverter cell to increase the voltage levels.

for each phase, only two separate dc sources are needed for one phase leg and six for a three-phase inverter. The configuration has mixed-level hybrid multilevel units because it embeds multilevel cells as the building block of the cascade inverter. The advantage of the topology is that it needs less separate dc sources. The disadvantage for the topology is that its control will be complicated due to its hybrid structure.

B. Asymmetrical Multilevel Inverter

Asymmetric multilevel inverters use different voltage levels among the cascaded inverter cells [4]. By addition and subtraction of these voltages, more unique output-voltage levels can be generated with the same number of components, compared to a symmetric multilevel inverter.

Higher output quality can be obtained with smaller circuit and control complexity, and even eliminate output filters. However, the resulting system is unstable, and, without control, the nonsupplied intermediate-circuit capacitor voltages will quickly run away from their nominal values. Veenstra and Rufer [22] have proposed a control method to stabilize a multiple of capacitor voltages without an equilibrium state. Power balancing is guaranteed by varying the common-mode voltage, using an online nonlinear model-predictive controller. Fig. 2.5 shows an improved three-phase asymmetrical multilevel inverter example proposed by Marithoz and Rufer [23]. This structure still has dc-dc converters, but depending on the configuration design, only from 20% to 50% of the power goes through them. The smallest part of the power goes through 3 secondary ac/dc converters and the 6-switch large inverter directly converts the largest part of the power.

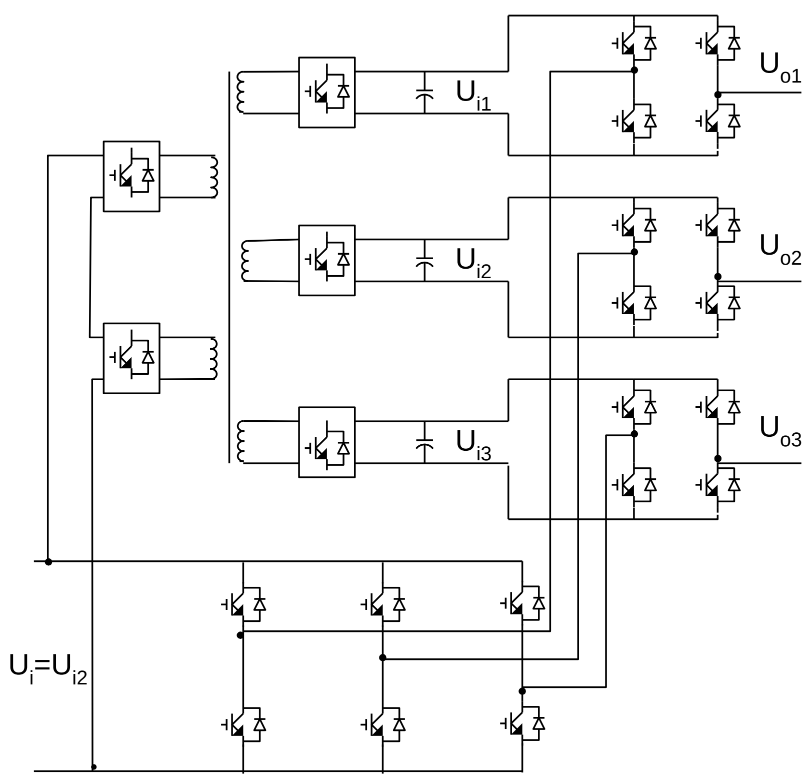

Fig. 2.5. An improved three-phase asymmetrical multilevel inverter structure.

C. Soft-Switching Multilevel Inverter

Several soft-switching methods can be implemented for different multilevel converters to reduce the switching loss and to increase efficiency. For the cascaded converter, because each converter cell is a two level circuit, the implementation of soft switching is not at all different from that of conventional bi-level converters. For capacitor-clamped or diode-clamped converters, soft-switching circuits have been proposed with different circuit combinations. One of the soft-switching circuits is a zero-voltage-switching type that includes auxiliary resonant commutated pole (ARCP), coupled inductor with zero-voltage transition (ZVT), and their combinations [4, 24].

2.3 MULTILEVEL INVERTER MODULATION CONTROL SCHEMES

The modulation control schemes for the multilevel inverter can be divided into two categories, fundamental switching frequency and high switching frequency PWM [2, 4] such as multilevel carrier-based PWM, selective harmonic elimination and multilevel space vector PWM as shown in Fig. 2.6. The multilevel SPWM and selective harmonic elimination (fundamental switching frequency) control methods are introduced in the next section.

2.3.1 Multilevel SPWM

Multilevel SPWM needs multiple carriers. Each DC source needs its own carrier. Several multi-carrier techniques have been developed to reduce the distortion in multilevel converters, based on the classical SPWM with triangular carriers. Some methods use carrier disposition and others use phase shifting of multiple carrier signals [2, 25, 26].

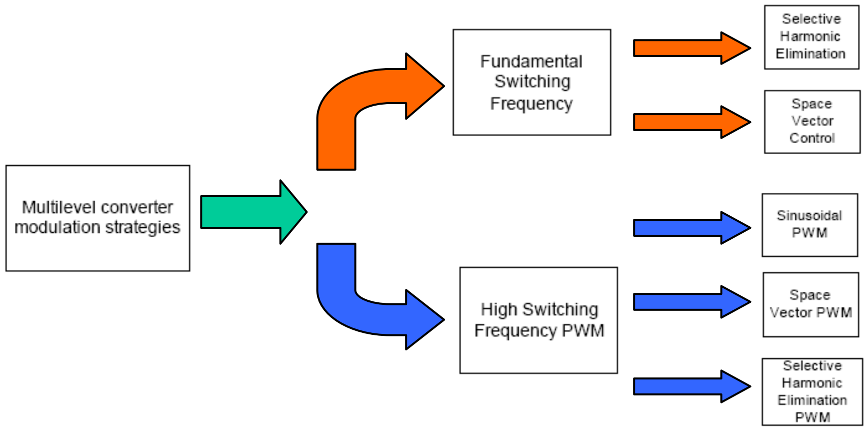

Fig. 2.6. Classification of multilevel inverter modulation control schemes.

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The most popular SPWM method is the extension of two levels SPWM. One reference signal is used to compare to the carriers. This can be shown in Fig. 2.7 (a). If the reference signal is higher than the carrier, the corresponding inverter cell outputs positive voltage; otherwise, the corresponding inverter cell outputs negative voltage. The output voltage of the converter is shown in Fig. 2.7 (b)

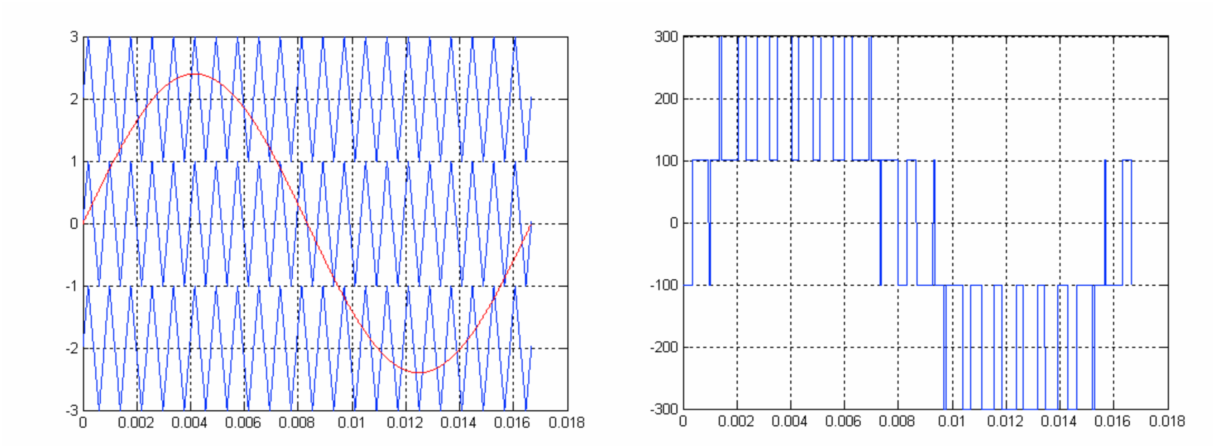
One of advantages of multilevel SPWM method is its simple implementation. Another is that the effective switching frequency of the load voltage is much higher than the switching frequency of each cell, as determined by its carrier signal.

In m-level multilevel inverters, the amplitude modulation index, m_a, and the frequency ratio, m_f, are defined as

$$m_a = \frac{A_m}{(m-1)\cdot A_c}, \tag{2.3}$$

$$m_f = \frac{f_c}{f_m}. \tag{2.4}$$

Where, A_m is the peak-to-peak reference waveform amplitude, A_c is the peak-to-peak carrier waveform amplitude, f_m is the reference waveform frequency, and f_c is the carrier waveform frequency.



(a) (b)

Fig. 2.7. (a) Modulation signals and (b) output voltage with multilevel SPWM.

2.3.2 Selective Harmonic Elimination

The method is also called fundamental switching frequency method based on the harmonic elimination theory proposed by Patel *et al* [27, 28]. As shown in Fig. 2.4, a multilevel converter can produce a quarter-wave symmetric stepped voltage waveform synthesized by several dc voltages [1]. Fig. 2.2 shows a typical 11-level multilevel converter output with fundamental frequency switching scheme. The Fourier series expansion of the output voltage waveform as shown in Fig. 2.2 is expressed in (2.1) and (2.2).

The conducting angles, θ_1, θ_2, ..., θ_s, can be chosen such that the voltage total harmonic distortion is a minimum. In general, the most significant low-frequency harmonics are chosen for elimination by properly selecting angles among different level converters, and high-frequency harmonic components can be readily removed by using additional filter circuits [1, 14].

For the 11-level case, the 5th, 7th, 11th, and 13th harmonics can be eliminated with the appropriate choice of the conducting angles. One degree of freedom is used so that the magnitude of the fundamental waveform corresponds to the reference waveform's amplitude or modulation index, m_a, which is defined as V_L^*/V_{Lmax}. V_L^* is the amplitude command of the inverter for a sine wave output phase voltage, and V_{Lmax} is the maximum attainable amplitude of the converter, i.e., $V_{Lmax} = s \cdot V_{dc}$, where s is the number of separate dc sources, V_{dc} is the dc voltage level. The equations from (2.2) will now be as follows:

$$\begin{aligned}
\cos(5\theta_1) + \cos(5\theta_2) + \cos(5\theta_3) + \cos(5\theta_4) + \cos(5\theta_5) &= 0 \\
\cos(7\theta_1) + \cos(7\theta_2) + \cos(7\theta_3) + \cos(7\theta_4) + \cos(7\theta_5) &= 0 \\
\cos(11\theta_1) + \cos(11\theta_2) + \cos(11\theta_3) + \cos(11\theta_4) + \cos(11\theta_5) &= 0 \\
\cos(13\theta_1) + \cos(13\theta_2) + \cos(13\theta_3) + \cos(13\theta_4) + \cos(13\theta_5) &= 0 \\
\cos(\theta_1) + \cos(\theta_2) + \cos(\theta_3) + \cos(\theta_4) + \cos(\theta_5) &= 5m_a
\end{aligned} \qquad (2.5)$$

These equations are nonlinear transcendental equations that can be solved by an iterative method such as the Newton-Raphson method and resultant theory [29]. To keep the number of eliminated harmonics at a constant level, all switching angles must satisfy the condition $0 < \theta_1 < \theta_2 < ... < \theta_s < \pi/2$, or the total harmonic distortion (THD) increases dramatically. Due to this reason, this modulation strategy basically provides a narrow range of modulation index, which is one of its disadvantages [4].

2.4 POWER CONVERTERS IN HEVS AND FCVS

With increasing oil price and global warming, automobile manufacturers are producing more hybrid electric vehicles and electrical vehicles. Many research efforts have been focused on developing efficient, reliable, and low-cost power conversion techniques for the future new energy vehicles.

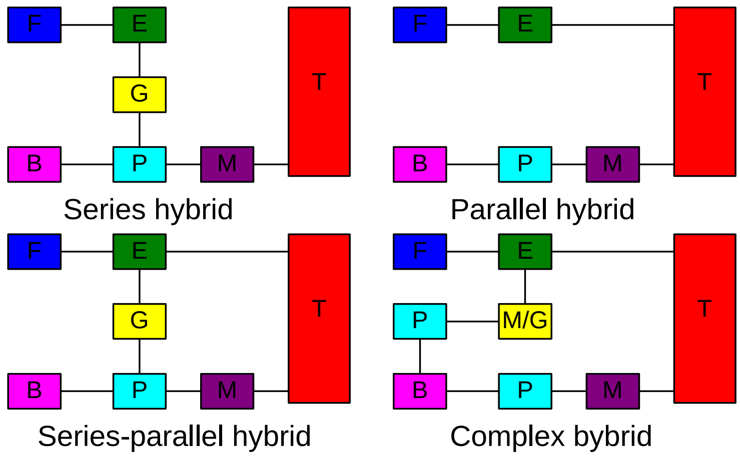
2.4.1 Architectures of HEVs and FCVs

A HEV combines a conventional internal combustion engine (ICE), a battery pack or super capacitor, and an electric motor. A HEV uses an electric energy source (battery, super capacitor) to assist the propulsion of the vehicle in addition to the primary energy source (ICE, fuel cell). The electric motor serves as a device to optimize the efficiency of the ICE, and to absorb the kinetic energy during braking [30]. This concept has been in existence for more than 100 years.

Traditionally, ICE HEVs can be categorized into two basic types based on the structure of the powertrain: namely series hybrid and parallel hybrid that have been introduced by Chan [9].

In series hybrid, the ICE drives a generator; the output of the generator charges a battery/super capacitor through a rectifier. The battery/super capacitor feeds an inverter, which drives the traction motor. In this configuration, all output mechanical power from the ICE is converted into electrical power first and then converts back into mechanical power and drives the vehicle through a motor/generator. In parallel hybrid, the ICE drives the wheel directly; also a motor/generator driven by an inverter powered by a battery is mechanically coupled with the ICE. The motor can assist ICE to drive the vehicle or take power back from ICE/regenerative braking to charge the battery when needed.

Some other configurations are derived from the above two. For example, series–parallel hybrid incorporates the features of both the series and parallel HEVs, but involving an additional mechanical link compared with the series hybrid and also an additional generator compared with the parallel hybrid. Complex hybrid is another different configuration with the above three kinds. Its bidirectional power flow can allow for versatile operating modes, especially the three



B: Battery, E: ICE, F: Fuel tank, G: Generator
M: Motor, P: Power converters, T: Transmissions

Fig. 2.8. Four architectures of HEV.

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propulsion power (due to the ICE and two electric motors) operating mode. Fig. 2.8 shows the various architectures of HEVs.

FCV can be considered as a series-type hybrid vehicle. The onboard fuel cell produces electricity, which is either used to provide power to the propulsion motor or stored in the onboard battery for future use.

2.4.2 Traction Motor in HEVs and FCVs

The major types of electric traction motors adopted or under serious consideration for HEVs as well as for FCVs include the dc motor, the induction motor (IM), the permanent magnet (PM) synchronous motor, and the switched reluctance motor (SRM).

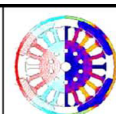
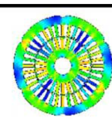
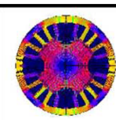
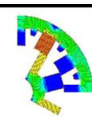
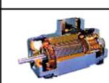
Based on the following major requirements of HEVs electric propulsion, Zeraoulia *et al.* made a comparative study in [31].

- High instant power and a high power density

- High torque at low speeds for starting and climbing, as well as a high power at high speed for cruising
- Very wide speed range, including constant-torque and constant-power regions
- Fast torque response
- High efficiency over the wide speed and torque ranges
- High efficiency for regenerative braking
- High reliability and robustness for various vehicle operating conditions
- Reasonable cost

Table 2.1 shows evaluation results of the four major motors [31]. The IM seems to be the most adapted candidate for the electric propulsion of HEVs. However, among the aforementioned motor electric propulsion features, the extended speed range ability and energy efficiency are the two basic characteristics that are influenced by vehicle dynamics and system architecture. Therefore, the selection of traction drives for HEVs demands special attention to

Table 2.1. Electric propulsion systems evaluation

Propulsion Systems / *Characteristics*	 DC	 IM	 PM	 SRM
Power Density	2.5	3.5	5	3.5
Efficiency	2.5	3.5	5	3.5
Controllability	5	5	4	3
Reliability	3	5	4	5
Technological maturity	5	5	4	4
Cost	4	5	3	4
Σ Total	 **22**	 **27**	 **25**	 **23**

these two characteristics. From this analysis, a conclusion that should be drawn is that a PM brushless motor is an alternative.

2.4.3 Power Converters in HEVs and FCVs

There are two basic configurations for power converters in HEVs/FCVs [32]. One is a traditional PWM inverter powered by a battery as shown in Fig. 2.9; the other is an inverter plus a dc/dc converter as shown in Fig. 2.10. The dc/dc converter is usually a boost converter because voltage boost is needed from lower battery voltage side to output high voltage side to drive the traction motor for high speed and high torque [32-34]. In addition, a bidirectional power transfer capability is needed in the power converters. Bidirectional power flow enables the energy capture of regenerative brake and energy release during startup and hill climbing. The regenerative brake energy is always desirable as this energy would otherwise be dissipated and lost as heat in the friction brakes. The inertia energy of the vehicle recovered by regenerative braking is originally imparted to the vehicle by the fuel conversion system [33]. So bidirectional

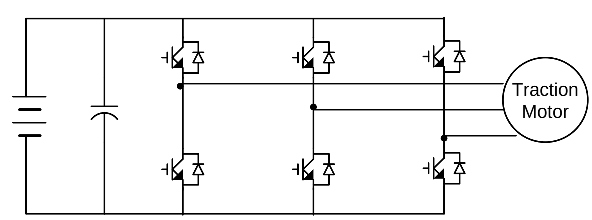


Fig. 2.9. Traditional PWM inverter for HEVs.

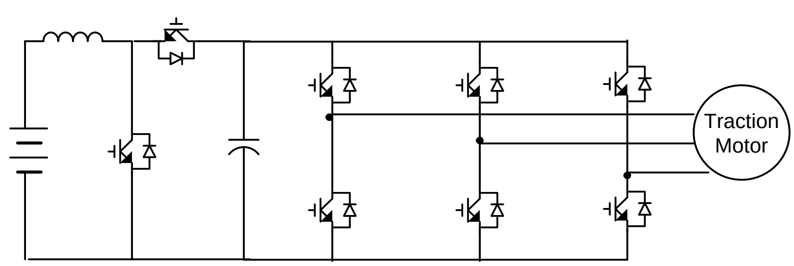


Fig. 2.10. dc/dc boost PWM inverter for HEVs

power transfer and conversion is of course desirable and leads to improved fuel efficiency for transient drive cycles.

The battery voltage variation in HEVs could be as large as 50% and depends on the battery type. With this voltage range, the traditional PWM inverter has to be oversized to handle full voltage and twice the current at 50% of the battery voltage to output full power. Thus the cost of the inverter increases. The dc/dc boosted PWM inverter can minimize the stress of the inverter with an extra dc/dc stage; however, this increases the system cost, complexity, and reduces the reliability.

Lai and Nelson [33] described some design examples of bidirectional dc-dc converters applied in HEV/FCV. These converters can be divided into isolated and nonisolated and widely use soft switching techniques. Figs. 2.11 and 2.12 show two kinds of typical bidirectional dc-dc converters, nonisolated buck-boost and isolated full-bridge current source. It is noted that the inductor in a typical bidirectional dc–dc converter is always the most bulky component, which is equivalent to the electric motor in an inverter-motor drive system. It is necessary to optimize the inductor design to minimize its size and loss.

