Improvement of Power Capability in Buck Boot Inverter by Using Space Vector Pulse Width Modulation

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ABSTRACT:

The project is about the space vector pulse width amplitude modulation (SVPWAM) method for a buck–boost voltage/current source inverter. For a voltage source inverter, the switching loss is reduced by 87%, compared to a conventional sinusoidal pulse width modulation (SPWM) method. For a current source inverter, the switching loss is reduced by 60%. In both cases, the power density is increased by a factor of 2 to 3. In addition, it is also verified that the output harmonic distortions of SVPWAM is lower than SPWM, by only using one-third switching frequency of the latter one.

A 1-kW boost-converter-inverter prototype has been built and tested using this modulation method. The maximum overall system efficiency of 96.7% has been attained at full power rating. The whole system power density reaches 2.3 kW/Land 0.5 kW/lb. The numbers are remarkable at this power rating. As a result, it is feasible to use SVPWAM to make the buck–boost inverter suitable for applications that require high efficiency, high power density, high temperature, and low cost. Such applications include electric vehicle motor drive or engine starter/alternator.

Key Words: Buck-boost, SVPWAM, switching loss reduction.

1. INTRODUCTION

Currently, two existing inverter topologies are used for hybrid electric vehicles (HEVs) and electric vehicles (EVs): the conventional three-phase inverter with a high voltage battery and a three-phase pulse width modulation (PWM)inverter with a dc/dc boost front end. The conventional PWM inverter imposes high stress on switching devices and motor thus limits the motor's constant power speed range (CPSR), which can be alleviated through the dc–dc boosted PWM inverter. The inverter is required to inject low harmonic current to the motor, in order to reduce the winding loss and core loss. For this purpose, the switching frequency of the inverter is designed within a high range from 15 to 20 kHz, resulting in the switching loss increase in switching device and also the core loss increase in the motor stator.

To solve this problem, various soft-switching methods have been proposed. Active switching rectifier or a diode rectifier with small DC link capacitor have been proposed Varies types of modulation method have been proposed previously such as optimized pulse-width-modulation , improved Space-Vector-PWM control for different optimization targets and applications and discontinuous PWM (DPWM). Different switching sequence arrangement can also affect the harmonics, power loss and voltage/current ripples .DPWM has been widely used to reduce the switching frequency, by selecting only one zero vector in one sector. It results in50% switching frequency reduction. However, if an equal output THD is required, DPWM cannot reduce switching loss than SPWM. Moreover, it will worsen the device heat transfer because the temperature variation. A double 120 flattop modulation method has been proposed, to reduce the period of PWM switching to only 1/3 of the whole fundamental period. However, these papers didn't compare the spectrum of this method with others, which is not fair. In addition, the method is only specified to a fixed topology, which cannot be applied widely.

This work proposes a novel generalized space vector pulse width amplitude modulation (SVPWAM) method for the buck/boost voltage source inverter (VSI) and current source inverter (CSI). By eliminating the conventional zero vectors in the space vector modulation, two-third and one-third switching frequency reduction can be achieved in VSI and CSI, respectively. If a unity power factor is assumed, an 87% switching loss reduction can be implemented in VSI, and a 74% reduction can be implemented in CSI. A 1-kW boost-converter inverter system has been developed and tested based on the SVPWAM method. A 90% power loss reduction compared to SPWM has been observed. The two stage efficiency reaches 96.7% at the full power rating. The power volume density of the prototype is2.3 kW/L. The total weight of the system is 1.51 lb. Therefore, a high-efficiency, high-power density, high-temperature, and lowcost1-kW inverter is achieved by using an SVPWAM method.

2. HARMONICS

The typical definition for a harmonic is "a sinusoidal component of a periodic wave or quantity having a frequency that is an integral multiple of the fundamental frequency". Some references refer to "clean" or "pure" power as those without any harmonics. But such clean waveforms typically only exist in a laboratory. Harmonics have been around for a long time and will continue to do so. In fact, musicians have been aware of such since the invention of the first string or woodwind instrument. Harmonics (called "overtones" in music) are responsible for what makes a trumpet sound like a trumpet, and a clarinet like a clarinet.

Electrical generators try to produce electric power where the voltage waveform has only one frequency associated with it, the fundamental frequency. In the North America, this frequency is 60 Hz, or cycles per second. In European countries and other parts of the world, this frequency is usually 50 Hz. Aircraft often uses 400 Hz as the fundamental frequency. At 60 Hz, this means that sixty times a second, the voltage waveform increases to a maximum positive value, then decreases to zero, further decreasing to a maximum negative value, and then back to zero. The rate at which these changes occur is the trigonometric function called a sine wave, as shown in figure 2.1. This function occurs in many natural phenomena, such as the speed of a pendulum as it swings back and forth, or the way a string on a violin vibrates when plucked.

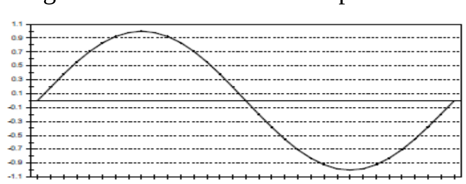


Fig. 2.1 Sine wave

The frequency of the harmonics is different, depending on the fundamental frequency. For example, the 2nd harmonic on a 60 Hz system is 2*60 or 120 Hz. At 50Hz, the second harmonic is 2* 50 or 100Hz.300Hz is the 5th harmonic in a 60 Hz system, or the 6th harmonic in a 50 Hz system.Figure 2.2 shows how a signal with two harmonics would appear on an oscilloscope-type display, which some power quality analysers provide.

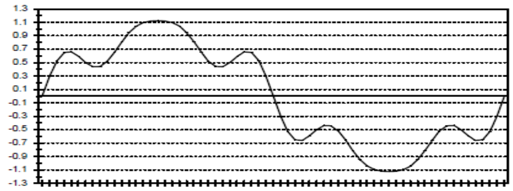


Figure2.2 Fundamental with two harmonics

In order to be able to analyse complex signals that have many different frequencies present, a number of mathematical methods were developed. One of the more popular is called the Fourier Transform. However, duplicating the mathematical steps required in a microprocessor or computer-based instrument is quite difficult. So more compatible processes, called the FFT for Fast Fourier transform, or DFT for Discrete Fourier Transform, are used.

These methods only work properly if the signal is composed of only the fundamental and harmonic frequencies in a certain frequency range (called the Nyquist frequency, which is one-half of the sampling frequency). The frequency values must not change during the measurement period. Failure of these rules to be maintained can result in mis-information. For example, if a voltage waveform is comprised of 60 Hz and 200 Hz signals, the FFT cannot directly see the 200 Hz. It only knows 60, 120, 180, 240,..., which are often called "bins".

The result would be that the energy of the 200 Hz signal would appear partially in the 180Hz bin, and partially in the 240 Hz bin. An FFT-based processer could show a voltage value of 115V at 60 Hz, 18 V at the 3rd harmonic, and 12 V at the 4th harmonic, when it really should have been 30 V at 200 Hz.

These in-between frequencies are called "inter harmonics". There is also a special category of inter harmonics, which are frequency values less than the fundamental frequency value, called sub-harmonics. For example, the process of melting metal in an electric arc furnace can result large currents that are comprised of the fundamental , inter harmonic, and sub harmonic frequencies being drawn from the electric power grid. These levels can be quite high during the melt-down phase, and usually effect the voltage waveform.

3. INVERETER

The main objective of static power converters is to produce an ac output waveform from a dc power supply. These are the types of waveforms required in adjustable speed drives (ASDs), uninterruptible power supplies (UPS), static var compensators, active filters, flexible ac transmission systems (FACTS), and voltage compensators, which are only a few applications. For sinusoidal ac outputs, the magnitude, frequency, and phase should be controllable. According to the type of ac output waveform, these topologies can be considered as voltage source inverters (VSIs), where the independently controlled ac output is a voltage waveform.

These structures are the most widely used because they naturally behave as voltage sources as required by many industrial applications, such as adjustable speed drives(ASDs), which are the most popular application of inverters; see Fig. 3.2. Similarly, these topologies can be found as current source inverters (CSIs), where the independently controlled ac output is a current waveform. These structures are still widely used in medium-voltage industrial applications, where high-quality voltage waveforms are required.

Static power converters, specifically inverters, are constructed from power switches and the ac output waveforms are therefore made up of discrete values. This leads to the generation of waveforms that feature fast transitions rather than smooth ones. For instance, the ac output voltage produced by the VSI of a standard ASD is a three-level.

