DEVELOPMENT OF A LOW COST AND LOW LOSS SINGLE PHASE GRID TIE INVERTER FOR PHOTOVOLTAIC APPLICATION

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LIST OF SYMBOLS

Symbols	Description
V_{rms}	Root-mean-square output voltage
v_o	Instantaneous output voltage
M	Amplitude modulation index
$v_{out}(t)$	Output voltage of the inverter
V_{dc}	Input DC voltage
σ	width of the control signal pulse
M_f	Frequency modulation
V_{norm}	Normal power grid voltage
f_{norm}	Normal power grid frequency
I_{ir}	Inrush current
$\lvert V_{inv}\rvert\angle\delta$	GTI output voltage
$\lvert V_{grid}\rvert\angle 0$	Grid voltage
$\lvert Z_t\rvert\angle\gamma$	Transmission line equivalent impedance
S	Complex power
P	Real power
Q	Reactive power
δ	Power angle
τ	Time constant
V_{gate}	Gate drive voltage
V_{th}	Threshold voltage
n	Transformer ratio
X_C	Filter capacitor impedance
X_L	Filter inductor impedance

Symbols	**Description**
f_o	resonance frequency
ζ	damping factor
V_{peak}	Peak output voltage
Z_t	Total link impedace
η	Efficiency

LIST OF ABBREVIATION

	Description
BTU	British Thermal Unit
U.S.	United State of America
kWh	Kilo-watt hour
RE	Renewable energy
FiT	Feed-in-tariff system
CO_2	Carbon dioxide
PV	Photovoltaic system
DC	Direct current
AC	Alternating current
UPS	Uninterrupted power supply
MOSFET	Metal oxide semiconductor field effect transistor
IGBT	Insulated gate bipolar transistor
PWM	Pulse width modulation
SPWM	Sinusoidal pulse width modulation
THD	Total harmonic distortion
BJT	Bipolar junction transistor
RMS	Root-mean-square
DCM	Discontinue connection mode
Tx	Transfomer
GTI	Grid tied inverter
EMI	Electromagnetic interference
FPGA	Field-programmable Gate Array
PAM	Pulse amplitude modulation

	Description
HSPWM	Hybrid sinusoidal pulse width modulation
DG	Distributed generator
IEEE	Institute of Electrical and Electronics Engineers
Op-Amp	Operational amplifier
IC	Integrated circuit
FFT	Fast Fourier transform
THD	Total harmonic distortion

LIST OF PUBLICATIONS & SEMINARS

PEMBANGUNAN PENYONGSANG SATU FASA KOS RENDAH DAN KEHILANGAN RENDAH IKATAN GRID UNTUK APLIKASI FOTOVOLTA

ABSTRAK

Tesis ini menbentangkan satu penyongsang ikatan grid satu fasa jenis jambatan-H dibangunkan untuk aplikasi fotovolta. Objektif – objektif untuk reka bentuk penyongsang ini adalah kesederhanaan, kecekapan, kestabilan dan saiz yang kompak. Berdasarkan objektif – objektif ini, topologi penyongsang jenis jambatan-H dipilih sebagai reka bentuknya. Selain itu, penapis harmonic pasif LC digunakan untuk mengeluarkan kandungan harmonik dan satu transformer berfrekuensi grid digunakan untuk meningkatkan voltan keluaran penyongsang ke aras voltan grid. Selain daripada itu, teknik pensuisan kacukan dipilih sebagai topologi pensuisan bagi penyongsang ini. Teknik pensuisan kacukan ini adalah teknik campuran daripada SPWM berfrekuensi tinggi dan gelombang segiempat berfrekuensi grid. Satu litar analog dibina untuk menghasilkan isyarat kawalan yang diperlukan oleh teknik pensuisan ini dengan kompoment utamanya adalah Op-Amp. Kelebihan bagi teknik pensuisan ini adalah kehilangan kuasa pensuisan dapat dikurangkan. Selain itu, teknik pensuisan ini juga menolong untuk menghapuskan kegunanan diod roda bebas untuk dua MOSFET yang digunakan dalam penyongsang ini. Untuk mengesahkan metodologi reka bantuk ini, penyongsang ikatan grid ini diuji dalam dua peringkat; simulasi and ujian prototaip. Di dalam ujian simulasi, MATLAB Simulink digunakan. Selepas ujian simulasi, satu prototaip dibina dan diuji dibawah keadaan berasingan dan keadaan ikatan grid. Untuk prototiap yang dibina di dalam tesis ini, kuasa keluaran maksimum adalah 70W. Walau bagaimanapun, kecekapan maksimum untuk penyongsang ini adalah 92% di mana berlaku di kuasa keluaran 60W

DEVELOPMENT OF A LOW COST AND LOW LOSS SINGLE PHASE GRID TIE INVERTER FOR PHOTOVOLTAIC APPLICATION

ABSTRACT

This thesis present a single phase H-bridge grid tie inverter developed for photovoltaic application. The objectives for this design are simplicity, efficiency, stability and compact size. Base on these objectives, the H-bridge inverter topology is chosen to be the design. Besides that, LC passive harmonic filter is used to remove the harmonic contains and a grid frequency transformer is used to step up the output voltage of the inverter to the grid voltage. Moreover, hybrid switching technique is chosen to be the switching topology of this designed inverter. This hybrid switching technique is a technique that combines the high frequency SPWM and grid frequency square wave. An analog circuit is build to generate the control signal needed for this switching technique with major components of this control circuit are Op-Amp. The advantage of this switching technique is the reduction of switching loss of the inverter. Besides that, this switching technique helps to eliminate the freewheeling diode in two of the MOSFETs used in the inverter. In order to verify this design methodology, the grid tie inverter is tested in two stages; simulation and prototype testing. In the simulation stage, MATLAB Simulink is used. After the simulation, a prototype is built and tested under the stand alone as well as grid tied conditions to verify the accuracy of the design. For the prototype built in this thesis, the maximum power output is 70W. However, the maximum efficiency of this inverter is 92%, which happened at 60W output power.

CHAPTER 1

INTRODUCTION

1.1 Background

The increase of human population, activities, and economic growth forced the earth to swallow huge amount of energies. On the year of 2003, the world only consumed 355 quadrillion British Thermal Unit (Btu) of energy. However after 4 years, in 2007 the world eat up 495 quadrillion Btu of energy and this exponential upward trend is predicted to be at 739 quadrillion Btu at the year 2035 which is more than double the energy consumed back in 2003. Electricity is one of those energy sources that faced this increasing trend. From 1990 to 2007, the growth of world net electricity generation outpaced the growth of the total energy consumed and this trend is predicted to be continued. (U.S. Energy Information Administration, 2010)

With the awareness of the environment protection issue and the increase of global crude oil price, using classical methods such as burning liquid petroleum, gas or coal to fulfill the electricity demand is no longer a popular ways. Besides, after many countries in the United Nation Framework Convention on Climate Change ratified the Kyoto Protocol, Bali Road Maps and Copenhagen Accord and start to reduce their own country carbon footprints, their leader has forced to look for alternative energy resources to fulfill the increasing electricity demand. This has given an opportunity to the renewable energy resources to play their role in fulfilling the energy demand. One of this renewable energy is the energy from the Sun or commonly known as solar energy. Base on the international energy outlook 2010 by the U.S. Energy Information Administration the electricity generated by solar energy in 2007 is 6 billion kWh and predicted to be increased until 165 billion kWh at the year 2035 with an average annual increase of 12.7%.

