بِسْمِ اللهِ الرَّحْمٰنِ الرَّحِيْمِ

Start with the name of Allah the most merciful and blessing.

Near East University

1988

Faculty of Engineering

Department of Electrical and Electronic Engineering

Graduation Project

Pulse Width Modulation Techniques

Theory and Applications

Supervisor:

Prof.
Dr. Khalil Ismailov

Submitted by:

Aftab Ahmed Malik

Dedications

I dedicate my graduation project to
The memory of my loving maternal grand mother,

Fatema Saifal Khan.

Who passed away while this work was in progress,

And to
My dear parents,

Mr. Abdul Khaliq Malik and Zubaida Begum Malik.

Acknowledgements

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Whom extreme patience, assistance and support, Played a key role during the formation of my graduation project. Dr. Khalil's profound knowledge, guidance and supervision lead me to greater understanding of the topic together with the enhancement of my knowledge in pulse width modulation techniques. Without his responsive and helpful suggestions it would not have been possible for me to indicate the clearest approach to the topic.

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My name is Aftab Ahmed Malik. I am from Islamic Republic of Pakistan. I belong to a landlord family from district Chakwal (Punjab). My father is also an electrical engineer. I have received my elementary education from my native district. I have studied at F.G higher secondary school G-8/4 Islamabad. I have obtained a hi-tech diploma in Computer Electronics and Telecommunications from university of the Punjab. I came to Turkish republic of northern Cyprus for higher education in Electrical and electronic engineering, in the year 1994. Inshallah I am going to graduate in spring semester 1998-99 this year.

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Chapter 1

INTRODUCTION TO PULSE WIDTH MODULATION

Introduction

The hi-tech technology can assist an electronics engineer in industry in the solution of two fundamental types of problems, viz. the transformation of electrical power and execution of process, such as measuring, converting controlling etc.

The branch of hi-tech technology, which has revolutionized the concept of power control and power conversion using solid state semiconductor devices, is power electronics. Power electronics combine power, control and electronics. The rapid development in recent years, primarily because of solid state semiconductor devices, make it possible to build an excellent switches to employ for the conversion and controlled switching operation of the parameters,

such as voltage, current, power, frequency and waveform.

Pulse width modulation is the most efficient and popular control technique which is widely used in many industrial applications, including power electronic converters, regulated power supplies, inverters, electric vehicles, choppers, transformers, modulators, amplifiers and in other motor control systems.

Pulse width modulation plays an important role in all sorts of systems and enable improved, more efficient, accurate control and regulation methods.In pulse width modulation there are different methods of varying the widths of the pulses. The pulse width modulation topic of graduation project is divided into ten chapters.

Chapter 2

PULSE WIDTH MODULATED CONVERTERS

In most practical applications it is necessary to change an electric power from one form to another. A circuit that performs this switching action is called a converter. The basic function of a static power converter is to convert **ac**-input voltage into a controllable dc output voltage.

A converter makes use of a configuration of power semiconductor devices (power diodes and thyristors) that function as switch. The choice of a particular device will depend on the voltage, current and speed requirements of a converter. These devices are made to turn on and turn off respectively in such a way as to implement the required conversion function.

In the terminology of power electronics, it has become common to describe the turn off switching of the device itself as "commutation". The power factor of phase-controlled converters depends on delay angle, and is in general low, especially at the low output voltage range. These converters generate harmonics into the supply. Forced commutation can improve the input power factor and reduce the harmonic levels. The forced commutation can be implemented in practical systems by the use of pulse-width modulation technique.

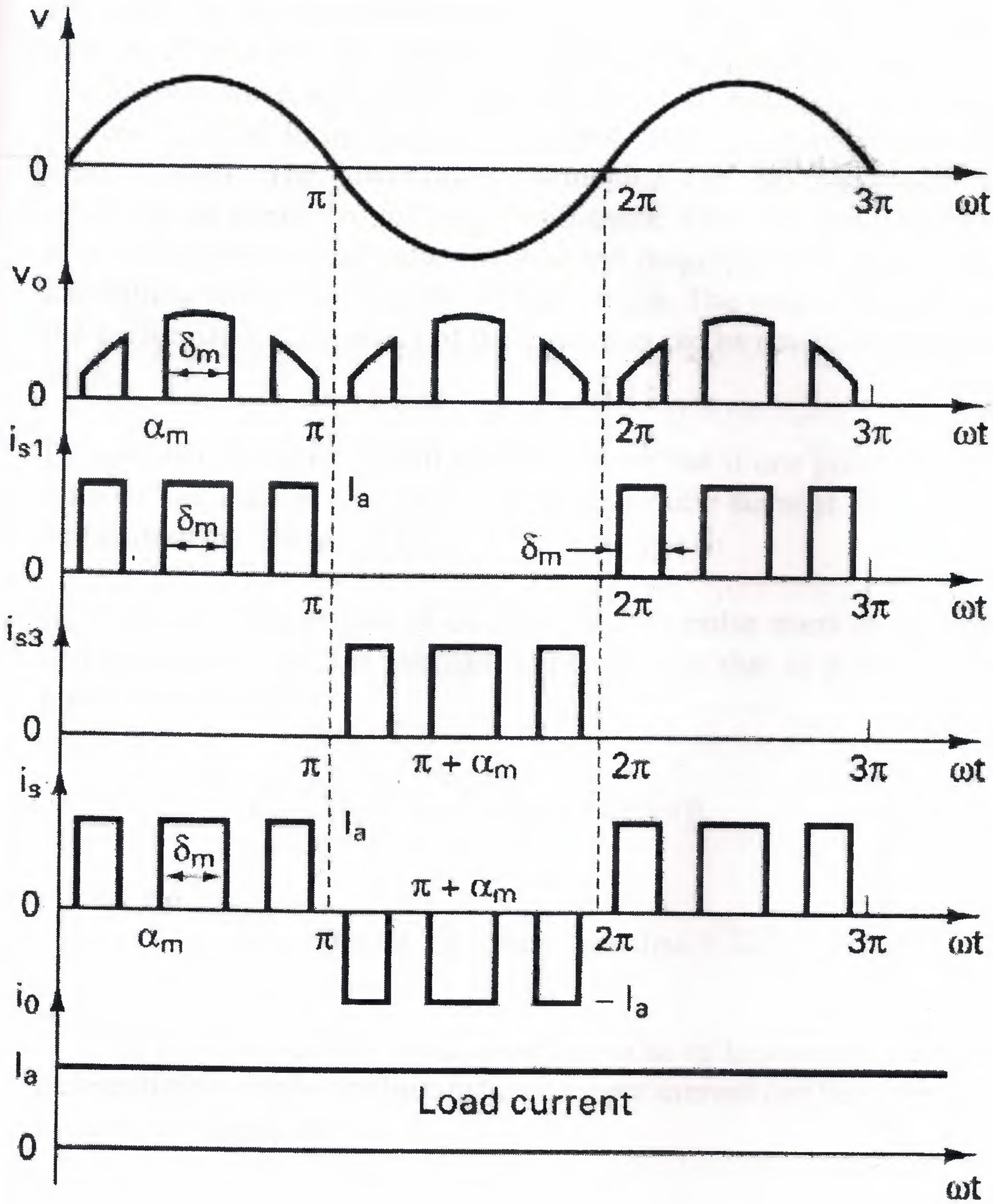

Figure 2.1
Input, output voltage and input current waveform.

In pulse width modulation techniques, the converter switches are turned on and off several times during a half-cycle and the output voltage is controlled by varying the width of firing pulses. Comparing a triangular wave with a dc signal as shown in figure 2.2 generates the gate signals. In the figure-a the input voltage output voltage and input current. The lower-order harmonics can be eliminated by selecting the number of pulses per half-cycle. However increasing the number of pulses would also increase the magnitude of higher-order harmonics, which could easily be filtered out. The output voltage and the performance parameters of the converter can be determined in two steps:

By considering only one pair of pulses such that if one pulse starts at $\omega t = \alpha_1$ and ends at $\omega t = \alpha_1 + \delta_1$, the other pulse starts at $\omega t = \pi + \alpha_1$ and ends at $\omega t = \pi + \alpha_1 + \delta_1$.

By combining the effects of all pairs. If m-th pulse starts at $\omega t = \alpha_m$ and its width is δ_m, the average output voltage due to p number of pulses is found from

$$V_{dc} = \sum_{m=1}^{P} \left[2 / 2\pi \int_{\delta m}^{\alpha m + \delta m} V_m \sin \omega t \, d(\omega t)\right]$$

$$= V_m / \pi \sum_{m=1}^{P} \left[\cos\alpha_m - \cos(\alpha_m + \delta_m)\right]$$

If the load current with an average value of I_a is continuous and has negligible ripple, the instantaneous input current can be expressed in a Fourier series as

$$i_s(t) = I_{dc} + \sum_{m=1,3,\ldots}^{\infty} \left[a_n \cos n\omega t - b_n \sin n\omega t\right]$$

Due to symmetry of the input current waveform, there will be no even harmonics and I_{dc} should be zero and the coefficient of

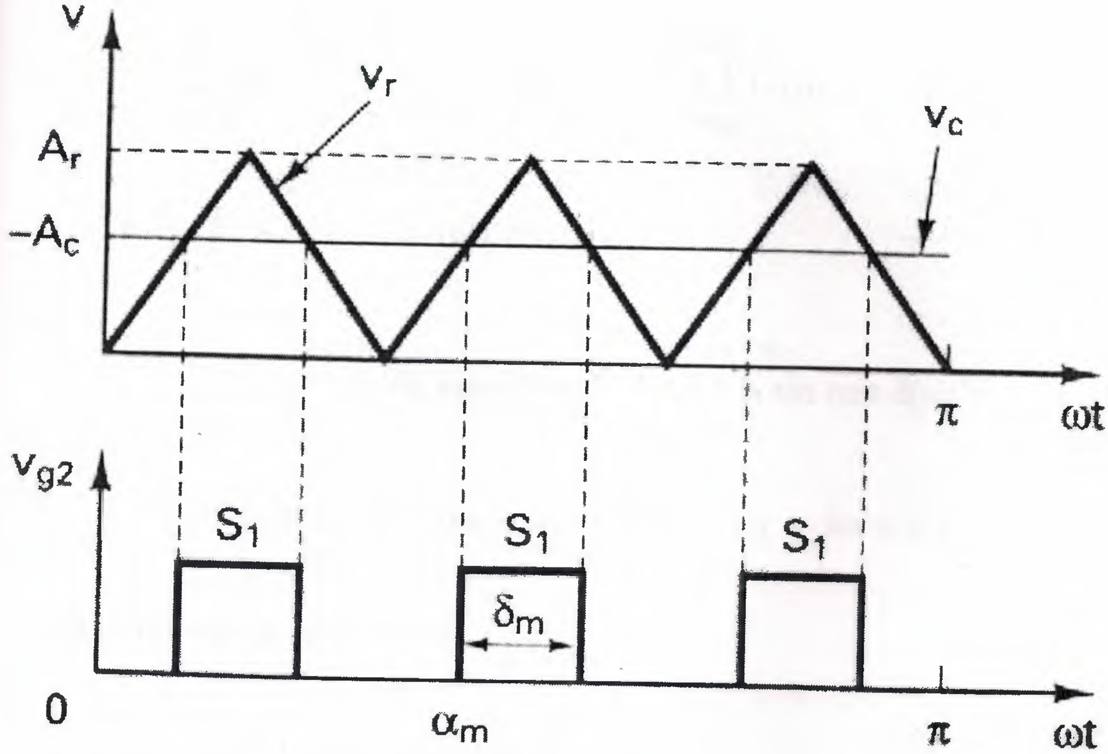

Figure 2.2
Pulse width modulated converter.

equation are

$$a_n = [1 / \pi \int_0^{2\pi} i_s(t) \cos n\omega t \; d(\omega t)]$$

$$= \sum_{m=1}^{P} [1 / \pi \int_{\alpha m}^{\alpha m + \delta m} I_a \cos n\omega t \; d(\omega t) \;-\; 1 / \pi \int_{\pi + \alpha m}^{\pi + \alpha m + \delta m} I_a \cos n\omega t \; d(\omega t)] = 0$$

$$b_n = [1 / \pi \int_0^{2\pi} i_s(t) \;\sin n\omega t \; d(\omega t)]$$

$$= \sum_{m=1}^{P} [\, 1 / \pi \int_{\alpha m}^{\alpha m + \delta m} I_a \sin n\omega t \; d(\omega t) \;-\; 1 / \pi \int_{\pi + \alpha m}^{\pi + \alpha m + \delta m} I_a \sin n\omega t \; d(\omega t)]$$

$$= \; 2I_a / n\pi \sum_{m=1}^{P} [\cos n\alpha_m \;-\; \cos n(\alpha_m + \delta_m)] \qquad \text{for } n = 1,3,5,.....$$

Equation can be rewritten as

$$= \sum_{n=1,3....}^{\infty} [\sqrt{2}\, I_n \,\pi \sin (n\omega t + \phi_n)]$$

Where $\phi_n = \tan -1(a_n / b_n) = 0$ and $In = \sqrt{[a_n^2 + b_n^2]} / \sqrt{2} = bn / \sqrt{2}$

Sinusoidal pulse width modulated converter

In Sinusoidal pulse modulation technique, the pulse widths are generated by comparing a triangular reference voltage V_r of amplitude A_r and frequency f_r with a carrier half-sinusoidal voltage V_c of variable amplitude A_c and frequency $2f_s$. The sinusoidal voltage V_c is in phase with the input phase voltage V_s and has the twice the supply frequency f_s. Changing the amplitude A_c varies the width of the pulses (and the output voltage). In sinusoidal pulse-width modulation, the displacement factor is unity and the power factor is improved. The lower order harmonics are eliminated. For example with four pulses per half-cycle the lowest-order harmonic is the fifth and with the six pulses per half-cycle the lowest-order harmonic is the seventh.

Definition

The modulation index is defined as

$$M = A_c / A_r$$

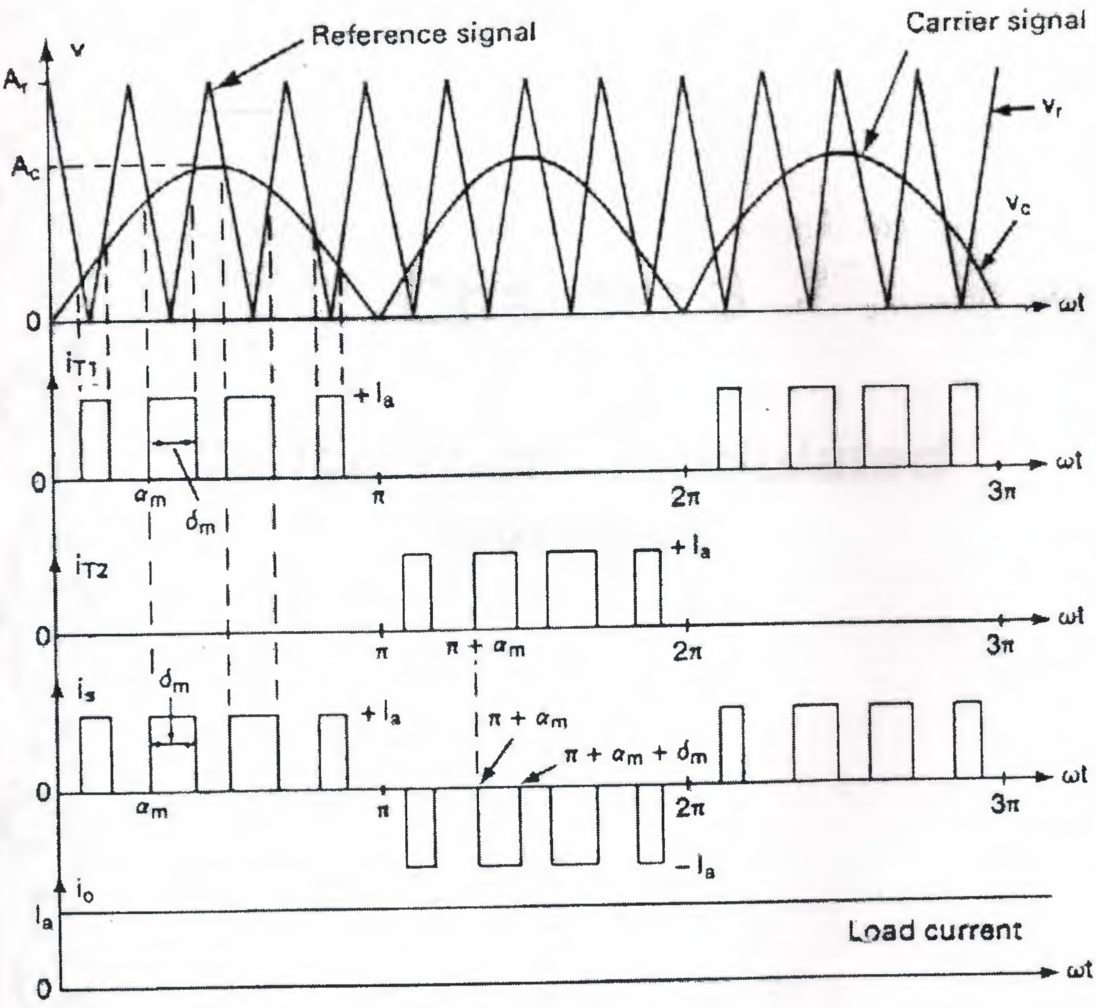

Figure 2.3
Sinusoidal pulse width modulated converter waveform.

Chapter 3

Pulse Width Modulated Inverters

Pulse Width Modulated Inverters

An inverter is a device, which converts from dc input into an ac output without any rotating machines. The power circuit configuration of an inverter consists of semiconductor power devices that function as a static switch. The inverter also has a switching control circuit that provides the necessary pulses to turn on and off each static-switching element with the correct timing and sequence.

For a practical power control applications of an inverter it is necessary to adjust the ac frequency and the magnitude of a voltage. Varying the input dc voltage to the inverter can make the voltage adjustment. The voltage control is external to the inverter and is independent of the switching the inverter configuration. The alternative way of ac voltage variation is within the inverter by a pulse width modulation technique, which is used for implementing voltage control.

A typical voltage waveform of a pulse-width modulation inverter is shown . It may treat the interval from t_1 to t_4 as one half-period of the ac voltage and t_4 and t_7 as the negative half-period. During the positive half-period, the output voltage consists of a single pulse of amplitude V_1 and of duration t_2 to t_3, which is shorter than the total half-period.

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Therefore the mean square value of the ac output voltage will be given by

$$Sqr(V_{ac}) = Sqr(DV_1)$$

Therefore we get the rms value of the ac output voltage as

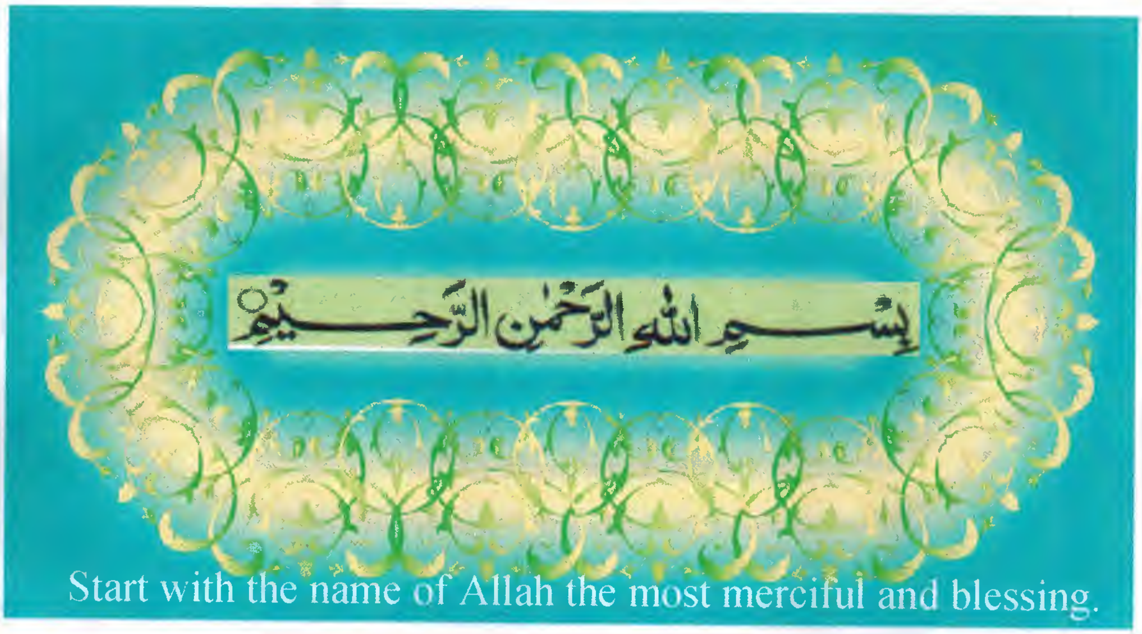
$$V = Sqr(D)\, V_1$$

If the pulse-width modulation is to be implemented in an interval according to this pattern, it is necessary to achieve the following.

During the interval t_1 and t_2 , the voltage across the load has to be maintained at zero. From t_2 to t_3, it has to be constant at V_1.Then from t_2 to t_4, it again has to be zero. Similarly statements apply for the next half-period , with due consideration for the voltage polarity.

The most commonly used pulse width modulation methods are the following.

Single pulse width modulation.
Multiple pulse width modulation.
Sinusoidal pulse width modulation.
Modified sinusoidal pulse width modulation.