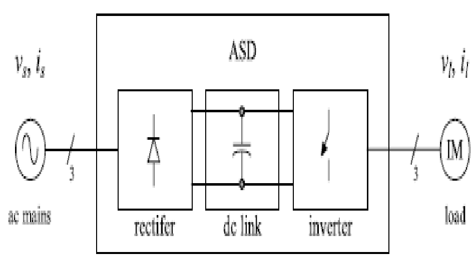


Fig. 3.1 Basic Diagram

Basic designs**:**

In one simple inverter circuit, DC power is connected to a transformer through the center tap of the primary winding. A switch is rapidly switched back and forth to allow current to flow back to the DC source following two alternate paths through one end of the primary winding and then the other. The alternation of the direction of current in the primary winding of the transformer produces alternating current (AC) in the secondary circuit.

The electromechanical version of the switching device includes two stationary contacts and a spring supported moving contact. The spring holds the movable contact against one of the stationary contacts and an electromagnet pulls the movable contact to the opposite stationary contact. The current in the electromagnet is interrupted by the action of the switch so that the switch continually switches rapidly back and forth. This type of electromechanical inverter switch, called a vibrator or buzzer, was once used in vacuum tube automobile radios. A similar mechanism has been used in door bells, buzzers and tattoo.As they became available with adequate power ratings, transistors and various other types of semiconductor switches have been incorporated into inverter circuit designs.

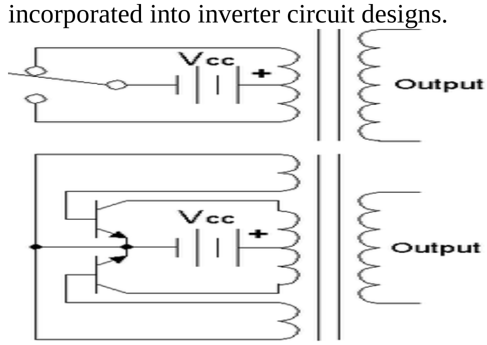


Fig3.2 Electromechanical switching device

Output waveforms**:**

The switch in the simple inverter described above, when not coupled to an output transformer, produces a square voltage waveform due to its simple off and on nature as opposed to the sinusoidal waveform that is the usual waveform of an AC power supply. Using Fourier analysis, periodic waveforms are represented as the sum of an infinite series of sine waves. The sine wave that has the same frequency as the original waveform is called the fundamental component. The other sine waves, called harmonics, that are included in the series have frequencies that are integral multiples of the fundamental frequency.

The quality of the inverter output waveform can be expressed by using the Fourier analysis data to calculate the total harmonic distortion (THD). The total harmonic distortion is the square root of the sum of the squares of the harmonic voltages divided by the fundamental voltage:

$$THD = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + \cdots + \cdots\cdots V_n^2}}{V1}$$

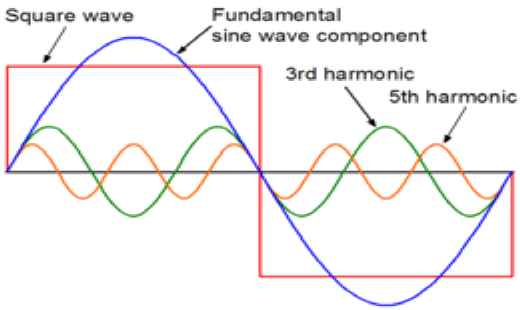


Fig.3.3 Output Waveform

Types of inverters:

Generally inverters are of Two Types:

1. VOLTAGE SOURCE INVERTER
2. CURRENT SOURCE INVERTER

3.1 Voltage source inverters

Single-phase voltage source inverters (VSIs) can be found as half-bridge and full-bridge topologies. Although the power range they cover is the low one, they are widely used in power supplies, single-phase UPSs, and currently to form elaborate high-power static power topologies, such as for instance, the multicell configurations that are reviewed. The main features of both approaches are reviewed and presented in the following.

Half-Bridge VSI:

The power topology of a half-bridge VSI, where two large capacitors are required to provide a neutral point N, such that each capacitor maintains a constant voltage=2. Because the current harmonics injected by the operation of the inverter are low-order harmonics, a set of large capacitors (C. and Cÿ) is required. It is clear that both switches S. and Sÿ cannot be on simultaneously because short circuit across the dc link voltage source v_i would be produced. There are two defined (states 1 and 2) and one undefined (state 3) switch state as shown in table. In order to avoid the short circuit across the dc bus and the undefined ac output voltage condition, the modulating technique should always ensure that at any instant either the top or the bottom switch of the inverter leg is on.

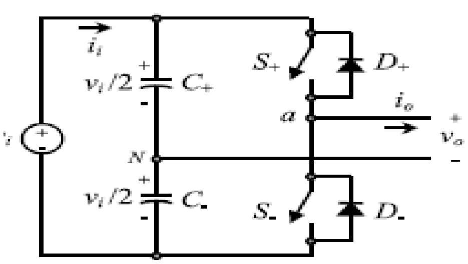


Fig 3.4 Single phase Half Bridge VSI

Shows the ideal waveforms associated with the half-bridge inverter shown in Fig.4. The states for the switches S. and Sÿ are defined by the modulating technique, which in this case is a carrier-based PWM.

(a) the amplitude of the fundamental component of the ac output voltage v_{01} satisfying the following expression:

$$m_a = \frac{v_i}{v_A}$$

$$m_f = \frac{f_a}{f_c}$$

$$v_{a1} = v_{aN1} = \frac{v}{2} m_a$$

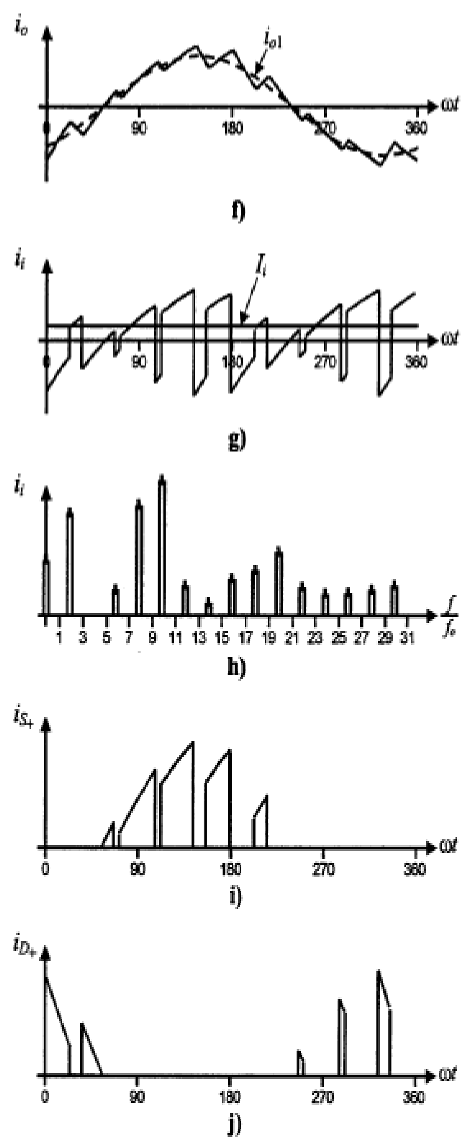


Fig 3.5 AC Output voltages and currents

(b) for odd values of the normalized carrier frequency mf the harmonics in the ac output voltage appear at normalized frequencies fh centred around mf and its multiples, specifically,

$$h = lm_f \pm k \ \ where\ l = 1,2,3 \ldots\ldots\ldots\ldots$$

Where k . 2; 4; 6; . . . for l . 1; 3; 5; . . . ; and k . 1; 3; 5; . . .for l . 2; 4; 6; . . . ; (c) the amplitude of the ac output voltage harmonics is a function of the modulation index ma and is independent of the normalized carrier frequency mf form f > 9; (d) the harmonics in the dc link current (due to the modulation) appear at normalized frequencies fp centred around the normalized carrier frequency mf and its multiples, specifically,

$$p = lm_f \pm k \pm 1 \ \ where\ l = 1,2,3 \ldots\ldots\ldots\ldots$$

where k . 2; 4; 6; . . . for l . 1; 3; 5; . . . ; and k . 1; 3; 5; . .for l . 2; 4; 6; . . . . Additional important issues are: (a) for small values of mf (mf < 21), the carrier signal v_D and the modulating signal v_c should be synchronized to each other(mf integer), which is required to hold the previous features; if this is not the case, sub harmonics will be present in the ac output voltage; (b) for large values of mf (mf > 21), the sub harmonics are negligible if an asynchronous PWMtechnique is used, however, due to potential very low-order sub harmonics, its use should be avoided; (c) in the over modulation region (ma > 1) some intersections between the carrier and the modulating signal are missed, which leads to the generation of low-order harmonics but a higher fundamental ac output voltage is obtained; unfortunately, the linearity between ma and vo1achieved in the linear region does not hold in the over modulation region, moreover, a saturation effect can be observed

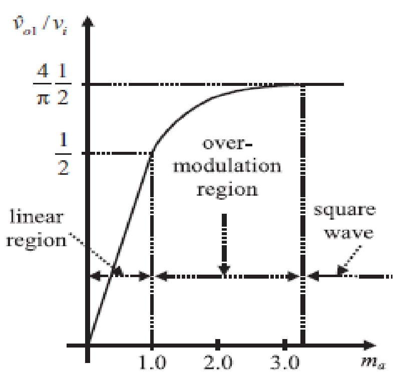


Fig 3.6 Change in harmonics

The PWM technique allows an ac output voltage to be generated that tracks a given modulating signal. A special case is the SPWM technique (the modulating signal is a sinusoidal) that provides in the linear region an ac output voltage that varies linearly as a function of the modulation index and the harmonics are at well-defined frequencies and amplitudes.