It can be seen that the major difficulty of designing a high-power bidirectional dc–dc

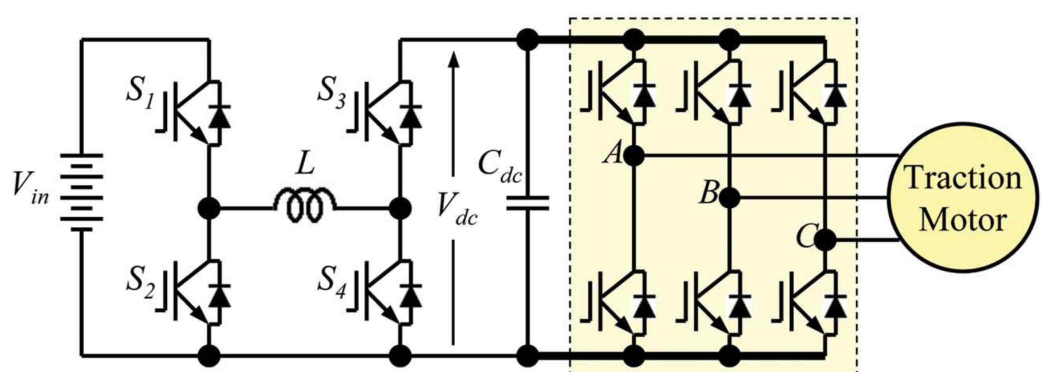


Fig. 2.11. Bidirectional buck-boost converter for high-power EV applications.

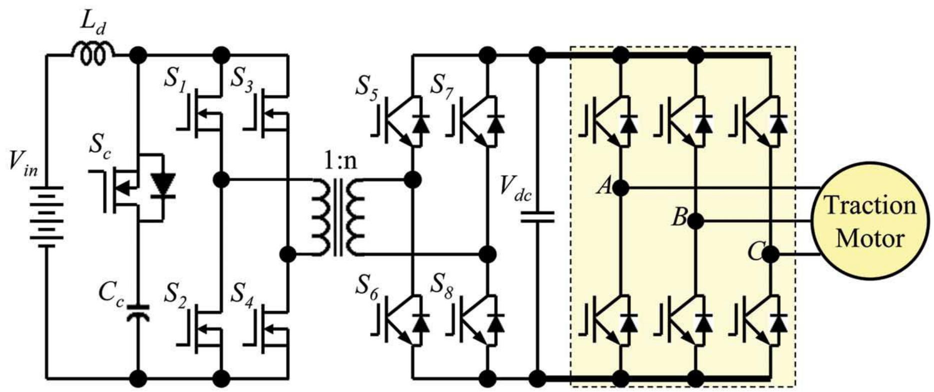


Fig. 2.12. Bidirectional dc–dc converter with full-bridge current source converter for LV side and full-bridge voltage source converter for HV side.

converter is the limited availability of high-power switching devices and magnetic components.

For high-power applications, a single converter requires multiple devices in parallel to handle high currents. Thus multiphase dc–dc converters will become the mainstream of high-power conversions for vehicle energy management systems. Figs. 2.13 and 2.14 show nonisolated and isolated three-phase bidirectional dc–dc converters. However, whether isolated or not, multiple phases allow significant ripple reduction and thus passive component size reduction and ultimately cost reduction. Similar to the component availability issue, the controller for multiphase bidirectional dc–dc converter is also not readily available, and much development effort is needed.

Peng and Shen [32][35] proposed a Z-source inverter for HEV/FCV as shown in Fig. 2.15. The Z-source inverter is suitable because of the following unique features and advantages: (1) less complex, and more cost effective than a dc–dc boosted inverter, while providing the same function (i.e., buck boost); (2) greater reliability, because shoot-through can no longer destroy the inverter; (3) no need for any dc–dc converters to control the battery state of charge, or boost the dc bus voltage, because the Z-source inverter has two independent control freedoms.

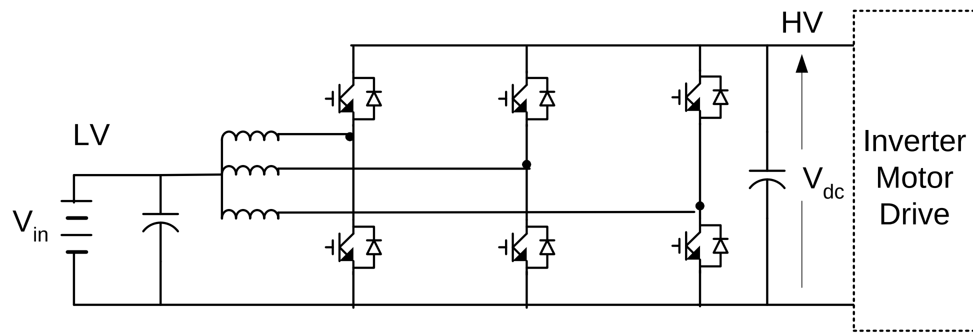


Fig. 2.13. Three-phase nonisolated bidirectional dc–dc converter.

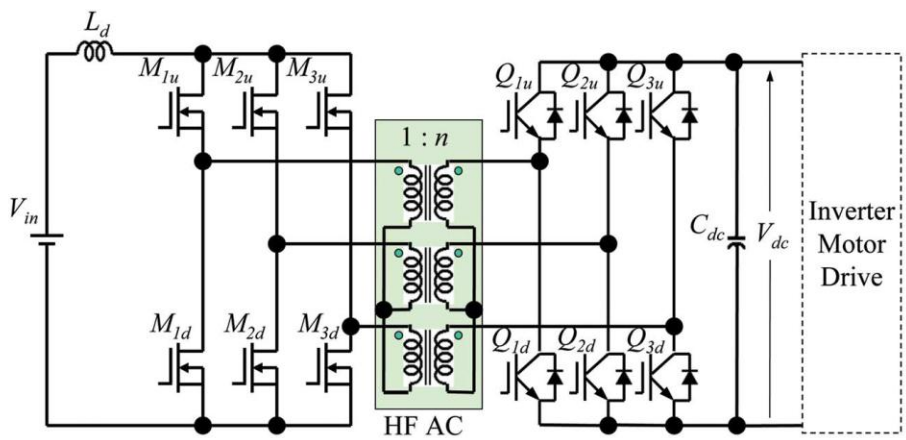


Fig. 2.14. Three-phase isolated bidirectional dc–dc converter.

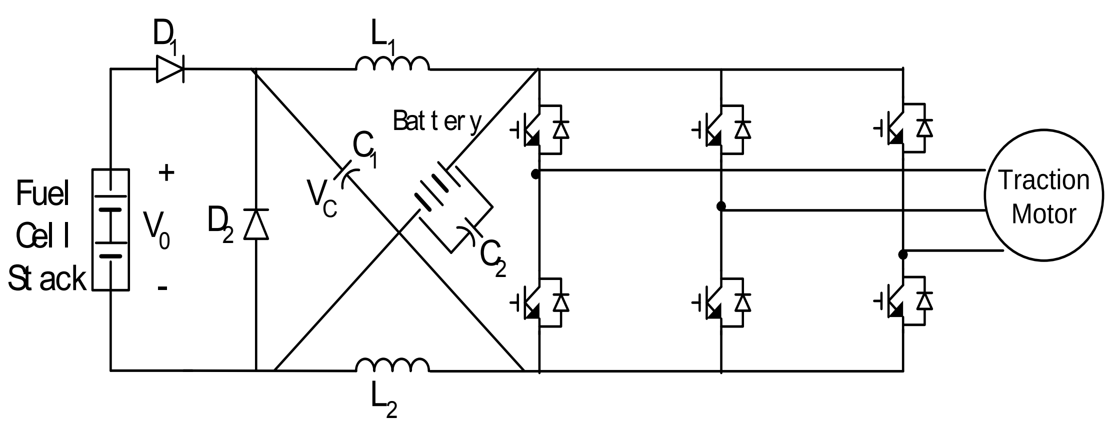


Fig. 2.15. Configuration of Z-source inverter for FCV.

As previously discussed, inductors are necessary in existing power inverters in HEVs/FCVs. Currently the common configuration is to use a dc-dc boost converter to boost the battery voltage for a traditional 3-phase inverter. When the motor is running on low to medium power, the dc-dc boost converter is not needed, and the battery voltage will be directly applied to the inverter to drive the traction motor. When it is running in high power mode, the dc-dc boost converter will boost the battery voltage to a higher voltage so that the inverter can provide higher power to the motor with high speed and high torque. The existence of bulky magnetics is a negative factor for power density, efficiency, and manufacturing cost for the present HEV/FCV traction drive inverters. Thus a multilevel inverter with combined rectifier and inverter functions and eliminated magnetics will be an attractive choice for HEV/FCV.

2.5 Power Converters Used As A Renewable Energy Utility Interface

As discussed in section 1.3, renewable energy systems should be capable of supplying ac electricity. In addition, because almost all renewable energy sources are of the intermittent nature, most renewable energy systems should include an energy storage device that is usually implemented by battery banks [36]. Accordingly, it is evident that a power converter device capable of converting a single dc voltage from a battery bank into an ac voltage is a key element of renewable energy systems. The development of high performance dc/ac converters is a challenge, although they have expanded quickly in the last decade.

There are two common configurations of power converters used for renewable energy sources. One uses a line frequency transformer after the dc/ac inverter. The line frequency transformer is of huge size, loud noise and high cost. Another uses a dc/dc step-up converter to boost the voltage. The existing inductors still bring a negative influence on the system efficiency

[35]-[38]. Additionally, Some new topologies based on the traditional structures have been developed for renewable energy applications [36]-[38]. The present challenges in designing a high power dc–dc step-up converter are the limited availability of high-power switching devices and magnetic components.

Multilevel inverters have been proposed for renewable energy utility interface applications because their high power possibility and high efficiency. Multilevel converter used to control the frequency and voltage output from renewable energy sources will provide significant advantages because of their fast response and autonomous control. Additionally, multilevel converters can also control the real and reactive power flow from a utility connected renewable energy source. These power electronic topologies are attractive for continuous control of system dynamic behavior and to reduce power quality problems. Cascaded multilevel inverter can generate high-resolution multilevel waveforms with a relatively low number of components. In addition, dc sources can be added or subtracted, which can increase the number of output levels. Although the original cascaded topology requires several isolated dc sources, in some systems, they may be available through batteries or solar panels. Thus it has been used to implement high-efficiency transformerless inverters.

Tolbert and Peng [5][6] firstly proposed an 11-level cascaded multilevel inverter for renewable energy utility applications. Its features include the least component count and modularity, which solve the major problems of the conventional inverter. A tremendous cost savings can be expected since the custom-designed transformers are eliminated. In [36], Daher *et al.* compared and analyzed most common topologies of multilevel converters and showed which ones are best suited to implement inverters for stand-alone photovoltaic applications in the range of a few kilowatts. A 63-level example prototype of 3 kVA was implemented, and peak efficiency of 96.0% was achieved.

2.6 CASCADED MULTILEVEL INVERTER WITH FEWER DC SOURCES

As described in section 2.2.2, each H-bridge cell of a cascaded multilevel inverter needs a separate dc source, which will limit its application to products and fields that multiple separate dc sources are available. Thus, to reduce or replace these dc sources becomes interesting and important. A capacitor is an appropriate alternate due to its characteristic of easily charging and discharging. Capacitor voltage regulation is the key issue.

The asymmetrical multilevel inverter introduced in section 2.2.3 uses different intermediate-circuit capacitor voltages in various parts of the inverter. By addition and subtraction of these voltages, more unique output-voltage levels can be generated with the same number of components, compared to a symmetric multilevel inverter. That means a decrease in the number of separate dc sources for the same level output voltage, compared to a symmetric multilevel inverter. The control method proposed by Veenstra and Rufer [22] is called model-predictive control (MPC), which can deal with all of these properties and requirements. It predicts the system evolution as a function of the control inputs. A cost function of system and control quantities is defined, and the optimal control input to be applied is obtained by iteratively minimizing this cost function in real time. The optimizer can handle possible hard constraints.

Corzine *et al.* [39] proposed a cascaded H-bridge multilevel inverter utilizing capacitor voltages sources as shown in Fig. 2.16. Each phase consist of p multilevel H-bridge cells. Typically, each cell requires a separate dc source. However, it was illustrated in [39] that the separate dc source is not necessary for the top inverter. In terms of the generalized model, for an n_p-level H-bridge cell, the n_1 level is supplied by an isolated dc source; the remaining levels from

n_2 to n_p are connected with some capacitors. The resulting inverter requires only one isolated dc source per phase. Capacitor voltages are controlled through redundant switching states.

Based on the similar topology in Fig. 2.16, a phase-shift modulation method was used to regulate the voltage of the capacitors replacing the dc sources by Liao *et al.* [40]. There are two H-bridge cells per phase. The one named main inverter is connected with a dc source; the other one named auxiliary inverter is connected with a capacitor. Voltage regulation of the capacitor in the auxiliary converter is a challenging task. In the proposed method, capacitor voltage regulation is achieved by adjusting the active and reactive power that the main converter injects to the load. The main converter injects only active power if the conduction angle of the main inverter is chosen appropriately. By shifting the voltage waveform synthesized by the main converter, one could also inject some reactive power, which can be used to charge or discharge the capacitor on the auxiliary converter. Phase-shift modulation is used to find the required phase shift. Du *et al.* have a similar approach in [41]. All of these schemes require at least one dc power source per phase.

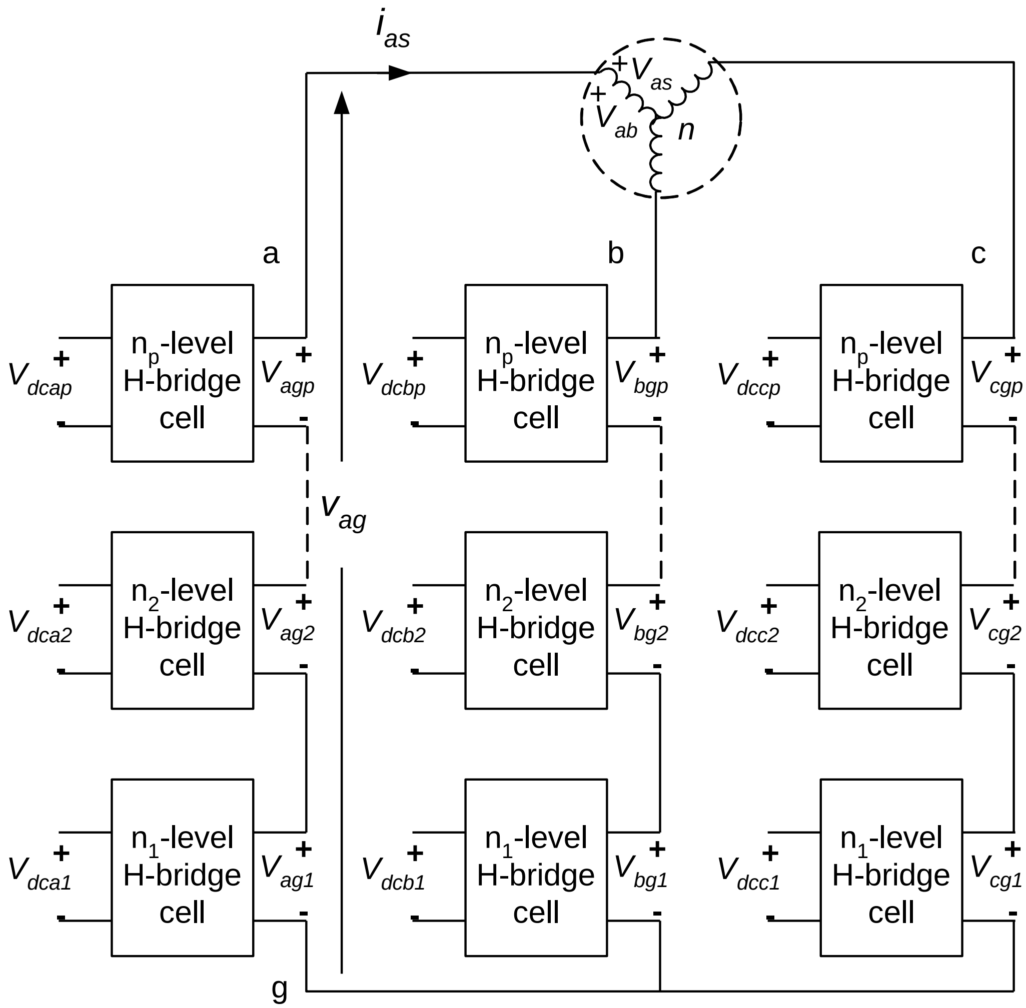


Fig. 2.16. Generalized topology of the cascaded multilevel H-bridge drive.

Chiasson *et al.* [42] proposed a three-phase hybrid cascade multilevel inverter, which consists of a standard 3-leg inverter (one leg for each phase) and H-bridge in series with each inverter leg. The single dc power source supplies the standard 3-leg inverter along with three full H-bridges supplied by capacitors. This means only one dc power source is needed for the three-phase system. In [42], the SIMULINK models are built and the simulation results for a PM synchronous motor drive are presented.

In this dissertation, an experimental five-level 5 kW prototype inverter based on the above topology is built and tested. Simulation results and analysis with SIMULINK and PSIM co-simulation platform are presented. The proposed inverter for fuel cell systems and renewable energy utility interface applications are researched.

2.7 Summary

In this chapter, the previous works on multilevel inverter structures and modulation strategies are presented firstly. There are three major multilevel inverter structures in industrial applications. Cascaded H-bridge inverter with separate dc sources and several other multilevel inverters based on H-bridges are introduced. Each H-bridge cell of a cascaded multilevel inverter needs a separate dc source, which will limit its application to products and fields that multiple separate dc sources are available. Thus, to reduce or replace these dc sources becomes interesting and important. Some cascaded multilevel inverters with fewer dc sources have been discussed.

Secondly, this chapter has provided a survey of most existing power converters for traction motor drive in HEVs/FCVs and renewable energy systems. Currently available power inverter systems use a dc-dc boost converter to boost the battery voltage for a traditional 3-phase inverter. Eliminating the magnetics for the dc-dc boost converters will improve their performance and reduce the manufacturing cost.

The survey suggests that a multilevel inverter that can output a boosted ac voltage and remove the bulky magnetic components is an interesting research topic.

3. HYBRID MULTILEVEL INVERTER FOR VOLTAGE BOOST

As discussed in the previous chapter, the power converter is the key part of the HEVs/FCVs and renewable energy systems. Currently available power inverter systems use a dc-dc boost converter to boost the battery voltage for a traditional 3-phase inverter. Thus the present inverters have low power density, are expensive, and have low efficiency because they need bulky inductors for the dc-dc boost converters.

The proposed hybrid multilevel inverter is a combination of standard 3-leg inverter and cascaded H-bridge inverter. It can output a boosted ac voltage and remove bulky and costly magnetic components to increase the power density. Moreover, this inverter can use only a single dc power source. In this chapter, its structure, operation, control and simulation models are presented.

3.1 STRUCTURES AND OPERATION PRINCIPLE

The hybrid multilevel inverter includes a standard 3-leg inverter (one leg for each phase) and H-bridge in series with each inverter leg as shown in Fig. 3.1. Fig 3.2 shows its simplified single-phase topology. 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. Traditionally, each H-bridge requires a dc power source [42-44].