Back in Malaysia, being a country that also rectified the Kyoto Protocol, Bali Road Maps and Copenhagen Accord, our Prime Minister under the 10^{th} Malaysia plan (2011 – 2015) had lunched the New National Renewable Energy (RE) and Action Plan. The vision of this plan, as stated by the Ministry of Energy, Green Technology and Water is to enhance the utilization of indigenous renewable energy resources to contribute towards National power grid security and sustainable social economic development (Ministry of Energy, Green Technology and Water, Malaysia, 2010). One of the RE source that the government put serious attention on is the photovoltaic system. Under this plan, the government is trying to introduce the feed in Tariff system (FiT) for the photovoltaic. With the FiT in place, now power grid consumers is no longer only buying electricity energy from the grid, they also able to sell their electricity energy generated by RE especially from photovoltaic to the grid. With this system, the government hopes that by 2050 the RE will contribute to somewhere 24% of the total electricity generated in this country and reduce the CO_2 emission by about 30 million tones. This has forced the local electricity industries to look for more efficient, user friendly FiT system for the photovoltaic.

Photovoltaic or PV technology is a technology where the Sun irradiation is converted to the electricity. This effect is first observed by A.E. Becquerel back in 1839 however not until 1954 in Bell Laboratories where Chapin, Fuller and Pearson developed the high efficient solar cell using diffused silicon p-n junction. Since then the PV technology had marked a tremendous progress, today few megawatt PV power generation plant has been build and install across a lot of places in the world. The materials in building the PV cell also come across huge changes to increase the efficiency and reduce the manufacturing cost. Starting with pure silicon by Chapin, Fuller and Pearson, until today PV is build from monocrystalline silicon, polycrystalline silicon, amorphous silicon, cadmium telluride, copper indium selenide/sulfide and etc. The PV cell price is on the downward trend since 2008 and it is predict by one of the research firm that this price will continue to fall over 70% by the year 2015. (The Economic, 2008)

Since this technology born into the world, it is believed to be the cleanest way to generate electricity. It discharges not things in the process of generating the electricity. Besides that, PV installation can be considered as a nearly static design. It only requires a minimum movement. This give advantages for the PV system over others renewable energy resources. Since it is static, it does not require a complex and strong structure to support the PV array. Moreover, it produces less vibration and hence less noise pollution to the nearby environment. Another attractive advantage of the PV system is the weight of the system. The PV system is light in weight. The power capability per unit weight is high. This means that the PV system is a portable, high power electricity generating system. Besides, long life time with minimum maintenance also gives the PV system an advantage over others.

A PV system can be commonly categorized into two types. One type is the stand alone system and the other is the grid tie system. For the stand alone system, it is more common installed in the rural area where there is no power transmission and distribution line or power supply provided by the power utilities. Also, it provides electricity supply to the electrical equipment where high mobility is a major factor such as electrical or recreational vehicle, satellite or even a small calculator and etc. However, the stand alone system will have a high maintenance cost compare to the grid tie system. This is due to the design of the system itself. The stand alone PV system requires a battery to store the excessive electricity energy generated by the PV array and deliver this power when the PV array is generating less power due to the low sun light irradiation. Since the sun light irradiation is a time varying factor, the battery will change from charging state to discharging state then back to charging state again frequently. The changing from charge to discharge or discharge state to charge state will result in lower battery life time. This is where the standalone system having the high maintenance cost.

Different from the standalone system, the grid tie PV system is normally install in the urban area where the power transmission line and distribution line is available. It is also employed in the large PV power generation plant to feed the electricity to the power grid. Compare these two designs; the standalone and grid tie system, the grid tie system does not require battery to store the excessive electricity generated by the PV array. The grid tie PV system will send any amount of generated power to the power grid.

Besides, the load of the two systems is totally different. For the standalone system, the load contain power far lesser than the system or even do not contain any power and purely absorb power. For the grid tie system, the load is the power grid where contain power far higher than the system. This requires the grid tie system to have specific design to synchronous between grid and system output voltage and force the power to flow into the power grid. All these are performed by the DC-AC converter which also known as inverter in the PV system.

The inverter is a power electronic device used to convert the direct current (DC) power to alternative current (AC) power at the desired voltage magnitude and frequency. It is broadly used in the industries application from acting as a load such as in the variable speed AC motor drive and induction heating where the output voltage magnitude and frequency is variable until acting as a AC power source such as in the uninterrupted power supply (UPS) and the gird tie application for a DC sources where the output voltage magnitude and frequency in most of the time is constant which is equal to the utilities grid value (230V, 50Hz for Malaysia).

The fundamental working theory for an inverter is switching. Where in the inverter, there will be a set of power electronic switches such as thyristor, metal oxide semiconductor field effect transistor (MOSFET), insulated gate bipolar transistor (IGBT) or etc. arrange in predesigned order and is switched with a specific control signal such as square wave, pulse width modulation (PWM) or sinusoidal pulse width modulation (SPWM). With the arrangement of the switches in the inverter, it can be categorized into single-stage or multiple-stage. A single stage inverter is where the power conversion, the stepping-up of DC voltage and the modulating of the sinusoidal current and voltage are done one stage. For the multiple-stage inverter, all these power conversions are done in more than one stage. (Yaosuo Xue et al., 2004)

For the pass few decade, may researches had put their effort to look into the design of the inverter however most of their objectives were the same. They were looking for a low loss, high output power, and low total harmonic distortion (THD) inverter. Recently, to reduce losses of the inverter some of the researchers try to reduce the power switching component. For example the buck-boost inverter by Kasa et al. in his paper published at 1999, the inverter only used 4 numbers of power switches to perform the inverting process. (Kasa et al., 1999) Besides of reduce the number of components of the inverter, a lot of researchers also looking into the switching technique of the inverter. Most of the switching technique proposed by the researcher is target to reduce switching loss and improve the total harmonic distortion of the output.