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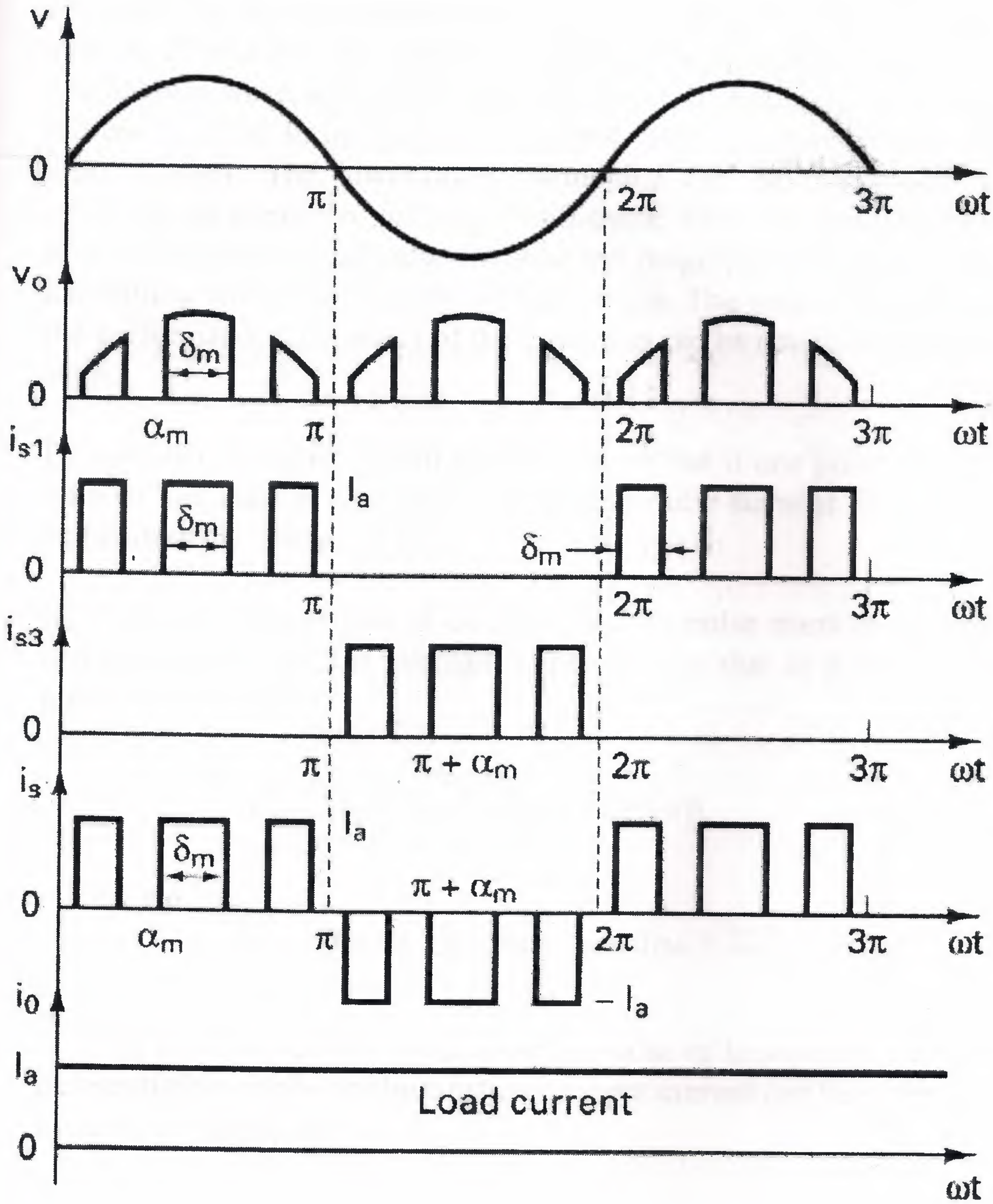

Figure 2.1
Input, output voltage and input current waveform.

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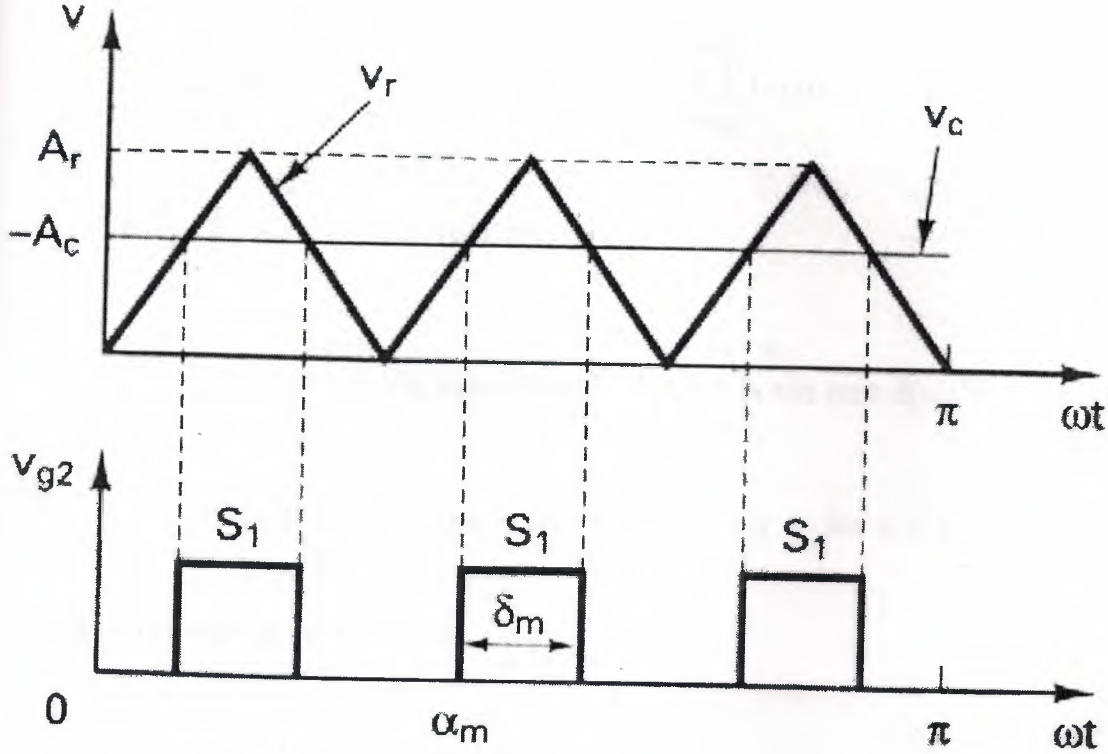

Figure 2.2
Pulse width modulated converter.

equation are

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Sinusoidal pulse width modulated converter

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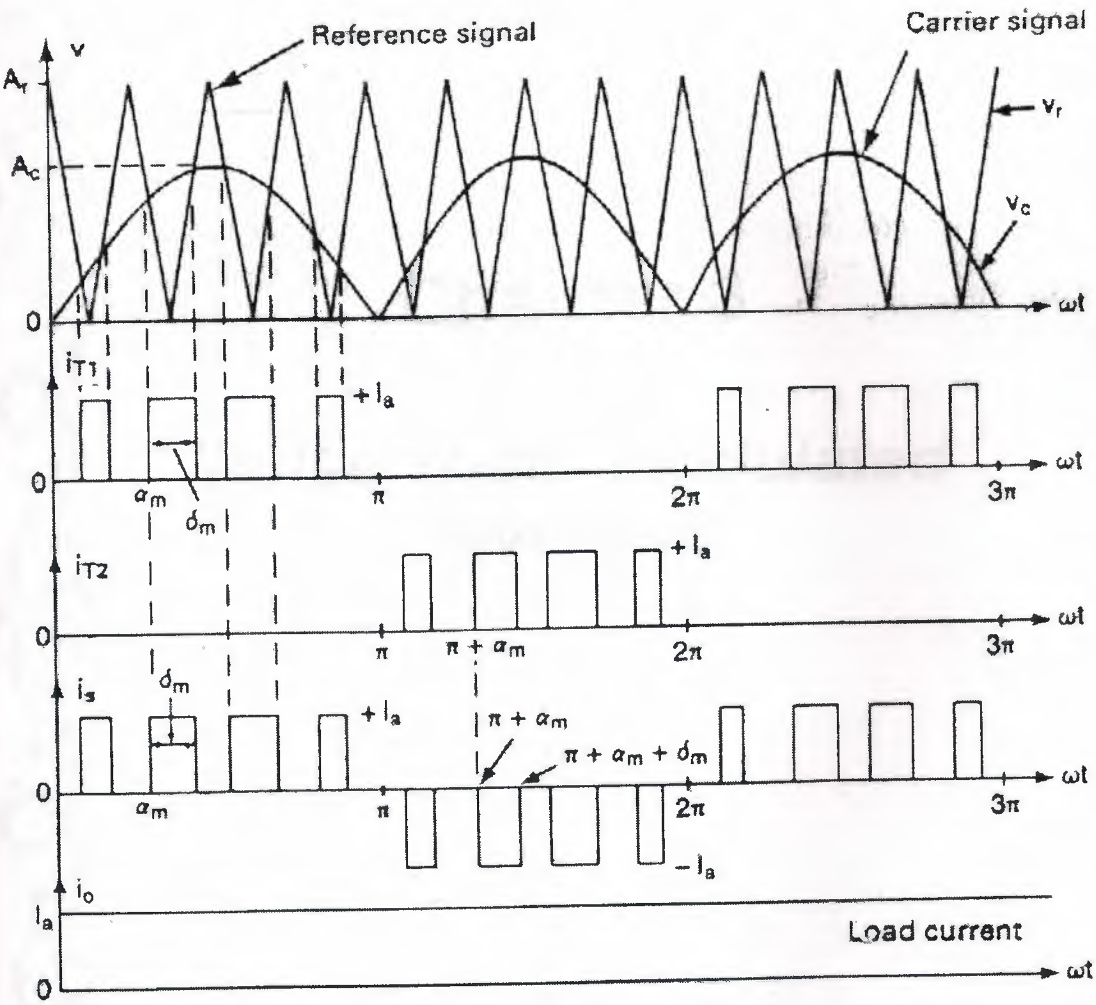

Figure 2.3
Sinusoidal pulse width modulated converter waveform.

Chapter 3

Pulse Width Modulated Inverters

Pulse Width Modulated Inverters

An inverter is a device, which converts from dc input into an ac output without any rotating machines. The power circuit configuration of an inverter consists of semiconductor power devices that function as a static switch. The inverter also has a switching control circuit that provides the necessary pulses to turn on and off each static-switching element with the correct timing and sequence.

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A typical voltage waveform of a pulse-width modulation inverter is shown . It may treat the interval from t_1 to t_4 as one half-period of the ac voltage and t_4 and t_7 as the negative half-period. During the positive half-period, the output voltage consists of a single pulse of amplitude V_1 and of duration t_2 to t_3, which is shorter than the total half-period.

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$$\mathrm{Sqr}\,(V_{ac}) = \mathrm{Sqr}\,(DV_1)$$

Therefore we get the rms value of the ac output voltage as

$$V = \mathrm{Sqr}\,(D)\,V_1$$

If the pulse-width modulation is to be implemented in an interval according to this pattern, it is necessary to achieve the following.

During the interval t_1 and t_2 , the voltage across the load has to be maintained at zero. From t_2 to t_3, it has to be constant at V_1.Then from t_2 to t_4, it again has to be zero. Similarly statements apply for the next half-period , with due consideration for the voltage polarity.

The most commonly used pulse width modulation methods are the following.

Single pulse width modulation.
Multiple pulse width modulation.
Sinusoidal pulse width modulation.
Modified sinusoidal pulse width modulation.

Single-pulse width modulation

In single-pulse width modulation method, there is only one pulse per half cycle and the width of the pulse is varied to control the output voltage of the inverter. In order to accomplish this modulation method independent commutation of SCRs is necessary. A circuit implying independent commutation for PWM regulation technique is shown in figure1, SCR_1 and SCR_2 are the two main load carrying SCRs and SCR_3 and SCR_4 are two auxiliary SCRs which are of smaller rating. C_1 and C_2 are two separate commutating capacitors. When SCR_1 is turned on, power is delivered to the load and at the same time, C_1 is charged to the voltage of the transformer section AB with a polarity as shown. SCR_1 can be turned off at any desired instant by triggering SCR3. After an interval, SCR_2 is turned on to deliver power in the negative half cycle. C_2 is charged at the same time by the voltage of the transformer section CD. Firing SCR4 turns off SCR2. This method produces a quasi-square wave output as shown in figure2.

The Fourier series can express a perfect square wave.

$$V_{\omega t} = 4V_{dc}/\pi[\sin\omega t + \sin 3\omega t / 3 + \sin 5\omega t / 5 + ...]$$

In the above series, only odd harmonics are present. The total harmonic distortion

$$\text{Total harmonic distortion} = [(\sum_{n=1,3,5,....}^{\infty} A_n^2)^{1/2} / A_1]$$

Where

$$A_1 = [4V_{dc} / \pi] \cos\theta$$

$$A_3 = [4V_{dc} / 3\pi] \cos 3\theta$$

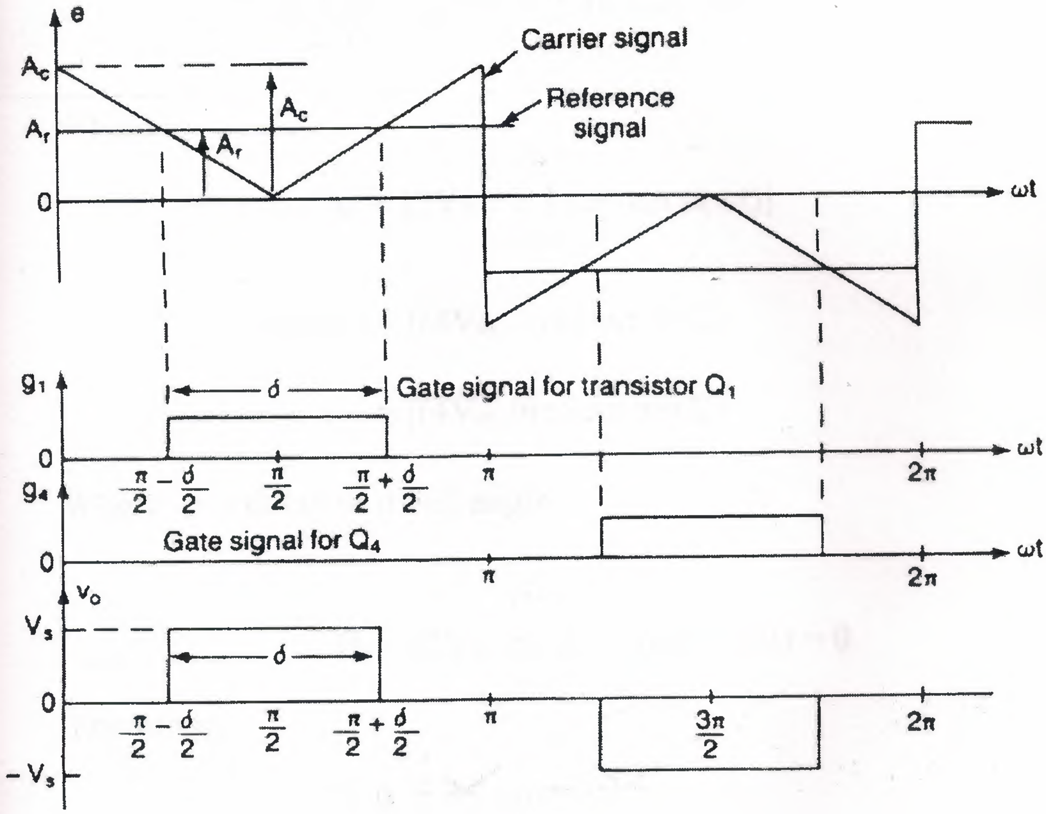


Figure 3.1
Single pulse width modulation.

$$A_5 = [4V_{dc} / 5\pi] \cos 5\theta$$

For a square-wave, total harmonic distortion is about 47%. The voltage waveform in the figure can be expressed by the series,

$$V_L = \sum_{n=1,3,5,....}^{\infty} A_n \sin n\omega t + \sum_{n=1,3,5,....}^{\infty} B_n \cos n\omega t$$

Where

$$A_n = [2V_{dc} / \pi \int_{(\pi - \delta)/2}^{(\pi + \delta)/2} \sin n\omega t \, d(\omega t)]$$

$$(\pi - \delta/2) = [(4V_{dc} / n\pi) \sin n\delta/2]$$

$$= [(4V_{dc} / n\pi) \cos n\alpha/2]$$

Where α = delay or dwell angle

$$B_n = (2V_{dc} / \pi) \int_{(\pi-\delta)/2}^{(\pi+\delta)/2} \cos n\omega t \, d(\omega t) = 0$$

Therefore,

$$V_L = \sum_{n=1,3,5,...}^{\infty} A_n \sin n\omega t$$

The rms value of each harmonic depends on the pulse width δ. That means it depends on magnitude of the output voltage. The rms value of the n-th harmonic is

$$V_n / V_{dc} = [(2\sqrt{2} / n\pi) \sin n\delta/2]$$

$$= [(2\sqrt{2} / n\pi) \cos n\delta/2]$$

The rms harmonic content is shown against delay angle α in figure 3.1. It is seen that the rms voltage of the fundamental component decreases with α together with the mean output voltage. But the ratio of higher harmonic components and the fundamental components decreases at the same time. The third harmonic is eliminated if α is equal to $\pi/3$.

Pulse width modulation for regulation is also possible in bridge and half-bridge inverters. In a bridge inverter, it is easier to accomplish that in the half bridge circuit; because in half bridge circuit the load voltage can never be reduced to zero for any interval of time but, it will be either $+V_{dc}/2$ or $-V_{dc}/2$.

In a half-bridge circuit the pulse width modulation accomplished by reversing the voltage for short intervals in each half cycle as shown in figure 3.2. In the wave form, there are two reverse voltages of duration (δ_2 - δ_1) per cycle. The waveform has quarter wave symmetry and hence can be represented by

$$V_L = \sum_{n=1,3,5,..}^{\infty} A_n \sin n\,\omega t$$

Where

$$A_n = 4/\pi(V_{dc}/2)\left[\int_0^{\delta 1} \sin n\omega t\, d(\omega t) - \int_{\delta 1}^{\delta 2} \sin n\omega t\, d(\omega t) + \int_{\delta 2}^{\pi/2} \sin n\omega t\, d(\omega t)\right]$$

$$= 4/n\pi(V_{dc}/2)[1- 2\cos n\delta_1 + 2\cos n\delta_2]$$

By the selection of proper values of δ_2 and δ_1 certain harmonics from the output can be eliminated. The third and the fifth harmonics are eliminated if δ_2 = 33.3degree and δ_1 =23.62 degree.

The regulation of the output voltage of a single phase inverter can also be obtained by connecting the outputs of two identical square-wave inverters of the same frequency in series, and there relative phases are controlled from 0 to π. The mean value of the combined output voltage decreases from 0 to π.

Multiple pulse-width modulation

In this method several pulses in each half-cycle are used. Multiple pulse-width modulation is effective in reducing the harmonic contents in the output voltage, particularly at lower output levels. Multiple pulses per half-cycle are produced by switching **on** and **off**,
a particular SCR many times before controlling the next SCR.

The control waveform is achieved by comparing a sine wave of variable amplitude of a particular frequency f_o and f_c, determines the number of pulses per half cycle, 'N'. The modulation index controls the output voltage. This type of modulation is also known as uniform pulse width modulation. The number of pulses per half-cycle is found from.

$$N = \underline{f_c / 2f_o}$$

Where $m_f = f_c / f_o$ is defined as the frequency modulation ratio.

The variation of modulation index M from 0 to1 varies the pulse width from 0 to π/N and the output voltage from 0 to V_s. The output voltage for single phase bridge inverters is shown in figure3.1 for multiple Pulse Width Modulation.

If δ is the width of each pulse, the rms output voltage can be found from

$$V_o = [2p/2\pi \int_{(\pi/P+\delta)/2}^{(\pi/P+\delta)/2} V_s \, d(\omega t)]^{1/2} = V_s (\sqrt{P\delta/\pi})$$

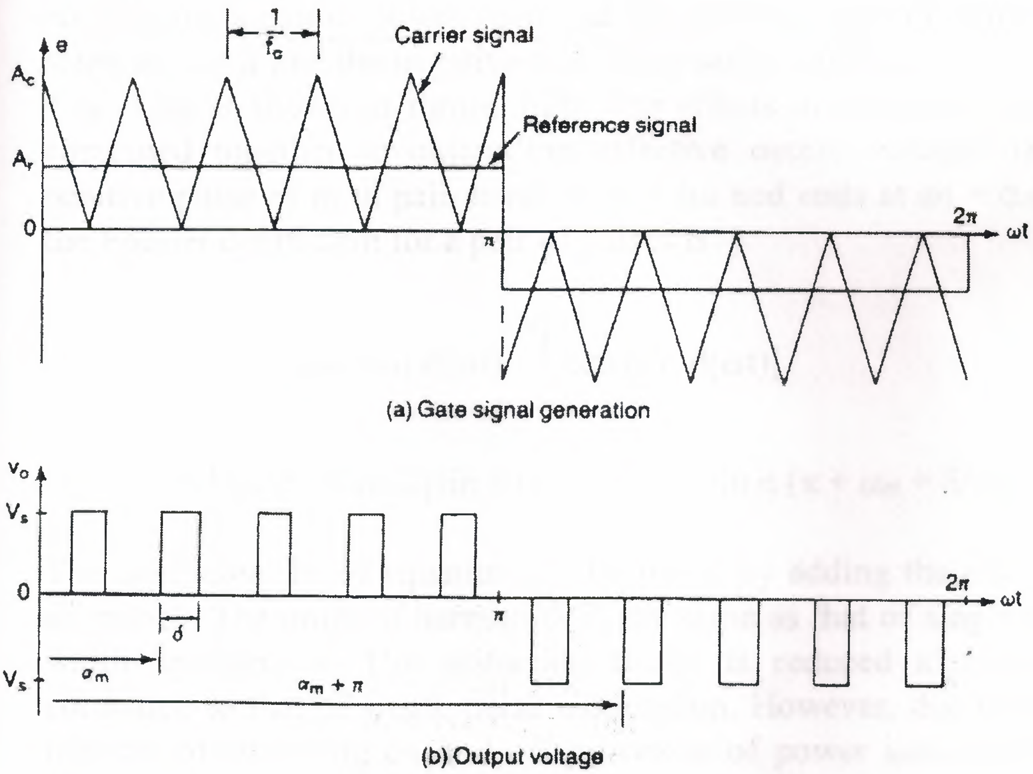


Figure 3.2
Multiple Pulse Width Modulation.

The general form of Fourier series for the instantaneous output voltage is

$$V_o(t) = \sum_{n=1,3,5,\ldots}^{\infty} B_n \sin n\omega t$$

The coefficient B_n in above equation can be determined by considering a pair of pulses such that the positive pulse of duration δ starts at $\omega t = \alpha$ and the negative one of the same width starts at $\omega t = \pi + \alpha$. This is shown in figure 3.2b. The effects of all pulses can be combined together to obtain the effective output voltage. If the positive pulse of m-th pair starts at $\omega t = \alpha_m$ and ends at $\omega t = \alpha_m + \pi$, the Fourier coefficient for a pair of pulses is

$$b_n = 1/\pi \left[\int_{\alpha m}^{\alpha m+\delta} \cos n\omega t \, d(\omega t) - \int_{\pi+\alpha m}^{\pi+\alpha m+\delta} \cos n\omega t \, d(\omega t) \right]$$

$$= 2V_s/n\pi \sin n\delta/2 [\sin n(\alpha_m + \delta/2) - \sin n(\pi + \alpha_m + \delta/2)]$$

The coefficient B_n of equation can be found by adding the effects of all pulses. The order of harmonics is the same as that of single pulse width modulation. The distortion factor is reduced significantly compared to that of single pulse modulation. However, due to larger number of switching on and off processes of power semiconductor devices, the switching losses would increase. With larger values of 'N', the amplitudes of lower-order harmonics would be lower, but the amplitudes of some higher-order harmonics would increase. However such higher-order harmonics produce negligible ripple or can easily be filtered out.