The bottom of the inverter is one leg of a standard 3-leg inverter with a dc power source. The top is a H-bridge in series with each standard inverter leg. The H-bridge can use a separate dc power source or a capacitor as the dc power source.

All the parameters of this inverter are listed as follows:

v_1: the bottom standard inverter output voltage

ϕ_1: phase angle of the bottom standard inverter output voltage

v_2: the top H-bridge output voltage

ϕ_2: phase angle of the top H-bridge output voltage

v: load voltage

i: load current

φ: phase angle of the top H-bridge output voltage

v_c: capacitor voltage

V_{dc}: power supply output voltage

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 that in turn is supplied by a capacitor voltage. If the capacitor is 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). An example output waveform that this topology can achieve is shown in Fig 3.3. When the output voltage $v = v_1 + v_2$ is required to be zero, one can either set $v_1 = +V_{dc}/2$ and $v_2 = -V_{dc}/2$ or $v_1 = -V_{dc}/2$ and $v_2 = +V_{dc}/2$. It is this flexibility in choosing how to make that output voltage zero that is exploited to regulate the capacitor voltage. When only a single dc power source is used in the three-phase inverter, that is, the H-bridge uses a capacitor as the dc source; the capacitor's voltage regulation control details are illustrated in Fig. 3.4.

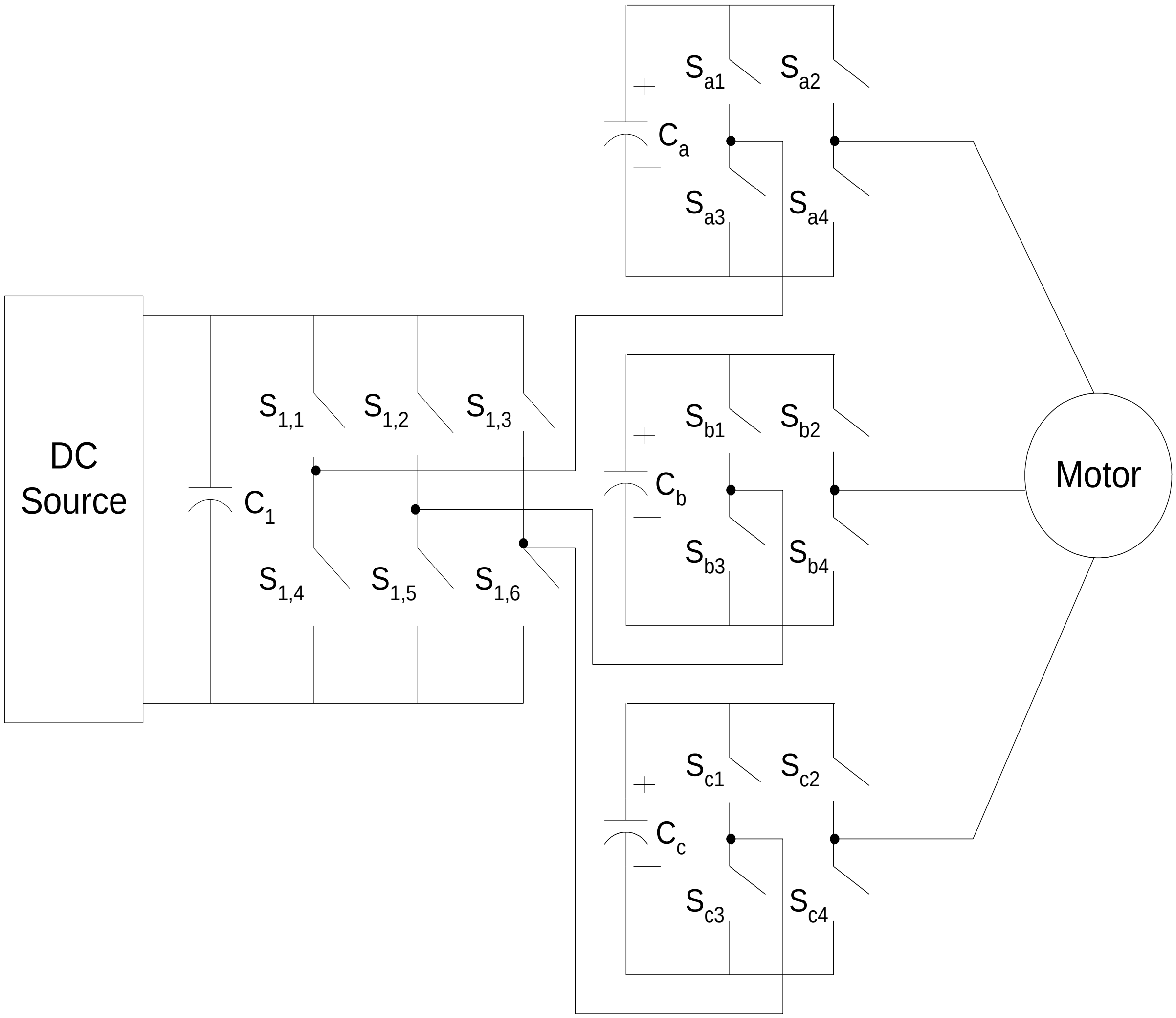


Fig. 3.1. Topology of the hybrid multilevel inverter.

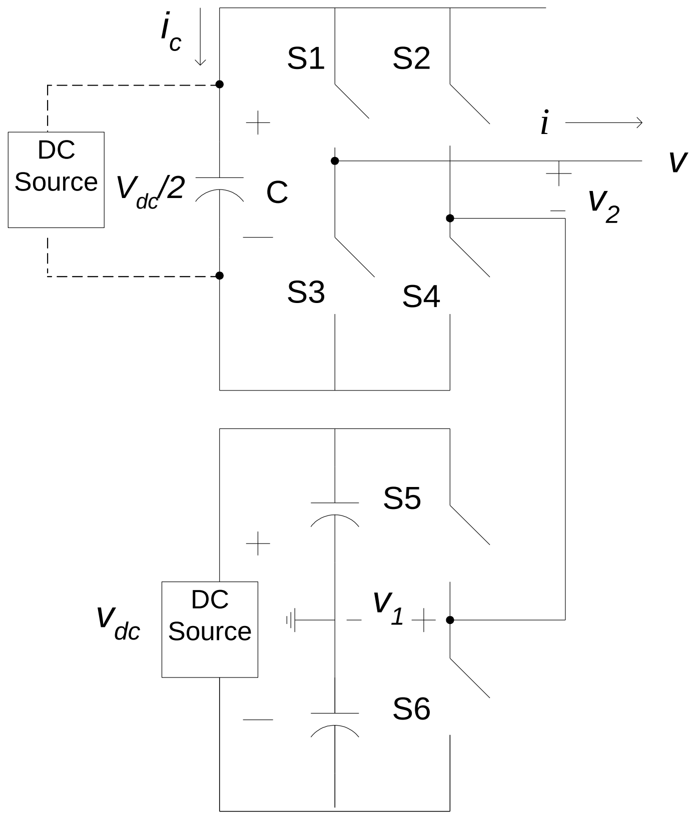


Fig. 3.2. Simplified single-phase topology of the hybrid multilevel inverter.

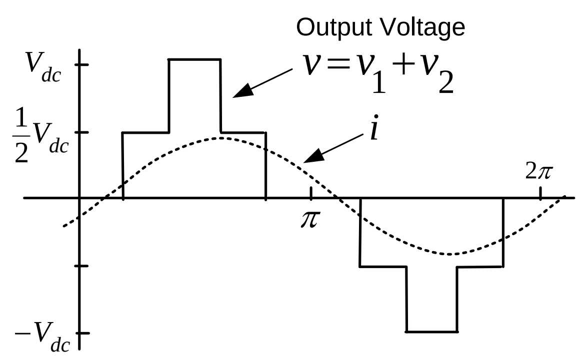


Fig. 3.3. Five level output waveform.

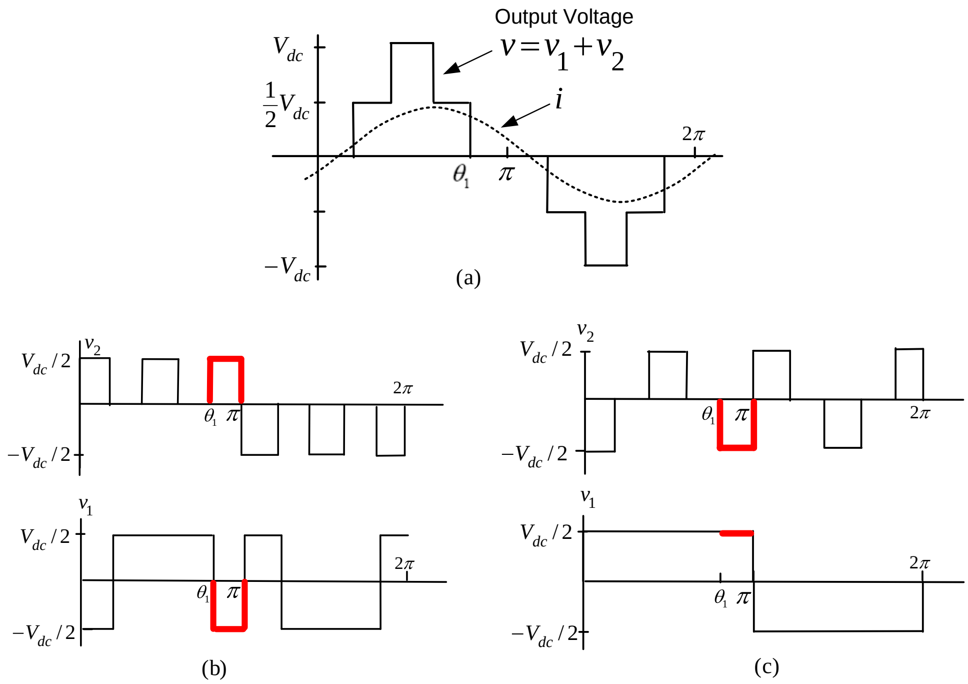


Fig. 3.4. Capacitor voltage regulation process.

During $\theta_1 \le \theta \le \pi$, the output voltage is zero and the current i > 0. If S_1, S_4 are closed (so that $v_2 = +V_{dc}/2$) along with S_6 closed (so that $v_1 = -V_{dc}/2$), then the capacitor is discharging ($i_c = -i < 0$ see Fig. 3.4 (b)) and $v = v_1 + v_2 = 0$. On the other hand, if S_2, S_3 are closed (so that $v_2 = -V_{dc}/2$) and S_5 is also closed (so that $v_1 = +V_{dc}/2$), then the capacitor is charging ($i_c = i > 0$ see Fig. 3.4 (c)) and $v = v_1+v_2 = 0$. When $i < 0$, if S_1, S_4 are closed (so that $v_2 = +V_{dc}/2$) along with S_6 closed (so that $v_1 = -V_{dc}/2$), then the capacitor is charging ($i_c = -i > 0$) and $v = v_1 + v_2 = 0$. On the other hand, if S_2, S_3 are closed (so that $v_2 = -V_{dc}/2$) and S_5 is also closed (so that $v_1 = +V_{dc}/2$), then the capacitor is discharging ($i_c = i < 0$). The $i < 0$ case is accomplished by simply reversing the switch positions of the $i > 0$ case for charge and discharge of the capacitor. Consequently, the 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.

As Fig. 3.4 illustrates, this method of regulating the capacitor voltage 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. It is noted that the above capacitor voltage regulation method is described using a fundamental frequency modulation scheme because it is easier to illustrate [42]. The realization of capacitor voltage regulation and inverter boost function depends on the phase angle difference of output voltage and current. Actually, that means they are related to the amount of reactive power required by the load. A single-phase analysis can be used to explain the issue.

For the bottom inverter, the output reactive power is

$$Q_1 = v_{1,rms} \times i_{rms} \times \sin(\phi_1) \qquad (3.1)$$

The top H-bridges deliver the reactive power,

$$Q_2 = v_{2,rms} \times i_{rms} \times \sin(\phi_2) \qquad (3.2)$$

The load reactive power demand is,

$$Q_L = v_{rms} \times i_{rms} \times \sin(\varphi) \qquad (3.3)$$

and,

$$Q_1 + Q_2 = Q_L \qquad (3.4)$$

Combining equations (3.1) to (3.4), it can be concluded that,

$$v_{1,rms_1} \sin(\phi_1) + v_{2,rms} \sin(\phi_2) = v_{rms} \sin(\varphi) \qquad (3.5)$$

Assuming sin (ϕ_1) = 0 (no reactive power is supplied by the bottom inverter), the maximum power is extracted from the power supply connected with the bottom inverter, which means it only delivers real power. This means the top H-bridges deliver all of the reactive power, i.e. sin (ϕ_2) = 1. From (3.5), if the load is resistive, i.e. sin (φ) = 0, then $v_{2,rms} = 0$. Thus the capacitor voltage regulation cannot be realized and a boosted voltage cannot be produced. The analysis shows that capacitor voltage regulation and inverter boost function depends on the phase angle difference of output voltage and current.

3.2 Modulation Schemes of the Hybrid Multilevel Inverter

The modulation control schemes for the multilevel inverter can be divided into two categories, fundamental switching frequency and high switching frequency PWM, 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.

3.2.1 Fundamental Frequency Control Method

The key issue of the fundamental frequency modulation control is to choose two switching angles θ_1 and θ_2. The goal is to output the desired fundamental frequency voltage and to eliminate the 5th harmonic. Mathematically, this can be formulated as the solution to the following equations:

$$\begin{aligned} \cos(\theta_1) + \cos(\theta_2) &= m_a \\ \cos(5\theta_1) + \cos(5\theta_2) &= 0 \end{aligned} \tag{3.6}$$

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

$$m = \frac{V_1}{V_{dc}/2} \quad (3.7)$$

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

$$m = \frac{4}{\pi} m_a \quad (3.8)$$

A practical solution set is shown in Fig. 3.5, 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. The load current displacement angle is φ as shown in Fig. 3.6.

To balance the capacitor voltage, the capacitor charging amount needs to be greater than the discharging amount [43]. That is, to regulate the capacitor's voltage with fundamental frequency switching scheme, the following equation must be satisfied,

$$\int i_{charging} d\theta - \int i_{discharging} d\theta > 0 \quad (3.9)$$

In detail, we have the following equations

$$i = I \sin(\omega t - \varphi) \quad (3.10)$$

and the displacement power factor

$$pf = \cos(\varphi) \quad (3.11)$$

The three cases are:

$0 \leq \varphi \leq \theta_1$

$$\int_0^{\varphi} |i| d\theta + \int_{\varphi}^{\theta_1} i d\theta + \int_{\pi-\theta_1}^{\pi} i d\theta - \int_{\theta_2}^{\pi-\theta_2} i d\theta > 0 \quad (3.12)$$

$\theta_1 < \varphi \leq \theta_2$

$$\int_0^{\theta_1} |i| d\theta + \int_{\pi-\theta_1}^{\pi} i d\theta - \int_{\theta_2}^{\pi-\theta_2} i d\theta > 0 \quad (3.13)$$

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

$$\int_0^{\theta_1} |i| d\theta + \int_{\pi-\theta_1}^{\pi} i d\theta - \int_{\theta_2}^{\pi-\theta_2} i d\theta > 0 \quad (3.14)$$

Combining (3.10), (3.11), (3.12), (3.13) and (3.14), it can be concluded that

for $0 \leq \varphi \leq \theta_1$,

$$pf \leq \frac{\pi}{4m} \quad (3.15)$$

and for $\theta_1 < \varphi \leq \pi/2$.

$$pf \leq \cos\left[\tan^{-1}\left(\frac{\cos(\theta_2)}{\sin(\theta_1)}\right)\right] \quad (3.16)$$

Therefore, equations (3.15) and (3.16) are the conditions for the fundamental frequency switching scheme to eliminate the 5^{th} harmonic and to regulate the capacitor's voltage. Furthermore, to use minimum phase displacement angles is a more convenient way to use equations (3.15) and (3.16). It means if the phase displacement angle is greater than the minimum angle, the voltage can be regulated anyway.

Fig. 3.7 is derived from equations (3.9)-(3.16). It can be seen in Fig. 3.7 that the highest output voltage modulation index depends on the displacement power factor. When the modulation index is less than 1.27, it can be applied on the load with any power factor. When the

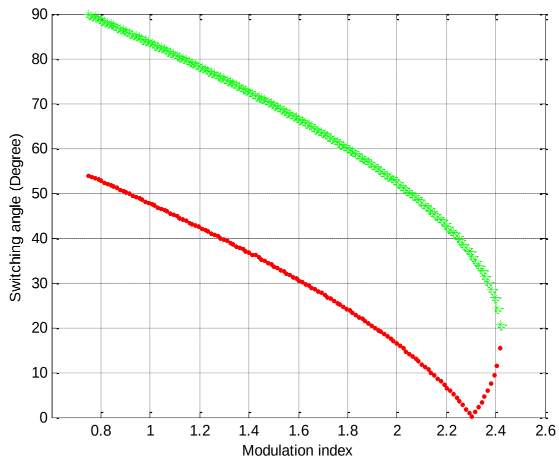


Fig. 3.5. Switching angles θ_1 (lower) and θ_2 (upper) vs. Modulation index.

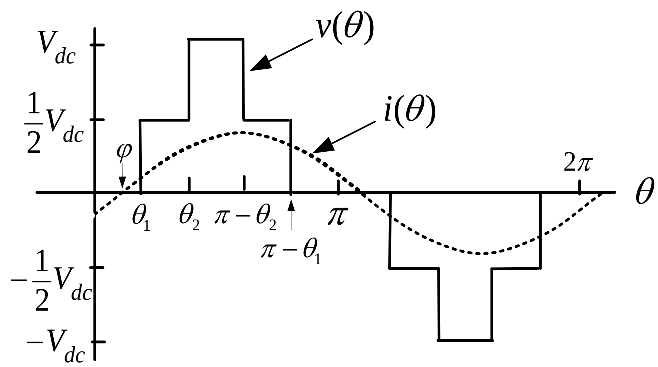


Fig. 3.6. Five level output waveform.

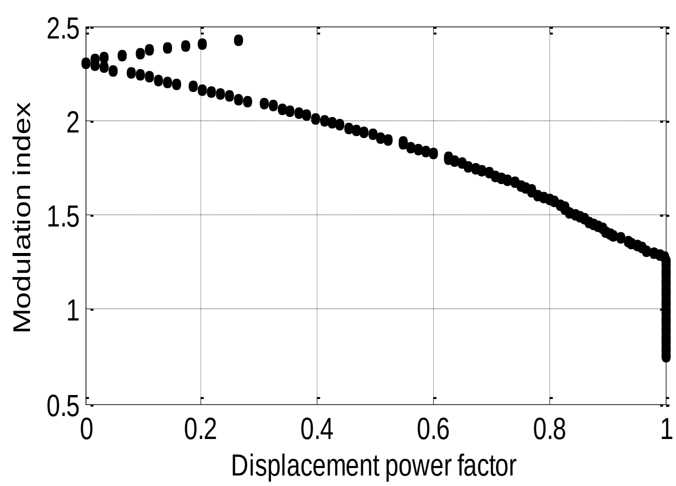


Fig. 3.7. Displacement power factor and output voltage modulation index.

modulation is between 1.27 and 2.42, it can be applied on the load with a corresponding highest power factor. For practical applications, the highest output voltage is determined when the load is determined. It is noted that the curve with the modulation index beyond 2.42 in Fig. 3.7 is not considered.