These features simplify the design of filtering components. Unfortunately, the maximum amplitude of the fundamental ac voltage is v_i=2 in this operating mode. Higher voltages are obtained by using the over modulation region (ma > 1); however, low-order harmonics appear in the ac output voltage.

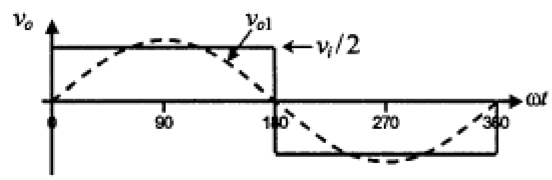
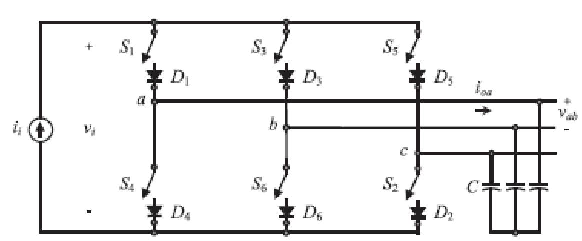


Fig 3.7Low-order harmonics

3.2Current Source Inverters:

The main objective of these static power converters is tom produce ac output current waveforms from a dc current power supply. For sinusoidal ac outputs, its magnitude, frequency, and phase should be controllable. Due to the fact that the ac line currents i_{oa}, i_{ob}, and i_{oc} (Fig 3.7) feature high di=dt, a capacitive filter should be connected at the ac terminals in inductive load applications (such as ASDs).

Thus, nearly sinusoidal load voltages are generated that justifies the use of these topologies in medium-voltage industrial applications, where high-quality voltage waveforms are required should be closed at any time; the dc bus is of the current-source type and thus it cannot be opened; therefore, there must be at least one top switch and one bottom switch (closed at all times. Note that both constraints can be summarized by stating that at any time, only one top switch and one bottom switch must be closed



. Fig 3.8 Current Source Inverters

There are nine valid states in three-phase CSIs. produce zero ac line currents. In this case, the dc link current freewheels through either the switches S_1 and S_4, switches S_3 and S_6, or switches S_5 and S_2.

The remaining states produce nonzero ac output line currents. In order to generate a given set of ac line current waveforms, the inverter must move from one state to another. Thus, the resulting line currents consist of discrete values of current, which are ii , 0, and ÿii . The selection of the states in order to generate the given waveforms is done by the modulating technique that should ensure the use of only the valid states.

Carrier-based PWM Techniques in CSIs:

It has been shown that carrier-based PWM techniques that were initially developed for three-phase VSIs can be extended to three-phase CSIs. Obtains the gating pattern for a CSI from the gating pattern developed for a VSI. As a result, the line current appears to be identical to the line voltage in a VSI for similar carrier and modulating signals.

It is composed of a switching pulse generator, a shorting pulsegenerator, a shorting pulse distributor, and a switching and shorting pulse combinatory. The circuit basically produces the gating signals ..S.1...6 . .S1 . . . S6.T . According to a carrier i_D and three modulating signals .i_c .abc . .i_{ca} i_{cb} i_{ca}.T .

Therefore, any set of modulating signals which when combined result in a sinusoidal line-to-line set of signals, will satisfy the requirement for a sinusoidal line current pattern. Examples of such a modulating signals are the standard sinusoidal, sinusoidal with third harmonic injection, trapezoidal, and dead band waveforms. The first component of this stage (Fig. 14.24) is the switching pulse generator, where the signals .S_a.123 are generated according to:

$$[S_a] = HIGH = 1 \qquad if[i_c] > v_c$$
$$= LOW = 0 \qquad otherwise$$

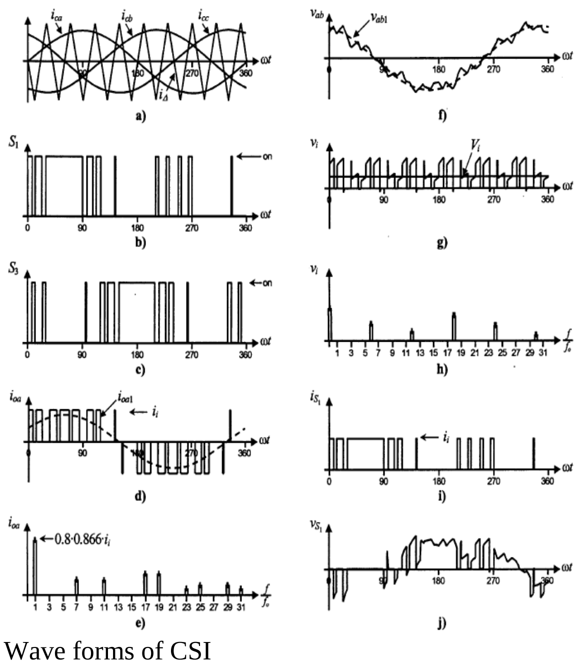
The outputs of the switching pulse generator are the signals .Sc .1...6, which are basically the gating signals of the CSI without the shorting pulses. These are necessary to freewheel the dc link current ii when zero ac output currents are required. Table1 shows the truth table of .Sc .1...6 for all combinations of their inputs .Sa.123. It can be clearly seen that at most one top switch and one bottom switch is on, which satisfies the first constraint of the gating signals as stated before.

In order to satisfy the second constraint, the shorting pulse .S_d . 1. is generated (shorting pulse generator (when none of the top switches .S_{c1} . S_{c3} . S_{c5} . 0. or none of the bottom switches .S_{c4} . S_{c6} . S_{c2} . 0. are gated. Then, this pulse is added (using OR gates) to only one leg of the CSI (either to the switches 1 and 4, 3 and 6, or 5 and 2) by means of the switching and shorting pulse combinatory./

The signals generated by the shorting pulse generator (a) only one leg of the CSI is shorted, as only one of the signals is high at any time; and (b) there is an even distribution of the shorting pulse, as .Se .123 is HIGH for 120_ in each period. This ensures that the rms currents are equal in all legs. the relevant waveforms if a triangular carrier i_D and sinusoidal modulating signals .ic .abc are used in combination with the gating pattern generator this is SPWM in CSIs.

It can be observed that some of the waveforms are identical to those obtained in three-phase VSIs, where a SPWM technique Specifically: (i) the load line VSI is identical to the load line current; and (ii) the dc link current is identical to the dc link voltage in the CSI. This brings up the duality issue between both topologies when similar modulation approaches are used. Therefore, for odd multiple of 3 values of the normalized carrier frequency mf , the harmonics in the ac output current appear at normalized frequencies fh centred around mf and its multiples, specifically, at

$$h = lm_f \pm k \qquad where \quad l = 1,2,3 \dots \dots \dots$$



Wave forms of CSI

thefundamentalacoutputlinecurrentis$i_{out} = \frac{\sqrt{3i_1}}{2}$ therefore one can write

$$i_{oa1} = m_a \frac{\sqrt{3}}{2} i_1 where \quad 0 < m_a \leq 1$$

To further increase the amplitude of the load current, the over modulation approach can be used. In this region, the fundamental line currents range in

$$\frac{\sqrt{3}}{2} i_1 < i_{oa1} = i_{ob1} = i_{oc1} < \frac{4}{\pi} \frac{\sqrt{3}}{2} i_1$$

APPLICATIONS:

DC power source utilization:

An inverter converts the DC electricity from sources such as batteries, solar panels, or fuel cells to AC electricity. The electricity can be at any required voltage; in particular it can operate AC equipment designed for mains operation, or rectified to produce DC at any desired voltage.

Grid tie inverters can feed energy back into the distribution network because they produce alternating current with the same wave shape and frequency as supplied by the distribution system. They can also switch off automatically in the event of a blackout.

Uninterruptible power supplies

Inverters convert low frequency main AC power to a higher frequency for use in induction heating. To do this, AC power is first rectified to provide DC power. The inverter then changes the DC power to high frequency AC power.

HVDC power transmission

With HVDC power transmission, AC power is rectified and high voltage DC power is transmitted to another location. At the receiving location, an inverter in a static inverter plant converts the power back to AC.