Sinusoidal Pulse Width Modulation

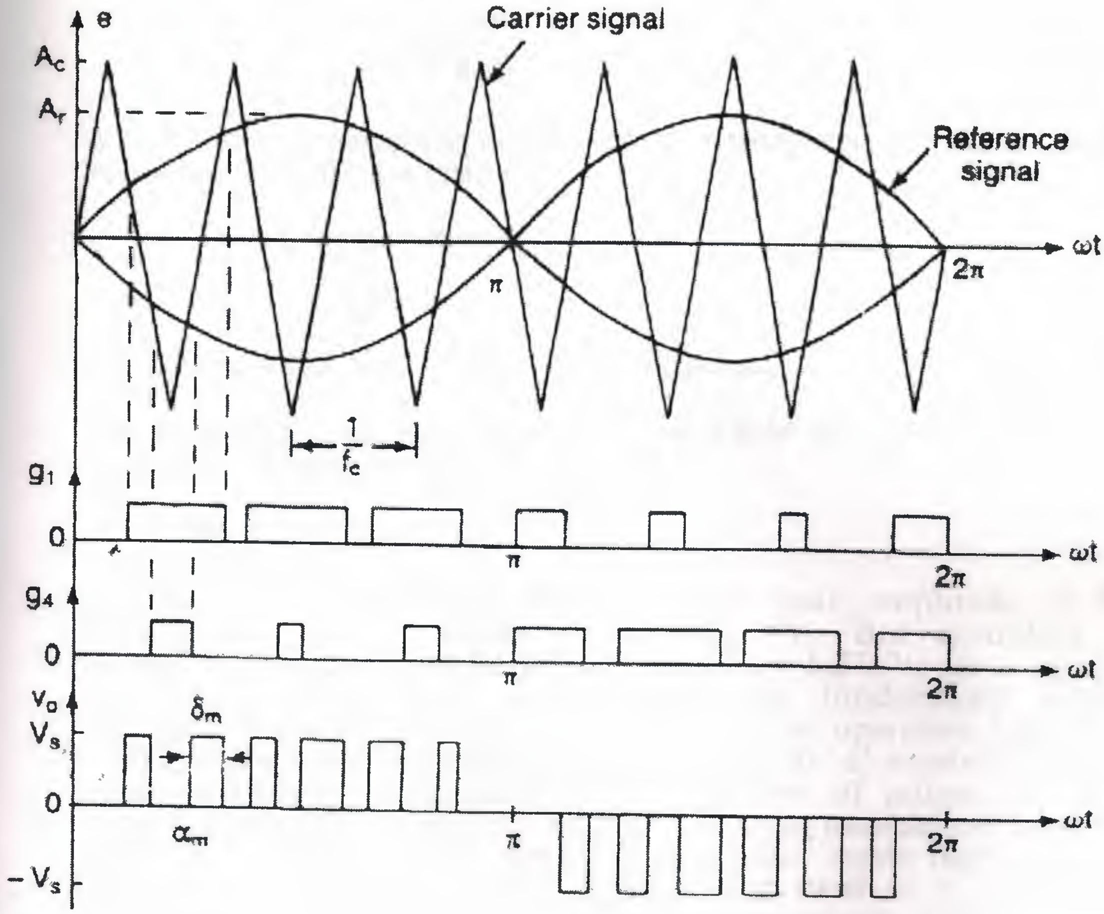
Instead of maintaining the width of all pulses the same as in the case of multiple-pulse modulation, the width of each pulse is varied in proportion to the amplitude of a sine wave evaluated at the center of the same pulse. The distortion factor and lower-order harmonics are reduced significantly. Comparing a sinusoidal reference signal with a triangular carrier wave of frequency fc as shown in Figure(a generates the gating signals. This type of modulation is commonly used in industrial applications and abbreviated as SPWM. The frequency of reference signal f_r determines the inverter output frequency f_o and its peak amplitude. A_r controls the modulation index, *M,* and then in turn the rms output voltage V_o. The number of pulses per half-cycle depends on the carrier frequency Within the constraint that two transistors of the same arm (Q_1 and Q_2) cannot conduct at the same time, the instantaneous output voltage is shown in figure1.3a.Using unidirectional triangular carrier wave as shown in Figure1.3b can generate the same gating signals.

The rms output voltage can be varied by varying the modulation index M. It can be observed that the area of each pulse corresponds approximately to the are under the sine wave between the adjacent midpoints of off periods on the gating signals. If δm is the width of m-th pulse, Equation can be extended to find the rms output voltage.

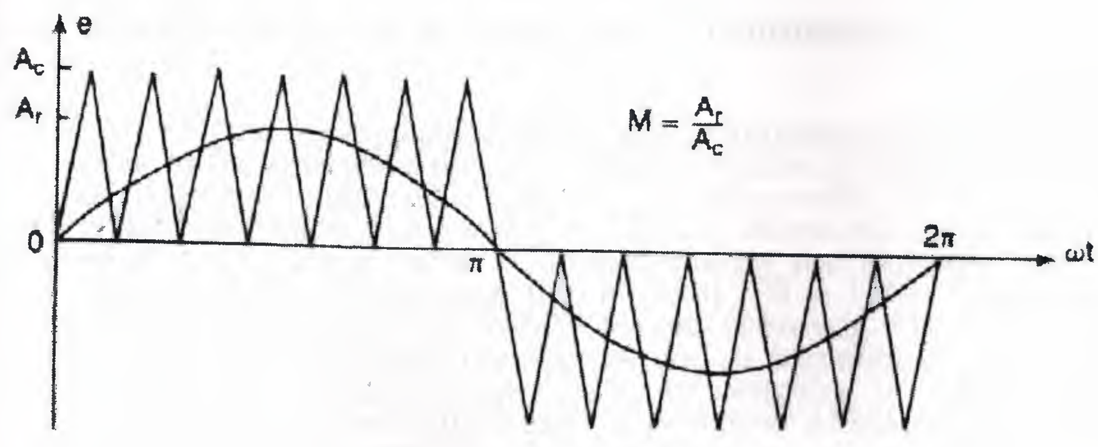
Equation can also be applied to determine the Fourier coefficient of output voltage as

$$B_n = \sum_{m=1}^{P} 2V_s/n\pi \sin n\delta/2[\sin n (\alpha_m + \delta/2) - \sin n (\pi + \alpha_m + \delta/2)]$$

This type of modulation eliminates all harmonics less than or equal to 2p - 1. For p = 5, the lowest-order harmonic is ninth. The output voltage of an inverter contains harmonics. The PWM pushes the harmonics into a high-frequency range around the switching frequency f_c. And its multiples, that is, around harmonics m_f, 2mf,3mf and so on. The frequencies at which the voltage harmonics occur can be related by



(a)



(b)

Figure 3.3
Sinusoidal pulse width modulation.

$$f_n = (jm_f + k) f_c$$

Where the n-th harmonic equals the k-th side band of j-th times the frequency-modulation ratio m_f.

$$n = jm_f + k$$

$$= 2jp + k$$

For $j = 1, 2, 3, \ldots$ and $k = 1, 3, 5, \ldots$

The peak fundamental output voltage for PWM and SPWM control can be found approximately from

$$V_{m1} = dV_s \qquad \text{for } 0 \leq d \leq 1.0$$

For d = 1,Equation gives the maximum peak amplitude of the fundamental output voltage as $V_{m1(max)} = V_s$. But according to Equation, $V_{m1(max)}$ could be as high as $4V_s = 1.278V_s$ for a square-wave output. In order to increase the fundamental output voltage,'d'must be increased beyond 1.0. The operation beyond d =1.0 is called over de-modulation. The value of 'd' at which $V_{m1(max)}$ equals $1.278V_s$ is dependent on the number of pulses per half-cycle'P'and is approximately 3 for P = 7. Over modulation basically leads to a square-wave operation and adds more harmonics as compared to operation in the linear range (with $d \leq 1.0$). Over modulation is normally avoided in applications requiring low distortion for example un-interruptible power supplies (UPS).

Modified Sinusoidal Pulse Width Modulation

Figure 3.3 indicates that the widths of pulses that are nearer the peak of the sine wave do not change significantly with the variation of modulation index. This is due to the characteristics of a sine wave, and the sinusoidal pulse-width modulation technique can be modified so that the carrier wave is applied during the first and last 60° intervals per half-cycle (e.g. 0 to 60° and 120 to 180°). This type of modulation is known as MSPWM and shown in Figure 3.4. The fundamental component is increased and its harmonic characteristics are improved. It reduces the number of switching of power devices and also reduces switching losses. The number of pulse 'q' in the 60-degree period is normally related to the frequency ratio, particularly in three-phase inverters, by

$$f_c / f_o = 6q + 3$$

Advanced modulation techniques

Trapezoidal modulation.
Staircase modulation.
Stepped modulation.
Harmonic injection modulation
Delta modulation.

Trapezoidal modulation.

Comparing a triangular carrier wave with a modulating trapezoidal wave as shown in Figure 3.5, generates the gating signals. The trapezoidal wave can be obtained from a triangular wave by limiting its magnitude to $\pm A_r$, which is related to the peak value $A_{r\,(max.)}$ by

$$A_r = \sigma A_{r\,(max.)}$$

Where σ is called the triangular factor, because the waveform becomes a triangular wave when $\sigma = 1$.The modulation index M is

$$M = A_r / A_c = \sigma A_{r\,(max.)} / A_c \quad \text{for } 0 \leq M \leq 1$$

The angle of the flat portion of the trapezoidal wave is given by

$$2\phi = (1 - \sigma)\,\pi$$

For fixed values of $A_{r\,(max)}$ and A_c, changing the triangular factor can vary M that varies with the output voltage,σ. This type of modulation increases the peak fundamental output voltage up to $1.05V_s$ but the output contains lower-order harmonics.

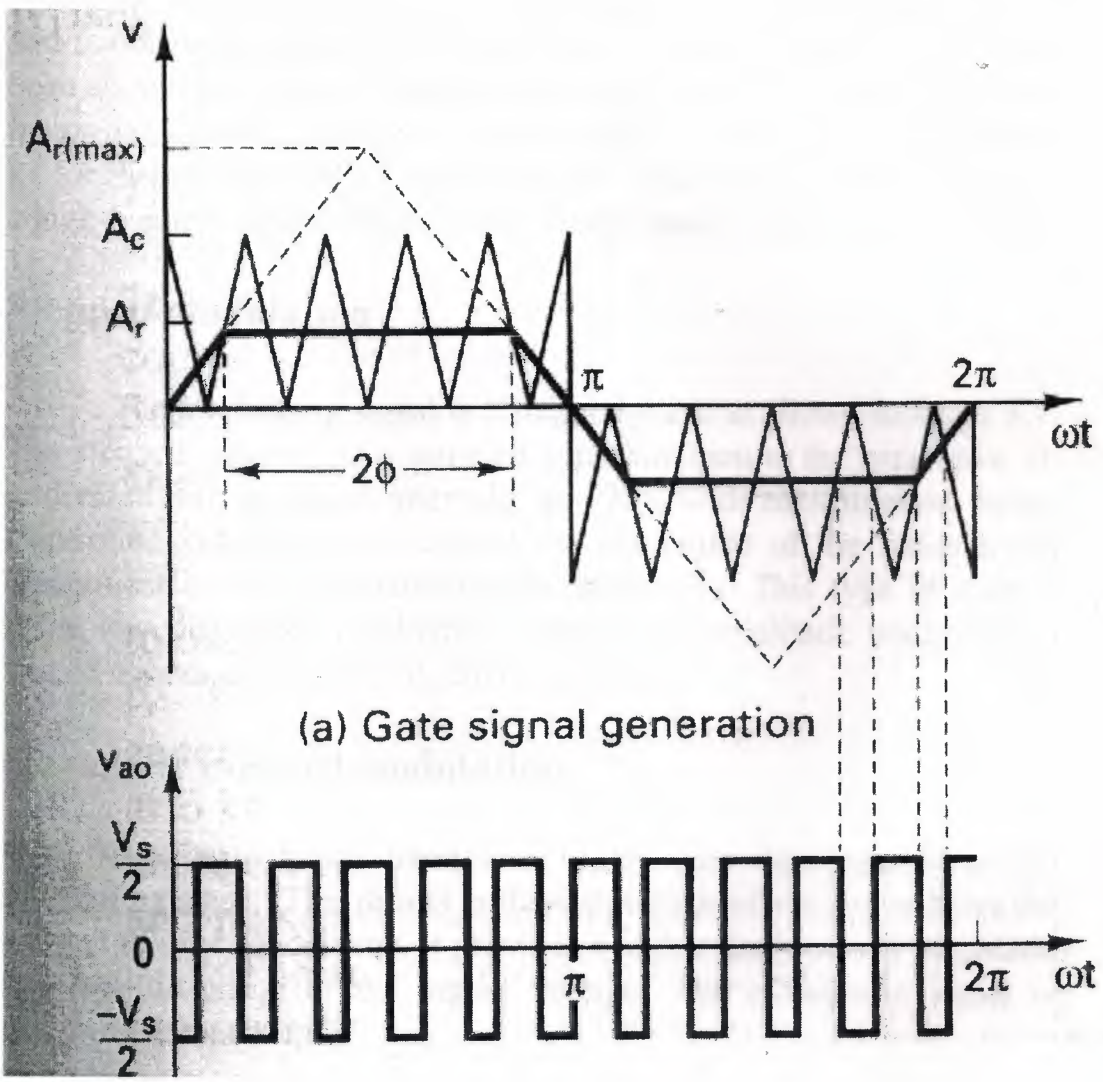


Figure 3.5
Trapezoidal modulation.

Staircase modulation

The modulating signal is a staircase wave as shown in Figure 3.6. The staircase is not a sampled approximation to the sine wave. The levels of the stairs are calculated to eliminate specific harmonics. The modulation frequency ratio m_f and the number of steps are chosen to obtain the desired quality of output voltage. This is an optimized PWM and is not recommended for fewer than 15 pulses in one cycle. It has been shown that for high fundamental output voltage and low distortion factor, the optimum number of pulses in one cycle is 15 for two levels, 21 for three levels and 27 for four levels. This type of control provides a high-quality output voltage with a fundamental value of up to $0.94V_s$.

Stepped modulation

The modulating signal is a stepped wave as shown in figure 3.7. The stepped wave is not a sampled approximation to the sine wave. It. is divided into specified intervals, say 20°, with each interval being. Controlled individually to control the magnitude of the fundamental component and to eliminate specific harmonics. This type of control gives low distortion, but higher fundamental amplitude compared to that of normal pulse width modulated control.

Harmonic injected modulation

Injecting selected harmonics to the sine wave generates the modulating signal. This results in flat-topped waveform and reduces the amount of over modulation. It provides a higher fundamental amplitude and low distortion of the output voltage. The modulating signal is generally composed of

$$V_r = 1.15 \sin\omega t + 0.27 \sin 3\omega t - 0.029 \sin 9\omega t$$

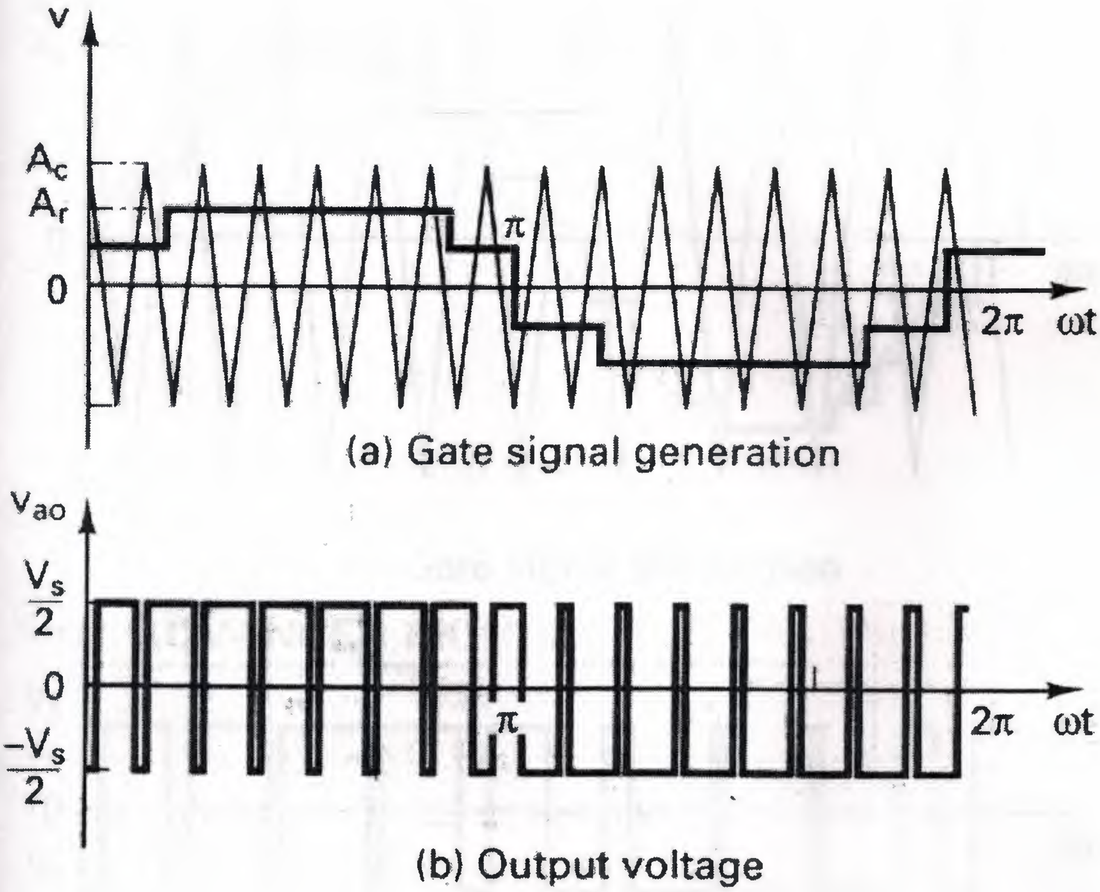


Figure 3.6
Staircase modulation.

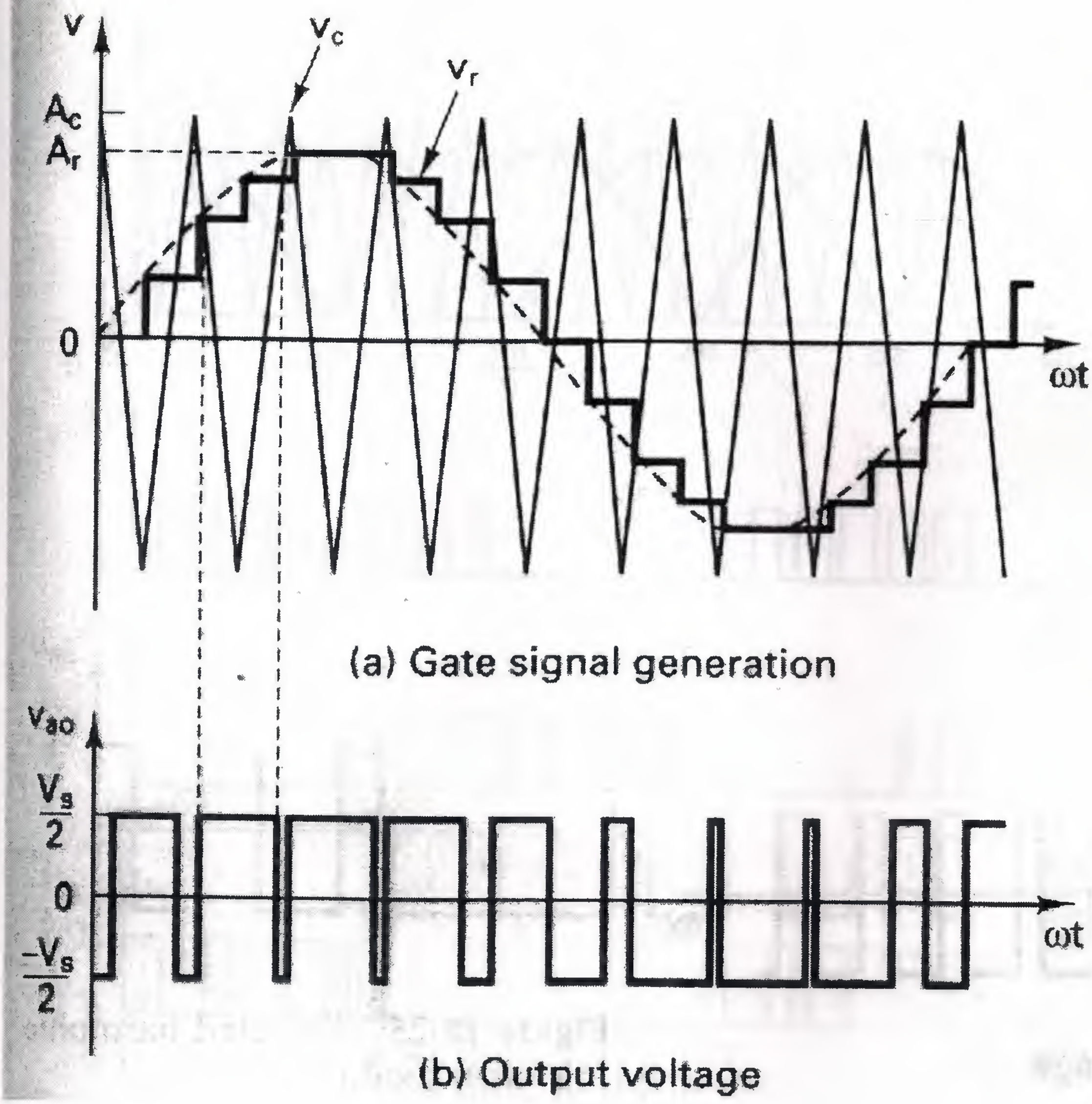


Figure 3.7
Stepped modulation.