1.2 Objective of the project

The objectives are to be achieved from this research is:

i. To design, simulate as well as implement a single phase inverter that able to perform the grid tie task.
ii. To reduce the switching loss, increase the efficiency and reduce total harmonic distortion (THD) of the inverter.
iii. Implement a hybrid switching strategy between the sinusoidal pulse width modulation (SPWM) and square wave for the inverter.

1.3 Problem statement

Theoretically, the output voltage from an ideal inverter should be a pure sinusoidal waveform with lowest THD percentage possible. However, in practical situation, the design inverter is hard to get 100% pure sinusoidal waveform and normally contain harmonics that resulted in higher percentage of THD. In order to reduce this harmonic contain, a filter (active or passive) is used. In the case of low frequency switching such as line frequency square wave, the filter needed will be bulky because the output of the inverter contain high amount of low frequency harmonic. So solution is given to reduce the size of the filter by using high frequency switching such as SPWM, modify PWM and etc. This kind of high frequency switching resulted only in higher order of harmonic at the output voltage of the inverter. This greatly reduces the size and simplifies the harmonic filter design. However, with high switching frequency, others problems appear. One of the problems is the switching loss. This is because as the switching frequency increase, the frequency of di/dt and dv/dt over a period across the power electronic switches of the inverter increase, this resulted in higher power losses across the power electronic switches.

Moreover, different from the stand alone inverter, the grid tied inverter requires specific requirements for the inverter to send the generated power to the utilities grid. The output voltage phase of the inverter must able to be controlled to be in phase or out phase (leading/ lagging) from the grid voltage so that this voltage can tie to the grid and send the generated power to the grid.

Hence in this thesis, a hybrid of high and low frequency switching is developed for the grid tie inverter so that the output voltage is in low THD and low switching loss across the power electronic switches.

1.4 Scope of Work

This research including the following scope of work:

1) Design and simulated the proposed inverter and switching topology.
2) Implement the prototype inverter.
3) Testing and verify the prototype.

1.5 Research outline

This research is prepared in 5 chapters. Each of these chapters contained different scope discussing about the working theory behind the proposed inverter and it performance. In chapter 1, the introduction of the whole research is presented. In this chapter, the global energy consumption and the solar energy usage is discussed. Besides, the PV system and its inverter are briefly evaluated. Moreover, the objectives, problem statement and scope of work for this thesis are also presented in this chapter.

Chapter 2 presents the literature review on the document related to this research. The design of single phase inverter proposed by other or in the text books is also being discussed. Besides, the switching strategy such as low frequency square wave and high frequency SPWM and their pros and cons are reviewed and discussed. Subsequently some of the grid tie strategy and requirement is also being discussed.

In chapter 3 discussions is made on the topology and design of the proposed inverter and it switching strategy. The power circuit and the control circuit are discussed and a simulation is carried out to determine their predicted performance. At the last part of this chapter, the realization of the proposed grid tied inverter into the prototype is being discussed.

Chapter 4 present and discuss all the simulation and experimental result for the proposed grid tie inverter. In the simulation stage, both control and power circuit result and performance is presented and discussed. After that the result getting from the experiment done to the prototype is also being discussed and analyzed. This include the switching control signal, dead time control for the control circuit and output voltage magnitude, frequency and harmonic for the power circuit. At the final parts of this chapter, a comparison is made to compare the result getting for the simulation and the experiment and the performance of the prototype is determined.

Last but not less, chapter 5 wrap up the research with the conclusion of this project and also propose some possible future work that can use to improve the performance of the grid tied inveter. Finally, appendices such as supplementary information and the published manuscripts will be added in to the end of the research.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Theoretically, the inverter works by turning on and off the power electronic switches also known as gates in a specific order to convert the DC supply to AC source. This switching pattern is pre-designed using the control circuit. For the pass few decade, a lot of researchers had looked into the design of the inverter and try to increase its performance. In this chapter the theory behind the inverter and some design proposed by other researchers and designer is discussed. Besides, the switching technique of the inverter such as low frequency square wave and high frequency SPWM is also been discussed.

2.2 Inverter

As discuss earlier, the power electronic device that converts the DC supply to a controlled voltage and frequency AC source is known as the inverter. In common, the definition of power electronic is known as the technology that used to process electricity energy rather than information. An inverter is operated base on a set of switching signal which used to switch the power electronic switches.

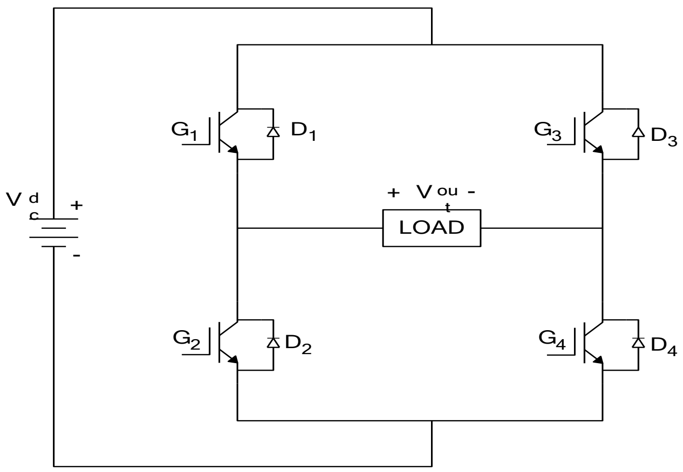

Figure 2.1: Basic circuit for the full bridge inverter

Figure 2.1 shows a classical full bridge single phase inverter which also known as H-bridge circuit due to the arrangement of the power electronic switches. The inverter is constructed using four numbers of power electronic switches (such as MOSFET, IGBT, Transistor, SCR, BJT or etc.). These switches are arranged into two legs; left and right. In each leg, it consists of two numbers of power electronic switches arrange in series to each others. Besides that, there is an anti-parallel diode connected in parallel to each of the power electronic switches. These anti-parallel diodes act as the current flowing part when the power switch is turning off. For example, when the power electronic switches G_2 and G_3 as shown in Figure 2.1 is on, the current will flow from positive V_{dc} terminal though G_3 to the load and return to negative terminal using G_2. However, when G_2 and G_3 finish their cycle and turn off, the current flow from D_4 to the load have to return by using anti-parallel diode, D_1.