Variable-frequency drives

A variable-frequency drive controls the operating speed of an AC motor by controlling the frequency and voltage of the power supplied to the motor. An inverter provides the controlled power. In most cases, the variable-frequency drive includes a rectifier so that DC power for the inverter can be provided from main AC power. Since an inverter is the key component, variable-frequency drives are sometimes called inverter drives or just inverters.

Electric vehicle drives

Adjustable speed motor control inverters are currently used to power the traction motors in some electric and diesel-electric rail vehicles as well as some battery electric vehicles and hybrid electric highway vehicles such as the Toyota Prius. Various improvements in inverter technology are being developed specifically for electric vehicle applications.[2] In vehicles with regenerative braking, the inverter also takes power from the motor (now acting as a generator) and stores it in the batteries.

4. CONVERTERS

Power electronic circuits in wind and photovoltaic (PV) power systems basicallyperform the following functions:

Convert alternating current (AC) to direct current (DC)

- Convert DC to AC
- Control voltage
- Control frequency
- Control frequency

These functions are performed by solid-state semiconductor devices periodically switched on and off at a desired frequency. Device costs in 2005 have declined to about a tenth of those in 1990, fueling an exponential growth in applications throughout the power industry. No other technology has brought about a greater change in power engineering, or holds a greater potential for bringing improvements in the future, than power electronic devices and circuits. In this chapter, we review the power electronic equipment used in modern wind and PV power systems.

4.1 Basic Switching Devices:

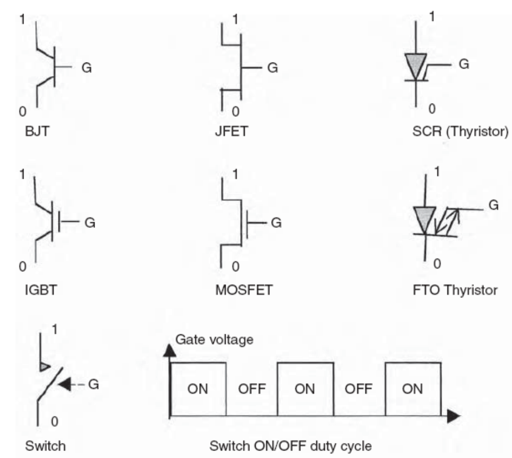


Fig 4.1 Basic semiconductor switching devices

Type	**Function**	**Voltage**	**Current**	**Upper Frequency**	**Switching Time**	**On State Resistance**
Diode	General Purpose High Speed Schottkey	5000 3000 <100	5000 1000 <100	1 10 20	100 2-5 0.25	0.1-0.2 1 10
Forced turned off thyristor	Reserve blocking High Speed Reverse Conducting GATT Light Triggered	5000 1200 2500 1200 6000	5000 1500 1000 400 1500	1 10 5 20 1	200 20 40 8 200-400	0.25 0.50 2 2 2
TRIAC	-	1200	300	1	200-400	0.5
Power Transistor	Single Darlington	400 1200	250 400	20 10	10 30	5 10
Power MOSFET	Single	500	10	100	1	1
IGBT	Single	1200	400	100	2	60
MCT	Single	600	60	100	2	20

TABLE 4.1: Characteristics Of Switching Devices

TABLE 4.2: Maximum Voltage And Current Ratings Of Switching Devices

Device	**Voltage Rating (volts)**	**Current rating (amperes)**	**Operating Features**
BJT	1500	400	Requires large current to turn on
IGBT	1200	400	Combines the advantages of BJT,MOSFET and GTO
MOSFET	1000	100	Higher Switching Speed
SCR	6000	3000	Once turned on requires heavy turn off circuit.

4.2 IGBT (Insulated Gate Bipolar Transistor):

IGBT is a three-terminal power semiconductor device, noted for high efficiency and fast switching. It switches electric power in many modern appliances: electric cars, trains, variable speed refrigerators, air-conditioners and even stereo systems with switching amplifiers. Since it is designed to rapidly turn on and off, amplifiers that use it often synthesize complex waveforms with pulse width modulation and low-pass filters.

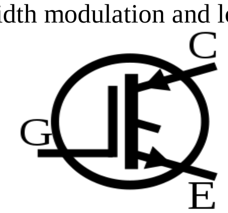


Fig 4.2: Electronic symbol for IGBT

The IGBT combines the simple gate-drive characteristics of the MOSFETs with the high-current and low–saturation-voltage capability of bipolar transistors by combining an isolated gate FET for the control input, and a bipolar power transistor as a switch, in a single device. The IGBT is used in medium- to high-power applications such as switched-mode power supply, traction motor control and induction heating. Large IGBT modules typically consist of many devices in parallel and can have very high current handling capabilities in the order of hundreds of amperes with blocking voltages of 6000 V, equating to hundreds of kilowatts.

The IGBT is a fairly recent invention. The first-generation devices of the 1980s and early 1990s were relatively slow in switching, and prone to failure through such modes as latch up (in which the device won't turn off as long as current is flowing) and secondary breakdown (in which a localized hotspot in the device goes into thermal runaway and burns the device out at high currents). Second-generation devices were much improved, and the current third-generation ones are even better, with speed rivaling MOSFETs, and excellent ruggedness and tolerance of overloads.

The extremely high pulse ratings of second- and third-generation devices also make them useful for generating large power pulses in areas like particle and plasma physics, where they are starting to supersede older devices like thyratrons and triggered spark gaps.

Their high pulse ratings, and low prices on the surplus market, also make them attractive to the high-voltage hobbyist for controlling large amounts of power to drive devices such as solid-state Tesla coils and coil guns.

Availability of affordable, reliable IGBTs is an important enabler for electric vehicles and hybrid cars.

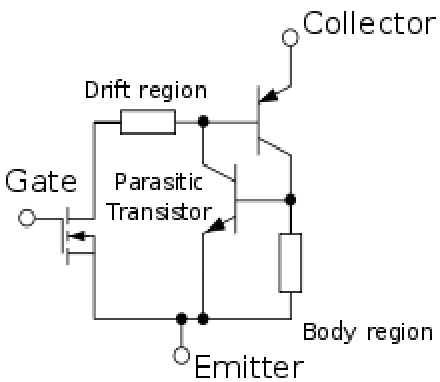


Fig 4.3 Equivalent circuit for IGBT

The IGBT is a semiconductor device with four alternating layers (P-N-P-N) that are controlled by a metal-oxide-semiconductor (MOS) gate structure without regenerative action.

4.3 AC–DC Rectifier

The circuit diagram of the full-bridge, three-phase, AC–DC rectifier is shown in next page. The power switch generally used in the rectifier is the SCR. The average DC output voltage is given by:

$$Vdc = \frac{3\sqrt{2}}{\pi} V_L \cos\alpha$$

Where

V_L = line-to-line voltage on the three-phase AC side of the rectifier

α = angle of firing delay in the switching

The delay angle is measured from the zero crossing in the positive half of the AC voltage wave. Equation 11.1 shows that the output DC voltage can be controlled by varying the delay angle α, which in turn controls the conduction (on-time) of the switch. Superimposed on the DC voltage at the rectifier output are high-frequency AC harmonics (ripples). A harmonic filter is, therefore, needed to reduce the AC component of the output voltage and increase the DC component. An L–C filter does this with an inductor connected in series and a capacitor in parallel with the rectified output voltage. The load determines the DC-side current as:

$$I_{dc} = \frac{\text{DC load Power}}{\text{Vdc}}$$

In steady-state operation, the balance of power must be maintained on both AC and DC sides. That is, the power on the AC side must be equal to the sum of the DC load power and the losses in the rectifier circuit. The AC-side power is therefore:

$$I_{dc} = \frac{\text{DC load Power}}{\text{Rectifier Efficiency}}$$

The three-phase AC power is given by:

$$P_{AC} = \sqrt{3} V_L I_L \cos\emptyset$$

where $\cos\emptyset$ is the power factor on the AC side. With a well-designed power electronic converter, the power factor on the AC side is approximately equal to that of the load.