3.2.2 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 hybrid multilevel inverter, the top H-bridge inverter is operated under the SPWM with unipolar voltage switching mode and the bottom standard 3-leg inverter is operated under square-wave mode in order to reduce switching loss [45]. Fig. 3.8 shows the PWM modulation signals applied on the H-bridges. They include six sinusoidal reference waveforms and two triangle carrier waveforms. The comparison of reference and carrier waveforms result in twelve modulation signals to control the twelve switches distributed in the three H-bridges shown in Fig. 3.1. Fig. 3.9 shows the square-wave modulation signal applied on the standard inverter. Unipolar switching scheme requires that the inverter needs to output $-V_{dc}/2$, 0 and $V_{dc}/2$ phase voltage. Traditional inverter can not use unipolar switching scheme since its one phase leg can only output $-V_{dc}/2$ and $V_{dc}/2$ phase voltage, and no 0 voltage. For the hybrid multilevel inverter, the combination of the bottom inverter output and the top H-bridge make it possible to employ unipolar switching scheme control because it can generate 0 voltage.

It is noted that the above capacitor voltage regulation method is described using a fundamental frequency modulation scheme in section 3.2.1 because it is easier to illustrate [42]. It is difficult to calculate with PWM method due to its complexity of output voltage waveform. Under multilevel PWM control method, the same regulation method is utilized. It means 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. Fig. 3.10 shows the simulation result on the relationship between the modulation index and the power factor. The result is similar with fundamental frequency modulation scheme. When the power factor increases, the highest output voltage modulation index decreases. It means that the highest output voltage is determined when the load is determined for practical applications.

3.2.3 Unipolar programmed PWM Control Method

An alternate method to realize unipolar PWM modulation scheme is unipolar programmed PWM method, which is similar with fundamental frequency method.

Fig. 3.11 shows its output voltage waveform. The key issue is to regulate the capacitor's voltage to $V_{dc}/2$ in order to realize the unipolar switching scheme control. To regulate the capacitor's voltage, if $i > 0$ and $V_c < V_{dc}/2$, the inverter controls the bottom inverter to output $V_{dc}/2$ and the top H-bridge to output $-V_{dc}/2$ for inverter's 0 voltage output; if $i > 0$ and $V_c > V_{dc}/2$, the inverter controls the bottom inverter to output $-V_{dc}/2$ and the top H-bridge to output $V_{dc}/2$ for inverter's 0 voltage output. Similarly, if $i < 0$ and $V_c < V_{dc}/2$, the inverter controls the bottom inverter to output $-V_{dc}/2$ and the top H-bridge to output $V_{dc}/2$ for inverter's 0 voltage output; if $i <$

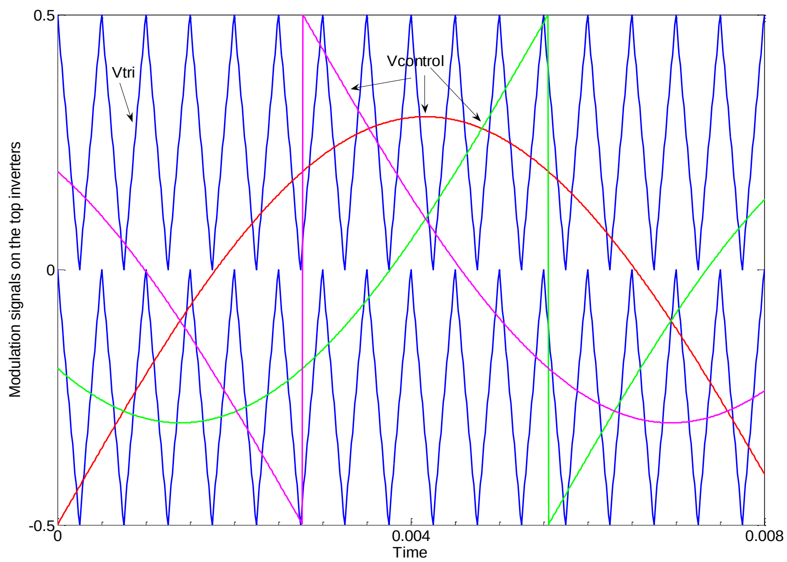


Fig. 3.8. PWM modulation signal.

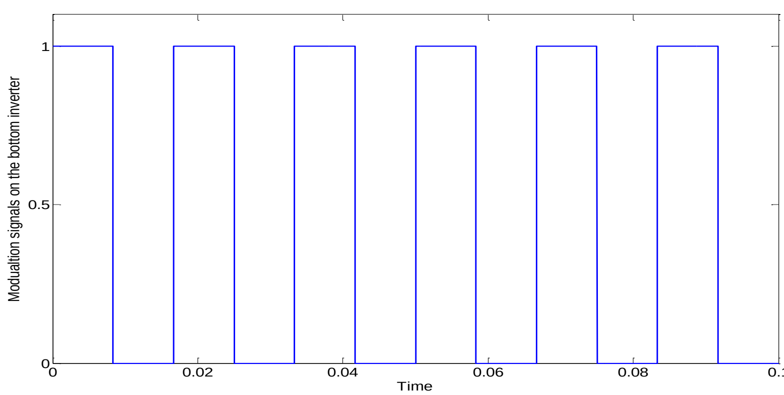


Fig. 3.9. Square-wave modulation signal.

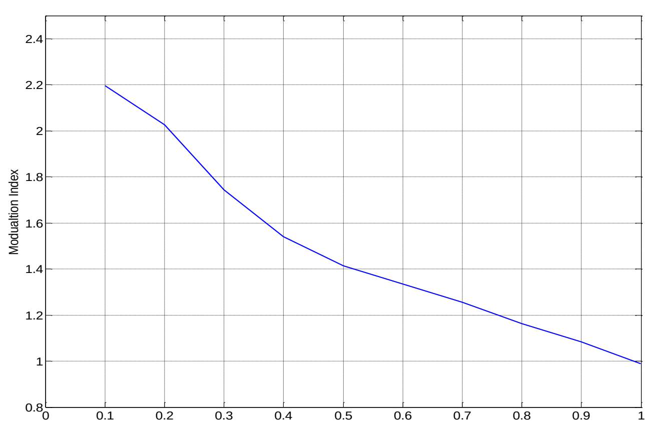


Fig. 3.10. Displacement power factor and output voltage modulation index.

0 and $V_c > V_{dc}/2$, the inverter controls the bottom inverter to output $V_{dc}/2$ and the top H-bridge to output $-V_{dc}/2$ for inverter's 0 voltage output.

It can be seen that the key issue of the unipolar switching control is to choose suitable switching angles. When the goal is to output the desired fundamental frequency voltage and to eliminate the low order 5th, 7th, 11th and 13th harmonics, mathematically this can be formulated as the solution to the following equations:

This is a system of 5 transcendental equations in the 5 unknowns θ_1, θ_2, θ_3, θ_4, and θ_5. There are many ways one can solve for the angles.

$$\begin{aligned}
&\cos(\theta_1)-\cos(\theta_2)+\cos(\theta_3)-\cos(\theta_4)+\cos(\theta_5)=m\\
&\cos(5\theta_1)-\cos(5\theta_2)+\cos(5\theta_3)-\cos(5\theta_4)+\cos(5\theta_5)=0\\
&\cos(7\theta_1)-\cos(7\theta_2)+\cos(7\theta_3)-\cos(7\theta_4)+\cos(7\theta_5)=0\\
&\cos(11\theta_1)-\cos(11\theta_2)+\cos(11\theta_3)-\cos(11\theta_4)+\cos(11\theta_5)=0\\
&\cos(13\theta_1)-\cos(13\theta_2)+\cos(13\theta_3)-\cos(13\theta_4)+\cos(13\theta_5)=0
\end{aligned} \tag{3.12}$$

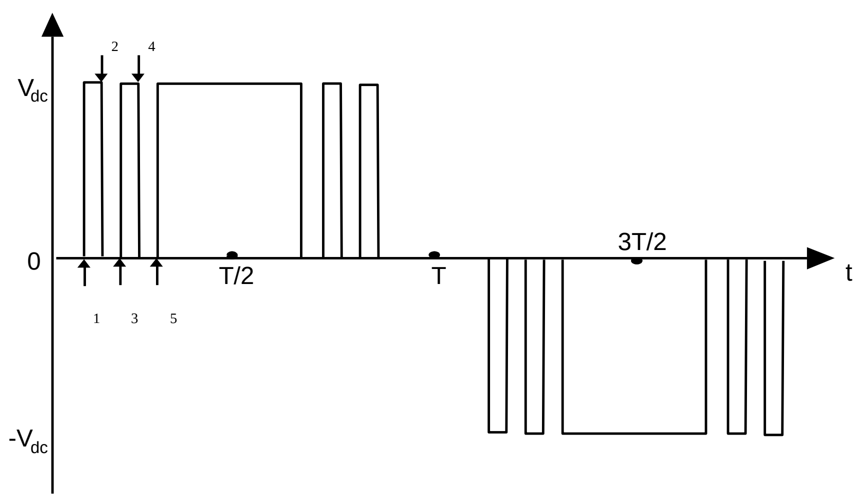


Fig. 3.11. Unipolar switching output waveform.

Traditionally, the maximum voltage amplitude 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 amplitude modulation index for linear operation can be as high as 1.9 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 HEV/FCV 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 [46].

When the hybrid 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-bridges use batteries separately as dc power source, which is charged by the solar panel. The battery charging process is much slower than the capacitor. When fundamental frequency control method is applied to the inverter, the low switching frequency makes it difficult to charge the battery to a required voltage level. The PWM method is a better choice due to the need of battery charging for the inverter.

3.3 Simulation Models with PSIM and MATLAB/SIMULINK

The simulation models on PSIM and MATALB/SIMULINK co-simulation platform are developed as the following.

The PSIM model for the power circuit is shown in Fig. 3.12. PSIM provides a simulation environment for power electronics applications. It is convenient and straightforward to build and adjust the power circuit model in PSIM because of its numerous modules, and a control model is shown in Fig. 3.13. A SimCoupler module provides the interface between PSIM and MATLAB/SIMULINK for co-simulation. The SimCoupler interface consists of two parts: the link nodes in PSIM, and the SimCoupler model block in Simulink. With the SimCoupler module, part of a system can be implemented and simulated in PSIM, and the rest of the system in MATLAB/SIMULINK. In PSIM, the SLINK_IN nodes receive values from SIMULINK, and the SLINK_OUT nodes send the values to SIMULINK. They are all control elements and can be used in the control circuit.

In SIMULINK, the SimCoupler model block is connected to the rest of the system through input/output ports. When running a simulation, all the input signals and feedback signals from the inverter are communicated with SimCoupler model. One can therefore make full use of PSIM's capability in power simulation and MATLAB/SIMULINK's capability in control simulation in a complementary way [45].

3.4 SUMMARY

The structure and operation principle of the proposed hybrid multilevel inverter have been presented in this chapter. As can be seen, the inverter includes a standard 3-leg inverter 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. The capacitor voltage regulation depends on the phase angle difference of output voltage and current. It can generate a boosted five level output voltage based on either fundamental frequency or PWM

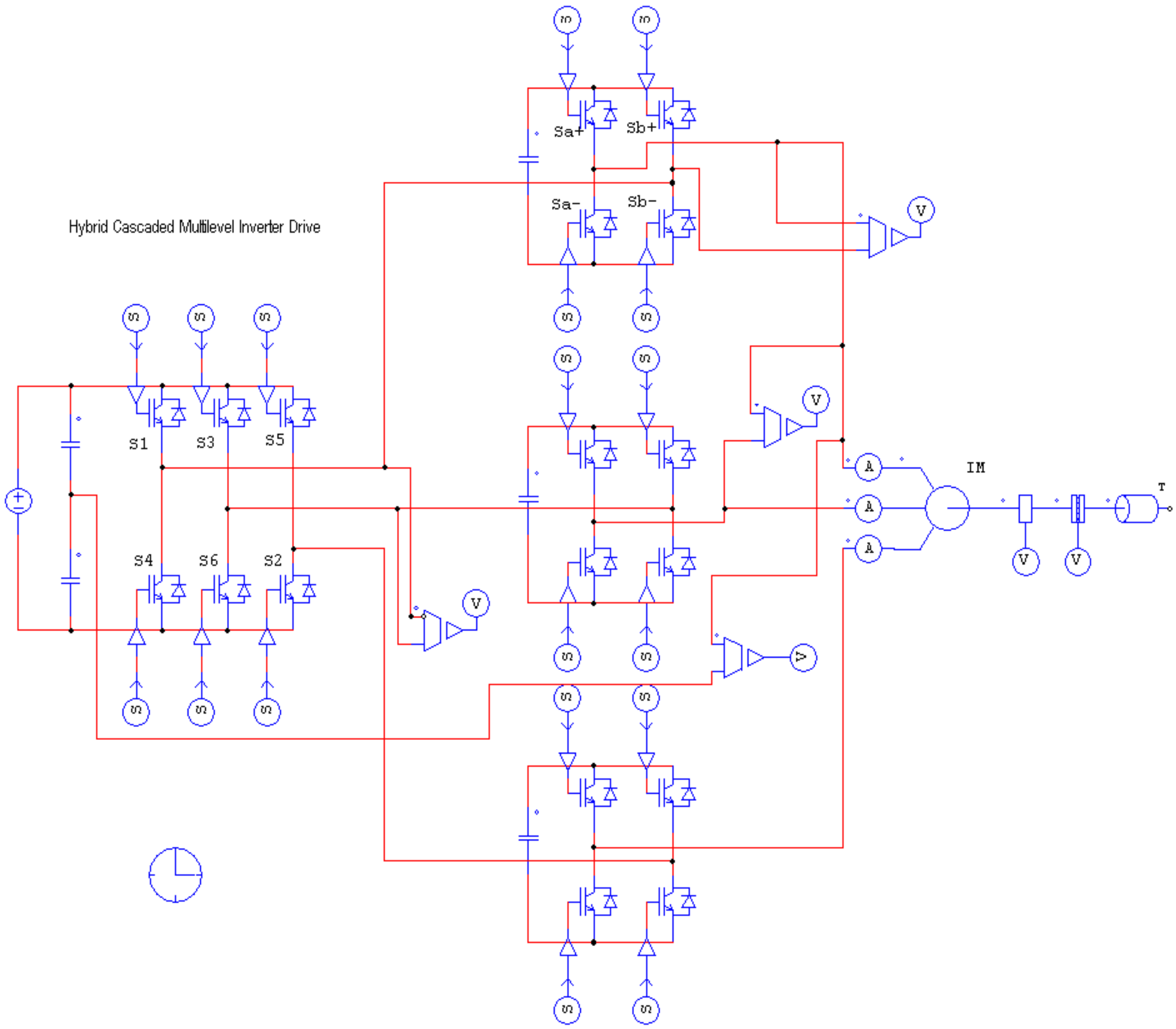


Fig. 3.12. PSIM model for the hybrid multilevel inverter.

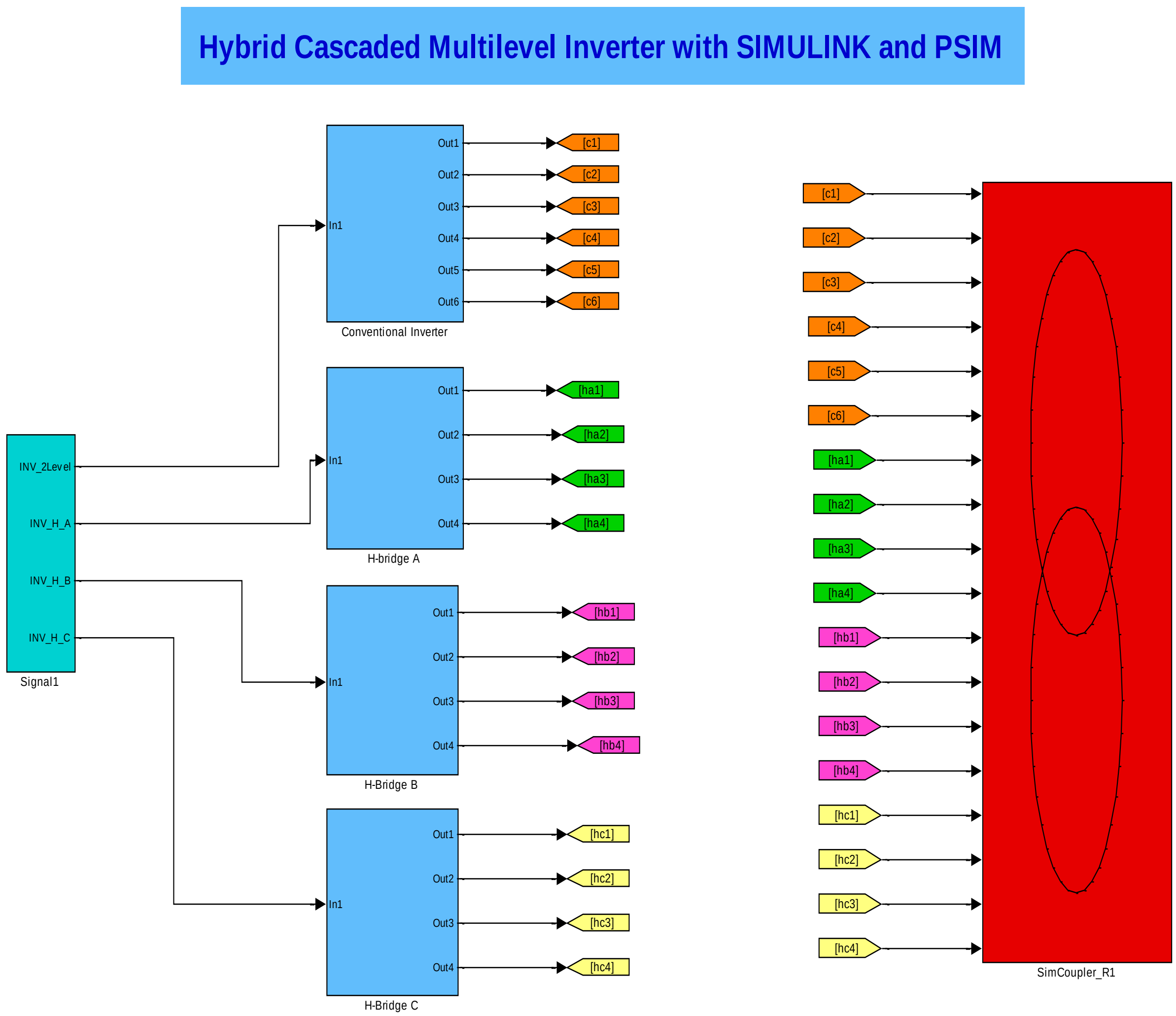


Fig. 3.13. SIMULINK control model for the hybrid multilevel inverter.

control method. The two modulation schemes applied to the inverter have been described in this chapter.

This chapter has provided the simulation models developed on PSIM and MATALB/SIMULINK co-simulation platform. The power circuit model is built in PSIM because of its numerous module and device sources. Its control functions are completed in MATLAB/SIMULINK. The simulation results and experiment validation will be presented in the next chapter.

4. SIMULATIONS AND EXPERIMENTAL VALIDATION

In this chapter, the simulation results with fundamental frequency and PWM control methods are presented firstly. Then the prototype inverter fabrication and experiment set-up are introduced. Finally, the experiment results are described and analyzed.