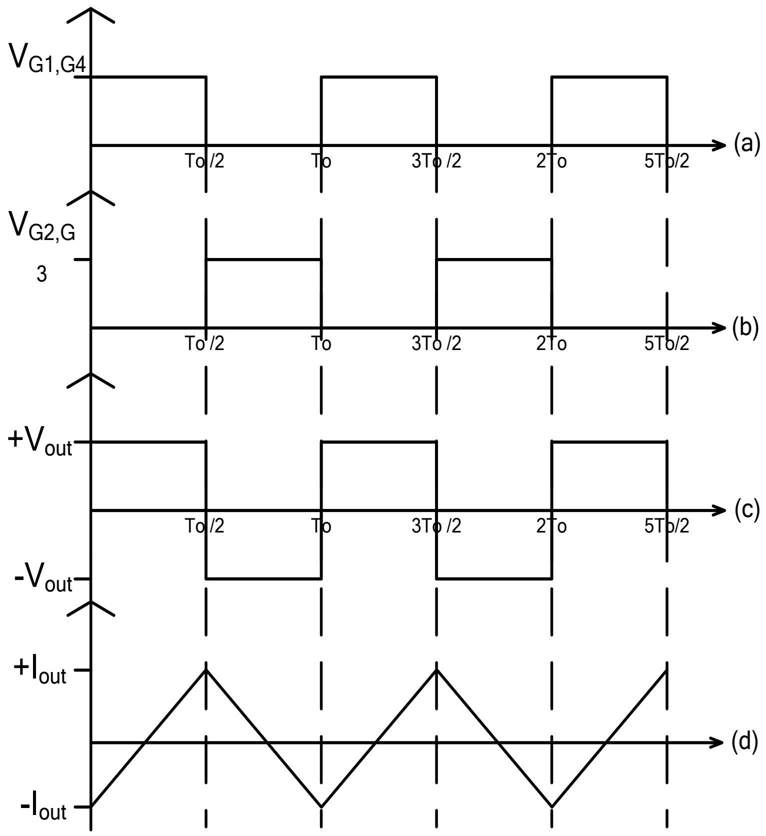

Figure 2.2: Waveform of control signal and output voltage

Based on the operation of the inverter shown in Figure 2.1, the power electronic switches can categorize into 2 groups. The first group consists of power electronic switches G_1 and G_4 and the second group is G_2 and G_3. When switches G_1 and G_4 are switching "ON" by signal $V_{G1,G4}$ shown in Figure 2.2(a), the voltage across the load is $+V_{dc}$. If G_2 and G_3 are switching "ON" by signal $V_{G2,G3}$ shown in Figure 2.2(b), then the voltage across the load is inverted and became $-V_{dc}$. The summary of control signal waveform for the power electronic switches and the output voltage is shown in Figure 2.2. However, the power electronic switches G_1 and G_2 or G_3 and G_4 cannot in "ON" state at the same time. This is because, if they are in conductivity mode at the same time, it will create a short circuit part for the DC supply and resulting in high current flow though the MOSFET and destroy it. Further study of the switching, it can be categorized into 5 states depend on the conductivity of each power electronic switches as shown in table 2.1. (Rashid, 2004)

Table 2.1: Switching state of the inverter

State No.	State	Conducting Components	Output Voltage
1	G_1 and G_4 are on G_2 and G_3 are off	G_1 and G_4 if $i_o > 0$ D_1 and D_4 if $i_o < 0$	V_{dc}
2	G_1 and G_4 are off G_2 and G_3 are on	G_2 and G_3 if $i_o < 0$ D_2 and D_3 if $i_o > 0$	$- V_{dc}$
3	G_1 and G_3 are on G_2 and G_4 are off	G_1 and D_3 if $i_o > 0$ D_1 and G_3 if $i_o < 0$	0
4	G_1 and G_3 are off G_2 and G_4 are on	G_2 and D_4 if $i_o > 0$ D_2 and G_4 if $i_o < 0$	0
5	G_1 and G_4 are off G_2 and G_3 are off	D_4 and D_3 if $i_o > 0$ D_4 and D_2 if $i_o < 0$	0

Referring to Figure 2.2(c), the root-mean-square (RMS) value of the output voltage shown in that figure can be expressed by equation 2.1.

$$V_{rms} = 2 \times \left(\frac{2}{T_o} \int_0^{T_0/2} \frac{V_{dc}^2}{4} dt \right)^{1/2}$$

$$= \left(\frac{2}{T_o} \int_0^{T_0/2} V_{dc}^2 \, dt \right)^{1/2} \qquad (2.1)$$

For the instantaneous output voltage in Figure 2.2(c), it can be expressed using Fourier theorem as an infinite sum of a constant, sine and cosine function as shown in equation 2.2. (Charles and Matthew, 2004)

$$v_o = \frac{a_0}{2} + \sum_{n=1}^{\infty} \left(a_n cos(n\omega t) + b_n sin(n\omega t) \right) \qquad (2.2)$$

Where, v_o = Instantaneous output voltage

ao, an, bn = Fourier constant

From Figure 2.2, since the output voltage is clearly an odd symmetry function. So the constant a_o, a_n and b_n in equation 2.2 become as shown in equation 2.3.

$$\left. \begin{aligned} a_o &= 0, \; a_n = 0 \\ b_n &= \frac{4V_{dc}}{n\pi} \end{aligned} \right\} \qquad (2.3)$$

Substituting equation 2.3 back into equation 2.2, the instantaneous output voltage of the inverter is as shown in equation 2.4.

$$v_o = \sum_{n=1,3,5,\ldots}^{\infty} \frac{2V_{dc}}{n\pi} sin(n\omega t) \quad (2.4)$$

Where, v_o = Instantaneous output voltage

V_{dc} = Input DC voltage

ωt = Period in radian

The inverter shown in Figure 2.1 and discussed in above is a very simple and easy design. However, its performance is stable and reliable. It is able to perform under various situations. But for past few decade, a lot of researcher had putting in their hard work into the inverter looking for better inverter design solution for specific cases.

Currently, the developed inverter can be classified into 2 categories depending of the stages require by the inverter to process the electrical power. A single-stage inverter is define as an inverter that require only single stage of power conversion to perform both stepping-up the voltage and modulating the sinusoidal output voltage. Another category of the inverter is the multi-stage inverter. It is define as an inverter that require more than one stages of power conversion which in mostly one or more stages to stepping-up the voltage and isolation and will end with a stage performing the DC-AC conversion. (Yaosuo Xue and et al. 2004)

For the single-stage inverter, since the power conversion is done in one stage only hence the power components of inverter will greatly reduce. Besides, most of the single-stage inverter proposed by the researcher replace the bulky line frequency transformer with the transformer-less design or employing high frequency transformer, this reduce the volume and the weight of the inverter.