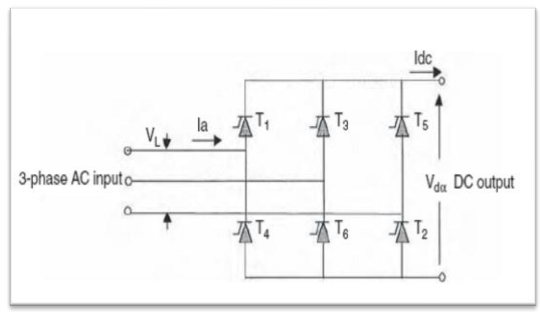
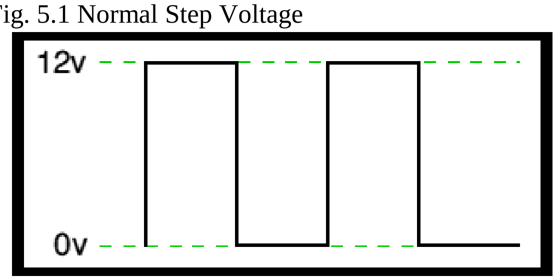


Fig 4.4 Three-phase, full-bridge, AC–DC controlled rectifier circuit

5. Pulse width Modulation

Pulse Width Modulation (PWM) is the most effective means to achieve constant voltage battery charging by switching the solar system controller's power devices. When in PWM regulation, the current from the solar array tapers according to the battery's condition and recharging needs consider a waveform such as this: it is a voltage switching between 0v and 12v. It is fairly obvious that, since the voltage is at 12v for exactly as long as it is at 0v, then a 'suitable device' connected to its output will see the average voltage and think it is being fed 6v - exactly half of 12v. So by varying the width of the positive pulse - we can vary the 'average' voltage.

Fig. 5.1 Normal Step Voltage



Similarly, if the switches keep the voltage at 12 for 3 times as long as at 0v, the average will be 3/4 of 12v - or 9v, as shown below.

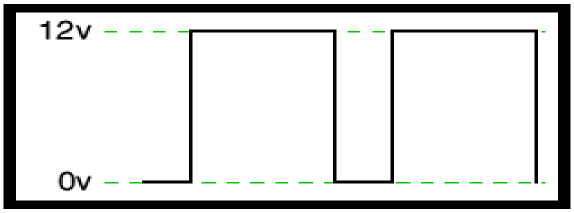


Fig. 5.2 Average Voltage after Switching

If the output pulse of 12v lasts only 25% of the overall time, then the average is

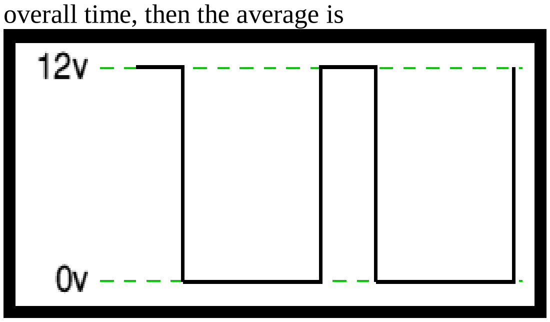


Fig.5.3 25% overall waveform

By varying - or 'modulating' - the time that the output is at 12v (i.e. the width of the positive pulse) we can alter the average voltage. So we are doing 'pulse width modulation'. I said earlier that the output had to feed 'a suitable device'. A radio would not work from this: the radio would see 12v then 0v, and would probably not work properly. However a device such as a motor will respond to the average, so PWM is a natural for motor control.

Pulse Width modulator

So, how do we generate a PWM waveform? It's actually very easy, there are circuits available in the TEC site. First you generate a triangle waveform as shown in the diagram below. You compare this with a d.c voltage, which you adjust to control the ratio of on to off time that you require. When the triangle is above the 'demand' voltage, the output goes high. When the triangle is below the demand voltage, the

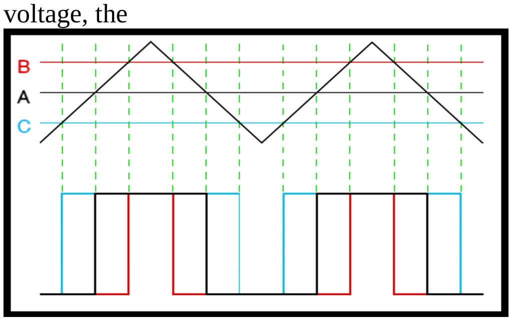


Fig 5.4 PWM Waveform

When the demand speed it in the middle (A) you get a 50:50 output, as in black. Half the time the output is high and half the time it is low. Fortunately, there is an IC (Integrated circuit) called a comparator: these come usually 4 sections in a single package. One can be used as the oscillator to produce the triangular waveform and another to do the comparing, so a complete oscillator and modulator can be done with half an IC and maybe 7 other bits.

The triangle waveform, which has approximately equal rise and fall slopes, is one of the commonest used, but you can use a saw tooth (where the voltage falls quickly and rinses slowly). You could use other waveforms and the exact linearity (how good the rise and fall are) is not too important.

Traditional solenoid driver electronics rely on linear control, which is the application of a constant voltage across a resistance to produce an output current that is directly proportional to the voltage. Feedback can be used to achieve an output that matches exactly the control signal. However, this scheme dissipates a lot of power as heat, and it is therefore very inefficient.

A more efficient technique employs **pulse width modulation** (PWM) to produce the constant current through the coil. A PWM signal is not constant. Rather, the signal is on for part of its period, and off for the rest. The **duty cycle**, D, refers to the percentage of the period for which the signal is on. The duty cycle can be anywhere
from 0, the signal is always off, to 1, where the signal is constantly on. A 50% D results in a perfect square wave. (Figure 5.1)

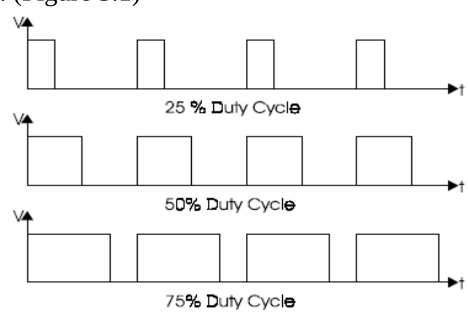


Fig 5.5 Perfect Square Wave

A solenoid is a length of wire wound in a coil. Because of this configuration, the solenoid has, in addition to its resistance, R, a certain **inductance**, L. When a voltage, V, is applied across an inductive element, the current, I, produced in that element does not jump up to its constant value, but gradually rises to its maximum over a period of time called the **rise time** (Figure 5.2). Conversely, I does not disappear instantaneously, even if V is removed abruptly, but decreases back to zero in the same amount of time as the rise time.

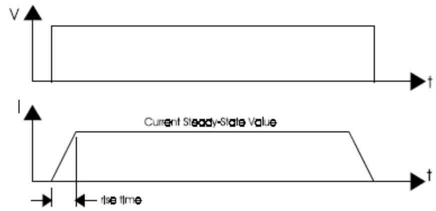


Fig 5.6 PWM for a Solenoid

Therefore, when a low frequency PWM voltage is applied across a solenoid, the current through it will be increasing and decreasing as V turns on and off. If D is shorter than the rise time, I will never achieve its maximum value, and will be discontinuous since it will go back to zero during V's off period (Figure 5.3). In contrast, if D is larger than the rise time, I will never fall back to zero, so it will be continuous, and have a DC average value. The current will not be constant, however, but will have a ripple (Figure 5.4)

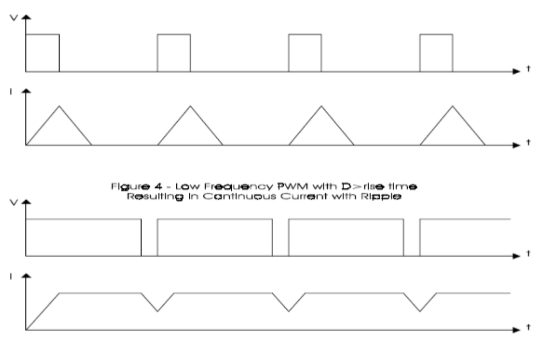


Fig 5.7 PWM for D>rise time

At high frequencies, V turns on and off very quickly, regardless of D, such that the current does not have time to decrease very far before the voltage is turned back on. The resulting current through the solenoid is therefore considered to be constant. By adjusting the D, the amount of output current can be controlled. With a small D, the current will not have much time to rise before the high frequency PWM voltage takes effect and the current stays constant. With a large D, the current will be able to rise higher before it becomes constant. (Figure 5.5)

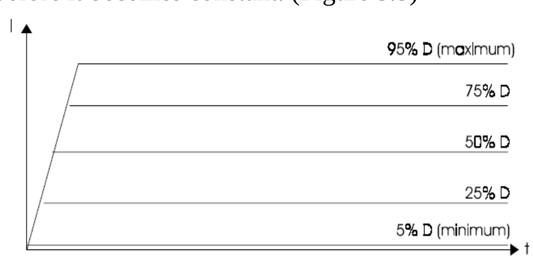


Fig 5.8 PWM for a Large Duty Cycle

6. SVM Technique

A different approach to SPWM is based on the space vector representation of voltages in the d, q plane. The d, q components are found by Park transform, where the total power,as well as the impedance, remains unchanged.

Fig 6.1 space vector shows 8 space vectors in according to 8 switching positions of inverter, V* is the phase-to-centre voltage which is obtained by proper selection of adjacent vectors V1 and V2.