4.1 SIMULATION RESULTS UNDER FUNDAMENTAL FREQUENCY AND PWM MODULATION MODES

4.1.1 Simulation Results

A. Fundamental Frequency Control Method

In section 2.3.2, the fundamental frequency modulation method has been introduced. When applying fundamental frequency modulation method, each device switches once per cycle in contrast to a PWM modulation method. Fig. 4.1 shows the simulation results including phase voltage, line-line voltage, and phase current. DC bus voltage is 40V. As discussed in section 3.1, capacitors voltages are regulated to $V_{dc}/2$ (20V). One can see that a five-level output phase voltage and a sinusoidal phase current is produced under the fundamental frequency method.

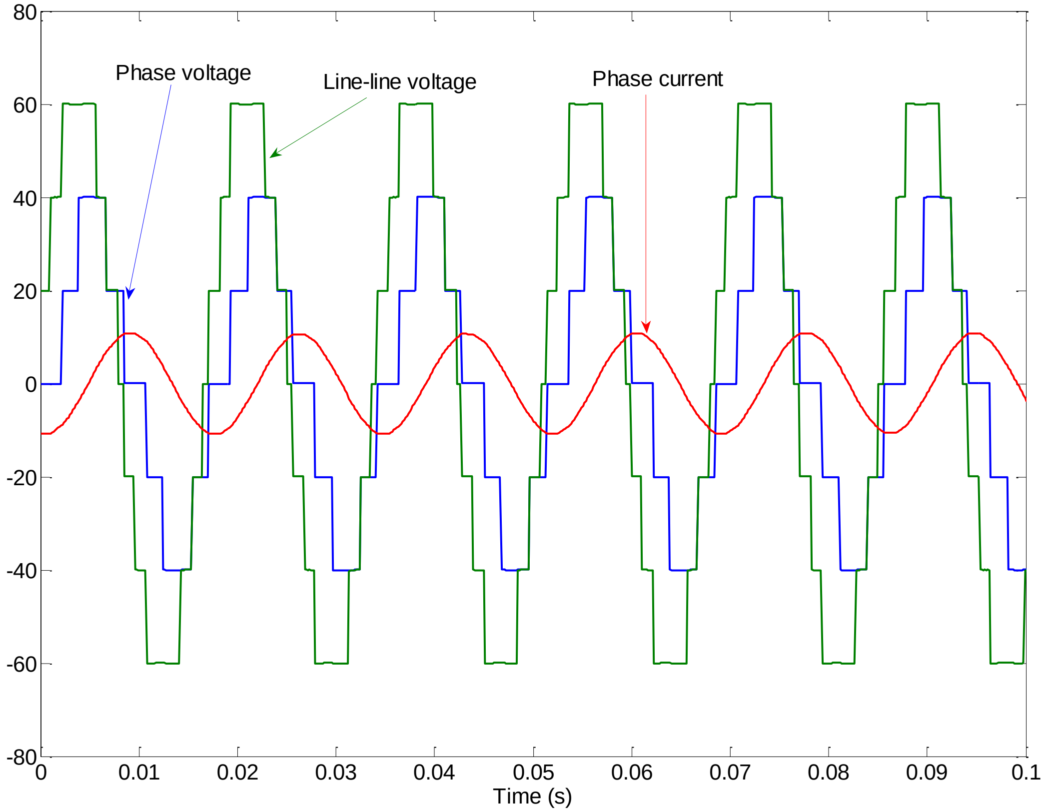


Fig. 4.1. Output line-line and phase voltage, phase current of the hybrid multilevel inverter (m=2).

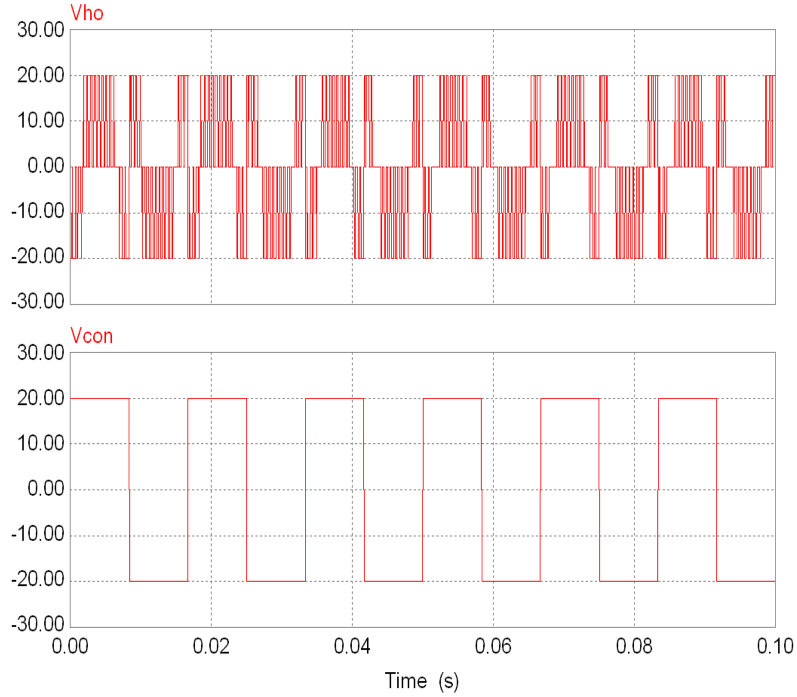


Fig. 4.2. H-bridge (top) and standard inverter (bottom) output voltage.

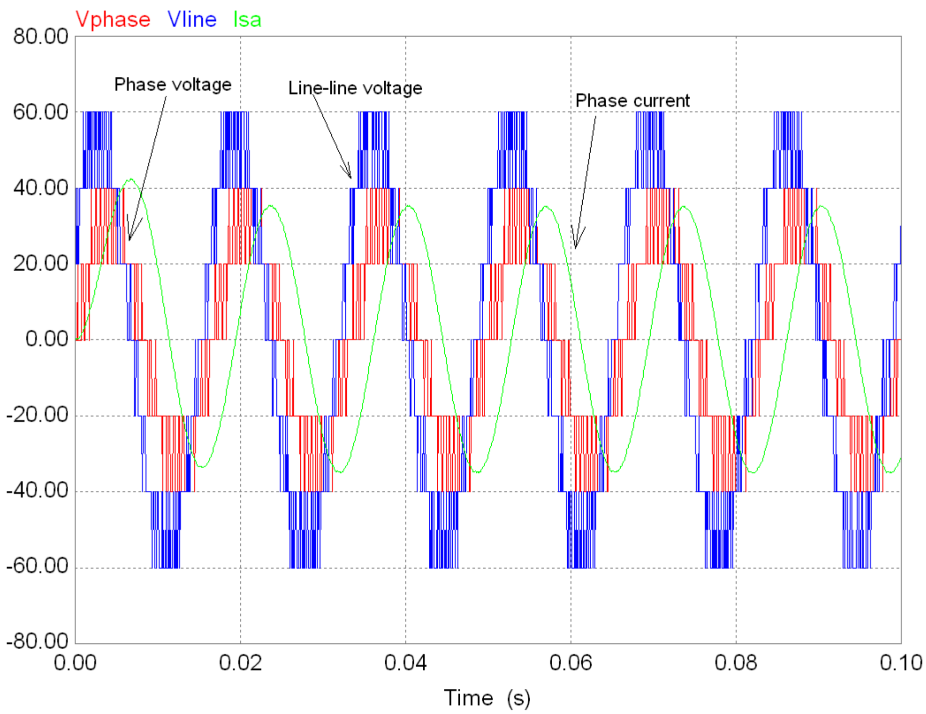


Fig. 4.3. Output line-line and phase voltage, phase current of the hybrid multilevel inverter (m=1.6).

B. Multilevel PWM Control Method

In the hybrid multilevel 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. The top H-bridge and bottom standard 3-leg inverter output voltage waveform are shown in Fig. 4.2. Fig. 4.3 shows the simulation results, which include phase voltage, line-line voltage, and phase current. DC bus voltage is the same 40V for this case. Capacitor voltages are regulated to $V_{dc}/2$ (20V). A five-level output phase voltage is produced. The phase current is a sinusoidal waveform.

4.1.2 Capacitor Voltage Regulation

As discussed in section 3.1, a key issue to realize the control method is that the capacitor voltages (v_c) need to be kept regulated to one half of the dc voltage ($V_{dc}/2$). To regulate the capacitor's voltage, if $i > 0$ and $v_c < V_{dc}/2$, the inverter controls the bottom inverter to output $V_{dc}/2$ and the top H-bridge to output $-V_{dc}/2$ for inverter's 0 voltage output; if $i > 0$ and $v_c > V_{dc}/2$, the inverter controls the bottom inverter to output $-V_{dc}/2$ and the top H-bridge to output $V_{dc}/2$ for inverter's 0 voltage output. The $i < 0$ situation is similar to the $i > 0$ situation, the controller just needs to reverse its switching signals as described in section 3.1.

From the above simulation results, one can find that the fundamental frequency and PWM scheme both make the inverter output zero voltage for significant time intervals so that the capacitor can be charged or discharged during these periods.

Fig 4.4 shows capacitor voltage, phase voltage and phase current to illustrate how to realize the capacitor voltage regulation. The dc bus voltage is 40 V. The capacitor voltage needs to be regulated to 20 V. From Fig. 4.4, one can find that the capacitor voltage decreases

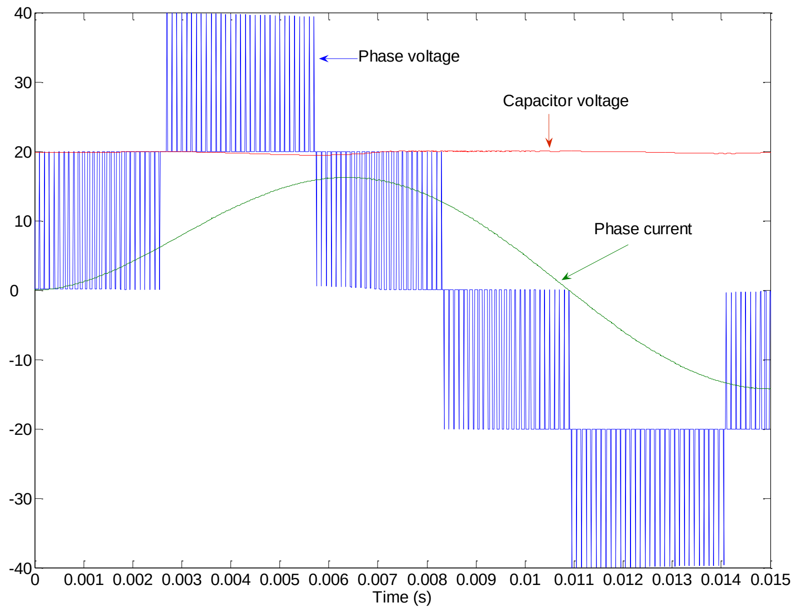


Fig. 4.4. Capacitor voltage, phase voltage and phase current.

(discharging) during those times the inverter is putting out ±40 V, is constant during those times the inverter is putting out ±20 V, and is increasing (charging) during those time intervals the inverter is putting out 0 V. It is necessary to make the inverter output zero voltage for significant time intervals so that capacitor voltage increases.

For the fundamental frequency scheme, 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. For the PWM fundamental scheme, it has the similar condition. When the load is fixed, after the modulation index reaches its possible maximum value, increasing modulation index may make the capacitor voltage regulation not work.

Figs. 4.5 and 4.6 compare two capacitor voltage regulation examples, which show the capacitor voltage as a function of time. In Fig. 4.5, the capacitor voltage is regulated within 0.3 V of the desired voltage. However, in Fig 4.6, it is kept more than 1 V below the desired voltage.

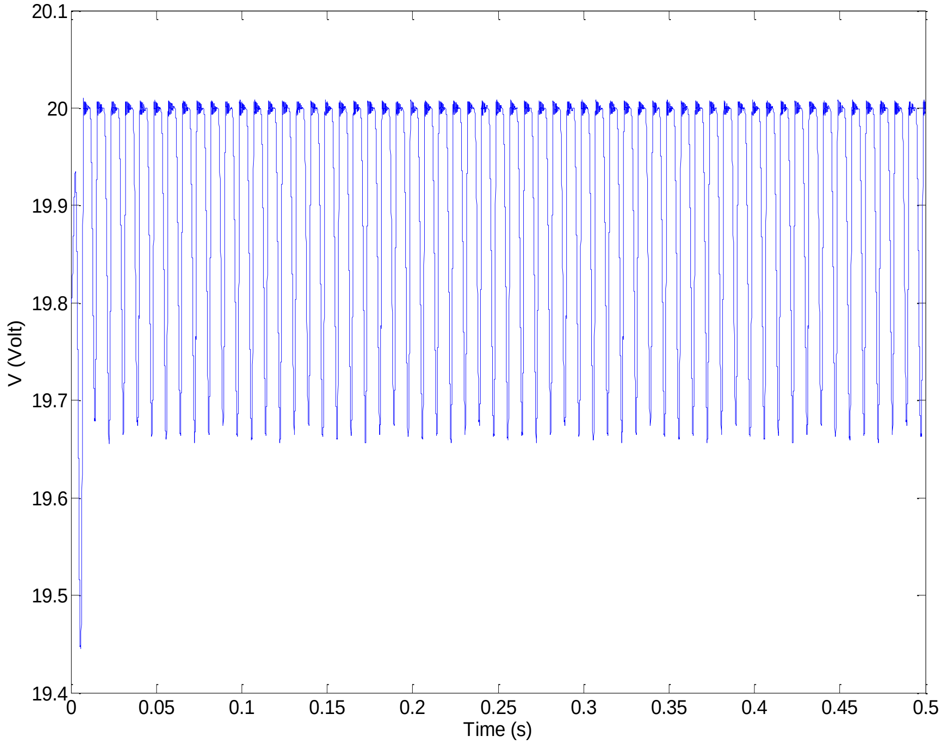


Fig. 4.5. Capacitor voltage (20 V) vs. time (PF=0.8, m=1.1).

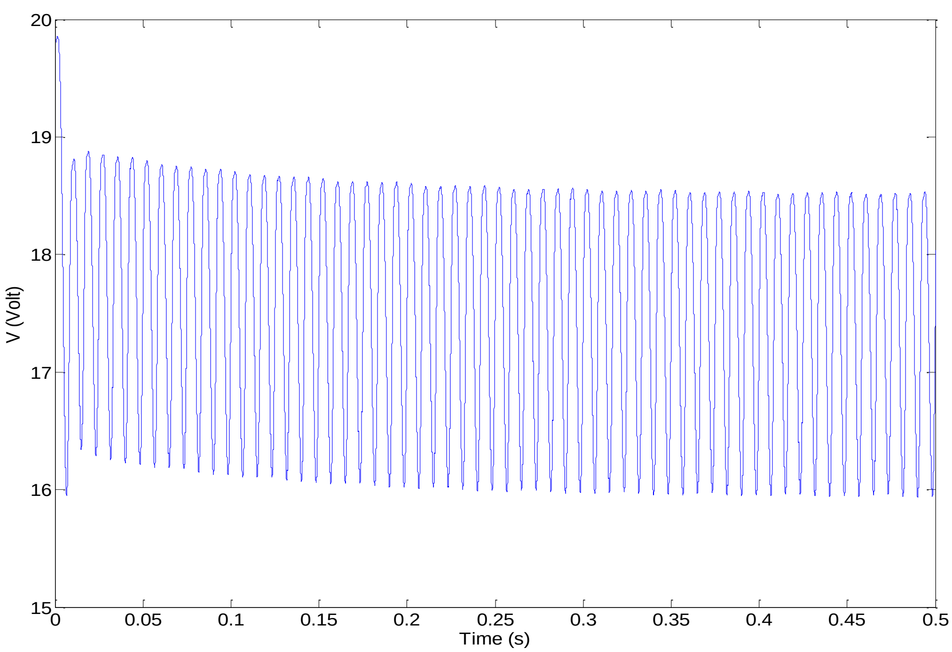


Fig. 4.6. Capacitor voltage (less than 20 V) vs. time (PF=0.8, m=1.2).

When the modulation index is lower than the highest modulation index with a specific power factor, the capacitor can be kept regulated to one half of the dc voltage ($V_{dc}/2$). When the modulation index is higher than the highest modulation index with a specific power factor, the capacitor cannot be regulated properly. It means that the highest output voltage is determined when the load is determined for practical applications.

4.2 EXPERIMENTAL VALIDATION

A 5 kW prototype using power MOSFETs (100V, 180A) as shown in Fig. 4.7 has been built in order to verify the proposed hybrid multilevel inverter. The load is a 15 hp three-phase induction motor, which is loaded less than 5 kW. An Altera FLEX 10K field programmable gate array (FPGA) controller is used to implement the control algorithm to drive the motor with the real-time variable output voltage and variable frequency [43][47].

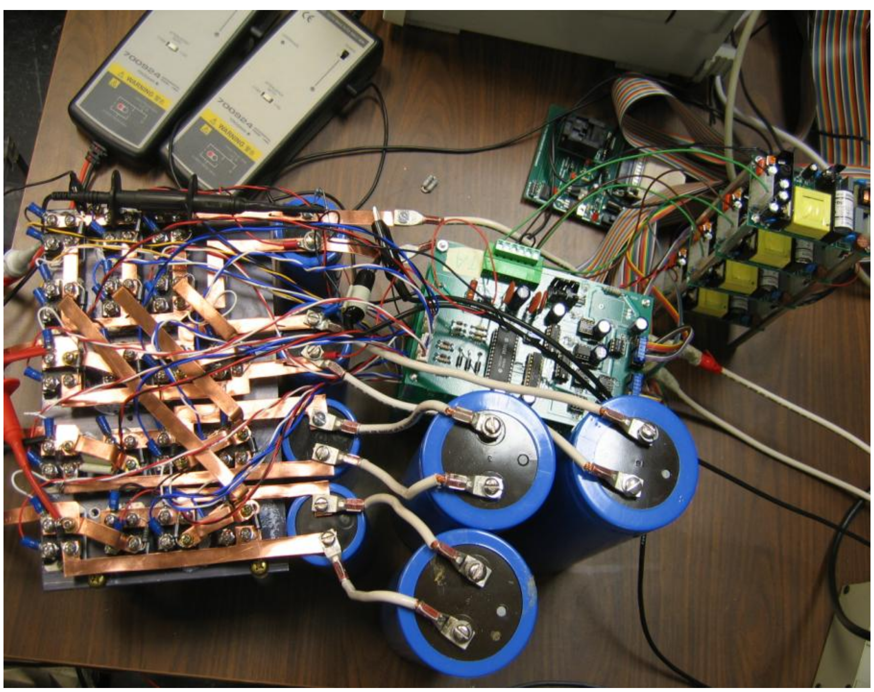


Fig. 4.7. 5 kW hybrid multilevel inverter prototype.

The FPGA controller is designed as a card to be plugged into a personal computer as shown in Fig. 4.8, which uses a peripheral component interconnect (PCI) bus to communicate with the microcomputer in which a Visual Basic interface is used to input and adjust the control schemes and parameters. For example, one can choose different modulation control methods or change modulation index easily through this interface.

The capacitor voltage is detected by a voltage sensor and fed into the FPGA controller to realize the capacitor voltage regulation. The block diagram of the FPGA controller is shown in Fig. 4.9. Switching signal data are stored in a 12×1024 bits in-chip RAM. An oscillator generates a fixed frequency clock signal, and a divider is used to generate the specified control clock signal corresponding to the converter output frequency. Three phase address generators share a public switching data RAM because they have the same switching data with only a different phase angle. The switching data is only for one half cycle because the switching data is symmetric. For each step, the three-phase signal controller controls the address selector to fetch the corresponding switching data from the RAM to the output buffer according to the capacitor's voltage.