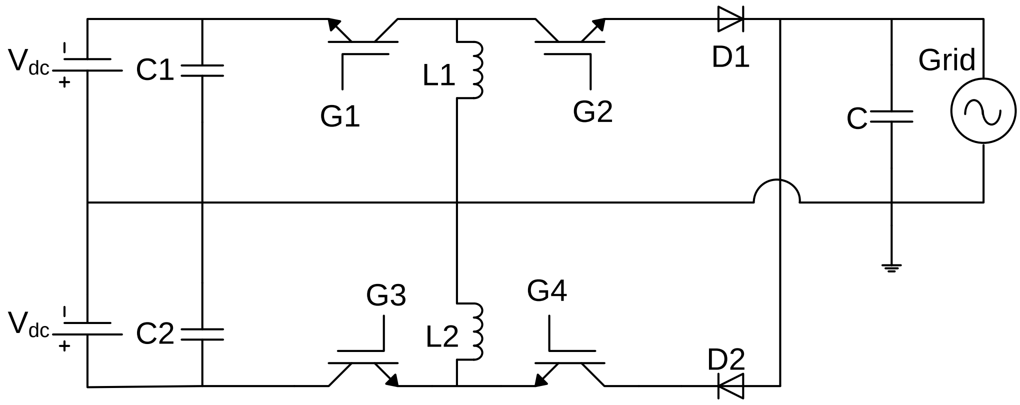

Figure 2.3: Four-switch buck boost inverter by Kasa *et al.*

One of the examples of this single-stage inverter is a buck-boost inverter proposed by Kasa *et al.* as shown in Figure 2.3. Kasa's design is a transformer-less single phase inverter for photovoltaic, PV application which mean that transformer and inductor require to link with the utility grid are not necessary in the design. This inverter is build up from two buck-boost converter connected in anti-parallel to the output capacitor which shares the same output and operation at each half cycle with its own DC source, this mean that the inverter requires two set of PV module. Base on Kasa also the choppers of the inverter is operate on the discontinue connection mode, DCM. (N. Kasa *et al.*, 1999)

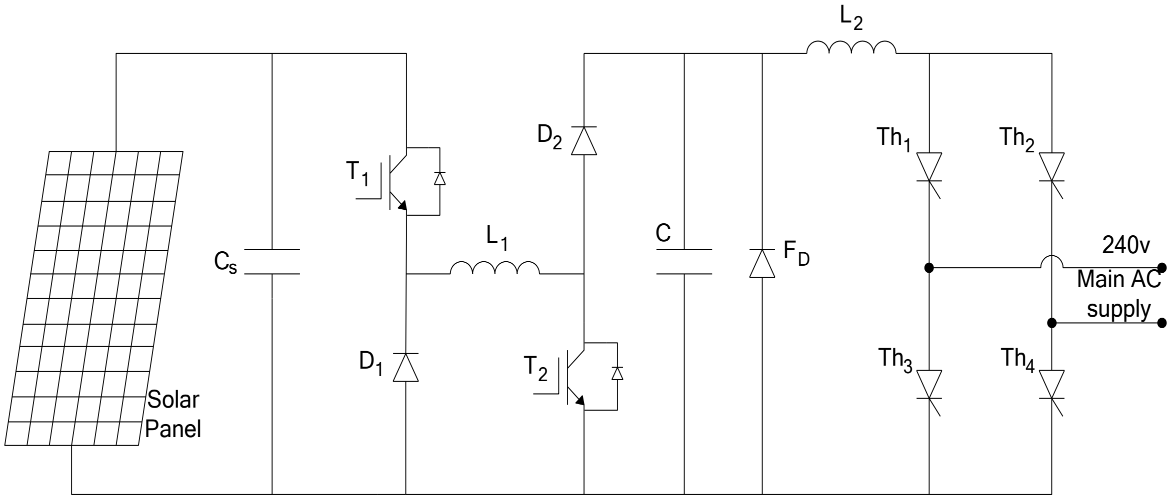

Figure 2.4: Two stage boost inverter by S. Saha and V.P. Sundarsingh

For the multi-stage inverter design, the most comment and simple design that able to perform under most of the situation is proposed by S. Saha and V.P. Sundarsingh as shown in Figure 2.4. The operation of this proposed inverter consists in transferring the solar energy intermittently to an inductor and then sent it into the power utilities grid. At the first stage, it involves T_1, T_2, D_1, D_2, C, L_1, L_2. Here, transformer T_1 and T_2 must be designed to ON and OFF at the same time. When T_1 and T_2 is ON, the energy generated by the solar penal is transferred and stored in L_1. This amount of energy is then transferred to capacitor C and inductor L_2 when T_1 and T_2 are OFF. For the second stage, it involves thyristor Th_1, Th_2, Th_3, Th_4. At here, the DC voltage from the solar penal is changed into AC voltage. Th_1 and Th_4 are designed into 1 group and provide the positive voltage. For the negative voltage, it is provide by Th_2 and Th_3. (S. Saha and V.P. Sundarsingh, 1996)

2.3 Switching Technique

For the inverter that discussed in section 2.2, there are some researchers such as Ned Mohan and *et al.*, in their publications, called this kind of inverter as switch-mode DC-AC inverter. As the name given, the switch-mode DC-AC inverter, switching play a major role in determining the performance of the inverter. Due to the importance of the switching, many of the researchers when designed and proposed their new design of the inverter will seriously look into the design if the switching technique of inverter. In this section, 2 kinds of switching techniques are discussed and which these 2 switching techniques is combined to produce as a kind of hybrid switching technique that is used in the design.

2.3.1 Single Pulse Width Modulation (Square Wave Switching)

For the inverter as shown in Figure 2.1 and as discuss in section 2.1, it require a control signal to switch the power electronic switches. One of these signals is the single pulse width modulation or also known as square wave switching signal. In single pulse width modulation technique, there is only a single pulse produce for each half cycle and which this pulse use to switch two numbers of power electronic switches in the inverter. (Rashid, 2004)