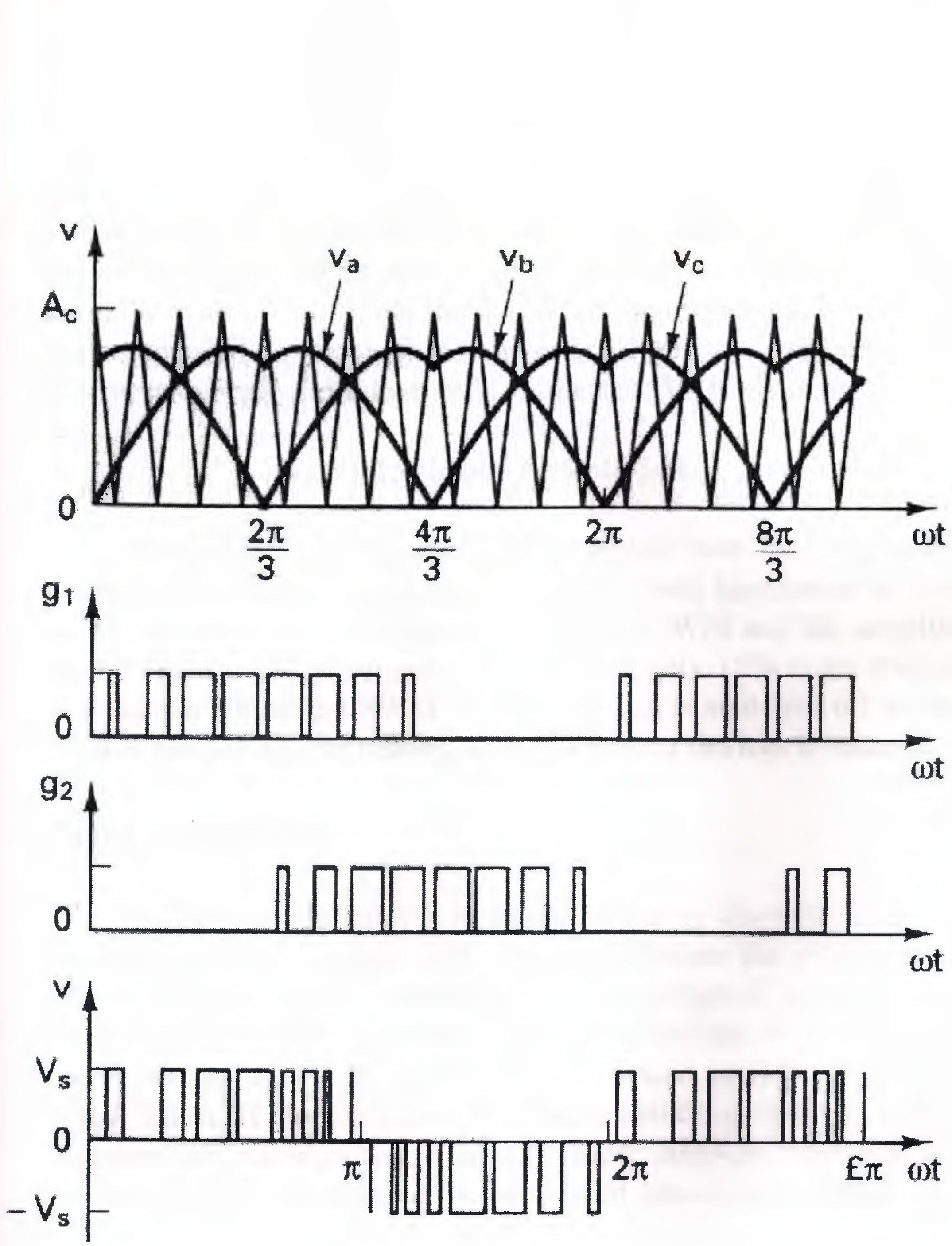


Figure 3.9
Harmonic injection modulation.

The modulating signal with third and ninth harmonic injections is shown in Figure 3.9. It should be noted that the injection of 3n-th harmonics would not affect the quality of the output voltage, because the output of a three-phase inverter does not contain triplen harmonics. If only third harmonic is injected, V_r, is given by

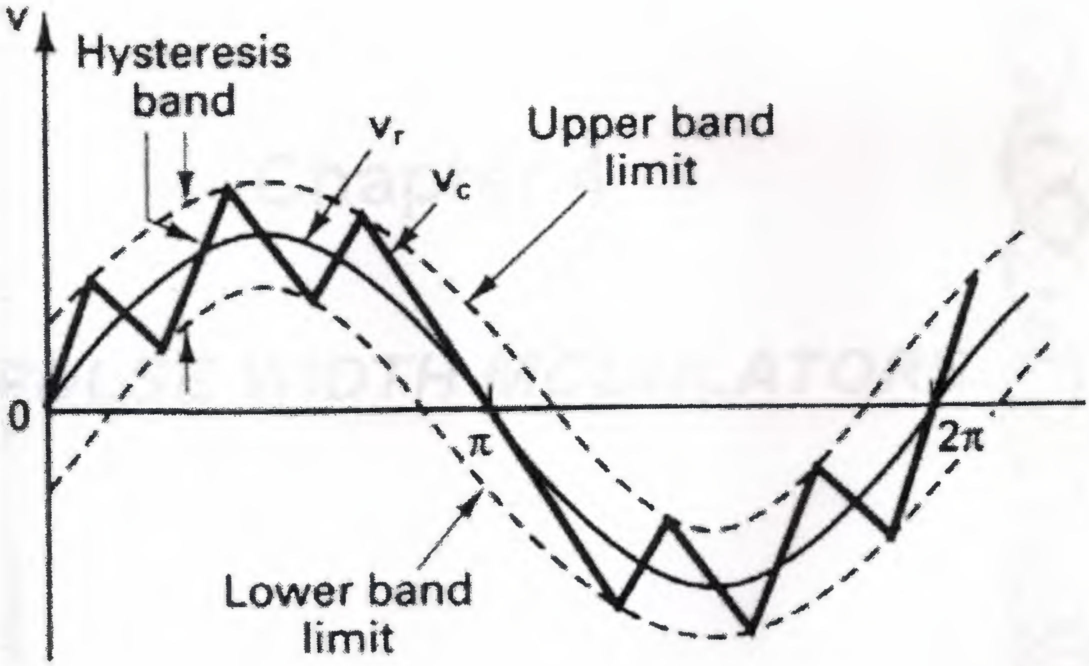
$$V_r = 1.15 \sin\omega t + 0.19 \sin 3\omega t$$

The modulating signal can be generated from $2\pi/3$ segments of a sine wave .This is the same as injecting 3nth harmonics to a sine wave. The line-to-line voltage is sinusoidal PWM and the amplitude of the fundamental component is approximately 15% more than that of a normal sinusoidal PWM. Since each arm is switched off for one-third of the period, the heating of the switching devices is reduced.

Delta modulation

In delta modulation a triangular wave is allowed to oscillate within a defined window ΔV above and below the reference sine wave V_r. The inverter switching function, which is identical to the output voltage V_0 is generated from the vertices of the triangular wave V_c. as shown in Figure 1.10. It is also known as hysteresis modulation. If the frequency of the modulating wave is changed keeping the slope of the triangular wave constant, the number of pulses and pulses widths of the modulated wave would change.

The fundamental output voltage can be up to 1 V, and is dependent on the peak amplitude A_r and frequency f_r of the reference voltage. The delta modulation can control the ratio of voltage to frequency, which is a desirable feature in ac motor control.



(a)

Figure 3.10
Delta Modulation.

Chapter 4

PULSE WIDTH MODULATORS

Pulse width modulators

Pulse width modulation is a modulation technique in which the width of each pulse varies in accordance with the instantaneous sample value of baseband signal m (t). The larger the sample value is the wider the corresponding pulse. Pulse width modulation is some times referred to as pulse duration or pulse length modulation.

Let T_s denotes the sample duration. Using the sample m (nT_s) of a baseband signal m (t) to modulate the width of the nth pulse, we obtain the PWM signal

$$S(t) = \sum_{n=-\infty}^{\infty} g(t - nT - k_P\, m(nT_s))$$

Where k_P is the sensitivity of the pulse-width modulator and g (t) denotes standard pulse of interest.

Generation of pulse width modulation

Pulse-width modulation may be generated by applying trigger pulses (at Nyquist rate) to control the starting time of pulses from a monostable multivibrator, and feeding in the signal to he sampled to control the duration of these pulses. The circuit diagram for such an arrangement. The emitter-coupled monostable multivibrator makes an excellent voltage-to-time converter, since its gate width is dependent on the voltage to which the capacitor C is charged. If this voltage is varied in accordance with a signal voltage series of rectangular pulses will be obtained, with widths varying as required. Note that the circuit does the twin jobs of sampling and converting the samples into PWM.

It will be recalled that the stable state for this type of multivibrator is with T_1 **off** and T_2 **on**. The applied trigger pulse switches T_1 **on**, whereupon the voltage at C_1 falls as T_1 now begins to draw collector current, the voltage at B1 follows suit and T_1 is switched off by regenerative action. As soon as this happens, however, C begins to charge up to the collector supply potential through R. After a time determined by the supply voltage and the RC time constant of the charging network, B_2 becomes sufficiently positive to switch T_2 **on**. Regenerative action and stays off until the arrival of the next trigger pulse simultaneously switch off T1. The voltage that the base of T_2 must reach to allow T_2 to turn on is slightly more positive than the voltage across the common emitter resistor R_k. This voltage depends on the current flowing through the circuit, which at the time is the collector current of T_1 (which is then **on**). The collector current depends on the base bias, which is governed by the instantaneous changes in the applied signal voltage. The applied modulation voltage controls the voltage to which B_2 must rise to switch T_2 **on**. Since this voltage rise is linear the modulation voltage is seen to control the period of time during which T_2 is **off**, that is, the pulse duration. It should be noted that this pulse duration is very short compared to even the highest signal frequencies, so that no real distortion arises through changes in signal amplitude while T_2 is **off**.

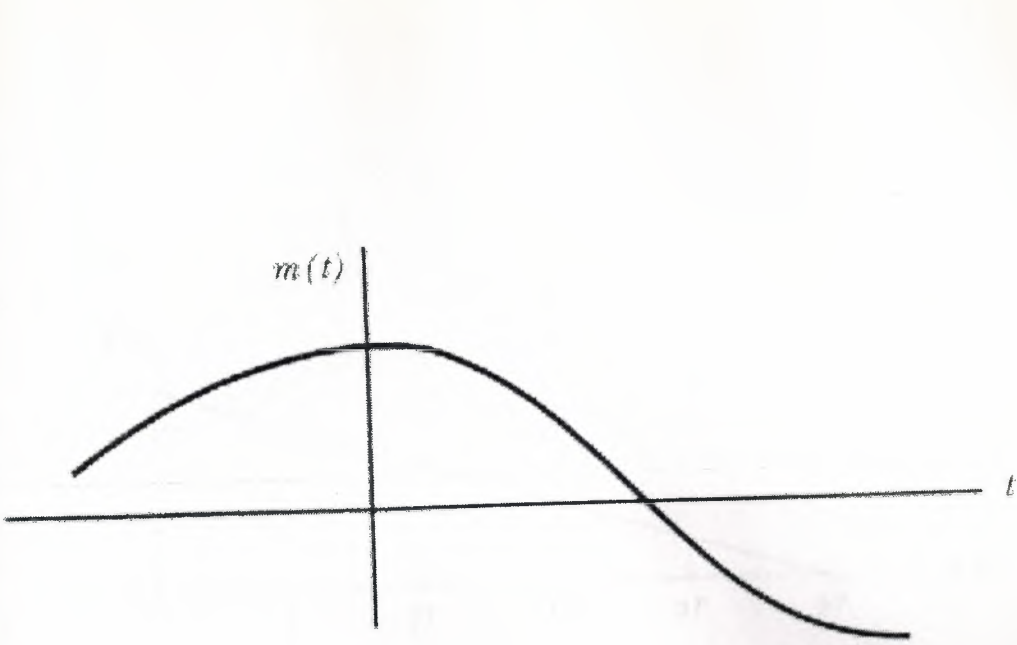


Figure a:
Message signal.

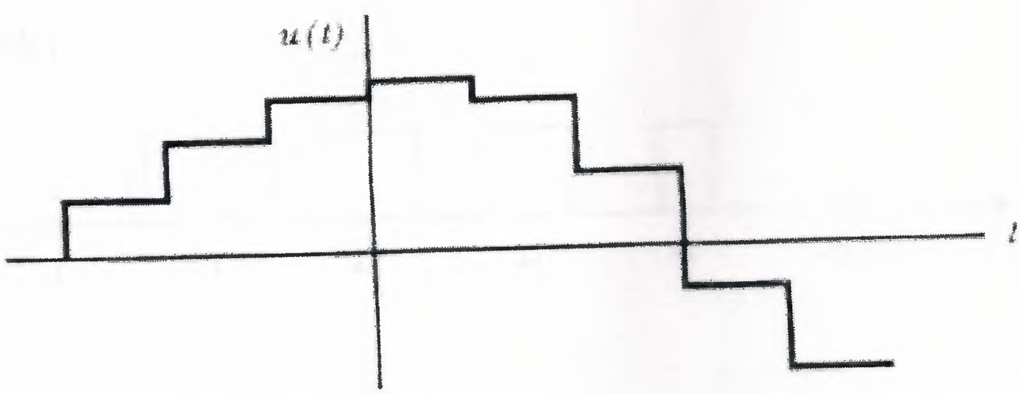
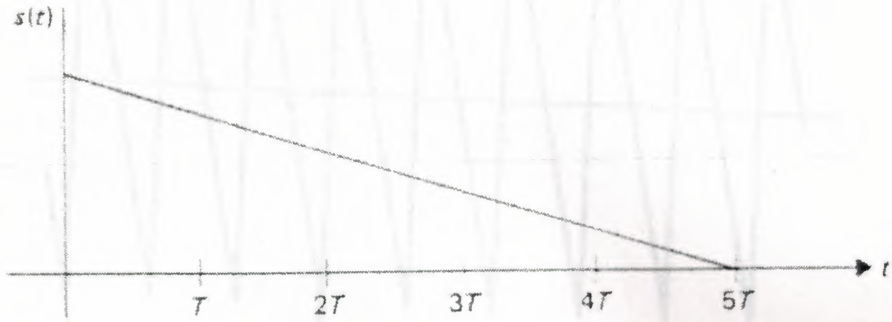
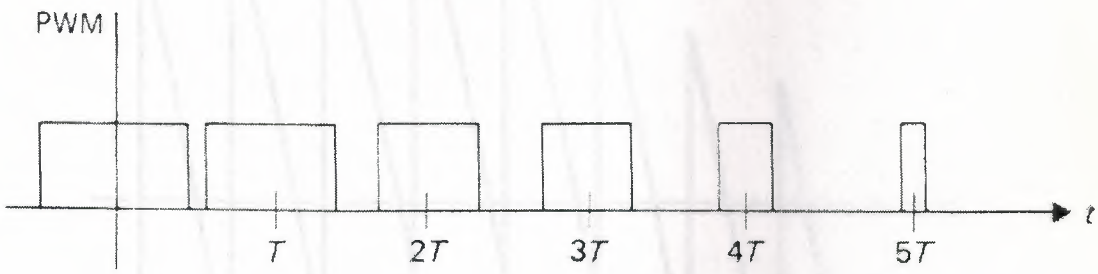


Figure b:
Staircase approximation of the message signal.



(a)



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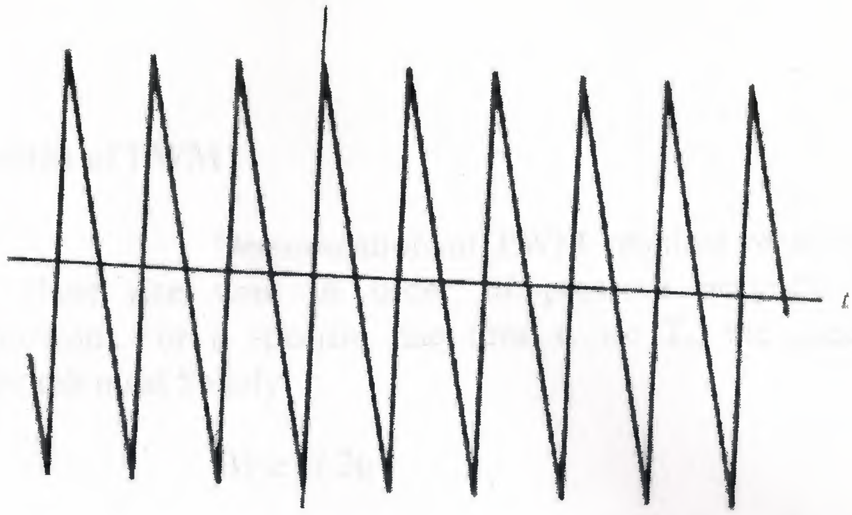
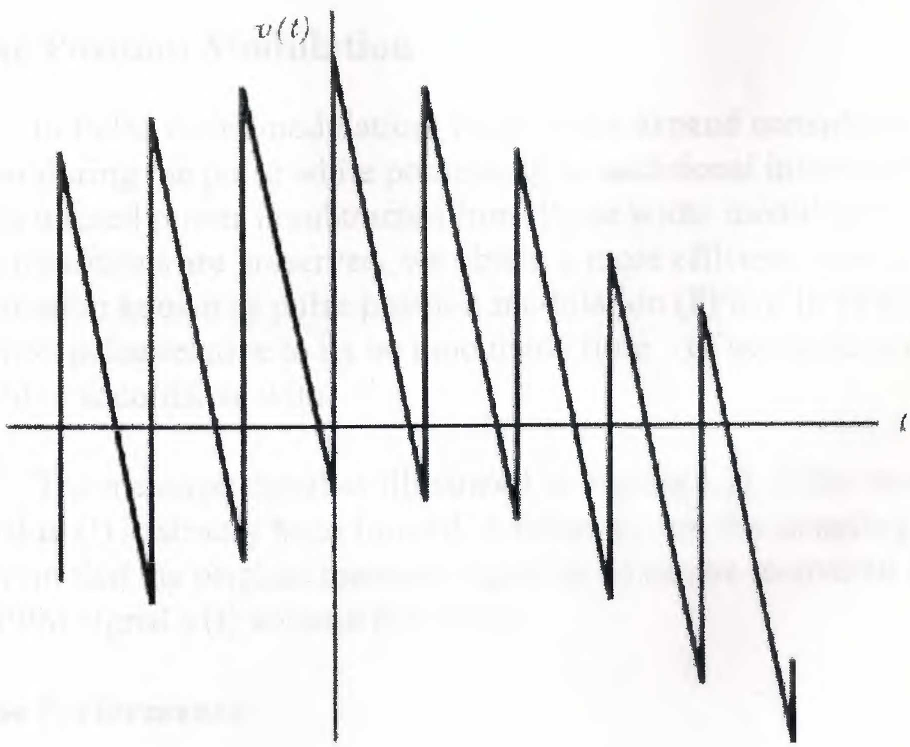


(c) Sawtooth waveform



(d)

Figure 4.1
Composite waveform obtained by adding (b) and (c)

Detection of PWM

Demodulation of PWM requires received pulses with short rise time in order to preserve accurate message information. For a specific rise time $t_r << T_s$, the transmission bandwidth must Satisfy

$$B_T \geq 1/ 2t_r$$

Which is will be substantially greater than the pulse amplitude transmission bandwidth. In exchange for the extra bandwidth, we gain the benefit of content amplitude pulses that suffer no ill effects from nonlinear distortion in transmission since nonlinear distortion does not alter pulse width.

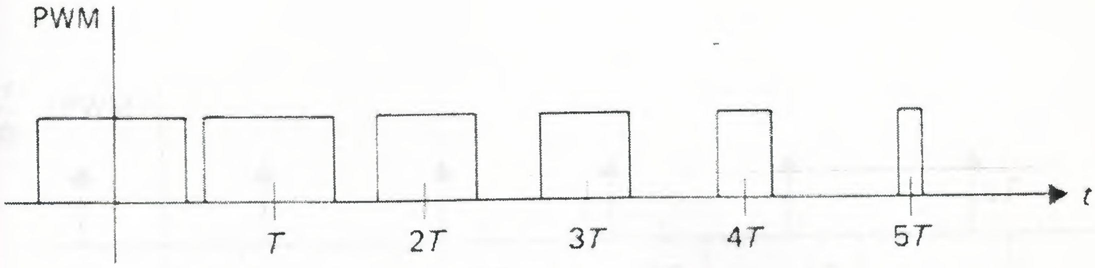
Pulse Position Modulation

In Pulse width modulation, long pulses expend considerable power during the pulse while possessing no additional information. If this unused power is subtracted from Pulse width modulation, only time transitions are preserved, we obtain a more efficient type of modulation known as pulse position modulation (PPM). In PPM, the position pulse relative to its un modulated time of occurrence is varied in accordance with

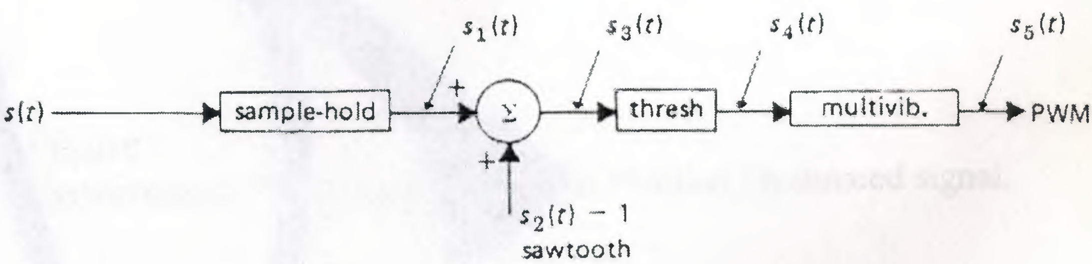
The message signal as illustrated in Figure(4.2). If the message signal m (t) is strictly band limited, it follows from the sampling theorem that the original message signal m (t) can be recovered from the PPM signal s (t) without distortion.

Noise Performance

Additionally Pulse Position Modulation has the potential for wideband noise reduction potential. The reason is that the information resides in the time location of the pulse edges, not in the pulses

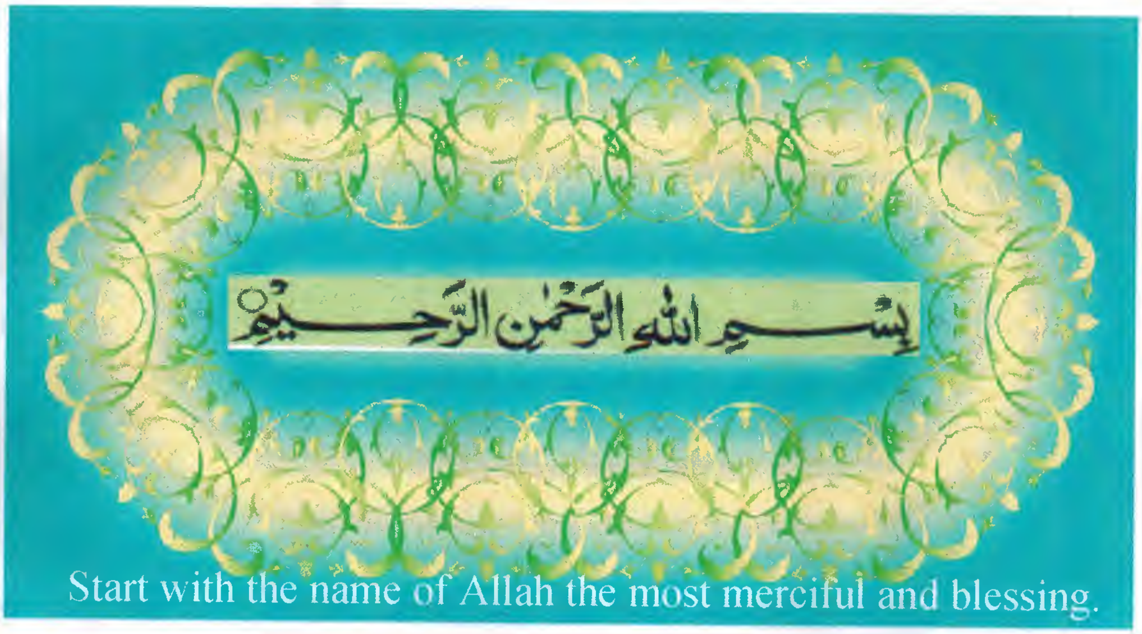


(e) Pulse width modulation waveform.