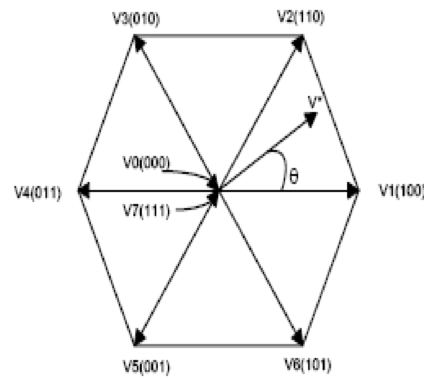


Fig 6.1 Inverter output voltage space vector

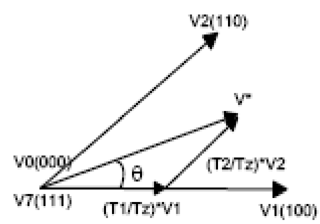


Fig 6.2 Determination of Switching times

The reference space vector V* is given by Equation (1), where T1, T2 are the intervals of application of vector V1 and V2 respectively, and zero vectors V0 and V7 are selected for T0.

$$V^{*}T_z = V_1 * T_1 + V_2 * T_2 + V_0 * (T_0/2) + V_7 * (T_0/2)$$

Fig. below shows that the inverter switching state for the period T1 for vector V1 and for vector V2, resulting switching patterns of each phase of inverter are shown in Fig. pulse pattern of space vector PWM.

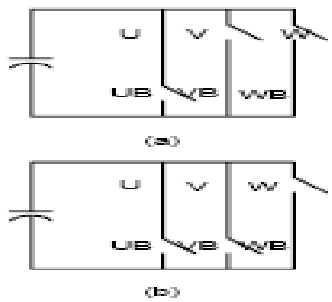


Fig 6.3 Inverter switching state for (a)V1, (b) V2

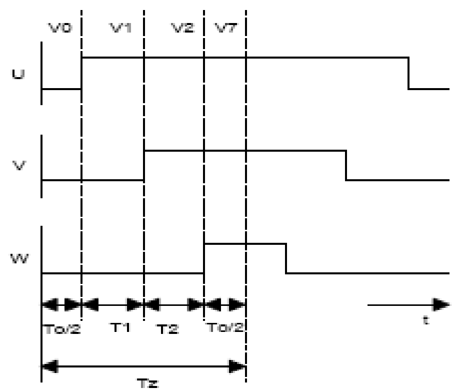


Fig 6.4 Pulse pattern of Space vector PWM

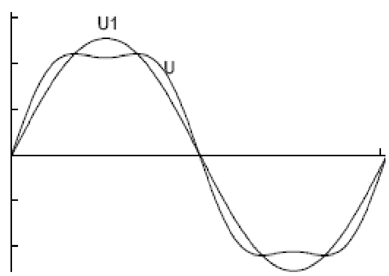


Fig 6.5 Comparison

In Fig 6.5 U is the phase to- centre voltage containing the triple order harmonics that are generated by space vector PWM, and U1 is the sinusoidal reference voltage. But the triple order harmonics are not appeared in the phase-to-phase voltage as well. This leads to the higher modulation index compared to the SPWM.

Comparison of SPWM and Space Vector PWM

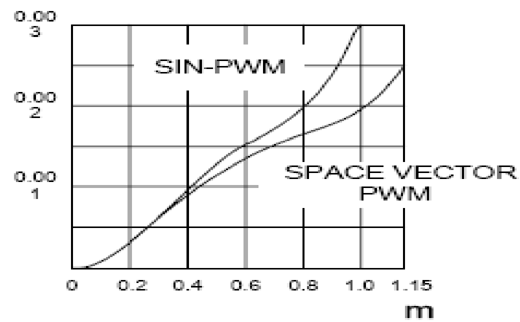
As mentioned above, SPWM only reaches to 78 percent of square wave operation, but the amplitude of maximum possible voltage is 90 percent of square-wave in the case of space vector PWM. The maximum phase-to-centre voltage by sinusoidal and space vector PWM are respectively

$V_{max} = V_{dc}/2$: Sinusoidal PWM

$V_{max} = V_{dc}/\sqrt{3}$: Space Vector PWM

Where, V_{dc} is DC-Link voltage.

This means that Space Vector PWM can produce about 15 percent higher than Sinusoidal PWM in output voltage.



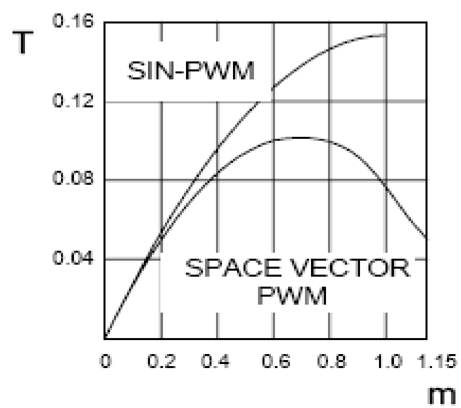


Fig 6.6 RMS harmonic current harmonics   Fig 6.7 Torque

The Pulse Width modulation technique permits to obtain three phase system voltages, which can be applied to the controlled output. Space Vector Modulation (SVM) principle differs from other PWM processes in the fact that all three drive signals for the inverter will be created simultaneously. The implementation of SVM process in digital systems necessitates less operation time and also less program memory.The SVM algorithm is based on the principle of the space vector u*, which describes all three output voltages u_a, u_b and u_c :

$$u^* = 2/3 \cdot (u_a + a.u_b + a_2 u_c)$$

Where a = -1/2 + j . v3/2 We can distinguish six sectors limited by eight discrete vectors u_0…u7 (fig:- inverter output voltage space vector), which correspond to the 23 = 8 possible switching states of the power switches of the inverter.

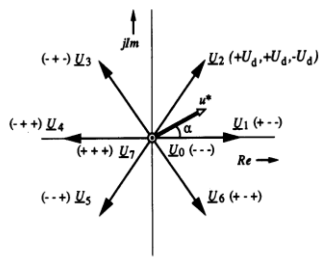


Fig 6.8Space vector Modulation

The amplitude of u_0 and u_7 equals 0. The other vectors u1…u6 have the same amplitude and are 60 degrees shifted.

By varying the relative on-switching time T_c of the different vectors, the space vector u* and also the output voltages u_a, u_b and u_c can be varied and is defined as:

$$u_a = Re(u^*)$$
$$u_b = Re(u^*.a-1)$$
$$u_c = Re(u^*.a-2)$$

During a switching period Tc and considering for example the first sector, the vectors u_0, u_1 and u_2 will be switched on alternatively.

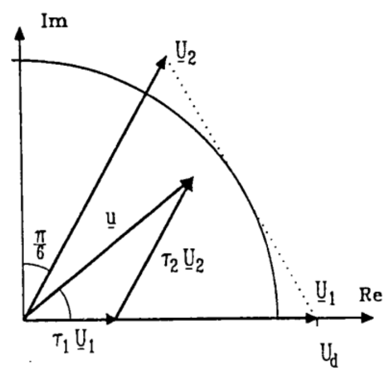


Fig 6.9 Definition of the Space vector

Depending on the switching times t_0, t_1 and t_2 the space vector u* is defined as:

$$u^* = 1/T_c \cdot (t_0u_0 + t_1u_1 + t_2u_2)$$
$$u^* = (t_0u_0 + t_1u_1 + t_2u_2)$$
$$u^* = 1/T_c \cdot (t_1u_1 + t_2u_2) \dots\dots\dots (4)$$

Where

$$t_0 + t_1 + t_2 = T_c$$
$$t_0 + t_1 + t_2 = 1$$

t_0, t_1 and t_2 are the relative values of the on switching times.

They are defined as$t_1 = m.\cos(a + p/6)$

$$t_2 = m.\sin a$$

$$t_0 = 1 - t_1 - t_2$$

Their values are implemented in a table for a modulation factor m = 1. Then it will be easy to calculate the space vector u* and the output voltages u_a, u_b and u_c. The voltage vector u* can be provided directly by the optimal vector control laws w1, v_{sa} and v_{sb}. In order to generate the phase voltages u_a, u_b and u_c corresponding to the desired voltage vector u* the above SVM strategy is proposed.