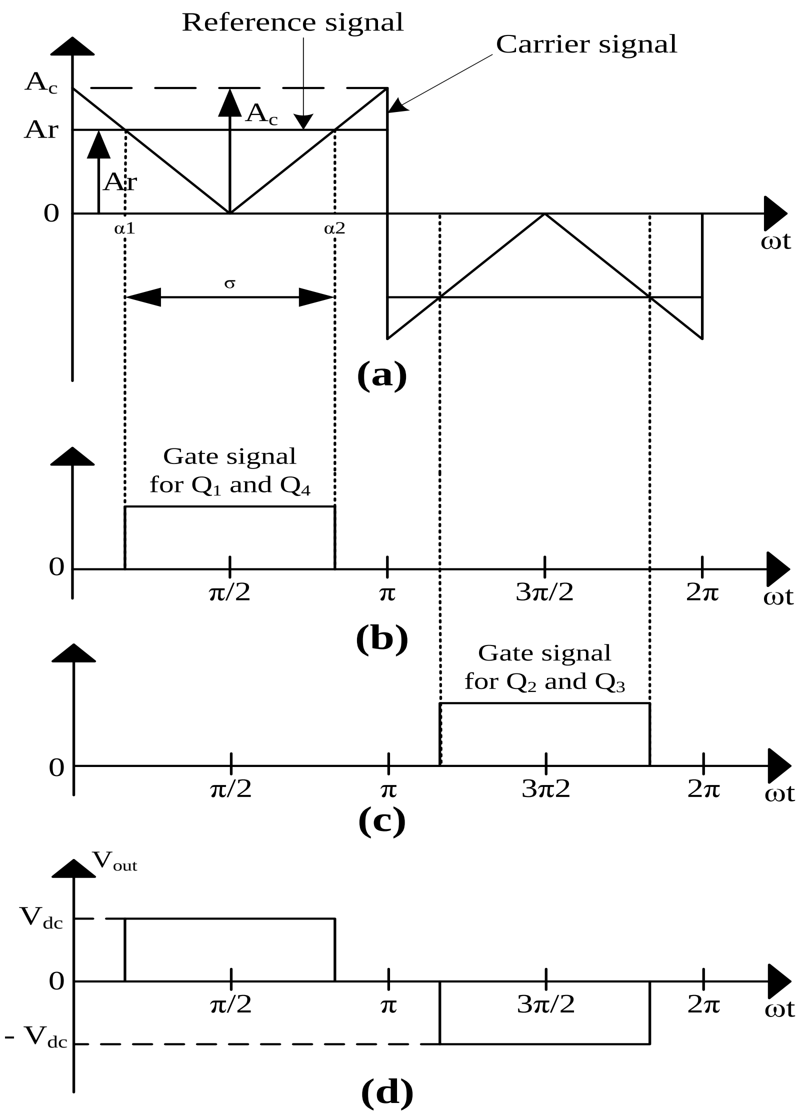

Figure 2.5: Gating signals and output voltage waveform

To produce the switching signal for the single pulse width modulation as shown in Figure 2.5(b) and (c), a rectangular reference signal with variable amplitude A_r and fundamental frequency is compared using a comparator with a triangular carrier signal with fixed amplitude of A_c as shown in Figure 2.5(a). When the magnitude of the instantaneous voltage of the reference signal is higher than the magnitude of the instantaneous voltage of the carrier signal, a pulse is being generated and this pulse signal is used to switch the power electronic switches. For Figure 2.5 (b), it will use to switch G_1 and G_4 in Figure 2.1 to produce a positive voltage across the output. For Figure 2.5 (c), it will use for G_2 and G_3 and will result in negative output voltage as shown in Figure 2.5 (d).

The fundamental frequency of the output voltage will follow the frequency of the reference signal. Any changes in the reference signal frequency will change the output fundamental frequency. So for the application such as UPS and grid tie inverter, the reference is fixed at the line frequency (50 Hz for Malaysia).

Another variable for the single pulse width modulation is the ratio of the maximum amplitude of the reference signal and the carrier signal. This ratio is commonly known as the amplitude modulation and mathematically is defined as shown in equation 2.5. This amplitude modulation will change the width of the control signal pulse. As the amplitude modulation is higher, the width of the control signal pulse become higher and this will result in higher level of output voltage.

$$\text{Amplitude modulation index}, M = \frac{A_r}{A_c} \tag{2.5}$$

Where, M = Amplitude modulation

A_r = Maximum amplitude of the reference signal

A_c = Maximum amplitude of the carrier signal

By applying Fourier series theorem for the output voltage shown in Figure 2.5(d), the instantaneous output voltage of the inverter using this kind of switching can be expressed as shown in equation 2.6.

$$v_{out}(t) = \sum_{n=1,3,5,\ldots}^{\infty} \frac{4V_{dc}}{n\pi} sin\frac{n\sigma}{2} \sin n\omega t \tag{2.6}$$

Where, v_{out} (t) = instantaneous output voltage

V_{dc} = input DC voltage

σ = width of the control signal pulse

ωt = period in radian

The RMS value for the output voltage can be determine using equation 2.7

$$V_{rms} = \left[\frac{2}{2\pi}\int_{\frac{\pi-\sigma}{2}}^{\frac{\pi+\sigma}{2}} V_{dc}^2 d(\omega t)\right]^{\frac{1}{2}} = V_{dc}\sqrt{\frac{\sigma}{\pi}} \tag{2.7}$$

The advantage to have this kind of switching for the inverter is that the switching loss across the power electronic switches of the inverter is lower. Since this switching technique switch the power electronic switches at the line frequency, the frequency of di/dt and dv/dt of the switches is low. Hence this reduces the power loss across the power electronic switches. However, there is a huge disadvantage of this switching technique. The output AC voltages produce by this switching technique is in a form of square wave. Base on the Fourier theorem, the square wave contain a lot of harmonics. These harmonics give negative impact to the load of the inverter, hence it should be eliminated. To reduce these harmonics, the harmonic filter is employed. However, the filter use in eliminating harmonic for square wave is bulky and complex to design. So, a high frequency switching technique is developed to further reduce the harmonic contain of the output voltage before a filter is employed.

2.3.2 Sinusoidal Pulse Width Modulation (SPWM)

In order to improve the weakness of the single pulse width modulation and increase the performance of the inverter, the Sinusoidal Pulse Width Modulation or in short known as SPWM is employed as the switching technique of the inverter. This SPWM is a multiple pulse width modulation, high frequency switching technique. Unlike the single pulse width modulation, the SPWM is having a multiple pulse with various pulse widths over a period for switching. This kind of high frequency, multiple pulse width switching technique gives great improvement the output voltage and current harmonic and minimizes the filter components.

Difference from the single pulse width modulation, the SPWM signal is generated by comparing the high frequency triangle waveform which is in several kHz (also known as Carrier Signal) with line frequency sinusoidal waveform (also known as Reference Signal) as shown in Figure 2.6(a).

As shown in Figure 2.6, the G_1 and G_4 in the inverter shown in Figure 2.1 will control by signal shown in Figure 2.6(b) and produce a positive cycle output voltage. This signal is produced by comparing the line frequency positive sine wave with high frequency triangle wave. For G_2 and G_3 in the inverter, they are controlled by signal

2.6(c) and produce the negative side of the output voltage. This signal however, is produced by comparing line frequency negative sine wave with high frequency triangle wave as shown in Figure 2.6(a). To produce these two SPWM switching signals by using difference polarity sine wave is a challenging and a complex to implement task involving extra circuitry in the control circuit. Fortunately, there is a more preferable and simple method to implement this switching signal as shown in Figure 2.7. In this method, instead of using two polarity sine waves, a unidirectional triangle wave is used. (Lokhande *et a.l*, 2005)