(f) Block diagram of pulse width modulator.

Figure 4.2
Generation of pulse width modulated waveform.



Start with the name of Allah the most merciful and blessing.

Near East University

1988

Faculty of Engineering

Department of Electrical and Electronic Engineering

Graduation Project

Pulse Width Modulation Techniques

Theory and Applications

Supervisor:

Prof.
Dr. Khalil Ismailov

Submitted by:

Aftab Ahmed Malik

Dedications

I dedicate my graduation project to
The memory of my loving maternal grand mother,

Fatema Saifal Khan.

Who passed away while this work was in progress,

And to
My dear parents,

Mr. Abdul Khaliq Malik and Zubaida Begum Malik.

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Prof. Dr Khalil Ismailov.

Whom extreme patience, assistance and support, Played a key role during the formation of my graduation project. Dr. Khalil's profound knowledge, guidance and supervision lead me to greater understanding of the topic together with the enhancement of my knowledge in pulse width modulation techniques. Without his responsive and helpful suggestions it would not have been possible for me to indicate the clearest approach to the topic.

I would also like to thank all my friends who help me with their valuable suggestions and comments during the completion of this project among them the most important names are ***Raja Imran Sohail, Muhammad Faisal Janjua, Amjad Sadique Toor and Muhammad Atif Malik.***

About the Student

My name is Aftab Ahmed Malik. I am from Islamic Republic of Pakistan. I belong to a landlord family from district Chakwal (Punjab). My father is also an electrical engineer. I have received my elementary education from my native district. I have studied at F.G higher secondary school G-8/4 Islamabad. I have obtained a hi-tech diploma in Computer Electronics and Telecommunications from university of the Punjab. I came to Turkish republic of northern Cyprus for higher education in Electrical and electronic engineering, in the year 1994. Inshallah I am going to graduate in spring semester 1998-99 this year.

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Chapter 1

INTRODUCTION TO PULSE WIDTH MODULATION

Introduction

The hi-tech technology can assist an electronics engineer in industry in the solution of two fundamental types of problems, viz. the transformation of electrical power and execution of process, such as measuring, converting controlling etc.

The branch of hi-tech technology, which has revolutionized the concept of power control and power conversion using solid state semiconductor devices, is power electronics. Power electronics combine power, control and electronics. The rapid development in recent years, primarily because of solid state semiconductor devices, make it possible to build an excellent switches to employ for the conversion and controlled switching operation of the parameters,

such as voltage, current, power, frequency and waveform.

Pulse width modulation is the most efficient and popular control technique which is widely used in many industrial applications, including power electronic converters, regulated power supplies, inverters, electric vehicles, choppers, transformers, modulators, amplifiers and in other motor control systems.

Pulse width modulation plays an important role in all sorts of systems and enable improved, more efficient, accurate control and regulation methods.In pulse width modulation there are different methods of varying the widths of the pulses. The pulse width modulation topic of graduation project is divided into ten chapters.

Chapter 2

PULSE WIDTH MODULATED CONVERTERS

Pulse Width Modulated Converters

In most practical applications it is necessary to change an electric power from one form to another. A circuit that performs this switching action is called a converter. The basic function of a static power converter is to convert **ac**-input voltage into a controllable dc output voltage.

A converter makes use of a configuration of power semiconductor devices (power diodes and thyristors) that function as switch. The choice of a particular device will depend on the voltage, current and speed requirements of a converter. These devices are made to turn on and turn off respectively in such a way as to implement the required conversion function.

In the terminology of power electronics, it has become common to describe the turn off switching of the device itself as "commutation". The power factor of phase-controlled converters depends on delay angle, and is in general low, especially at the low output voltage range. These converters generate harmonics into the supply. Forced commutation can improve the input power factor and reduce the harmonic levels. The forced commutation can be implemented in practical systems by the use of pulse-width modulation technique.

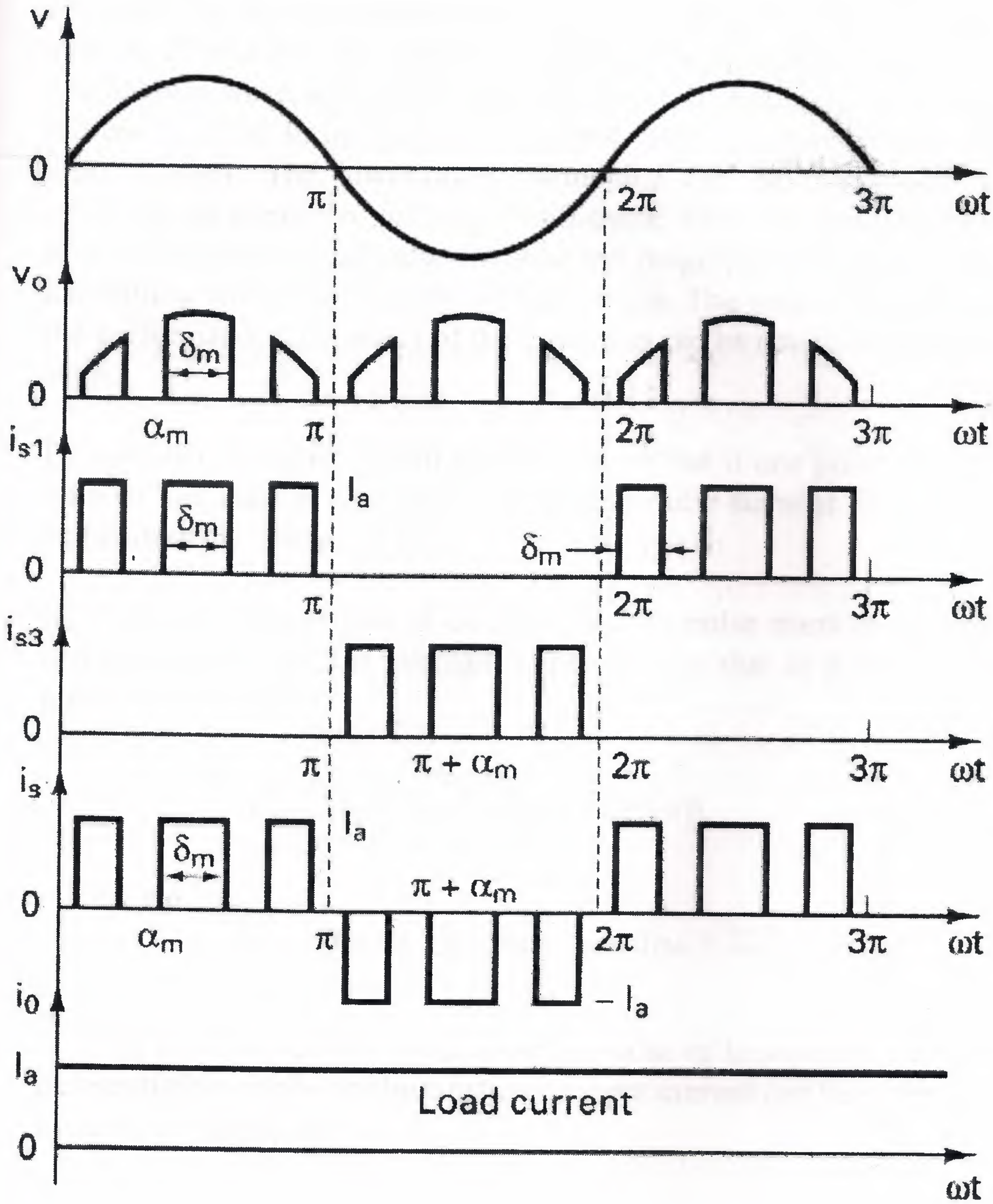


Figure 2.1
Input, output voltage and input current waveform.

In pulse width modulation techniques, the converter switches are turned on and off several times during a half-cycle and the output voltage is controlled by varying the width of firing pulses. Comparing a triangular wave with a dc signal as shown in figure 2.2 generates the gate signals. In the figure-a the input voltage output voltage and input current. The lower-order harmonics can be eliminated by selecting the number of pulses per half-cycle. However increasing the number of pulses would also increase the magnitude of higher-order harmonics, which could easily be filtered out. The output voltage and the performance parameters of the converter can be determined in two steps:

By considering only one pair of pulses such that if one pulse starts at $\omega t = \alpha_1$ and ends at $\omega t = \alpha_1 + \delta_1$, the other pulse starts at $\omega t = \pi + \alpha_1$ and ends at $\omega t = \pi + \alpha_1 + \delta_1$.

By combining the effects of all pairs. If m-th pulse starts at $\omega t = \alpha_m$ and its width is δ_m, the average output voltage due to p number of pulses is found from

$$V_{dc} = \sum_{m=1}^{P} \left[2 / 2\pi \int_{\delta m}^{\alpha m + \delta m} V_m \sin \omega t \, d(\omega t)\right]$$

$$= V_m / \pi \sum_{m=1}^{P} [\cos\alpha_m - \cos(\alpha_m + \delta_m)]$$

If the load current with an average value of I_a is continuous and has negligible ripple, the instantaneous input current can be expressed in a Fourier series as

$$i_s(t) = I_{dc} + \sum_{m=1,3,\ldots}^{\infty} [\, a_n \cos n\omega t - b_n \sin n\omega t]$$

Due to symmetry of the input current waveform, there will be no even harmonics and I_{dc} should be zero and the coefficient of

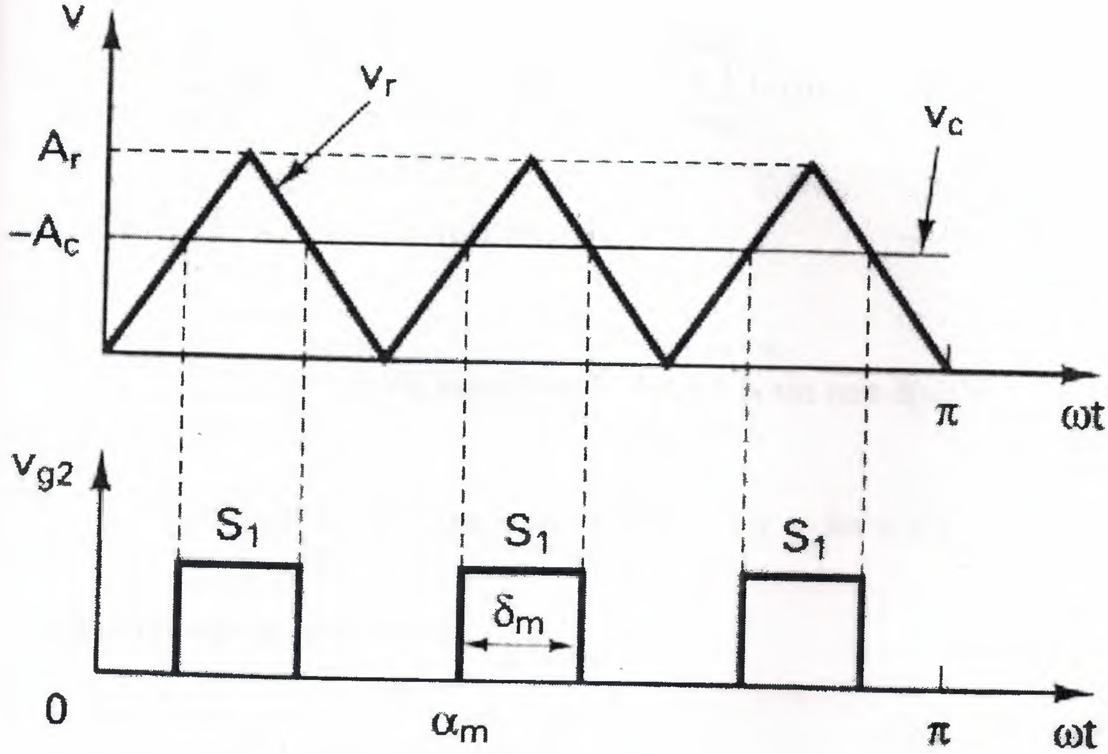


Figure 2.2
Pulse width modulated converter.

equation are

$$a_n = [1 / \pi \int_0^{2\pi} i_s(t) \cos n\omega t \, d(\omega t)]$$

$$= \sum_{m=1}^{P} [1 / \pi \int_{\alpha m}^{\alpha m + \delta m} I_a \cos n\omega t \, d(\omega t) - 1 / \pi \int_{\pi + \alpha m}^{\pi + \alpha m + \delta m} I_a \cos n\omega t \, d(\omega t)] = 0$$

$$b_n = [1 / \pi \int_0^{2\pi} i_s(t) \sin n\omega t \, d(\omega t)]$$

$$= \sum_{m=1}^{P} [1 / \pi \int_{\alpha m}^{\alpha m + \delta m} I_a \sin n\omega t \, d(\omega t) - 1 / \pi \int_{\pi + \alpha m}^{\pi + \alpha m + \delta m} I_a \sin n\omega t \, d(\omega t)]$$

$$= 2I_a / n\pi \sum_{m=1}^{P} [\cos n\alpha_m - \cos n(\alpha_m + \delta_m)] \qquad \text{for } n = 1,3,5,.....$$

Equation can be rewritten as

$$= \sum_{n=1,3....}^{\infty} [\sqrt{2}\, I_n\, \pi \sin(n\omega t + \phi_n)]$$

Where $\phi_n = \tan^{-1}(a_n / b_n) = 0$ and $I_n = \sqrt{[a_n^2 + b_n^2]} / \sqrt{2} = b_n / \sqrt{2}$

Sinusoidal pulse width modulated converter

In Sinusoidal pulse modulation technique, the pulse widths are generated by comparing a triangular reference voltage V_r of amplitude A_r and frequency f_r with a carrier half-sinusoidal voltage V_c of variable amplitude A_c and frequency $2f_s$. The sinusoidal voltage V_c is in phase with the input phase voltage V_s and has the twice the supply frequency f_s. Changing the amplitude A_c varies the width of the pulses (and the output voltage). In sinusoidal pulse-width modulation, the displacement factor is unity and the power factor is improved. The lower order harmonics are eliminated. For example with four pulses per half-cycle the lowest-order harmonic is the fifth and with the six pulses per half-cycle the lowest-order harmonic is the seventh.

Definition

The modulation index is defined as

$$M = A_c / A_r$$

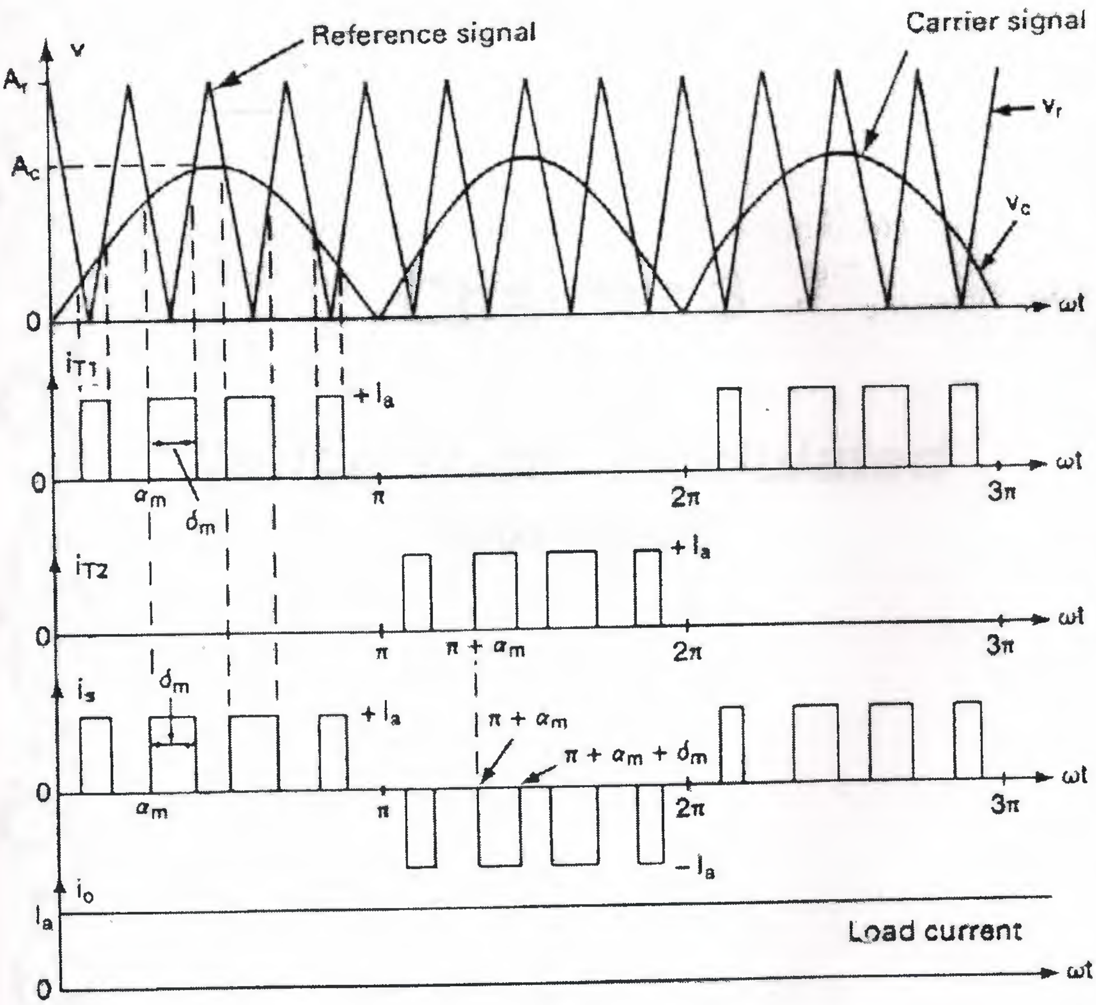


Figure 2.3
Sinusoidal pulse width modulated converter waveform.

Chapter 3

Pulse Width Modulated Inverters

Pulse Width Modulated Inverters

An inverter is a device, which converts from dc input into an ac output without any rotating machines. The power circuit configuration of an inverter consists of semiconductor power devices that function as a static switch. The inverter also has a switching control circuit that provides the necessary pulses to turn on and off each static-switching element with the correct timing and sequence.

For a practical power control applications of an inverter it is necessary to adjust the ac frequency and the magnitude of a voltage. Varying the input dc voltage to the inverter can make the voltage adjustment. The voltage control is external to the inverter and is independent of the switching the inverter configuration. The alternative way of ac voltage variation is within the inverter by a pulse width modulation technique, which is used for implementing voltage control.

A typical voltage waveform of a pulse-width modulation inverter is shown . It may treat the interval from t_1 to t_4 as one half-period of the ac voltage and t_4 and t_7 as the negative half-period. During the positive half-period, the output voltage consists of a single pulse of amplitude V_1 and of duration t_2 to t_3, which is shorter than the total half-period.

The pule duty cycle (D) is defined as:

$$\text{Duty cycle} = \frac{\text{Actual duration of the pulse in a half period } t_2 \text{ to } t_3}{\text{duration of one half-period } (t_1 \text{ to } t_4)}$$

Therefore the mean square value of the ac output voltage will be given by

$$\text{Sqr}(V_{ac}) = \text{Sqr}(DV_1)$$

Therefore we get the rms value of the ac output voltage as

$$V = \text{Sqr}(D)\ V_1$$

If the pulse-width modulation is to be implemented in an interval according to this pattern, it is necessary to achieve the following.

During the interval t_1 and t_2 , the voltage across the load has to be maintained at zero. From t_2 to t_3, it has to be constant at V_1.Then from t_2 to t_4, it again has to be zero. Similarly statements apply for the next half-period , with due consideration for the voltage polarity.

The most commonly used pulse width modulation methods are the following.

Single pulse width modulation.
Multiple pulse width modulation.
Sinusoidal pulse width modulation.
Modified sinusoidal pulse width modulation.

Single-pulse width modulation

In single-pulse width modulation method, there is only one pulse per half cycle and the width of the pulse is varied to control the output voltage of the inverter. In order to accomplish this modulation method independent commutation of SCRs is necessary. A circuit implying independent commutation for PWM regulation technique is shown in figure1, SCR_1 and SCR_2 are the two main load carrying SCRs and SCR_3 and SCR_4 are two auxiliary SCRs which are of smaller rating. C_1 and C_2 are two separate commutating capacitors. When SCR_1 is turned on, power is delivered to the load and at the same time, C_1 is charged to the voltage of the transformer section AB with a polarity as shown. SCR_1 can be turned off at any desired instant by triggering SCR3. After an interval, SCR_2 is turned on to deliver power in the negative half cycle. C_2 is charged at the same time by the voltage of the transformer section CD. Firing SCR4 turns off SCR2. This method produces a quasi-square wave output as shown in figure2.