6.1 SVPWAM FOR VSI

Principle of SVPWAM Control in VSI:

The principle of an SVPWAM control is to eliminate the zerovector in each sector. The modulation principle of SVPWAM isshown in Fig. 2. In each sector, only one phase leg is doingPWMswitching; thus, the switching frequency is reduced by two-third. The dc-link voltage thus is directly generatedfrom the output line-to-line voltage. In sector I, no zero vectoris selected. Therefore, (3)S1 and *S*2 keep constant ON, and *S*3 and*S*6 are doing PWM switching. As a result, if the output voltageis kept at the normal three-phase sinusoidal voltage, the dc-linkvoltage should be equal to line-to-line voltage *V*ac at this time.Consequently, the dc-link voltage should present a 6ω variedfeature to maintain a desired output voltage. The correspondingwaveform is shown in solid line in Fig. 3. A dc–dc conversionis needed in the front stage to generate this 6ω voltage. Thetopologies to implement this method will be discussed later.The original equations for time period *T*1 and *T*2 arewhere $\theta \in [0, \pi/3]$ is relative angle from the output voltagevector to the first adjacent basic voltage vector like in Fig. 2. If the time period for each vector maintains the same, the switchingfrequency will vary with angle, which results in a variableinductor current ripple and multifrequency output harmonics.Therefore, in order to keep the switching period constant butstill keep the same pulsewidth as the original one, the new timeperiods can be calculated

$$T_1 = \frac{\sqrt{3}}{2} m\sin\left(\frac{\pi}{3} - \theta\right); T_2 = \frac{\sqrt{3}}{2} m\sin(\theta)$$

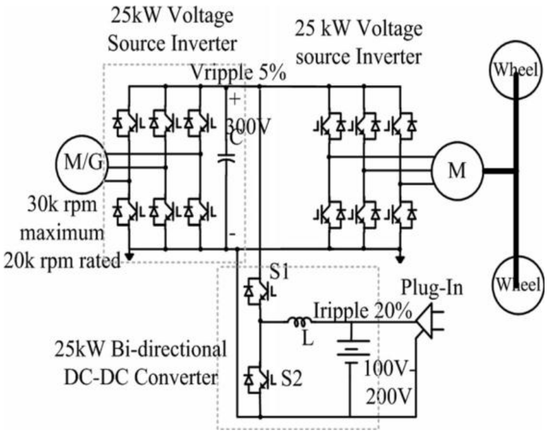


Fig 6.1.1 VSI

The vector placement within one switching cycle in each sector is shown it shows the output line-to-line voltage and the switching signals of $S1$.

$$T_1'/T_s = T_1/(T_1 + T_2)$$

Inverter Switching Loss Reduction for VSI:

For unity power factor case, the inverter switching loss is reduced by 86% because the voltage phase for PWM switching is within [−60◦, 60◦], at which the current is in the zero-crossing region. In VSI, the device voltage stress is equal to dc-link voltage V_{DC}, and the current stress is equal to output current ia . Thus the switching loss for each switch can be given as

$$P_{sw\_I} = \frac{1}{2\pi}\left[\int_{-\pi/6}^{\pi/6} E_{SR}\frac{I_m \sin\omega t \,.V_{dc}}{V_{ref}I_{ref}}.f_{sw}.d\omega t\right] + \left[\int_{5\pi/6}^{7\pi/6} E_{SR}\frac{I_m \sin\omega t \,.V_{dc}}{V_{ref}I_{ref}}.f_{sw}.d\omega t\right] = \frac{2\sqrt{3}}{\pi}\frac{I_m V_{dc}}{V_{ref}I_{ref}}E_{SR}f_{sw}$$

where ESR, V_{ref}, I_{ref} are the references

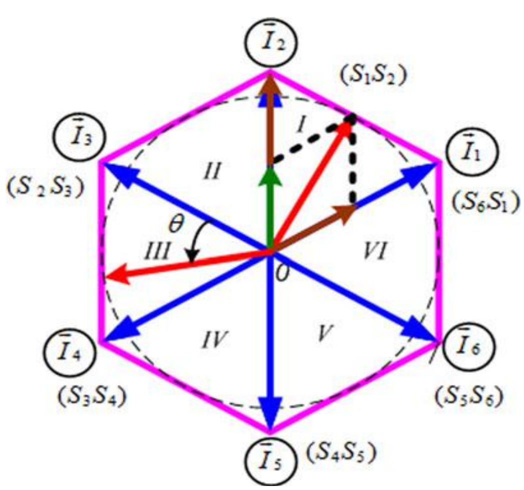


Fig.6.1.2 Space vector analysis

Since the SVPWAM only has PWM switching in two 60◦sections, the integration over 2π can be narrowed down into integration within two 60◦

$$P_{sw\_I} = \frac{2\sqrt{3}}{\pi}\frac{I_m.V_{dc}}{V_{ref}I_{ref}}E_{SR}.f_{sw}$$

The switching loss for a conventional SPWM method is given above.In result, the switching loss of SVPWAM over SPWM is$f$ = 13.4%.However, when the power factor decreases, the switchingloss reduction amount decreases because the switching current increases.As indicated, the worst case happens when power factor isequal to zero, where the switching loss reduction still reaches50%. In conclusion, SVPWAM can bring the switching lossdown by 50–87%.

$$P_{sw\_I} = \frac{2}{\pi}\frac{I_m.V_{dc}}{V_{ref}I_{ref}}E_{SR}.f_{sw}$$

6.2 SVPWAM FOR CSI

Principle of SVPWAM in CSI:

The principle of SVPWAM in CSI is also to eliminate the zero vectors. As shown in Fig. 6.2.1, for each sector, only two switches are doing PWM switching, since only one switch in upper phase legs and one switch in lower phase legs are conducting together at any moment. Thus, for each switch, it only needs to do PWM switching in two sectors, which is one-third of the switching period. Compared to SVPWM with single zero vector selected in each sector, this method brings down the switching frequency by one-third. Similarly, the dc-link current in this case is a 6ω varied current.

It is the maximum envelope of six output currents: I_a, I_b, I_c ,$-I_a$,$-I_b$,$-I_c$. For example, in sector I, S1 always keeps ON, so the dc-link current is equal to I_a. The difference between dc-link current in CSI and dc-link voltage in VSI is dc-link current in CSI is overlapped with the phase current, but dc-link voltage in VSI is overlapped with the line voltage, not the phase voltage. The time intervals for two adjacent vectors can be calculated in the same way as (1) and (2). According to diagram in Fig above the vector placement in each switching cycle for six switches can be plotted in graph.The SVPWAM is implemented on conventional CSI through simulation. Fig. shows the ideal waveforms of the dc current I_{dc}, the output phase ac current and the switching signals of S_1 . The switching signal has two sections of PWM in positive cycle, but no PWM in negative cycle at all.

When compared to discontinuous SVPWM, if the half switching frequency is utilized, then the switching loss of it becomes half of the result. The corresponding switching loss ratio between SVPWAM and discontinuous SVPWM

SPECTRUM ANALYSIS OF SVPWAM

A fair comparison in switching loss should be based on an equal output harmonics level. Thus, the switching loss may not be reduced if the switching frequency needs to be increased in order to compensate the harmonics. For example, discontinuous SVPWM has to have double switching frequency to achieve the same THD as continuous PWM. So the switching loss reductionis much smaller than 50%. Therefore, for the newlyproposed SVPWAM, a spectrum analysis is conducted to be compared with other methods on the basis of an equal average switching
frequency, which has not been considered.

Spectrum Comparison between SVPWAM, SPWM, and SVPWM

The object of spectrum analysis is the output voltage or current before the filter. The reason is that certain orders of harmonics can be eliminated by sum of switching functions inVSI or subtraction of switching functions in CSI. The comparison is between SVPWAM, DPWM, and continuous SVPWM in VSI/CSI. The switching frequency selected for each methodis different, because the comparison is built on an equalized average switching frequency over a whole fundamental cycle, in order to make the harmonics comparable at both low modulation and high modulation range.

Assume that the base frequency is f_0 = 10.8 kHz. Thus, 3f0 should be selected for SVPWAM, and f_0 should be selected for continuous SVPWM in VSI. In CSI, $3f_0$, $2f_0$, and f_0 should be selected for SVPWAM, discontinuous SVPWM, and continuous SVPWM, respectively. The modulation index selected here is the maximum modulation index 1.15, since the SVPWAM always only has the maximum modulation index. Theoretically, the THD varies with modulation index. The dc-link voltage is designed to be a constant for SVPWM and an ideal 6ω envelope of the output six line-to-line voltages for SVPWAM. Thus, the harmonic of the SVPWAM here does not contain the harmonics from the dc–dc converter output. It is direct comparison between two modulation methods from mathematics point of view.