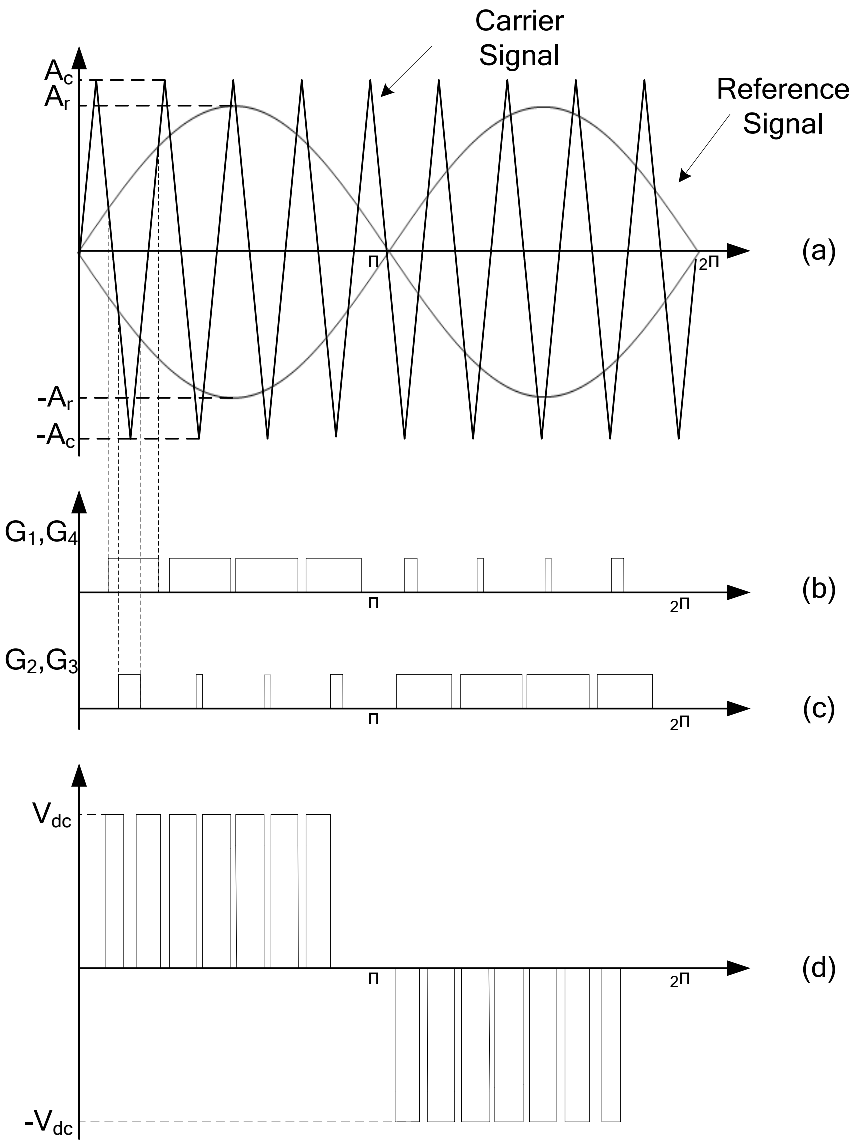

Figure 2.6: SPWM signals and output voltage waveform

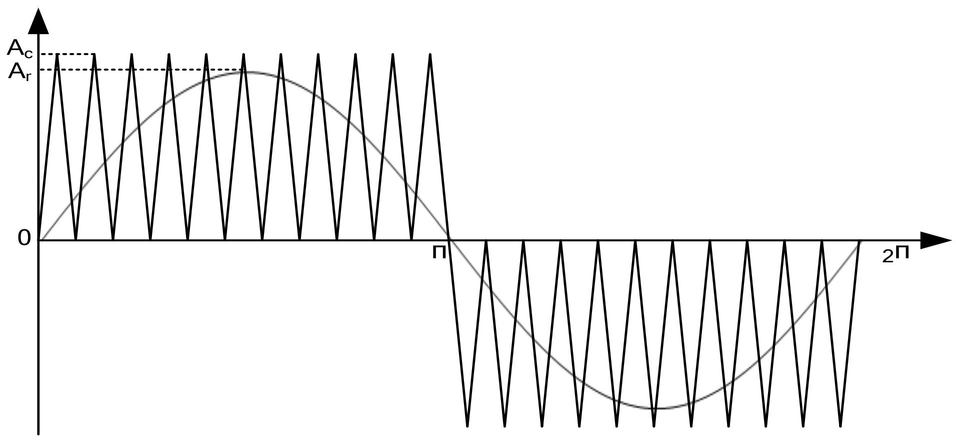

Figure 2.7: Unidirectional triangle wave for generating SPWM.

The RMS output voltage of the inverter that using this switching technique as shown in Figure 2.6 (d) can be given in term of the width of the pulse, δ_m as in equation 2.8.

$$V_{rms} = V_{dc}\left(\sum_{m=1}^{2p}\frac{\sigma_m}{\pi}\right)^{1/2} \qquad (2.8)$$

Where, σ_m = width of pulse m

V_{dc} = input DC voltage

For the instantaneous output voltage of the inverter as shown in Figure 2.6(d) can be express using Fourier Theorem as shown in equation 2.9 and the Fourier constant is shown in equation 2.10.

$$v_o(t) = \sum_{n=1,3,5,..}^{\infty} B_n \sin n\omega t \qquad (2.9)$$

$$B_n = \sum_{m=1}^{2p}\frac{4V_s}{n\pi}\sin\frac{n\sigma_m}{4}\left[\sin n\left(\alpha_m + \frac{3\sigma_m}{4}\right) - \sin n\left(\pi + \alpha_m + \frac{\sigma_m}{4}\right)\right] \qquad (2.10)$$

One of the parameter for the SPWM switching technique that will influence the performance of the inverter is the ratio of the maximum voltage level of the reference signal, A_r and maximum voltage level of the carrier signal, A_c. This ratio is commonly known as the amplitude modulation, M. Mathematically it can be shown in equation 2.5 same as in the square wave switching technique. (Cheng and Cheng, 1999)

This amplitude modulation will greatly influence the peak of the output voltage. The fundamental output voltage of the inverter which having the SPWM as control signal can be approximately found by equation 2.12 for the amplitude modulation that less then unity. (Rashid, 2004)

$$V_{m1} = \mathrm{M} \times \mathrm{V_{dc}} \qquad for\ 0 \leq \mathrm{m} \leq 1 \qquad (2.11)$$

The amplitude modulation also has a possibility to growth over the unity value. The operation beyond M =1 is known as over-modulation. Normally, over-modulation will increase the magnitude of the fundamental output voltage. However, it also will adds more harmonic contain to the output voltage and result it to be more square wave. (H. Patil *et al.*,2008) When M = 4/π = 1.278, the output voltage be become a square wave as the output of the single pulse width modulation. (Mohan *et al., 2004)* So, for the application where the output voltage waveform with low harmonic contains is importance such as UPS or GTI, over-modulation is avoided.