The Fourier series can express a perfect square wave.

$$V_{\omega t} = 4V_{dc} / \pi[\sin\omega t + \sin 3\omega t / 3 + \sin 5\omega t / 5 + ...]$$

In the above series, only odd harmonics are present. The total harmonic distortion

$$\text{Total harmonic distortion} = [(\sum_{n=1,3,5,....}^{\infty} A_n^2) / A_1]^{1/2}$$

Where

$$A_1 = [4V_{dc} / \pi] \cos\theta$$

$$A_3 = [4V_{dc} / 3\pi] \cos 3\theta$$

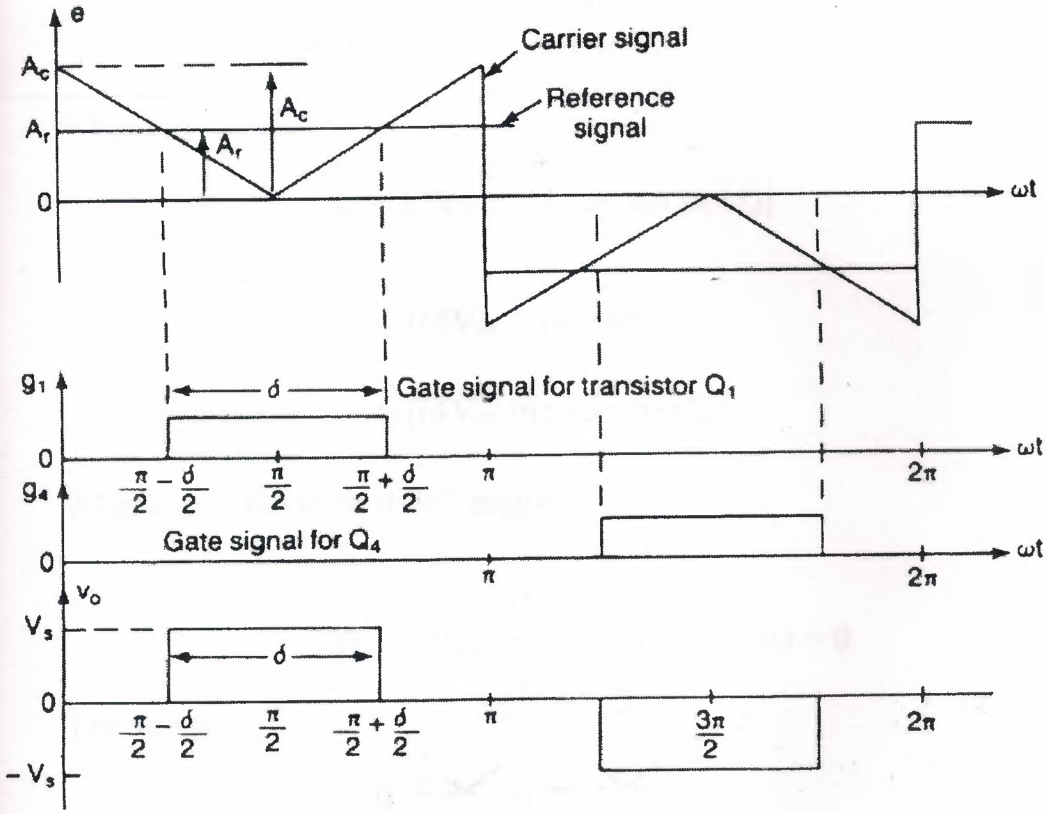


Figure 3.1
Single pulse width modulation.

$$A_5 = [4V_{dc} / 5\pi] \cos 5\theta$$

For a square-wave, total harmonic distortion is about 47%. The voltage waveform in the figure can be expressed by the series,

$$V_L = \sum_{n=1,3,5,....}^{\infty} A_n \sin n\omega t + \sum_{n=1,3,5,....}^{\infty} B_n \cos n\omega t$$

Where

$$A_n = [2V_{dc} / \pi \int_{(\pi - \delta)/2}^{(\pi + \delta)/2} \sin n\omega t \, d(\omega t)]$$

$$(\pi\text{-}\delta/2) = [(4V_{dc} / n\pi) \sin n\delta/2]$$

$$= [(4V_{dc} / n\pi) \cos n\alpha/2]$$

Where α = delay or dwell angle

$$B_n = (2V_{dc} / \pi) \int_{(\pi-\delta)/2}^{(\pi+\delta)/2} \cos n\omega t \, d(\omega t) = 0$$

Therefore,

$$V_L = \sum_{n=1,3,5,...}^{\infty} A_n \sin n\omega t$$

The rms value of each harmonic depends on the pulse width δ. That means it depends on magnitude of the output voltage. The rms value of the n-th harmonic is

$$V_n / V_{dc} = [(2\sqrt{2} / n\pi) \sin n\delta/2]$$

$$= [(2\sqrt{2} / n\pi) \cos n\delta/2]$$

The rms harmonic content is shown against delay angle α in figure 3.1. It is seen that the rms voltage of the fundamental component decreases with α together with the mean output voltage. But the ratio of higher harmonic components and the fundamental components decreases at the same time. The third harmonic is eliminated if α is equal to $\pi/3$.

Pulse width modulation for regulation is also possible in bridge and half-bridge inverters. In a bridge inverter, it is easier to accomplish that in the half bridge circuit; because in half bridge circuit the load voltage can never be reduced to zero for any interval of time but, it will be either $+V_{dc}/2$ or $-V_{dc}/2$.

In a half-bridge circuit the pulse width modulation accomplished by reversing the voltage for short intervals in each half cycle as shown in figure 3.2. In the wave form, there are two reverse voltages of duration $(\delta_2 - \delta_1)$ per cycle. The waveform has quarter wave symmetry and hence can be represented by

$$V_L = \sum_{n=1,3,5,..}^{\infty} A_n \sin n\,\omega t$$

Where

$$A_n = 4/\pi(V_{dc}/2)\left[\int_0^{\delta 1} \sin n\omega t \, d(\omega t) - \int_{\delta 1}^{\delta 2} \sin n\omega t \, d(\omega t) + \int_{\delta 2}^{\pi/2} \sin n\omega t \, d(\omega t)\right]$$

$$= 4/n\pi(V_{dc}/2)[1 - 2\cos n\delta_1 + 2\cos n\delta_2]$$

By the selection of proper values of δ_2 and δ_1 certain harmonics from the output can be eliminated. The third and the fifth harmonics are eliminated if $\delta_2 = 33.3$degree and $\delta_1 = 23.62$ degree.

The regulation of the output voltage of a single phase inverter can also be obtained by connecting the outputs of two identical square-wave inverters of the same frequency in series, and there relative phases are controlled from 0 to π. The mean value of the combined output voltage decreases from 0 to π.

Multiple pulse-width modulation

In this method several pulses in each half-cycle are used. Multiple pulse-width modulation is effective in reducing the harmonic contents in the output voltage, particularly at lower output levels. Multiple pulses per half-cycle are produced by switching **on** and **off**,
a particular SCR many times before controlling the next SCR.

The control waveform is achieved by comparing a sine wave of variable amplitude of a particular frequency f_o and f_c, determines the number of pulses per half cycle, 'N'. The modulation index controls the output voltage. This type of modulation is also known as uniform pulse width modulation. The number of pulses per half-cycle is found from.

$$N = \underline{f_c / 2f_o}$$

Where $m_f = f_c / f_o$ is defined as the frequency modulation ratio.

The variation of modulation index M from 0 to1 varies the pulse width from 0 to π/N and the output voltage from 0 to V_s. The output voltage for single phase bridge inverters is shown in figure3.1 for multiple Pulse Width Modulation.

If δ is the width of each pulse, the rms output voltage can be found from

$$V_o = \left[2p/2\pi \int_{(\pi/P+\delta)/2}^{(\pi/P+\delta)/2} V_s \, d(\omega t)\right]^{1/2} = V_s (\sqrt{P\delta/\pi})$$

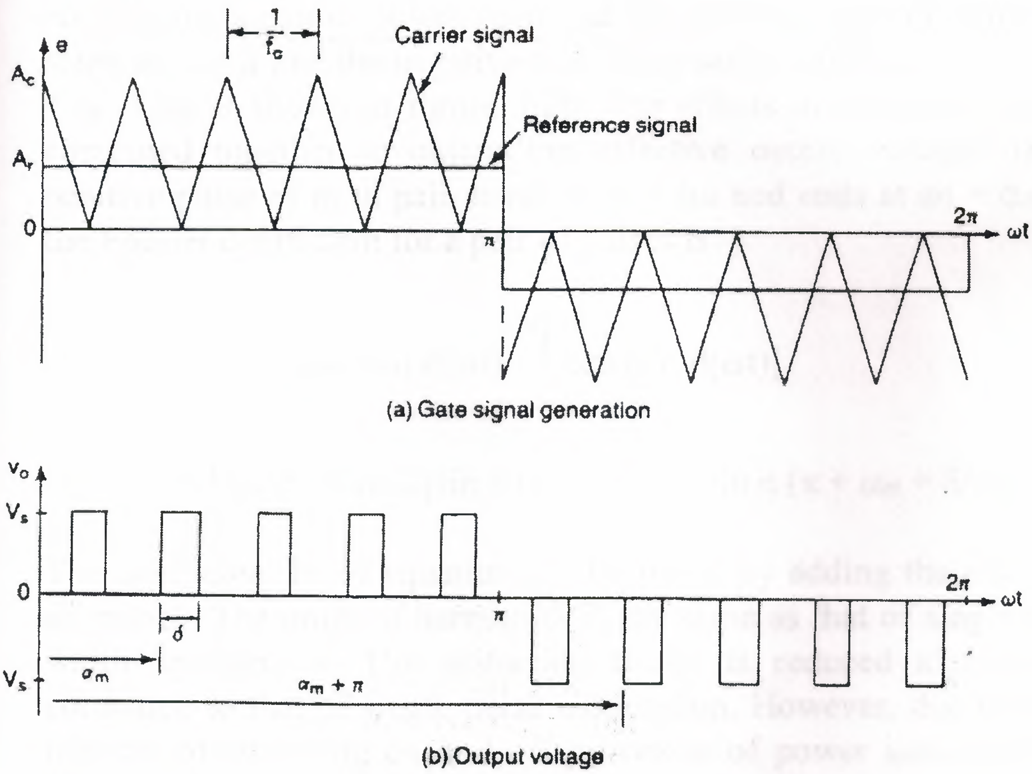


Figure 3.2
Multiple Pulse Width Modulation.

The general form of Fourier series for the instantaneous output voltage is

$$V_o(t) = \sum_{n=1,3,5,\ldots}^{\infty} B_n \sin n\omega t$$

The coefficient B_n in above equation can be determined by considering a pair of pulses such that the positive pulse of duration δ starts at $\omega t = \alpha$ and the negative one of the same width starts at $\omega t = \pi + \alpha$. This is shown in figure 3.2b. The effects of all pulses can be combined together to obtain the effective output voltage. If the positive pulse of m-th pair starts at $\omega t = \alpha_m$ and ends at $\omega t = \alpha_m + \pi$, the Fourier coefficient for a pair of pulses is

$$b_n = 1/\pi \left[\int_{\alpha m}^{\alpha m+\delta} \cos n\omega t \, d(\omega t) - \int_{\pi+\alpha m}^{\pi+\alpha m+\delta} \cos n\omega t \, d(\omega t) \right]$$

$$= 2V_s/n\pi \sin n\delta/2[\sin n(\alpha_m + \delta/2) - \sin n(\pi + \alpha_m + \delta/2)]$$

The coefficient B_n of equation can be found by adding the effects of all pulses. The order of harmonics is the same as that of single pulse width modulation. The distortion factor is reduced significantly compared to that of single pulse modulation. However, due to larger number of switching on and off processes of power semiconductor devices, the switching losses would increase. With larger values of 'N', the amplitudes of lower-order harmonics would be lower, but the amplitudes of some higher-order harmonics would increase. However such higher-order harmonics produce negligible ripple or can easily be filtered out.

Sinusoidal Pulse Width Modulation

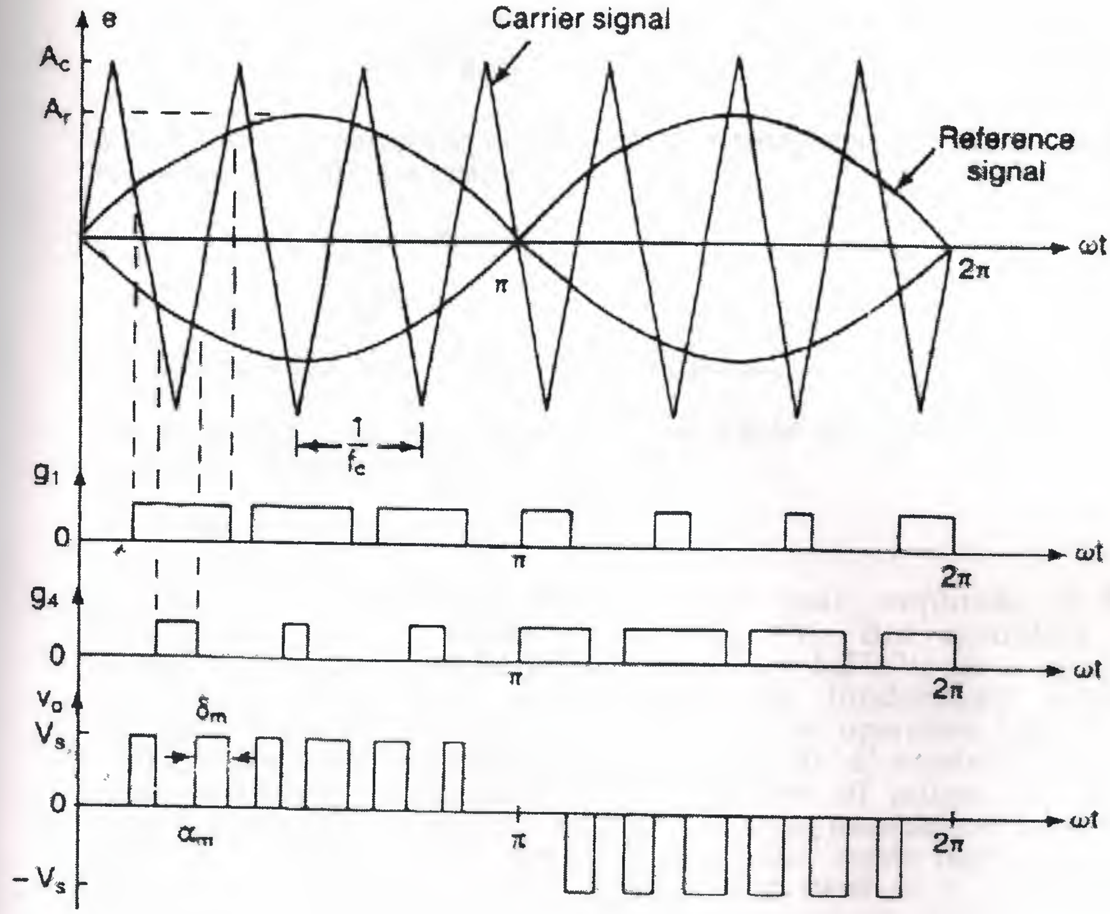
Instead of maintaining the width of all pulses the same as in the case of multiple-pulse modulation, the width of each pulse is varied in proportion to the amplitude of a sine wave evaluated at the center of the same pulse. The distortion factor and lower-order harmonics are reduced significantly. Comparing a sinusoidal reference signal with a triangular carrier wave of frequency fc as shown in Figure(a generates the gating signals. This type of modulation is commonly used in industrial applications and abbreviated as SPWM. The frequency of reference signal f_r determines the inverter output frequency f_o and its peak amplitude. A_r controls the modulation index, *M,* and then in turn the rms output voltage V_o. The number of pulses per half-cycle depends on the carrier frequency Within the constraint that two transistors of the same arm (Q_1 and Q_2) cannot conduct at the same time, the instantaneous output voltage is shown in figure1.3a.Using unidirectional triangular carrier wave as shown in Figure1.3b can generate the same gating signals.

The rms output voltage can be varied by varying the modulation index M. It can be observed that the area of each pulse corresponds approximately to the are under the sine wave between the adjacent midpoints of off periods on the gating signals. If δm is the width of m-th pulse, Equation can be extended to find the rms output voltage.

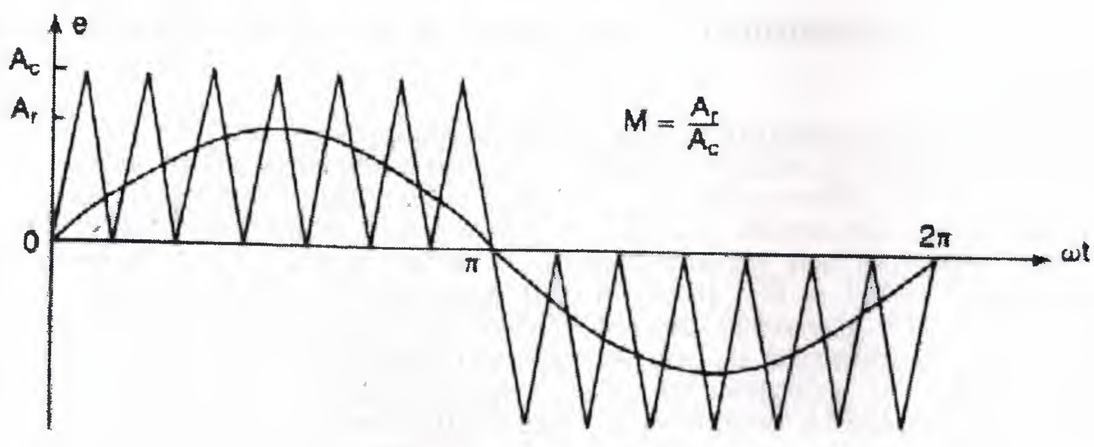
Equation can also be applied to determine the Fourier coefficient of output voltage as

$$B_n = \sum_{m=1}^{P} 2V_s/n\pi \sin n\delta/2[\sin n(\alpha_m + \delta/2) - \sin n(\pi + \alpha_m + \delta/2)]$$

This type of modulation eliminates all harmonics less than or equal to 2p - 1. For p = 5, the lowest-order harmonic is ninth. The output voltage of an inverter contains harmonics. The PWM pushes the harmonics into a high-frequency range around the switching frequency f_c. And its multiples, that is, around harmonics m_f, 2mf,3mf and so on. The frequencies at which the voltage harmonics occur can be related by



(a)



(b)

Figure 3.3
Sinusoidal pulse width modulation.

$$f_n = (jm_f + k) f_c$$

Where the n-th harmonic equals the k-th side band of j-th times the frequency-modulation ratio m_f.

$$n = jm_f + k$$

$$= 2jp + k$$

For $j = 1, 2, 3, \ldots$ and $k = 1, 3, 5, \ldots$

The peak fundamental output voltage for PWM and SPWM control can be found approximately from

$$V_{m1} = dV_s \qquad \text{for } 0 \leq d \leq 1.0$$

For d = 1,Equation gives the maximum peak amplitude of the fundamental output voltage as $V_{m1(max)} = V_s$. But according to Equation, $V_{m1(max)}$ could be as high as $4V_s = 1.278V_s$ for a square-wave output. In order to increase the fundamental output voltage,'d'must be increased beyond 1.0. The operation beyond d =1.0 is called over de-modulation. The value of 'd' at which $V_{m1(max)}$ equals $1.278V_s$ is dependent on the number of pulses per half-cycle'P'and is approximately 3 for P = 7. Over modulation basically leads to a square-wave operation and adds more harmonics as compared to operation in the linear range (with d ≤ 1.0). Over modulation is normally avoided in applications requiring low distortion for example un-interruptible power supplies (UPS).

Modified Sinusoidal Pulse Width Modulation

Figure 3.3 indicates that the widths of pulses that are nearer the peak of the sine wave do not change significantly with the variation of modulation index. This is due to the characteristics of a sine wave, and the sinusoidal pulse-width modulation technique can be modified so that the carrier wave is applied during the first and last 60° intervals per half-cycle (e.g. 0 to 60° and 120 to 180°). This type of modulation is known as MSPWM and shown in Figure 3.4. The fundamental component is increased and its harmonic characteristics are improved. It reduces the number of switching of power devices and also reduces switching losses. The number of pulse 'q' in the 60-degree period is normally related to the frequency ratio, particularly in three-phase inverters, by

$$f_c / f_o = 6q + 3$$

Advanced modulation techniques

Trapezoidal modulation.
Staircase modulation.
Stepped modulation.
Harmonic injection modulation
Delta modulation.

Trapezoidal modulation.

Comparing a triangular carrier wave with a modulating trapezoidal wave as shown in Figure 3.5, generates the gating signals. The trapezoidal wave can be obtained from a triangular wave by limiting its magnitude to $\pm A_r$, which is related to the peak value $A_{r\,(max.)}$ by

$$A_r = \sigma A_{r\,(max.)}$$

Where σ is called the triangular factor, because the waveform becomes a triangular wave when $\sigma = 1$.The modulation index M is

$$M = A_r / A_c = \sigma A_{r\,(max.)} / A_c \quad \text{for } 0 \leq M \leq 1$$

The angle of the flat portion of the trapezoidal wave is given by

$$2\phi = (1 - \sigma)\,\pi$$

For fixed values of $A_{r\,(max)}$ and A_c, changing the triangular factor can vary M that varies with the output voltage,σ. This type of modulation increases the peak fundamental output voltage up to $1.05V_s$ but the output contains lower-order harmonics.

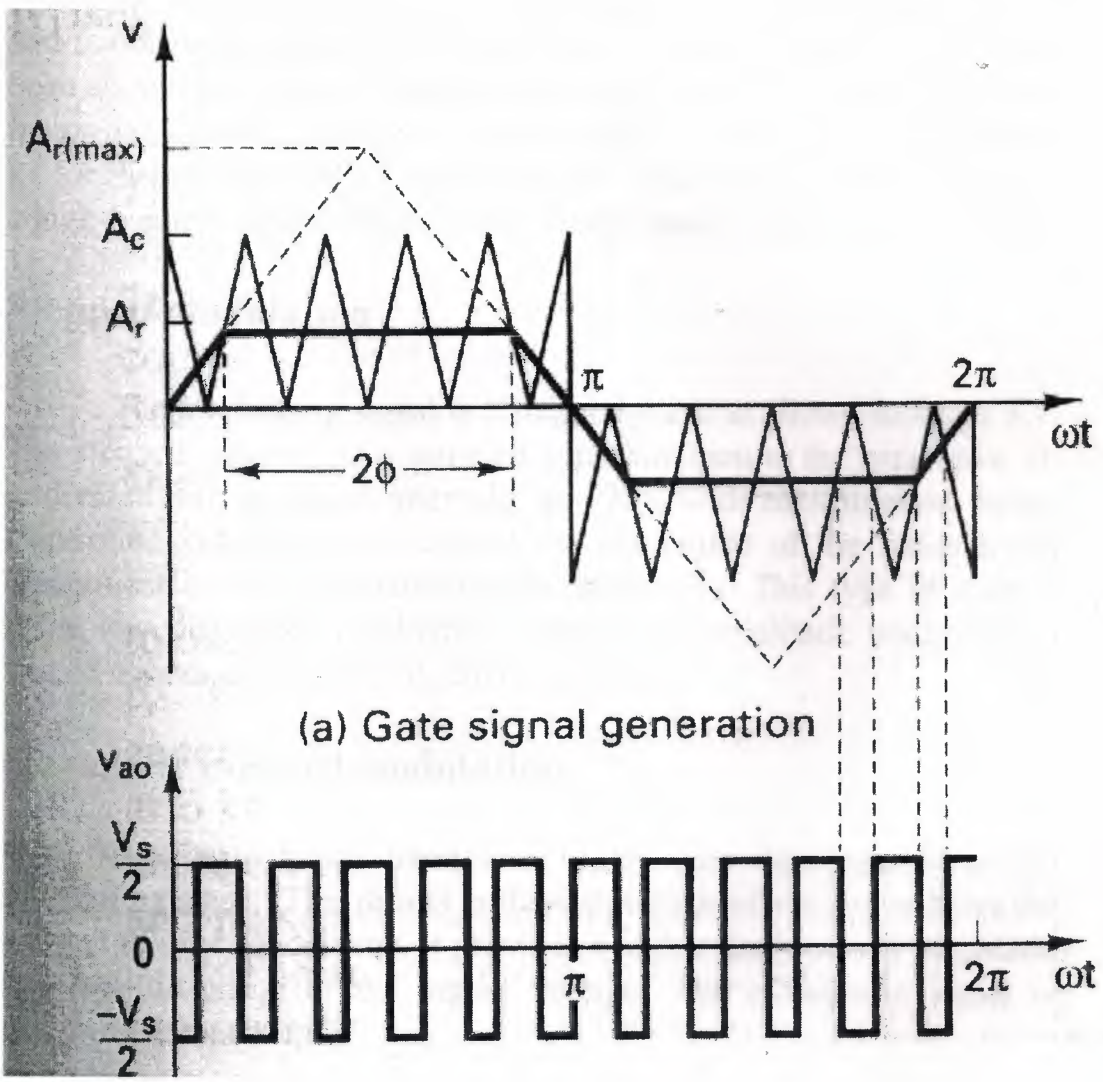


Figure 3.5
Trapezoidal modulation.