The expression of double Fourier coefficient is

$$A_{mn} + jB_{mn} = \frac{1}{2\pi^2}\sum_{1}^{u} x \int_{y_{s(i)}}^{y_{c(i)}} \int_{x_{r(i)}}^{x_{f(i)}} I_{dc} e^{j(mx+ny)}\, dxdy$$

TOPOLOGIES FOR SVPWAM

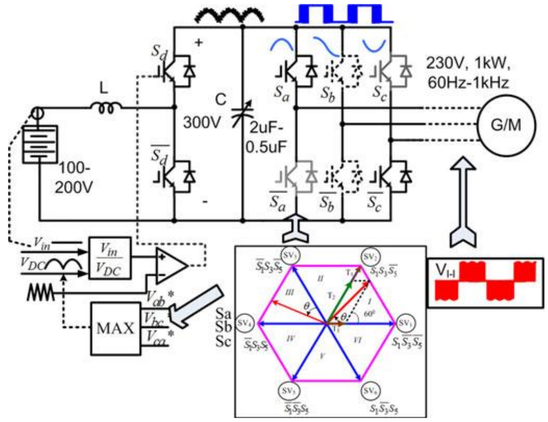
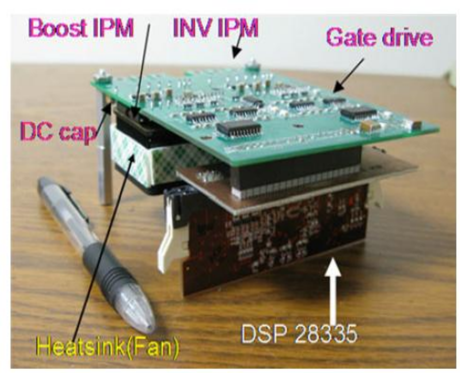


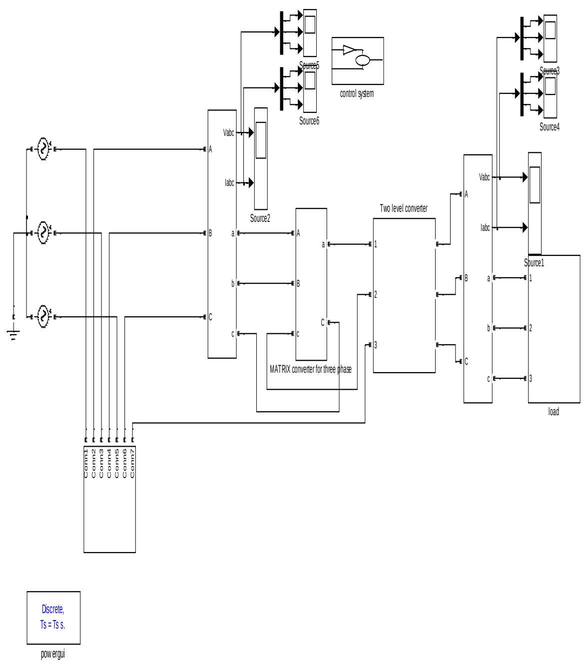
Fig 6.2 SVPWAM CSI

Basically, the topologies that can utilize SVPWAM have two stages: dc–dc conversion which converts a dc voltage or current into a 6ω varied dc-link voltage or current; VSI or CSI for which SVPWAM is applied. One typical example of this structure is the boost converter inverter discussed previously. However, the front stage can also be integrated with inverter to form a single stage. Take current-fed quasi-Z-source inverter as an SVPWAM-based boost-converter-inverter motor drive system example. Instead of controlling the dc-link current I_{pn} to havea constant average value, the open zero state duty cycle D_{op}will be regulated instantaneously to control I_{pm} to have a 6ωaverage value, resulting in a pulse type 6ω waveformat the real dc-link current I_{pn}, since I_1 is related to the input dccurrent I_{in} by a transfer function

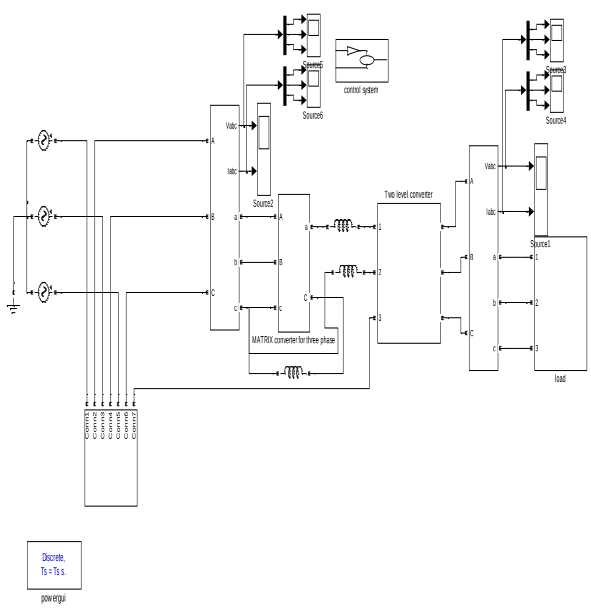
7. SIMULINK MODEL of SVPWAM



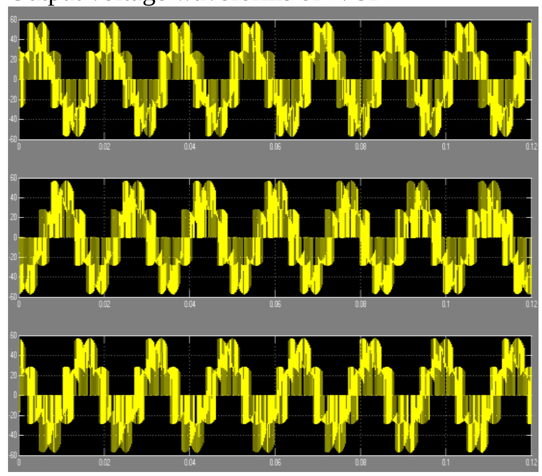
7.1 WithVSI



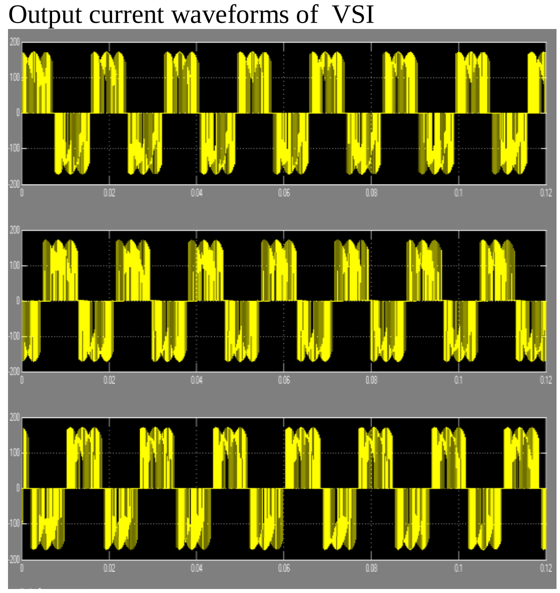
7.2 With CSI



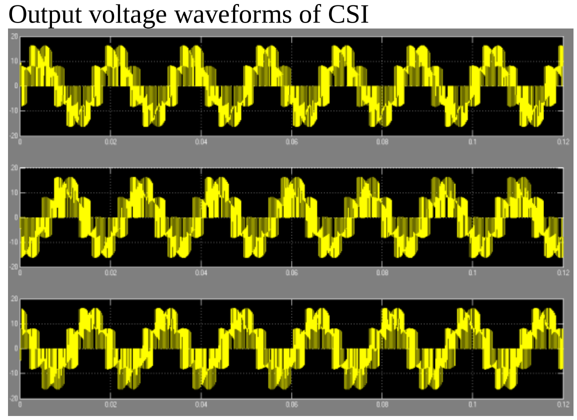
Output voltage waveforms of VSI



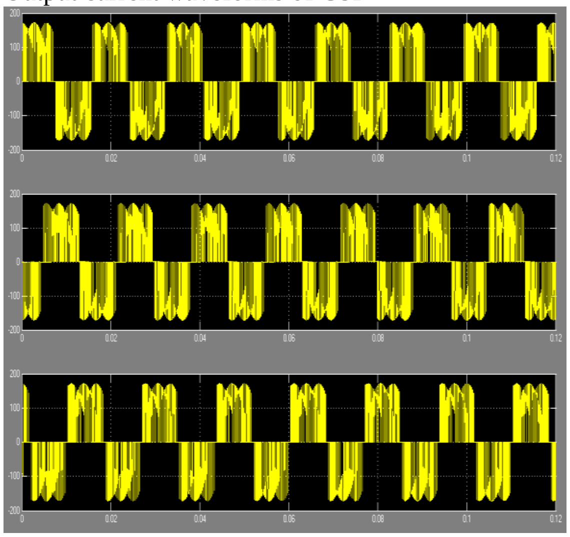
Output current waveforms of VSI



Output voltage waveforms of CSI



Output current waveforms of CSI



8. Conclusion

The SVPWAM control method preserves the following advantages compared to traditional SPWM and SVPWM method.

1) The switching power loss is reduced by 90% compared with the conventional SPWM inverter system.
2) The power density is increased by a factor of 2 because of reduced dc capacitor (from 40 to 6 μF) and small heat sink is needed.
3) The cost is reduced by 30% because of reduced passives,heat sink, and semiconductor stress.A high-efficiency, high-power density, high-temperature, andlow-cost 1-kW inverter engine drive system has been developedand tested.

The effectiveness of the proposed method in reduction of power losses has been validated by the experimental results that were obtained from the laboratory scale prototype.

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