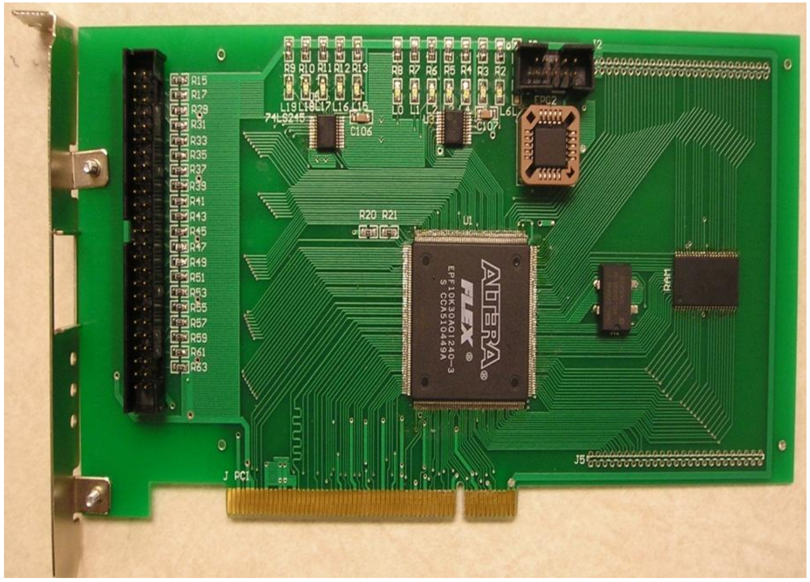


Fig. 4.8. FPGA controller.

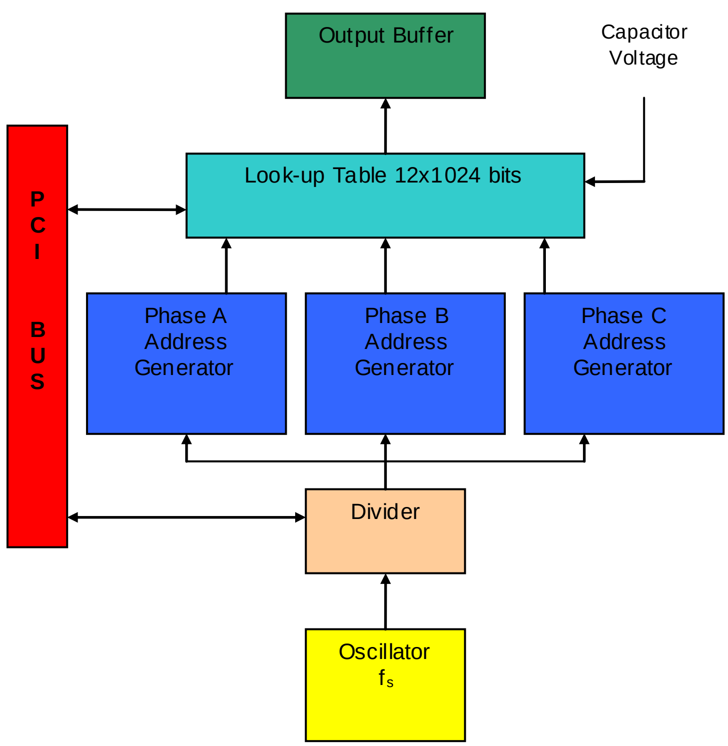


Fig. 4.9. FPGA controller block diagram.

4.3 Experimental Results

Both fundamental frequency and PWM control methods are applied on the 5 kW prototype inverter.

Experimental results with fundamental frequency method including phase voltage, line-line voltage, and phase current are shown in Fig. 4.10. Fig. 4.11 and 4.12 show the normalized FFT analysis result of phase voltage and current. Total harmonic distortion (THD) is derived respectively. THD is defined as the ratio of the sum of the amplitudes of all harmonic components to the amplitudes of fundamental frequency as follows:

$$THD = \frac{\sqrt{X_5^{\,2} + X_6^{\,2} + X_7^{\,2} + \ldots + X_{97}^{\,2} + X_{99}^{\,2}}}{X_1} \times 100\% \qquad (4.1)$$

Where, X represents the voltage or current.

The THD of voltage and current with fundamental frequency method is 6.54% and 1.35% respectively.

The experimental results and normalized FFT analysis with PWM method are shown in Fig. 4.13, 4.14 and 4.15. The THD of voltage and current is 12.29% and 3.14% respectively.

One can see that both methods produce a five-level output phase voltage. The same load is used to test the output voltage and current based on the two control methods. DC bus is the same 40V for both cases. Both methods are of low harmonic and their phase currents are close to sinusoidal. The THD with fundamental frequency method is lower than the one with PWM method. It exhibits the fundamental frequency method can reduce the harmonics based on its low

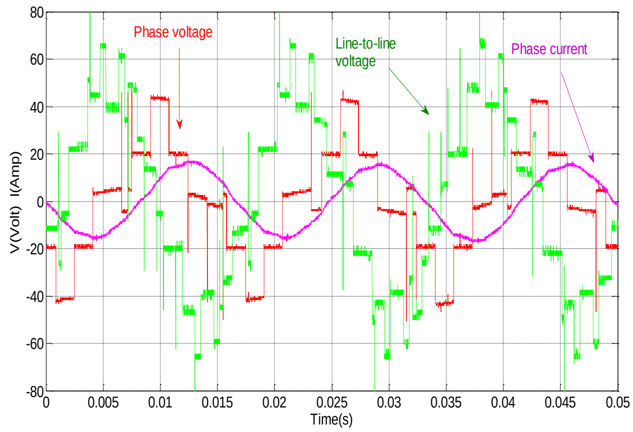


Fig. 4.10. Output line-line and phase voltage, phase current of the hybrid multilevel inverter with fundamental frequency method (m=1.4).

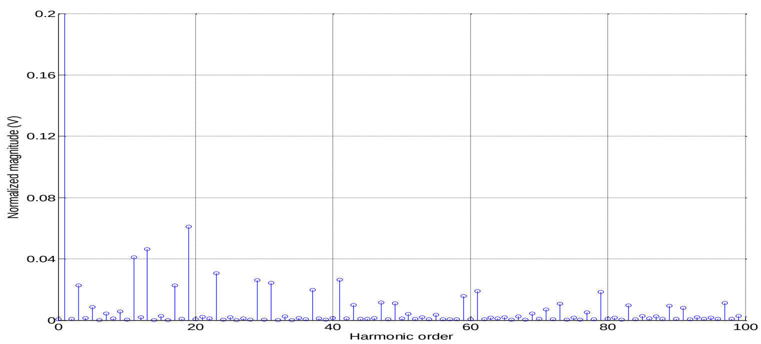


Fig. 4.11. Normalized FFT analysis of phase voltage, THD=6.54%.

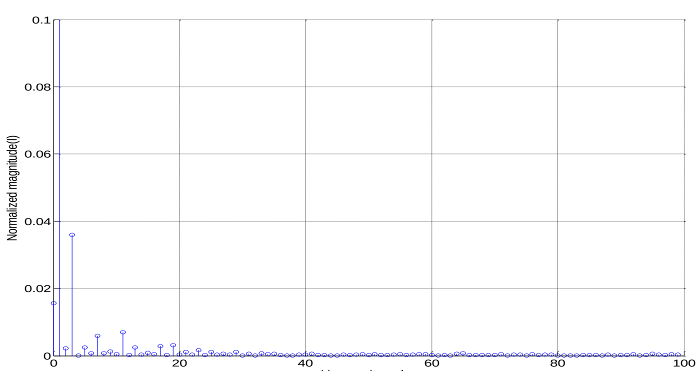


Fig. 4.12. Normalized FFT analysis of phase current, THD=1.35%.

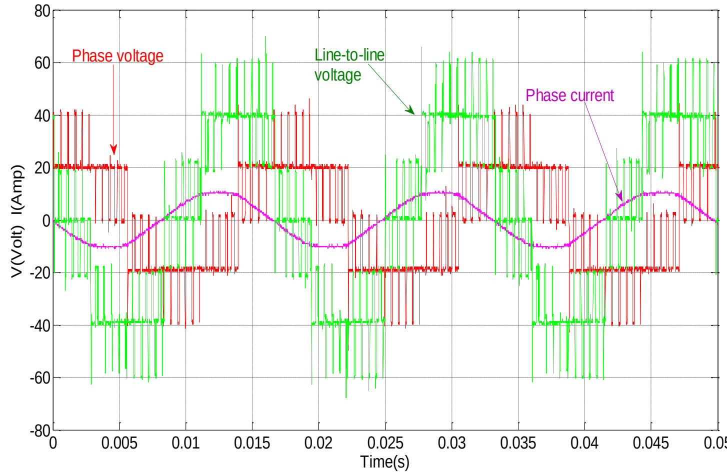


Fig. 4.13. Output line-line and phase voltage, phase current of the hybrid multilevel inverter with PWM method (m=1.4).

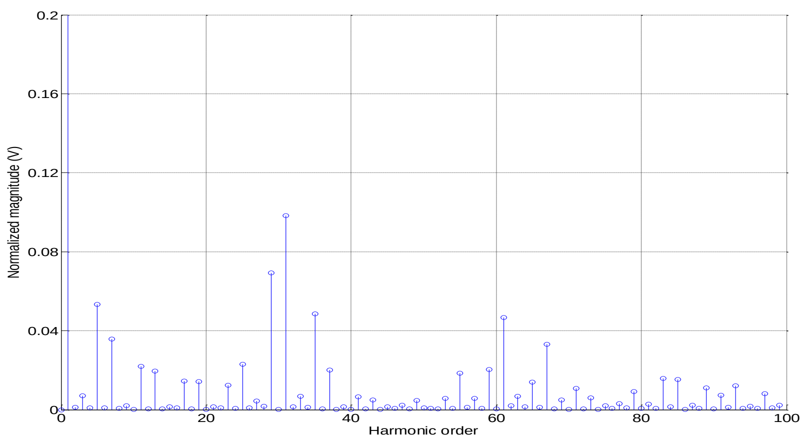


Fig. 4.14. Normalized FFT analysis of phase voltage, THD=12.29%.

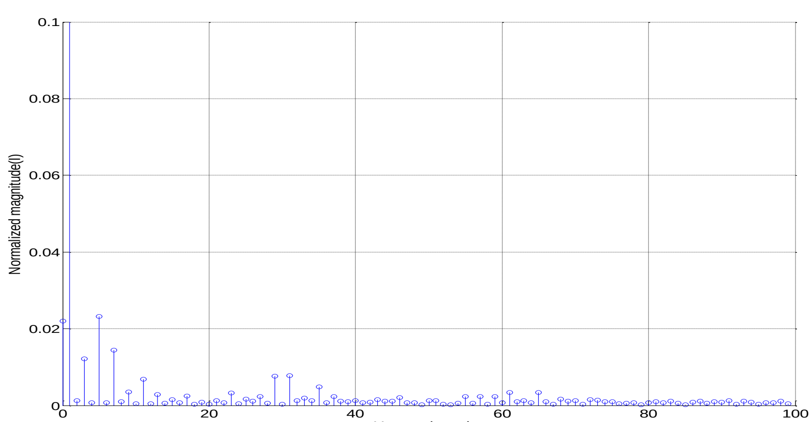


Fig. 4.15. Normalized FFT analysis of phase current, THD=3.14%.

switching frequency. Moreover, under the above two modulation methods, the low order harmonics (5th, 7th, 11th, and 13th) have been eliminated obviously. Their highest normalized value is no more than 5%. That means it could reduce the filter cost involved in the system. Fundamental frequency and PWM methods could be chosen for high power and low power stage in practical application in the consideration of the implementation of modulation control methods. Additionally, the PWM method is a better choice for renewable energy utility interface application, which will be introduced in the next chapter.

The hybrid multilevel inverter can output a boosted AC voltage from input voltage. This boost function is reflected on the change of load current when modulation index is changed. For fundamental frequency, the tests to show the relationship between and modulation index are implemented with a three-phase load bank consisting of resistors and inductors (R = 4.55 Ω, L = 0.024 H).

Different load current curves for different frequencies of 60 Hz, 100 Hz, 150 Hz, 200 Hz are shown in Fig. 4.16. When the frequency decreases, the load current increases with a lower

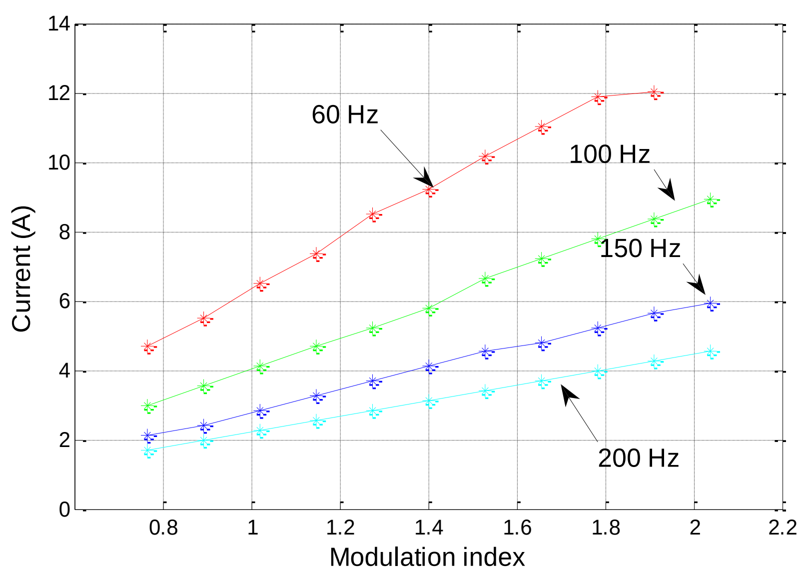


Fig. 4.16. Load current vs. modulation index under different fundamental frequency.

impedance value of the inductor. When the modulation increases, the load current curve rise shows the boost ability of the inverter, which means better dc link utilization.

The above feature can be proved by other test methods, comparing the achieved highest load voltage using the hybrid multilevel inverter and only using the bottom conventional inverter with the same dc bus voltage.

Fig. 4.17 shows that the highest output voltages of the hybrid multilevel inverter are much higher than those of the conventional inverter. The lowest voltage boost ratio is 1.4 in the testing frequency coverage.

The highest output voltage of the inverter is increasing when the frequency is increasing because the impedance of the inductor is increasing. Voltage boost ratio is increasing as well when the frequency is increasing. The reason is that the power factor is decreasing for fixed R-L load.

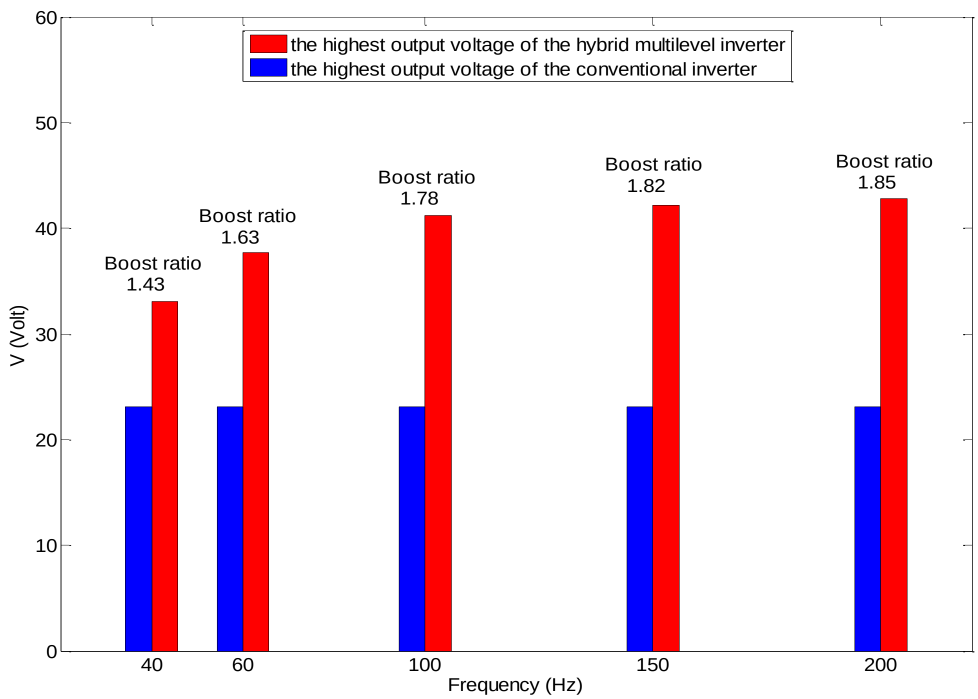


Fig. 4.17. Highest output voltage comparison

4.4 SUMMARY

The proposed inverter has been validated in simulation and experiment. In this chapter, the simulation results with fundamental frequency and PWM modulation methods have been presented, which include phase voltage, line-line voltage, and phase current. A key issue to realize the control method is that the capacitor voltages need to be kept regulated to one half of the dc voltage. The capacitor voltage regulation results have been described. From the simulation results, one can find that the fundamental frequency and PWM scheme both make the inverter output zero voltage for significant time intervals so that the capacitor can be charged or discharged during these periods.

This chapter has introduced a 5 kW prototype of the proposed inverter. Both fundamental frequency and PWM control methods are applied on the 5 kW prototype inverter. The experimental results including phase voltage, line-line voltage, phase current and normalized FFT analysis are presented. Both methods produce a five-level output phase voltage and are of low harmonic and close-to-sinusoidal phase currents. The relationship among the highest voltage, load current and different fundamental frequency has been illustrated.

5. FUEL CELL AND RENEWABLE ENERGY APPLICATIONS

In this chapter, the proposed hybrid multilevel inverter with fuel cell system is introduced firstly. Then the prototype inverter is adaptively used for solar grid application and experiment after modification. Finally, the experiment results for the above two kinds of application are described and analyzed.

5.1 FUEL CELL APPLICATION

Fuel cells are regarded as a future source of generating energy due to their efficient and clean characteristics. They have been applied in a variety of areas such as traction, utility, and residential and commercial building. The Ballard Nexa™ power module shown in Fig. 5.1 is connected to the proposed hybrid multilevel inverter as the power dc source. It is a small, low maintenance and fully automated system. The fuel cell can provide up to 1.2 kW of unregulated dc power at a nominal output voltage of 26 V. With the use of an external hydrogen fuel, its operation is continuous and quiet and limited only by the amount of hydrogen fuel storage.

The fuel cell has a unique *V-I* characteristic and wide voltage range, which means the output dc voltage of the fuel cell changes with different load condition and different modulation index, which is not like the power supply that can output a stable dc voltage as required. This feature of fuel cell brings some challenges on the interface circuits, which may result in difficulty for high-speed, high-power operation to achieve a constant power speed ratio (CPSR) in FCVs applications. In addition, because the voltage of the fuel cell drops at high power mode, the inverter has to be an oversized design.