Staircase modulation

The modulating signal is a staircase wave as shown in Figure 3.6. The staircase is not a sampled approximation to the sine wave. The levels of the stairs are calculated to eliminate specific harmonics. The modulation frequency ratio m_f and the number of steps are chosen to obtain the desired quality of output voltage. This is an optimized PWM and is not recommended for fewer than 15 pulses in one cycle. It has been shown that for high fundamental output voltage and low distortion factor, the optimum number of pulses in one cycle is 15 for two levels, 21 for three levels and 27 for four levels. This type of control provides a high-quality output voltage with a fundamental value of up to $0.94V_s$.

Stepped modulation

The modulating signal is a stepped wave as shown in figure 3.7. The stepped wave is not a sampled approximation to the sine wave. It. is divided into specified intervals, say 20°, with each interval being. Controlled individually to control the magnitude of the fundamental component and to eliminate specific harmonics. This type of control gives low distortion, but higher fundamental amplitude compared to that of normal pulse width modulated control.

Harmonic injected modulation

Injecting selected harmonics to the sine wave generates the modulating signal. This results in flat-topped waveform and reduces the amount of over modulation. It provides a higher fundamental amplitude and low distortion of the output voltage. The modulating signal is generally composed of

$$V_r = 1.15 \sin\omega t + 0.27 \sin 3\omega t - 0.029 \sin 9\omega t$$

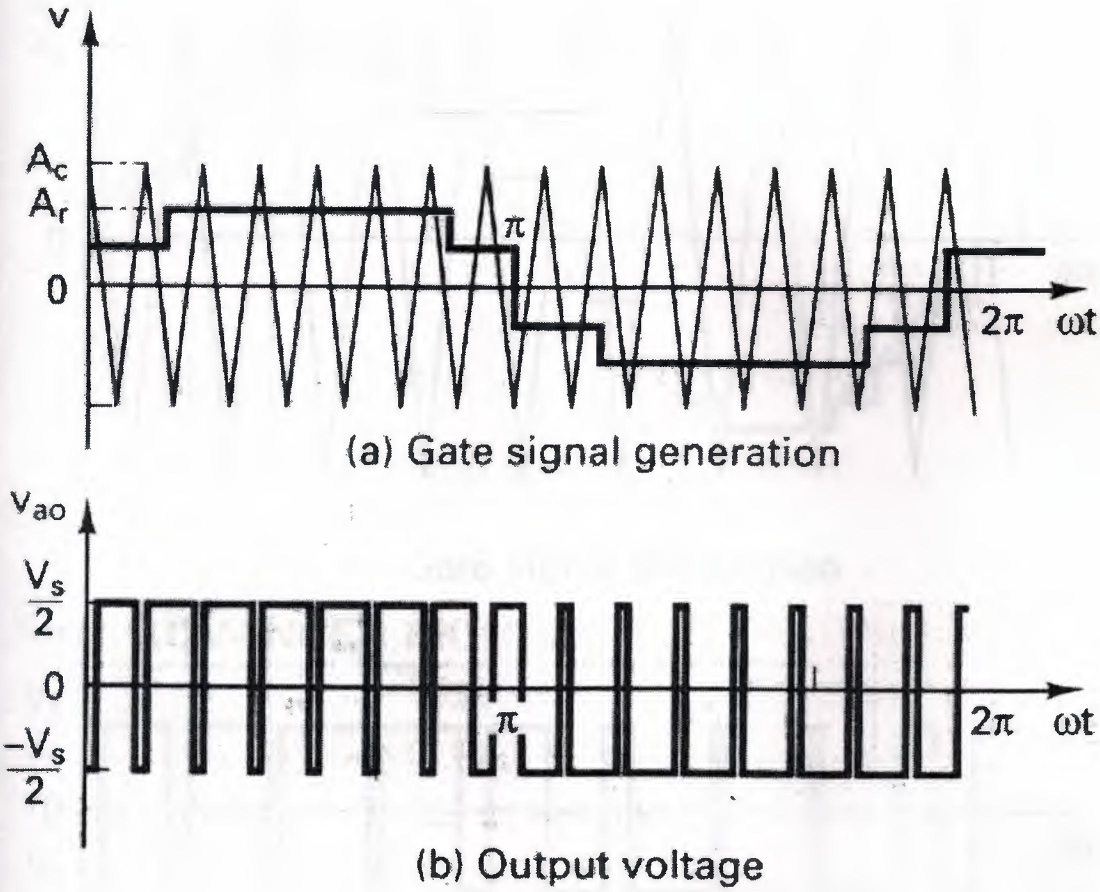


Figure 3.6
Staircase modulation.

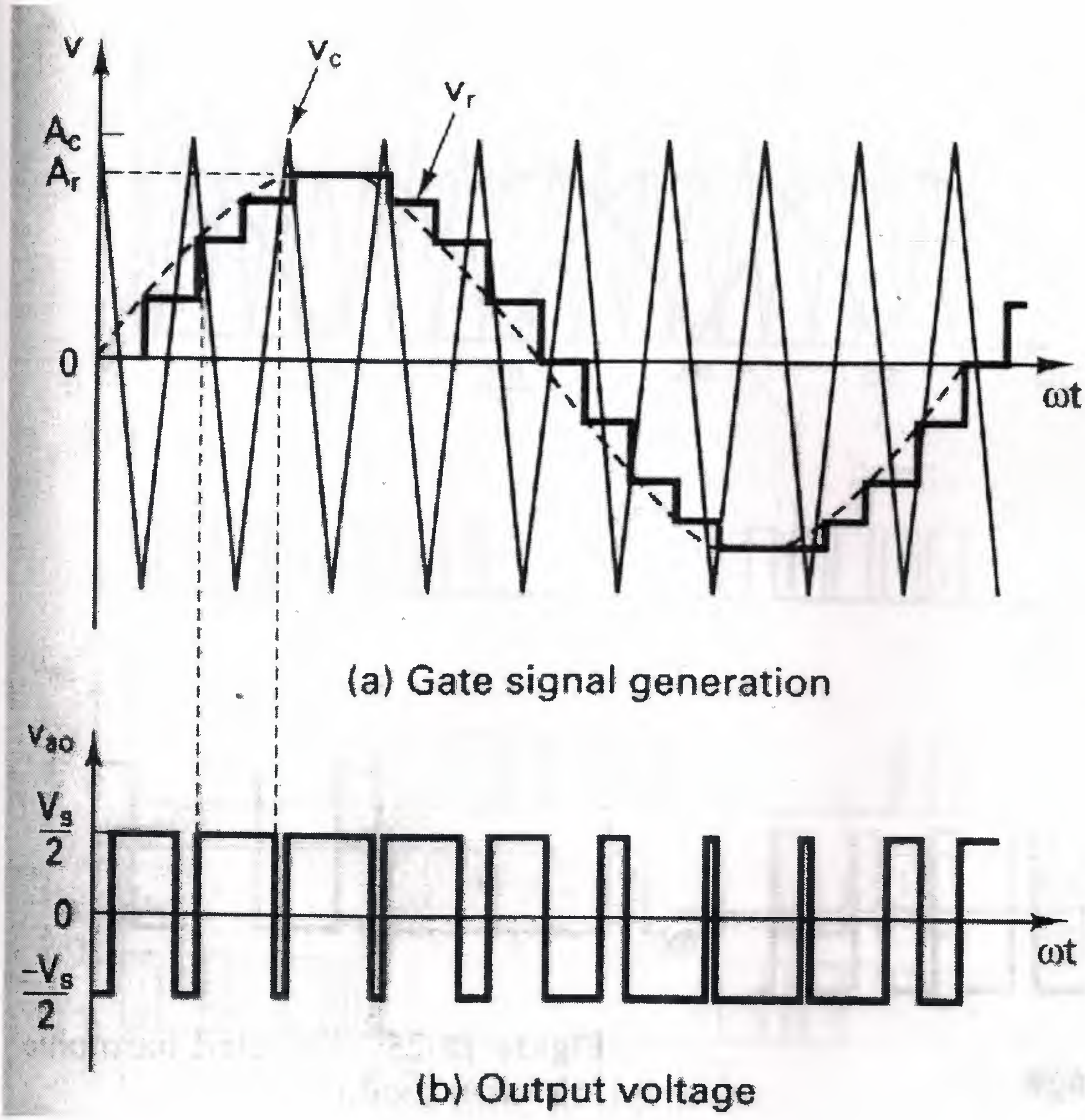


Figure 3.7
Stepped modulation.

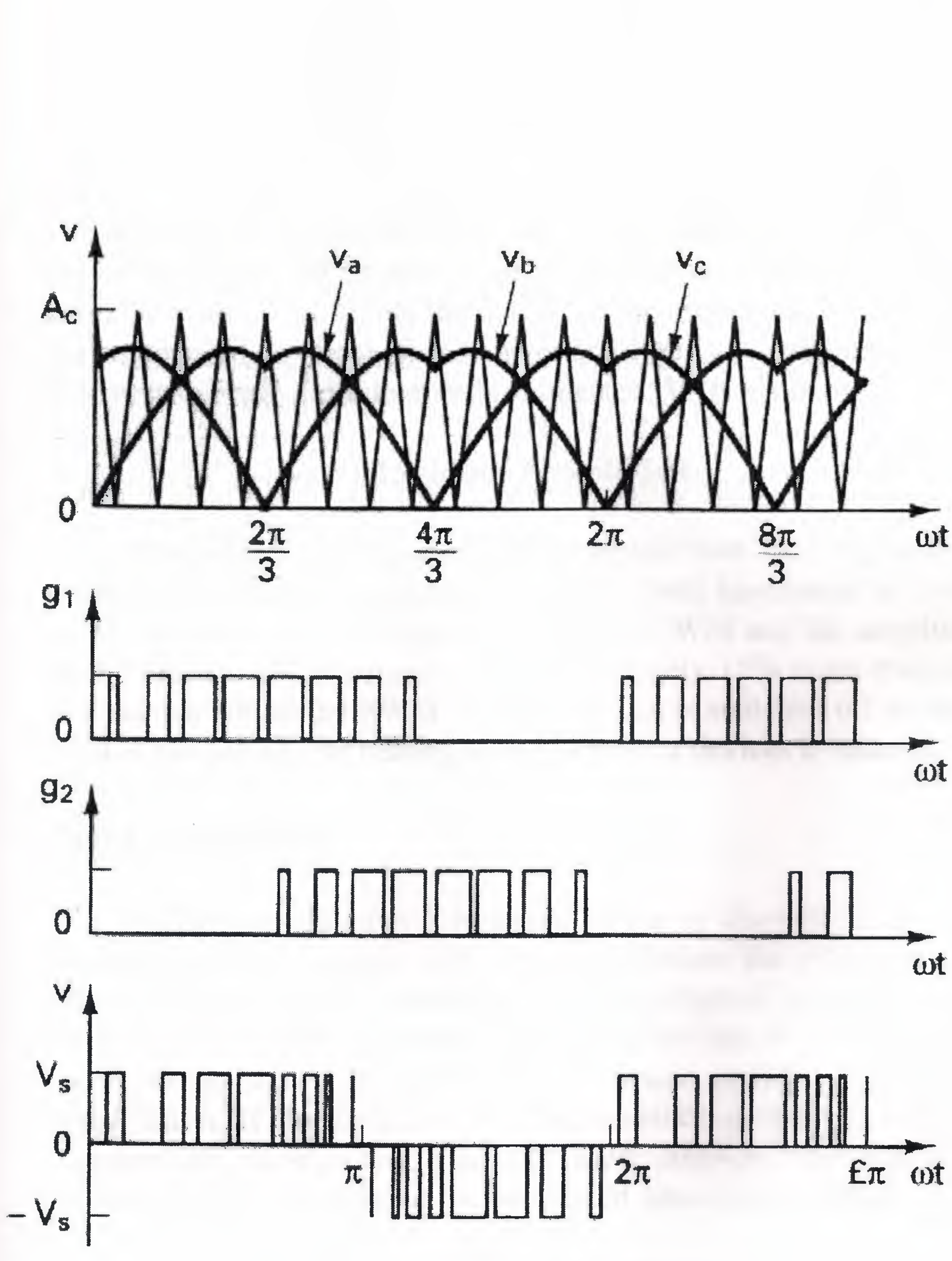


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Figure 3.9
Harmonic injection modulation.

The modulating signal with third and ninth harmonic injections is shown in Figure 3.9. It should be noted that the injection of 3n-th harmonics would not affect the quality of the output voltage, because the output of a three-phase inverter does not contain triplen harmonics. If only third harmonic is injected, V_r, is given by

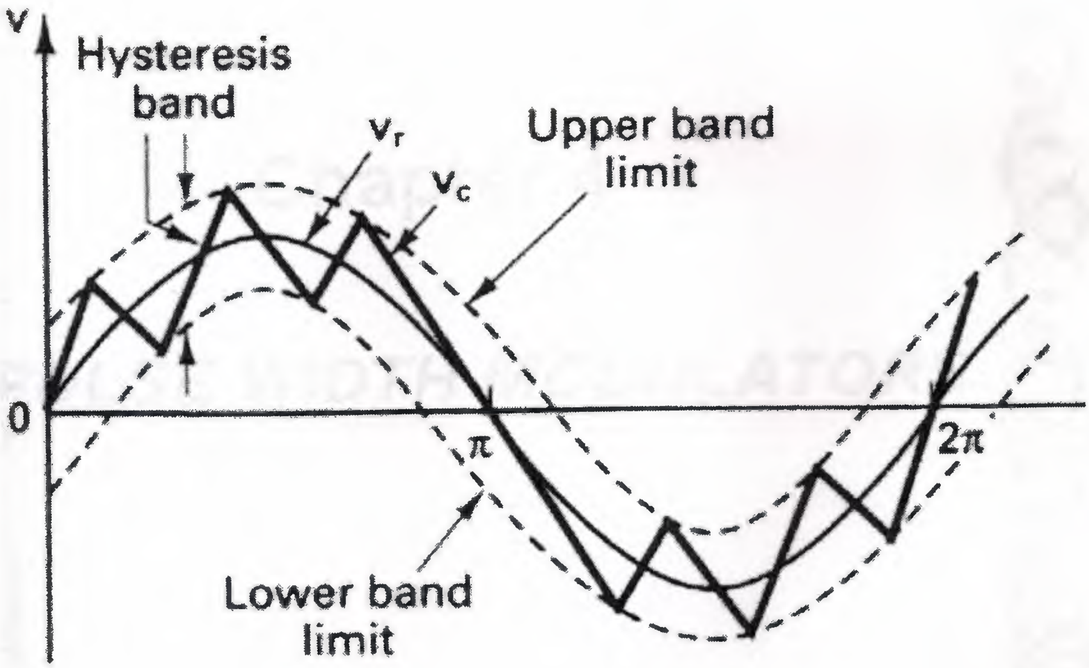
$$V_r = 1.15 \sin\omega t + 0.19 \sin 3\omega t$$

The modulating signal can be generated from $2\pi/3$ segments of a sine wave .This is the same as injecting 3nth harmonics to a sine wave. The line-to-line voltage is sinusoidal PWM and the amplitude of the fundamental component is approximately 15% more than that of a normal sinusoidal PWM. Since each arm is switched off for one-third of the period, the heating of the switching devices is reduced.

Delta modulation

In delta modulation a triangular wave is allowed to oscillate within a defined window ΔV above and below the reference sine wave V_r. The inverter switching function, which is identical to the output voltage V_0 is generated from the vertices of the triangular wave V_c. as shown in Figure 1.10. It is also known as hysteresis modulation. If the frequency of the modulating wave is changed keeping the slope of the triangular wave constant, the number of pulses and pulses widths of the modulated wave would change.

The fundamental output voltage can be up to 1 V, and is dependent on the peak amplitude A_r and frequency f_r of the reference voltage. The delta modulation can control the ratio of voltage to frequency, which is a desirable feature in ac motor control.



(a)

Figure 3.10
Delta Modulation.

Chapter 4

PULSE WIDTH MODULATORS

Pulse width modulators

Pulse width modulation is a modulation technique in which the width of each pulse varies in accordance with the instantaneous sample value of baseband signal m (t). The larger the sample value is the wider the corresponding pulse. Pulse width modulation is some times referred to as pulse duration or pulse length modulation.

Let T_s denotes the sample duration. Using the sample m (nT_s) of a baseband signal m (t) to modulate the width of the nth pulse, we obtain the PWM signal

$$S(t) = \sum_{n=-\infty}^{\infty} g(t - nT - k_P\, m(nT_s))$$

Where k_P is the sensitivity of the pulse-width modulator and g (t) denotes standard pulse of interest.

Generation of pulse width modulation

Pulse-width modulation may be generated by applying trigger pulses (at Nyquist rate) to control the starting time of pulses from a monostable multivibrator, and feeding in the signal to he sampled to control the duration of these pulses. The circuit diagram for such an arrangement. The emitter-coupled monostable multivibrator makes an excellent voltage-to-time converter, since its gate width is dependent on the voltage to which the capacitor C is charged. If this voltage is varied in accordance with a signal voltage series of rectangular pulses will be obtained, with widths varying as required. Note that the circuit does the twin jobs of sampling and converting the samples into PWM.

It will be recalled that the stable state for this type of multivibrator is with T_1 **off** and T_2 **on**. The applied trigger pulse switches T_1 **on**, whereupon the voltage at C_1 falls as T_1 now begins to draw collector current, the voltage at B1 follows suit and T_1 is switched off by regenerative action. As soon as this happens, however, C begins to charge up to the collector supply potential through R. After a time determined by the supply voltage and the RC time constant of the charging network, B_2 becomes sufficiently positive to switch T_2 **on**. Regenerative action and stays off until the arrival of the next trigger pulse simultaneously switch off T1. The voltage that the base of T_2 must reach to allow T_2 to turn on is slightly more positive than the voltage across the common emitter resistor R_k. This voltage depends on the current flowing through the circuit, which at the time is the collector current of T_1 (which is then **on**). The collector current depends on the base bias, which is governed by the instantaneous changes in the applied signal voltage. The applied modulation voltage controls the voltage to which B_2 must rise to switch T_2 **on**. Since this voltage rise is linear the modulation voltage is seen to control the period of time during which T_2 is **off**, that is, the pulse duration. It should be noted that this pulse duration is very short compared to even the highest signal frequencies, so that no real distortion arises through changes in signal amplitude while T_2 is **off**.

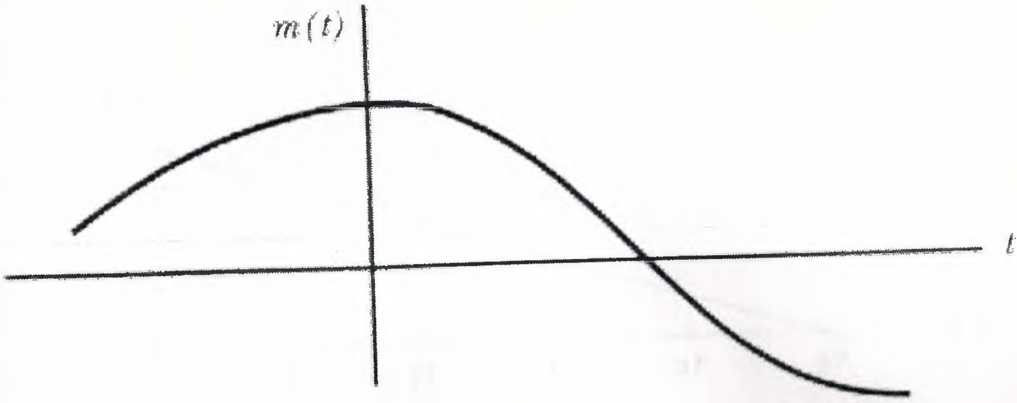


Figure a:
Message signal.