Another parameter that play improtance role in determine the performance of the inverter which having SPWM as switching technique is the frequency modulation, M_f. It is define as the ratio of the frequency of the carrier signal, f_c and the frequency of the reference signal, f_r. (Chen and Cheng, 2004). Mathematically it is given in equation 2.12. The value of M_f will strongly influence the output voltage harmonic contains. This value should be in odd integer. This is because odd integer of

M_f will result in odd symmetry waveform. So, base of Fourier theorem the output voltage will only have odd harmonic contain and the even harmonic is cancel out. (Mohan *et al.*, 2004)

$$M_f = \frac{f_c}{f_r} \tag{2.12}$$

Where, M_f = Frequency modulation

f_r = Frequency of the reference signal

f_c = Frequency of the carrier signal

The advantage of the inverter to have SPWM as switching signal is the output voltage will contain lesser harmonic and hence require smaller and simple harmonic filter. This is very importance factor for the inverter that requires a nearly perfect sine wave AC output such as GTI or UPS. However, this kind of switching technique will result in higher loss across the power electronic switches of the inverter. Since SPWM is a high frequency switching technique, the frequency of di/dt and dv/dt happen across the MOSFET is more then the single pulse width modulation, so this changing of voltage and current will result in the power losses. Since this power loss happen across the switches, the lost power will heat it up and result in shorter life time of the switches. Besides, the SPWM switching technique also will result in an audio able sound across the switches and result in electromagnetic interference (EMI).

Using SPWM for the switching of the inverter had been proposed by a lot of the designer and researcher, one group of them is leading by C. Sanabria. Sanabria and his term in their research paper named “PWM switching patterns optimization for multilevel inverter using FPGA” had proposed using a pre-program FPGA to generate the switching signal of PWM as shown in the block diagram of Figure 2.8. This design uses one PWM signal sinusoidal. The signal has phase shifted applied by counters for obtaining the signals remaining. These phases shifted are function of levels number and of the switching frequency. (C. Sanabria *et al.*, 2004)

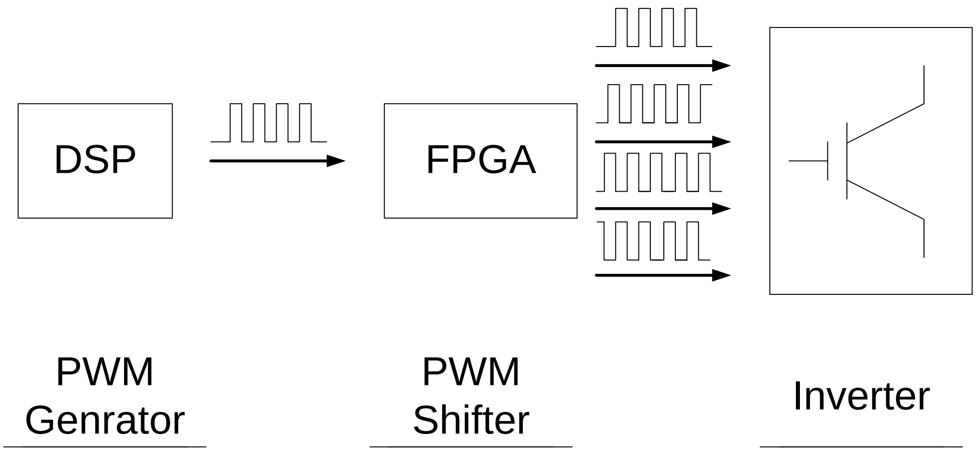

Figure 2.8: Block diagram for Sanabria proposed scheme.

Another group of researcher leading by Katsunori Taniguchi in their paper title "Novel strategy for soft-switching PAM inverter system" published in Power Conversion Conference at Osaka, Japan proposed a modify of PWM which call pulse amplitude modulation (PAM) as the switching.

Base on Katsunori Taniguchi and his team, the PAM signal is produce by replacing the sinusoidal modulating signal in PWM with the modified trapezoidal modulating signal and the triangular carrier signal is replaced by a modified saw-tooth wave that has the flat portion as shown in Figure 2.9. (Katsunori Taniguchi *et al.*, 2002)

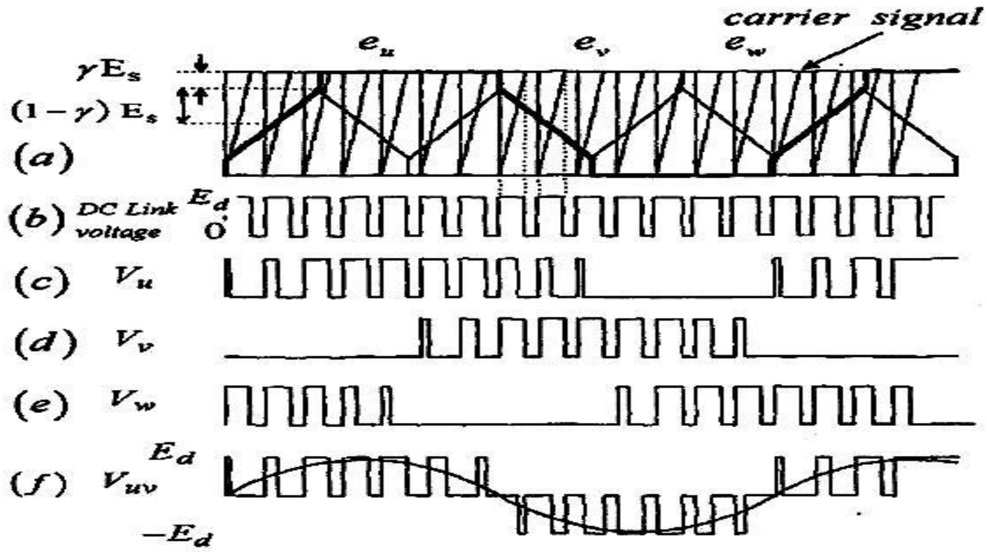

Figure 2.9: Switching signal for PAM inverter

Besides that, there is a group of researcher from University of Florida, R.S. Lai and K.D.T. Ngo had proposed a kind of hybrid switching system named hybrid sinusoidal pulse width modulation (HSPWM) to reduce the switching loss of the inverter. Base on the paper the published by them, two of the four switches in the H-bridge inverter can operate at the output frequency and the other two of that switches in the inverter can operate at the high frequency pulse width modulation. With this kind of switching, base on the author the switching loss can be reduce by the factor of two. (R.S. Lai and K.D.T. Ngo, 1995)

Moreover, a group of Taiwan researchers on year 2001 using a modify version of HSPWM by Lai and Ngo to manage the switches temperature of the inverter. According to the researchers, HSPWM developed by Lai and Ngo result in uneven temperature distributed in the four switches. They had proposed that the switches are control by both high and low frequency signal. For one half of the cycle, the switch is control using low frequency signal and for the next one half, it will control by high