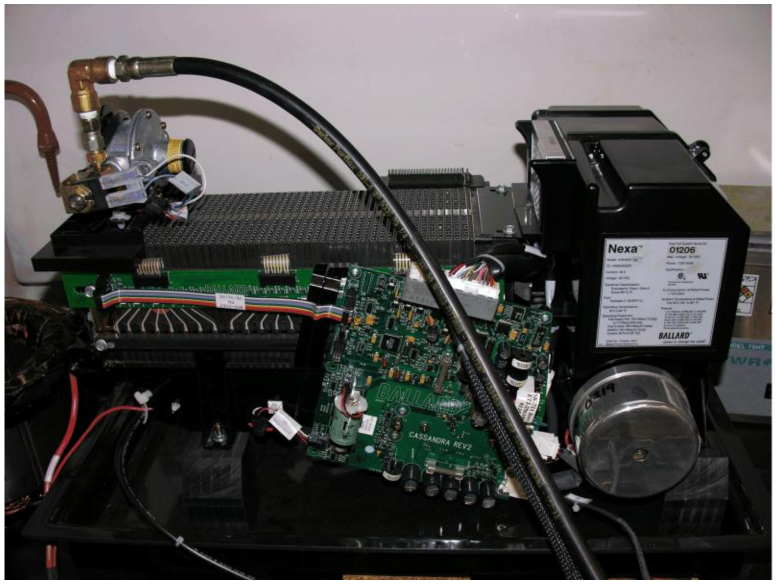


Fig. 5.1. The Ballard Nexa^{TM} power module applied in the proposed system

5.2 Experimental Results for Fuel Cell Application

The fuel cell is connected to the proposed hybrid multilevel inverter to do the test. Fundamental frequency and PWM control methods are both applied on the 5 kW prototype inverter systems.

Fig. 5.2 shows the experimental results with fundamental frequency method including phase voltage, line-line voltage, and phase current. Fig. 5.3 and Fig. 5.4 show the normalized FFT analysis result of phase voltage and current. The THD of voltage and current is 9.52% and 2.60% respectively.

The experiment results and normalized FFT analysis with PWM method are shown in Fig. 5.5, 5.6 and 5.7 respectively. The THD of voltage and current is 12.93% and 3.68% respectively.

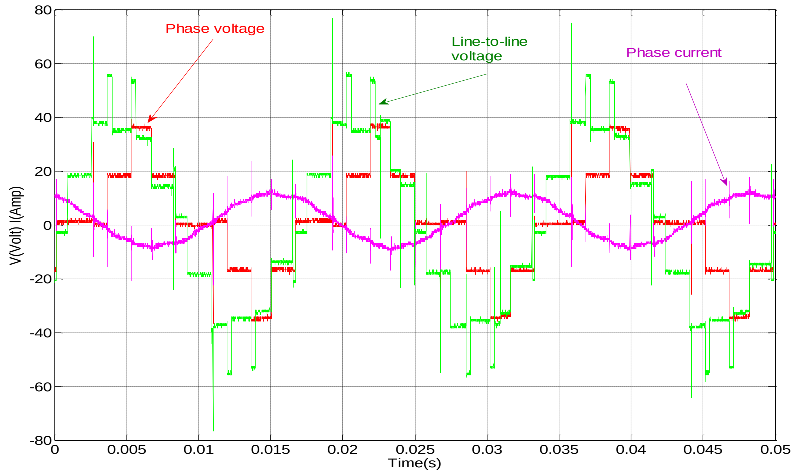


Fig. 5.2. Output line-line and phase voltage, phase current of the hybrid cascaded multilevel inverter with fundamental frequency method (m=1.4).

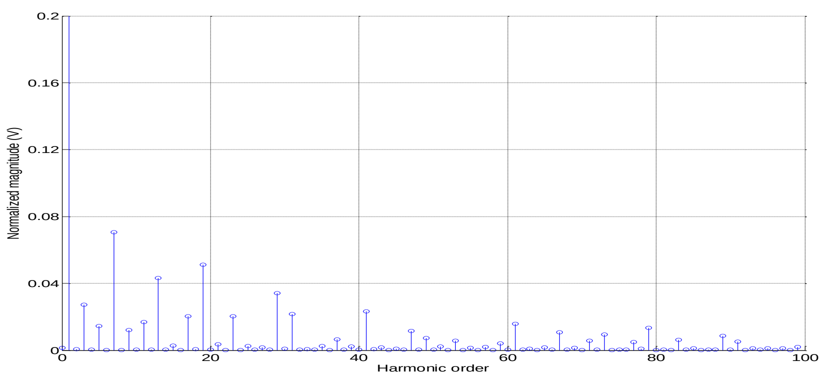


Fig. 5.3. Normalized FFT analysis of phase voltage, THD=9.52%.

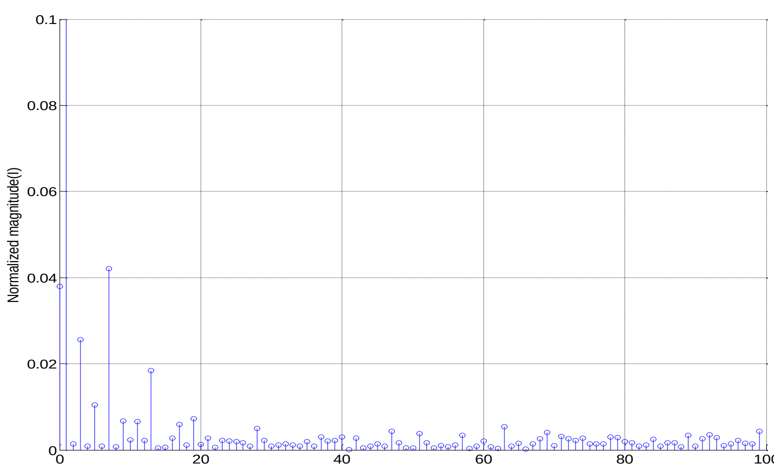


Fig. 5.4. Normalized FFT analysis of phase current, THD=2.60%.

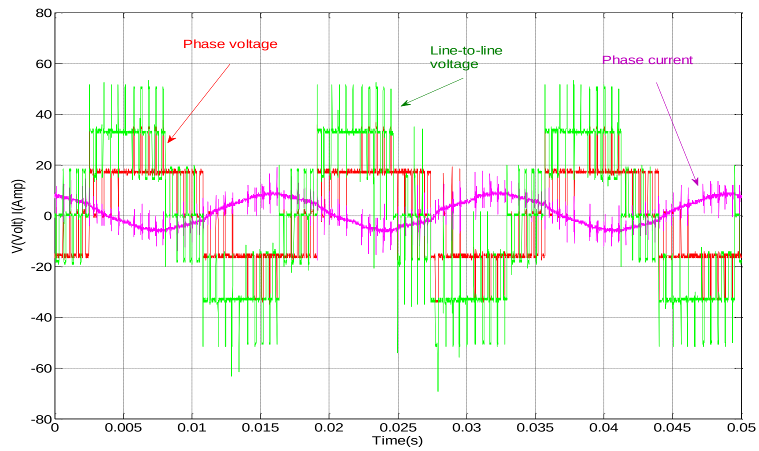


Fig. 5.5. Output line-line and phase voltage, phase current of the hybrid cascaded multilevel inverter with PWM frequency method (m=1.4).

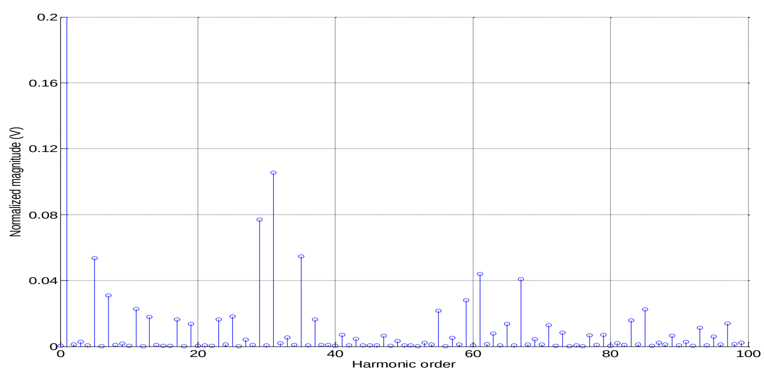


Fig. 5.6. Normalized FFT analysis of phase voltage, THD=12.93%.

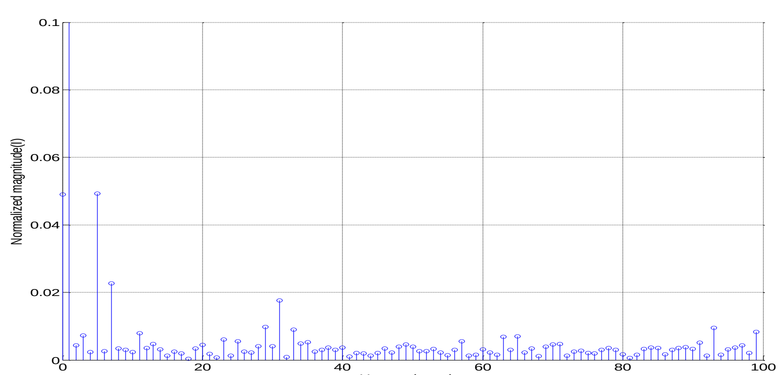


Fig. 5.7. Normalized FFT analysis of phase current, THD=3.68%.

The five-level output phase voltage waveform is produced under the above modulation methods. Both methods are of low harmonic and their phase currents are close to sinusoidal, especially, the highest normalized value of low order harmonics (5^{th}, 7^{th}, 11^{th}, and 13^{th}) is below 5%. The THD with fundamental frequency method is lower than the one with PWM method. The results are similar with the proposed inverter connected with power supply, which confirm the inverter operation for fuel cell system. It is noted that the unregulated fuel cell dc output voltage could result in the higher THD of ac output voltage than the one with a power supply.

A three-phase R-L load (R = 4.55 Ω, L = 0.024 H) is used to test the fuel cell output voltage and load current with the different modulation index. Fig. 5.8 shows the relationship between the fuel cell voltage and modulation index based on different frequencies 40 Hz, 60 Hz, 100 Hz, 150 Hz, and 200 Hz. The fuel cell output voltage goes down with the increasing modulation index, which shows the instability of fuel cell output voltage. But the linear relationship means that it is feasible to adjust the modulation index to acquire a step up voltage based on the load demand.

Fig. 5.9 shows the load current changes with different modulation index based on different frequencies 40 Hz, 60 Hz, 100 Hz, 150 Hz, and 200 Hz. When the frequency decreases, the load current increases with a lower impedance value of the inductor. When the modulation increases, the load current curve rise shows the boost ability of the inverter, which means better dc link utilization.

Fig. 5.10 shows the efficiency of the proposed hybrid multilevel inverter and standard 3-leg inverter at the acquired highest power point. The highest power is shown in Table 5.1. When they are applied into the fuel cell system, the efficiency of the proposed inverter is higher than

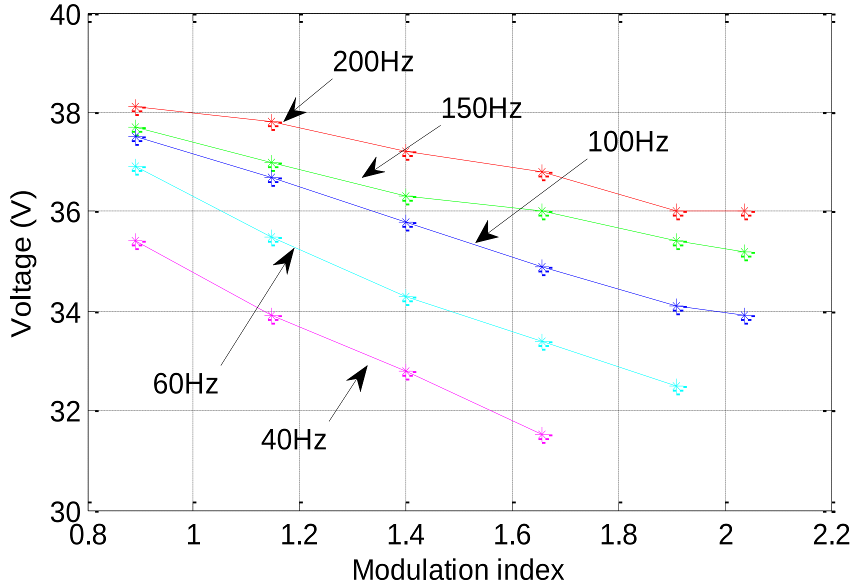


Fig. 5.8. Fuel cell voltage vs. modulation index under different fundamental frequency.

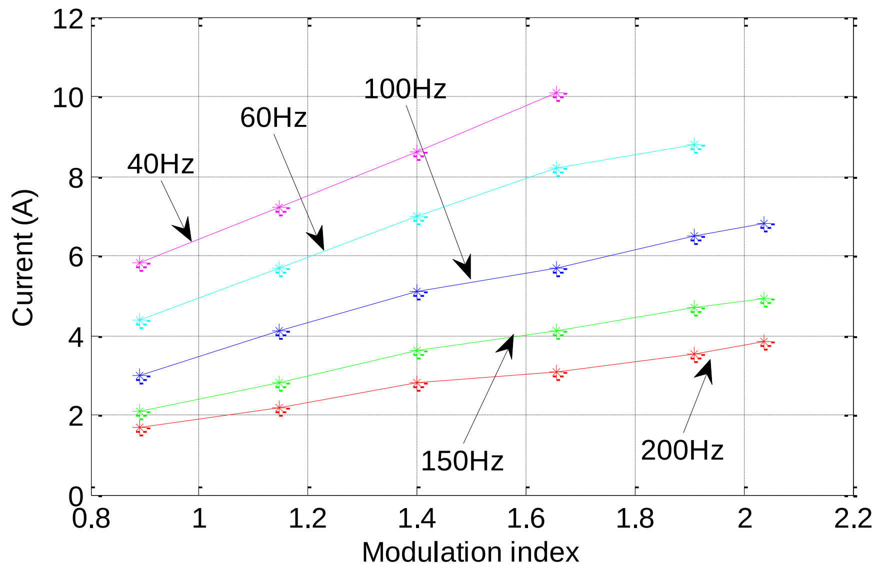


Fig. 5.9. Load current vs. modulation index under different fundamental frequency.

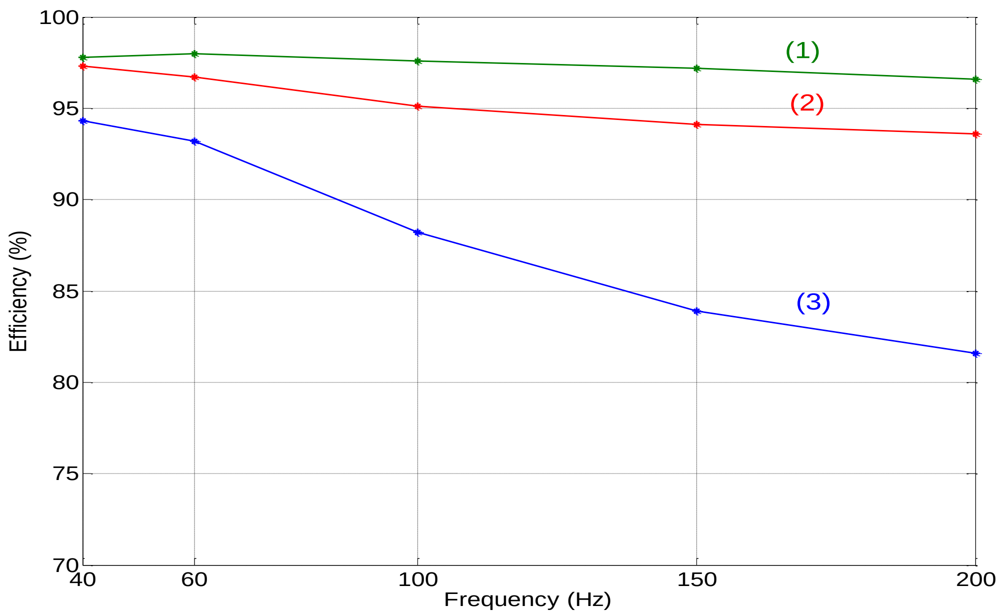


Fig. 5.10. The efficiency of the proposed inverter with power supply (1), with fuel cell (2), and the standard inverter with fuel cell (3) at the highest power point.

Table 5.1. The highest power (W) with different configurations

Type	Frequency (Hz)				
	40	60	100	150	200
Hybrid Multilevel Inverter with Power Supply	5083	4442	3179	2026	1256
Hybrid Multilevel Inverter with Fuel Cell	1322	1047	629	396	291
Standard inverter with Fuel Cell	1060	644	320	185	121

the standard 3-leg inverter. Fig. 5.10 also shows the efficiency when the proposed inverter is connected with power supply, which is higher than the one with fuel cell. Because the highest power that the power supply can support is more than the design rated power of the inverter system 5 kW; the nominal power of the used fuel cell is 1.2 kW.

5.3 SOLAR GRID APPLICATION

As previously discussed in section 2.5 and 3.2, a multilevel inverter is ideal for utility interface applications with renewable energy sources due to its functions and features. Like most renewable energy sources, solar is intermittent. The energy storage devices that are usually implemented by battery banks are included in renewable energy system in order to supply ac electricity.

Fig. 5.11 shows a solar panel installed at Oak Ridge National Laboratory. Fig 5.12 shows its *V-I* characteristic, which exhibits the voltage and current measured at the load bank varies

Fig. 5.11. Solar panel.

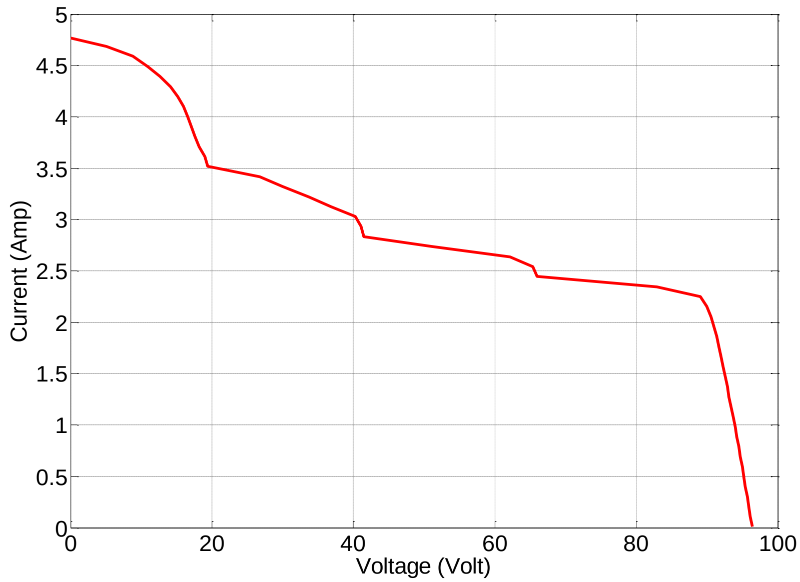


Fig. 5.12. Current vs. voltage measured at the load bank of a solar panel.

during a day. The intermittence nature of solar panel output voltage requires some additional capabilities for the solar inverter. That means there are two key issues of the hybrid multilevel inverter for this application. One is the inverter can output an appropriate phase voltage along with a close-to-sinusoidal phase current; the other is the battery can follow the voltage command to decide charging or discharging.

5.4 Experimental Results for Solar Grid Application

When the hybrid multilevel inverter is used for solar panel utility interface, the bottom standard 3-leg inverter can be connected with a solar panel, and the top H-bridges use batteries separately as dc power source, which is charged by the solar panel. It is noted that the charging and discharging condition of the battery is different with the capacitor. The battery charging process is much slower than the capacitor. When fundamental frequency control method is applied on the inverter, the low switching frequency makes it difficult to charge the battery to a required voltage level. Therefore the PWM method is a better choice due to the need of battery charging for the inverter. In this experiment, each full H-bridge is supplied by two lead-acid batteries (12 V, 10 Ah) in series respectively, which is charged by the power supply connected to the standard 3-leg inverter.

The experimental output phase voltage, line-line voltage, and phase current under battery charging, battery discharging and battery only condition are shown in Fig. 5.13, 5.14 and 5.15 respectively, which illustrates that the proposed inverter can output an appropriate phase voltage along with a close-to-sinusoidal phase current for the solar panel utility interface application under the above different conditions.

Fig. 5.16 shows the battery charging process when the given voltage command value is higher than the actual voltage value. A 13 V voltage command is given when the actual battery voltage is 11.7 V. The battery is charged and the voltage increases immediately. It proves that the battery in this system can follow the voltage command to decide charging or discharging.

5.5 SUMMARY

The applications of the proposed inverter on fuel cell system and solar grid have been researched in this chapter.

When the proposed inverter is connected with the fuel cell, a five-level output phase voltage waveform and close to sinusoidal current are produced under the fundamental frequency and PWM modulation methods. The experimental results also show the proposed inverter system is of higher efficiency than the conventional inverter system.

When the proposed inverter is used for solar panel interface, the batteries replaced the

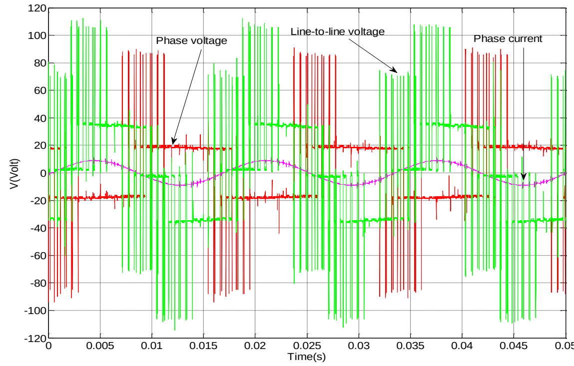


Fig. 5.13. Output line-line and phase voltage, phase current of the hybrid multilevel inverter when battery charging (V_{dc}=80 V, $V_{battery}$=20 V).

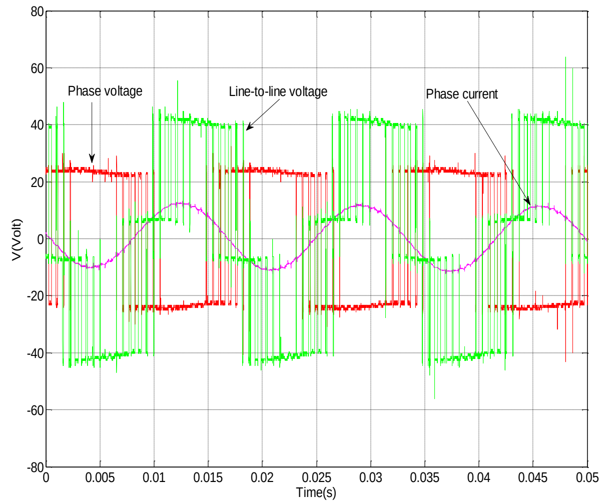


Fig. 5.14. Output line-line and phase voltage, phase current of the hybrid multilevel inverter when battery discharging (V_{dc}=10 V, $V_{battery}$=20 V).

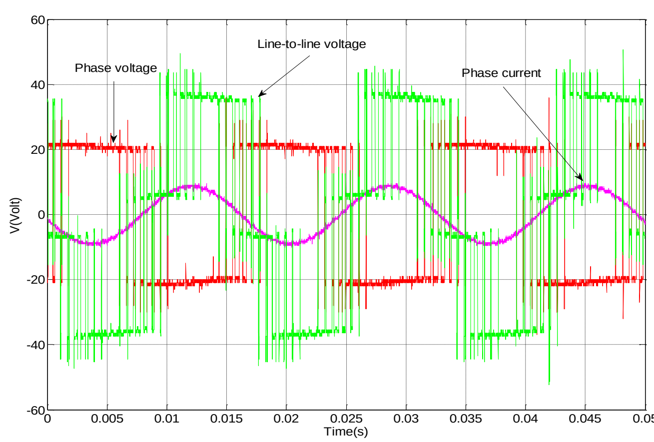


Fig. 5.15. Output line-line and phase voltage, phase current of the hybrid multilevel inverter when battery only (V_{dc}=0 V, $V_{battery}$=20 V).

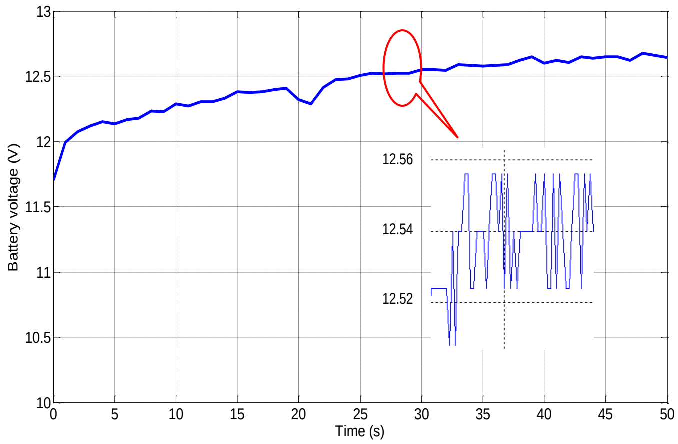


Fig. 5.16. Battery charging.

capacitors in the H-bridge as the energy storage devices. The experimental results show that the inverter system has two important features for solar grid applications. One is the inverter can output an appropriate phase voltage along with a close-to-sinusoidal phase current under battery charging, discharging, and battery only, which can make it work with an intermittent solar source; the other is the battery can follow the voltage command to decide charging or discharging.

6. CONCLUSIONS AND FUTURE WORK

In this chapter, the dissertation is summarized and the future works are proposed.

6.1 CONCLUSIONS AND CONTRIBUTIONS

Multilevel inverters are attracting an increasing interest in power conversion field because they can offer high power possibility with low output harmonics. They can be used in a variety of areas such as traction motor drive or renewable energy utility interface. This dissertation systematically reviews the existing multilevel inverter technologies and presents a new hybrid multilevel inverter for voltage boost. Its structure, simulation models and results, development of prototype inverter, experimental results, and applications are provided. In this dissertation,

1. The previous works on multilevel inverter structures and modulation strategies have been reviewed. The disadvantage of current available power converters for HEVs /FCVs and renewable energy utility interface applications is that the inverters have low power density, are expensive, and have low efficiency due to the existence of bulky inductors.
2. A cascaded multilevel inverter is a good choice. But its disadvantage is that separate dc sources are required for each of the H-bridges.
3. A new hybrid multilevel inverter for voltage boost is proposed, which consists of a standard 3-leg inverter (one leg for each phase) and H-bridge in series with each inverter leg.

4. 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. It is of voltage boosting capability and eliminates the magnetics.
5. The simulation models and results with PSIM and MATLAB/SIMULINK are developed. Fundamental frequency and PWM control methods can be both applied on the proposed inverter.
6. An experimental 5 kW prototype inverter is built and tested. The experimental results confirm the simulation results and validate the proposed inverter.
7. The proposed inverter could be applied in HEVs/ FCVs. Additionally, it could act as a renewable energy utility interface. The experimental results exhibit its advantages for the above two applications.

6.2 RECOMMENDED FUTURE WORK

The following work is interesting in the future.

1. This dissertation focuses on the development of a new hybrid multilevel inverter for voltage boost. A FPGA controller has been used to implement the control algorithm to drive the motor with the real-time variable output voltage and variable frequency. Additionally, the capacitor voltage is detected by a voltage sensor and fed into the FPGA controller to realize the capacitor voltage regulation. With the developed FPGA controller, a closed loop control strategy for traction motor could be considered in the future.
2. Efficiency is an important criterion for a power converter system. In this dissertation, the efficiency of the proposed inverter and conventional inverter has been acquired and

compared. It is recommended to do an accurate semiconductor loss calculation under fundamental frequency, PWM and other modulation schemes respectively.

3. When the proposed inverter is applied as the renewable energy utility interface, the lead-acid battery banks are used as the energy storage devices to supply ac electricity. The operation has been validated with the experiments. It is needed to develop the battery simulation models including battery capacity analysis and charging/discharging management algorithm. A charging/discharging control circuit could be added into the prototype inverter system based on the simulation results.
4. This proposed inverter can be a combination of rectifier and boost converter so that it could be applied to carry out the plug-in function in future HEVs. The feature makes it possible to operate the inverter in fuel cell mode or plug-in mode such that the converter would have dual uses and not require an additional converter for charging.

REFERENCES

[1] L. M. Tolbert, F. Z. Peng, and T. Habetler, "Multilevel converters for large electric drives," *IEEE Trans. Ind. Applicat.*,vol.35,pp. 36-44, Jan./Feb. 1999.

[2] J. S. Lai and F. Z. Peng, "Multilevel converters-a new breed of power converters," *IEEE Trans. Ind. Applicat.*, vol.32,pp. 509-517, May/June 1996.

[3] R. H. Baker and L. H. Bannister, "Electric power converter," U.S. Patent 3 867 643, Feb. 1975.

[4] J. Rodriguez, J. S. Lai and F. Z. Peng, "Multilevel inverters: survey of topologies, controls, and applications," *IEEE Transactions on Industry Applications*, vol. 49, no. 4, Aug. 2002, pp. 724-738.

[5] L. M. Tolbert, F. Z. Peng, "Multilevel converters as a utility interface for renewable energy systems," in *Proceedings of 2000 IEEE Power Engineering Society Summer Meeting*, pp. 1271-1274.

[6] F. Z. Peng, J. W. McKeever, D. J. Adams, "Cascade multilevel inverters for utility applications," *IEEE IECON* , vol. 2, July 2000, pp. 437-442.

[7] L. M. Tolbert, F. Z. Peng, T. G. Habetler, "A multilevel converter-based universal power conditioner," *IEEE Transactions on Industry Applications*, vol. 36, no. 2, Mar./Apr. 2000, pp. 596-603.

[8] L. M. Tolbert, F. Z. Peng, T. G. Habetler, "Multilevel inverters for electric vehicle applications," *IEEE Workshop on Power Electronics in Transportation*, Oct 22-23, 1998, Dearborn, Michigan, pp. 1424-1431.

[9] C. C. Chan, "The state of the art of electric, hybrid, and fuel cell vehicles," *Proceedings of the IEEE,* vol.95, no. 4, Apr. 2007, pp. 704-718

[10] A. Nabae, I. Takahashi, and H. Akagi, "A new neutral-point clamped PWM inverter," *IEEE Trans. Ind. Applicat.*, vol. IA-17, pp. 518-523, Sept./Oct. 1981.

[11] K. Corzine, Y. Familiant, "A new cascaded multilevel H-bridge drive," *IEEE Transactions on Power Electronics,* vol. 17, no. 1, Jan 2002, pp. 125-131.

[12] T. A. Meynard, H. Foch, "Multi-level conversion: high voltage choppers and voltage-source inverters," *IEEE Power Electronics Specialists Conference*, 1992, pp. 397-403.

[13] G. Sinha, T. A. Lipo, "A new modulation strategy for improved dc bus utilization in hard and soft switched multilevel inverters," *IECON,* 1997, pp. 670-675.

[14] R. W. Menzies, Y. Zhuang, "Advanced static compensation using a multilevel GTO thyristor inverter," *IEEE Transactions on Power Delivery,* vol. 10, no. 2, April 1995, pp. 732-738

[15] L. M. Tolbert, F. Z. Peng, T. Cunnyngham, J. N. Chiasson, "Charge balance control schemes for multilevel converter in hybrid electric vehicles," *IEEE Transactions on Industrial Electronics*, vol. 49, no. 5, October 2002, pp. 1058-1065

[16] F. Z. Peng, J. S. Lai, J. W. McKeever, J. VanCoevering, “A multilevel voltage-source inverter with separate dc sources for static var generation,” *IEEE Transactions on Industry Applications,* vol. 32, no. 5, Sept. 1996, pp. 1130-1138.

[17] F. Z. Peng, J. S. Lai, “Dynamic performance and control of a static var generator using cascade multilevel inverters,” *IEEE Transactions on Industry Applications,* vol. 33, no. 3, May 1997, pp. 748-755.

[18] F. Z. Peng, J. W. McKeever, D. J. Adams, “A power line conditioner using cascade multilevel inverters for distribution systems,” *Conference Record - IEEE Industry Applications Society 32nd Annual Meeting,* 1997, pp. 1316-1321.

[19] G. Joos, X. Huang, B. T. Ooi, “Direct-coupled multilevel cascaded series var compensators,” *Conference Record – IEEE Industry Applications Society 32nd Annual Meeting*, 1997, pp. 1608-1615.

[20] E. Cengelci, S. U. Sulistijo, B. O. Woom, P. Enjeti, R. Teodorescu, and F. Blaabjerg, “A new medium voltage PWM inverter topology for adjustable speed drives,” in *Conf. Rec. IEEE-IAS Annu. Meeting*, St. Louis, MO, Oct. 1998, pp. 1416-1423.

[21] W. A. Hill and C. D. Harbourt, “Performance of medium voltage multilevel converters,” in *Conf. Rec. IEEE-IAS Annu. Meeting*, Phoenix, AZ, Oct. 1999, pp. 1186–1192.

[22] M. Veenstra, A. Rufer, “Control of a hybrid asymmetric multilevel inverter for competitive medium-voltage industrial drives,” *IEEE Transactions on Industry Applications*, vol. 41, no. 2, Mar./Apr. 2005, pp. 665-664.

[23] S. Mariethoz, A. Rufer, “Resolution and efficiency improvements for three-phase cascade multilevel inverters,” *IEEE Power Electronics Specialists Conference*, vol. 6, Jun. 2004, pp. 4441-4446.

[24] B. M. Song and J. S. Lai, “A multilevel soft-switching inverter with inductor coupling,” *IEEE Trans. Ind. Applicat*., vol. 37, pp. 628-636, Mar./Apr. 2001.

[25] L. M. Tolbert, T. G. Habetler, “Novel multilevel inverter carrier-based PWM method,” *IEEE Transactions on Industry Applications,* vol. 25, no. 5, Sep/Oct. 1999, pp. 1098-1107.

[26] L. M. Tolbert, F. Z. Peng, T. G. Habetler, “Multilevel PWM methods at low modulation indices,” *IEEE Transactions on Power Electronics*, vol. 15, no. 4, Jul. 2000, pp. 719-725.

[27] H. S. Patel and R. G. Hoft, “Generalized harmonic elimination and voltage control in thyristor converters: part i – harmonic elimination,” *IEEE Transactions on Industry Applications*, vol. 9, May/June 1973, pp. 310-317.

[28] H. S. Patel and R. G. Hoft, “Generalized harmonic elimination and voltage control in thyristor converters: part ii –voltage control technique,” *IEEE Transactions on Industry Applications*, vol. 10, Sept./Oct. 1974, pp. 666-673.

[29] J. N. Chiasson, L. M. Tolbert, K. J. McKenzie, Z. Du, “A Complete Solution to the Harmonic Elimination Problem,” *IEEE Transactions on Power Electronics*, March 2004, vol. 19, no. 2, pp. 491-499.

[30] K. T. Chau, C. C. Chan, “Emerging energy-efficient technologies for hybrid electric vehicles,” *Proceedings of the IEEE*, vol. 95, no. 4, Apr. 2007, pp. 704-718

[31] M. Zeraoulia, M. E. H. Benbouzid, D Diallo, “Electric motor drive selection issues for HEV propulsion systems: a comparative study,” *IEEE Transactions on Vehicular Technology*, vol. 55, no. 6, Nov. 2006, pp. 1756-1764.

[32] M. Shen, F. Z. Peng, “Converter systems for hybrid electric vehicles,” *International Conference on Electrical Machines and Systems,* Oct. 2007, pp. 2004-2010.

[33] J. S. Liao, D. Nelson, “Energy management power converters in hybrid electric and fuel cell vehicles,” *Proceedings of the IEEE*, vol. 95, no. 4, Apr. 2007, pp. 766-777.

[34] K. Rajashekara, “Power conversion and control strategies for fuel cell vehicles,” *IEEE Industrial Electronics Annual*, vol. 3, Nov. 2003, pp. 2865-2870.

[35] F. Z. Peng, M. Shen, K. Holland, “Application of Z-Source inverter for traction drive of fuel cell-battery hybrid electric vehicles,” *IEEE Transactions on Power Electronics,* vol. 22, no. 3, May. 2007, pp. 1054-1061.

[36] S. Daher, J. Schmid, F. Antunes "Multilevel inverter topologies for stand-alone PV systems," *IEEE Transactions on Industrial Electronics*, vol. 55, no. 7, July 2008, pp. 2703-2712

[37] W. Li, X. Lv, Y. Deng, J. Liu, X. He, “A review of non-Isolated high step-Up DC/DC converters in renewable energy applications,” *IEEE Applied Power Electronics Conference*, February 15-19, 2009, Washington, DC, pp. 364-369.

[36] S. Alepuz, S. Busquets-Mongo, J. Bordanau, J. Gago, D. Gonzalez, J. Barcells, "Interfacing renewable energy sources utility grid using a three-level inverter," *IEEE Transactions on Industrial Electronics*, vol. 53, no. 5, October 2006, pp. 1504-1511.

[39] K.A. Corzine, F.A. Hardrick, and Y.L. Familiant, “A cascaded multi-level H-bridge inverter utilizing capacitor voltages sources,” *Proceedings of the IASTED Internatinal Conference, Power and Energy Systems*, Feb. 24-26, 2003, pp. 290-295.

[40] J. Liao, K. Corzine, M. Ferdowsi, “A new control method for single-dc-source cascaded H-bridge multilevel converters using phase-shift modulation,” *IEEE Applied Power Electronics Conference and Exposition*, Feb. 2008, pp.886-890.

[41] Z. Du, L. M. Tolbert, J. N. Chiasson, “A cascade multilevel inverter using a single dc source,” *IEEE Applied Power Electronics Conference,* March 19-23, 2006, pp. 426-430.

[42] J. N. Chiasson, B. Özpineci, and L. M. Tolbert, “A five-level three-phase hybrid cascade multilevel inverter using a single dc source for a pm synchronous motor drive,” *IEEE Applied Power Electronics Conference*, February 25 - March 1, 2007. Anaheim CA, pp. 1504-1507.

[43] Z. Du, B. Ozpineci, L. M. Tolbert, J. N. Chiasson, “Inductorless DC-AC cascaded H-Bridge multilevel boost inverter for electric/hybrid electric vehicle applications,” *IEEE Industry Applications Conference*, Sept. 2007, pp. 603-608.

[44] J. N. Chiasson, B. Özpineci, Z. Du, L. M. Tolbert, “Conditions for capacitor voltage regulation in a five-level cascade multilevel inverter: application to voltage-boost in a PM drive,” *IEEE International Electric Machines and Drives Conference*, May, 2007, pp. 731-735.

[45] Haiwen Liu, Leon M. Tolbert, Burak Ozpineci, Zhong Du, “Hybrid multilevel Inverter with single DC source,” *IEEE International Midwest Symposium on Circuits and Systems*, Knoxville, TN, Page 538-541, August 10-13, 2008

[46] Haiwen Liu, Leon M. Tolbert, Burak Ozpineci, Zhong Du, “Comparison of fundamental frequency and PWM methods applied on a hybrid cascaded multilevel inverter,” *IEEE Industrial Electronics Society Annual Conference,* Orlando, FL, Nov. 10-13, 2008

[47] Haiwen Liu, Leon M. Tolbert, Surin Khomfoi, Burak Ozpineci, Zhong Du, “Hybrid cascaded multilevel inverter with PWM method,” *IEEE Power Electronics Specialist Conference*, Island of Rhodes, Greece, Page 162-166, June 15-19, 2008

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