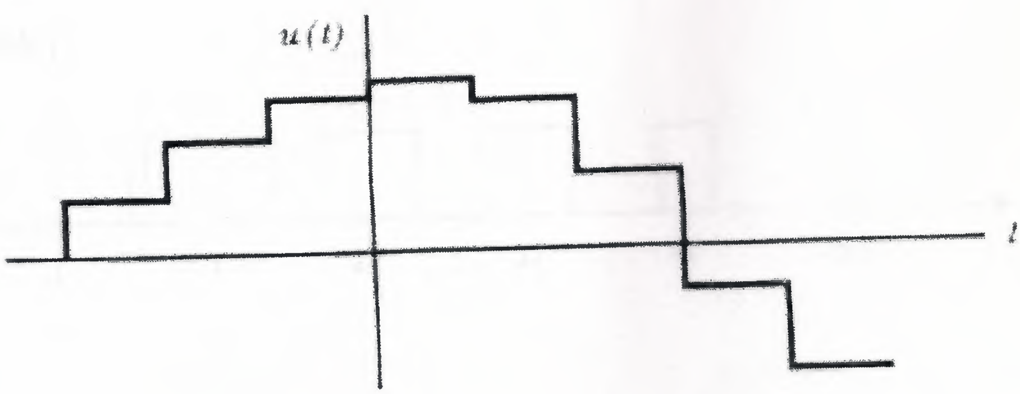
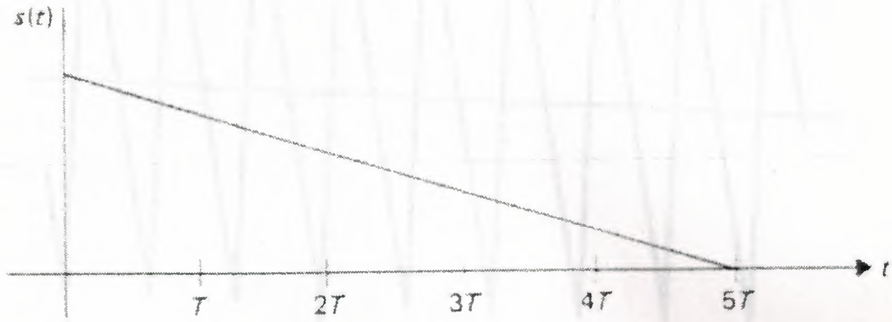
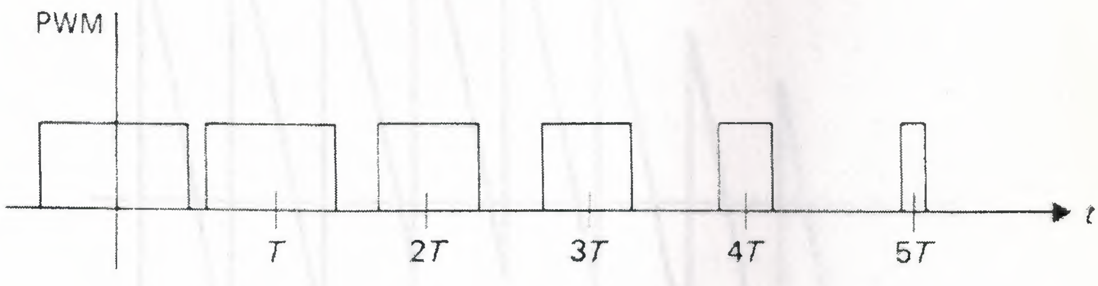


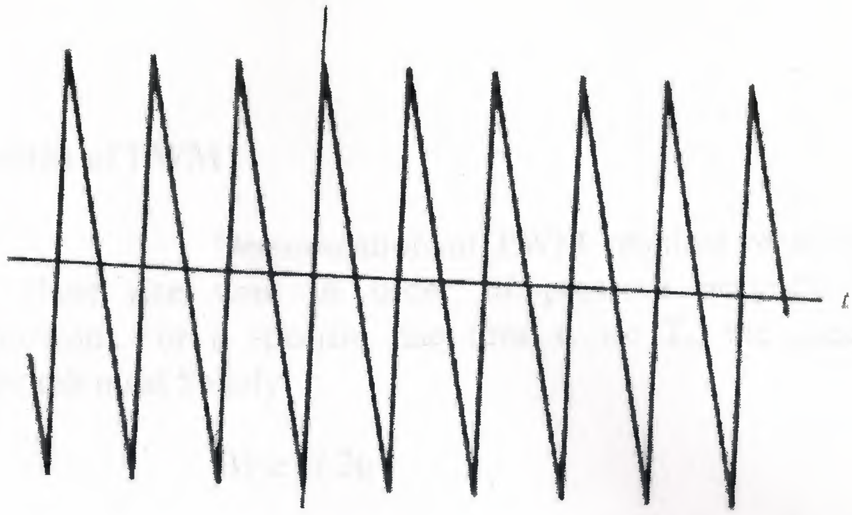
Figure b:
Staircase approximation of the message signal.



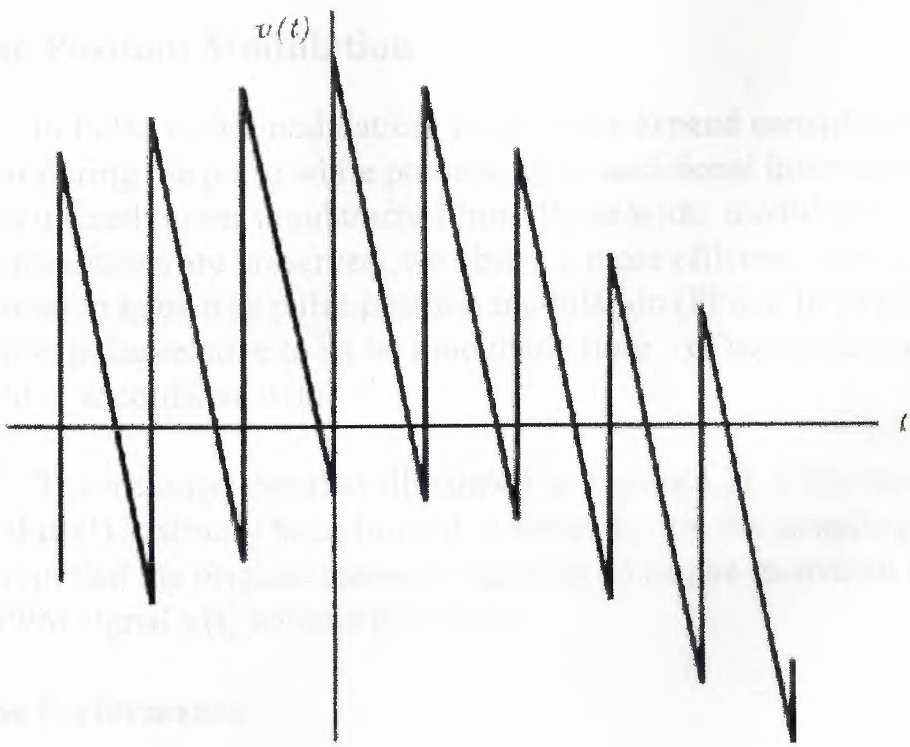
(a)



(b)



(c) Sawtooth waveform



(d)

Figure 4.1
Composite waveform obtained by adding (b) and (c)

Detection of PWM

Demodulation of PWM requires received pulses with short rise time in order to preserve accurate message information. For a specific rise time $t_r \ll T_s$, the transmission bandwidth must Satisfy

$$B_T \geq 1/2t_r$$

Which is will be substantially greater than the pulse amplitude transmission bandwidth. In exchange for the extra bandwidth, we gain the benefit of content amplitude pulses that suffer no ill effects from nonlinear distortion in transmission since nonlinear distortion does not alter pulse width.

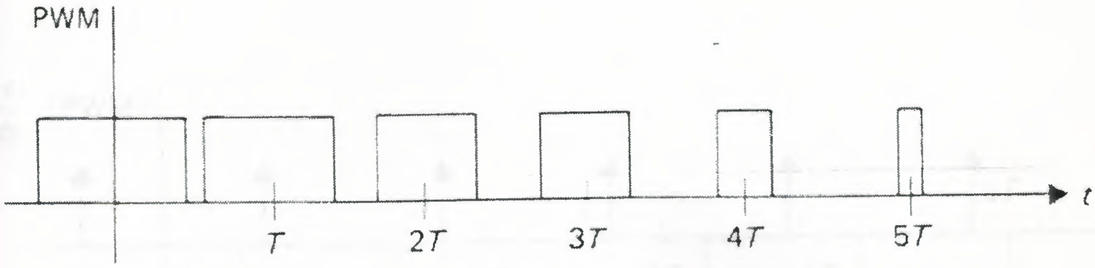
Pulse Position Modulation

In Pulse width modulation, long pulses expend considerable power during the pulse while possessing no additional information. If this unused power is subtracted from Pulse width modulation, only time transitions are preserved, we obtain a more efficient type of modulation known as pulse position modulation (PPM). In PPM, the position pulse relative to its un modulated time of occurrence is varied in accordance with

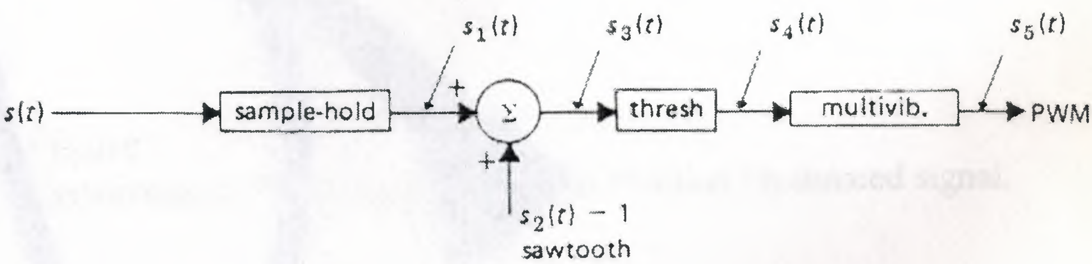
The message signal as illustrated in Figure(4.2). If the message signal m (t) is strictly band limited, it follows from the sampling theorem that the original message signal m (t) can be recovered from the PPM signal s (t) without distortion.

Noise Performance

Additionally Pulse Position Modulation has the potential for wideband noise reduction potential. The reason is that the information resides in the time location of the pulse edges, not in the pulses

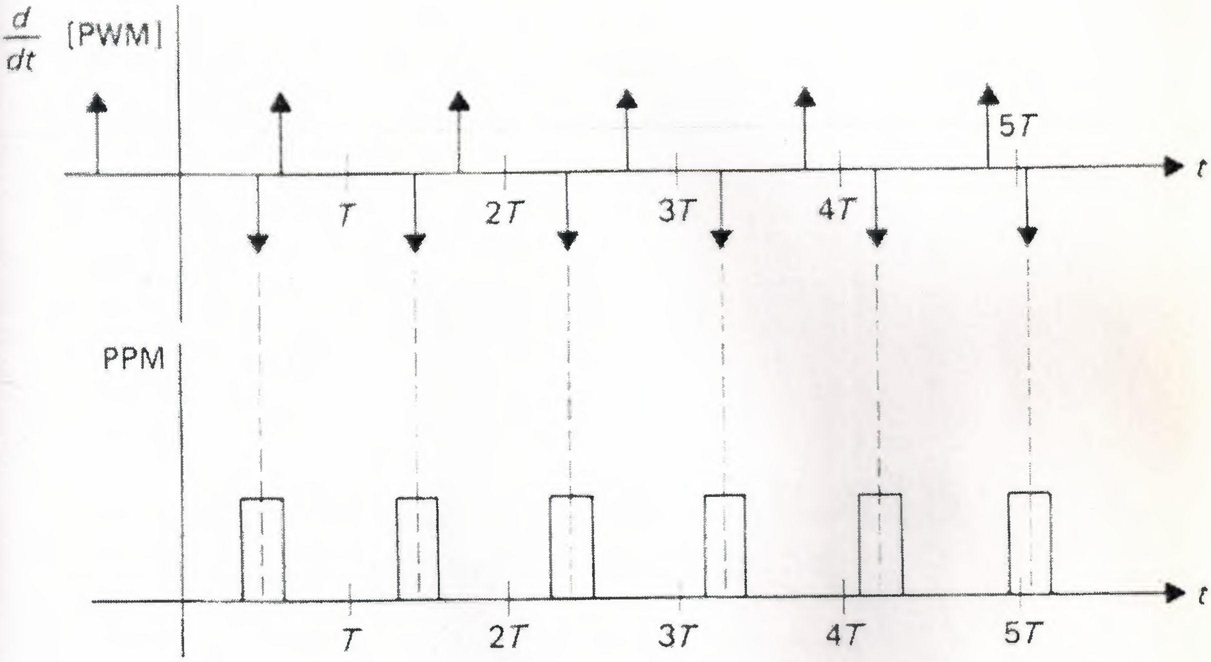


(e) Pulse width modulation waveform.



(f) Block diagram of pulse width modulator.

Figure 4.2
Generation of pulse width modulated waveform.



(c)

Figure:
Conversion of PWM signal into Pulse Position Modulated signal.

themselves. The pulse power of pulse width modulation is wasted power and it would be more efficient to suppress the pulses and just transmit edges without transmitting the pulses to define them.

Chapter 5

PULSE WIDTH MODULATED TRANSFORMERS

Pulse Width Modulated Transformer .

The pulse width modulated transformers found many of its applications such as radar, television, and digital computers, because the voltage and current waveforms are pulses. They are inserted for the same general reasons that they appear in the more conventional electronic circuits to change the amplitude of a pulse, to couple successive stages of pulse amplifiers, to change impedance levels, to isolate direct current from a circuit element, etc.

In fulfilling these requirements, it is important that the transformer reproduce the input pulse as faithfully as possible at its secondary terminals. Figure 5.1 shows a square-wave input pulse. The pulse width will usually range from a fraction of a microsecond to about 20μ s, and a relatively long time will elapse before the pulse repeats. To determine the output waveform requires a transient rather than a steady state examination. A typical result is that shown in Figure 5.2.

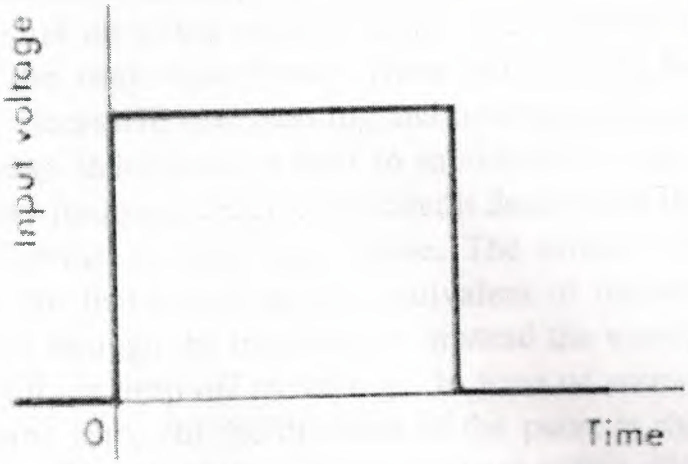


Figure 5a
Pulse width modulated transformers input voltage.

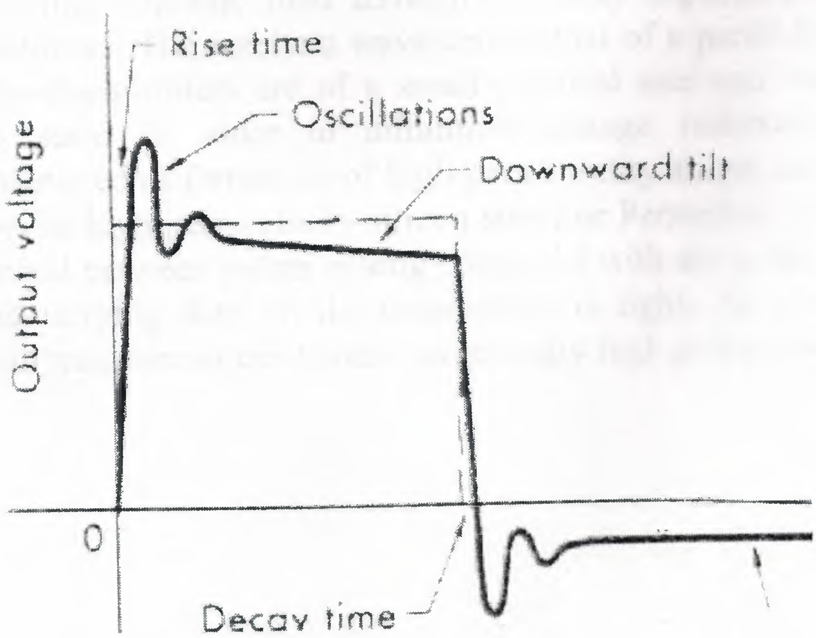


Figure5b
Pulse width modulated transformers output voltage waveform.

The high-frequency equivalent circuit determines the response to the leading edge of the pulse. Because of the presence of the leakage inductance, an appreciable time is required for the output voltage to build up to the desired value. This is called the rise time. Because of the stray capacitance. There will usually be oscillations resulting in successive overshooting and undershooting of the desired value. Leakage inductance is kept to minimum for the shortest rise time. The low-frequency equivalent circuit determines the response to the flattop portion of the input pulse. The output voltage cannot remain flat, for that would be the equivalent of transmitting steady direct current through the transformer. Instead the waveform shows a downward tilt, or drop-off of voltage. In time of course the voltage would become zero, but the duration of the pulse is short compared with this time. The tilt of the pulse top is kept within allowable limits by having high magnetizing inductance that is, by constructing the core of high-permeability material. When the input voltage is removed at the termination of the pulse, there is an appreciable decay time before the secondary voltage reaches zero. There's also a significant backswing associated with a damped oscillation and a long-duration negative overshoot of the voltage. In effect, during this period, the magnetizing inductance is discharging the energy of the decaying magnetic field through the stray capacitance and circuit resistances. The resultant waveform is that of a parallel RLC circuit. Pulse-transformers are of a small physical size and have relatively few turns in order to minimize leakage inductance. The are constructed of ferrites or of high-permeability alloys such as Hipersil (special high-permeability silicon steel) or Permalloy. Since the time interval between pulses is long compared with the pulse duration, the load-carrying duty on the transformer is light. As a result, a very small transformer can handle surprisingly high pulse-power levels.

Chapter 6

Pulse Width Modulated Choppers

Pulse width modulated choppers

In ac applications, the transformer serves to convert electric power efficiently from one voltage level to another. The principle of operation of ac transformer is based on an alternating magnetic flux. But in dc applications solid state semiconductor devices (power diode, thyristor) which can easily switch at a high repetition frequency achieve same function. The switching principle is known as chopper. The switching action of chopper circuit can be designed either to step down from a higher input voltage to a lower output voltage or to step up from a lower input voltage to a higher output voltage.

Chopper circuits are of the following three types.

Step-up chopper.

Step-down chopper.

Two-quadrant chopper.

In any chopper circuit, the voltage conversion ratio is defined as

Voltage conversion ratio = [output voltage / input voltage]

Step-up chopper

When the voltage conversion ratio (a) is less than unity then we have a voltage step-up chopper.

Step-down chopper

If the voltage conversion ratio (a) is greater than unity then we get a voltage step-down chopper.

Two-quadrant chopper

The chopper circuit, which incorporates both the step up and step down switching action is called two-quadrant chopper.

In any chopper circuit, the voltage conversion ratio is determined by the switching times of the solid state semiconductor switches that constitutes the chopper circuits. It is easy to vary the voltage conversion ratio smoothly and continuously, by means of adjustable voltage input into the chopper control circuit, to suitably modify the timing of switching control pulses to the switching

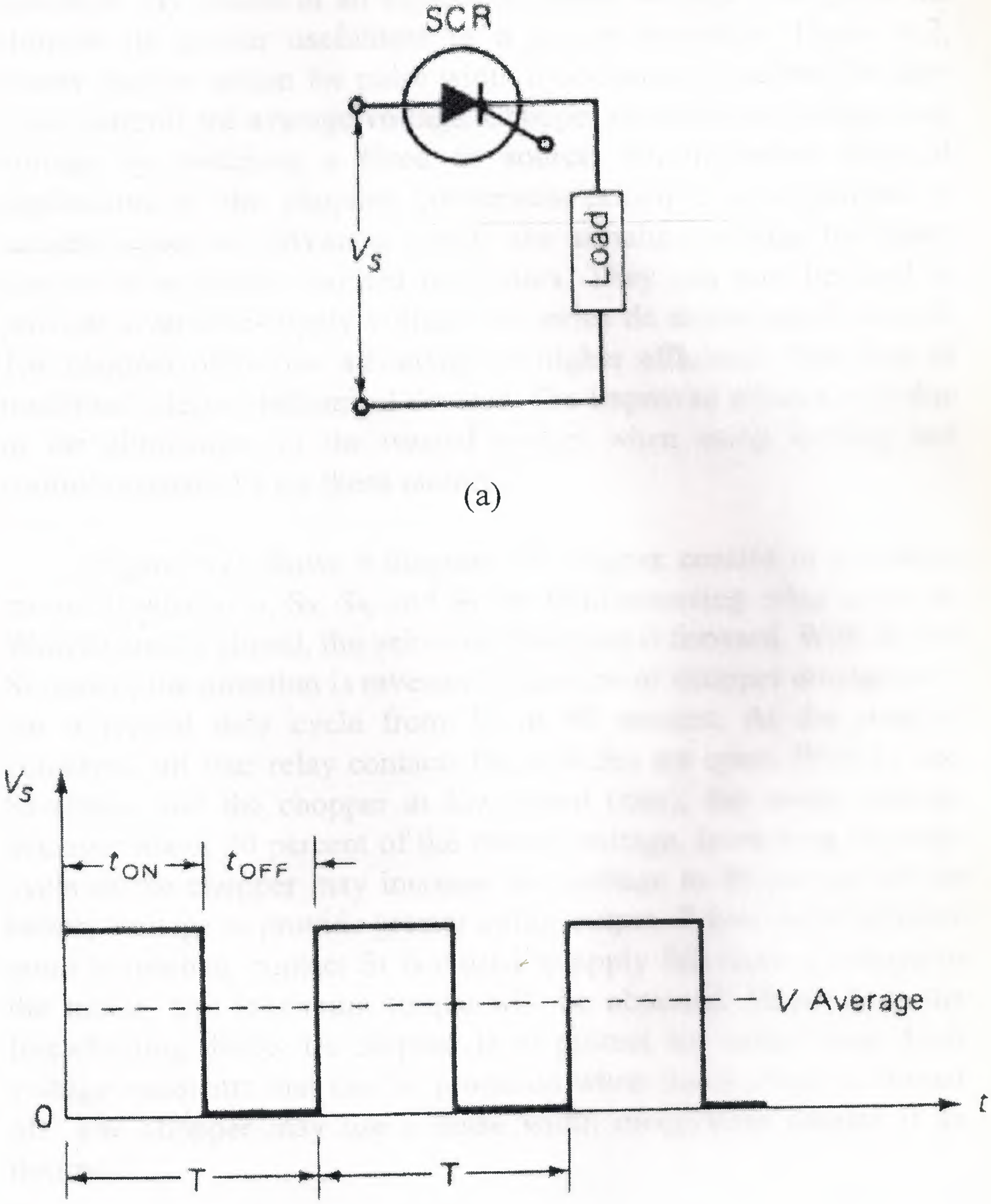


Figure 6.1
Basic Chopper waveform.

devices. This can be done in both step-up and step-down modes of operation. By means of an adjustable control voltage, that gives the chopper its greater usefulness as a power controller. Figure 6.2, shows chopper action for pulse width modulation. Note that the duty cycle controls the average voltage. Chopper controls the average load voltage by switching a fixed dc source. An important practical application of the chopper conversion principle is employed in variable speed dc drives to supply the armature voltage for speed control of separately excited dc motors. They can also be used to provide a variable-supply voltage for series dc motor-speed control. The chopper offers the advantage of higher efficiency than that of traditional electromechanical devices. The improved efficiency is due to the elimination of the wasted energy when using starting and control resistance's for these motors.

Figure 6.2, shows a diagram of chopper control of a vehicle motor. Contacts S_2, S_3, S_4, and S_5 are field-reversing relay contacts. With S_2 and S_5 closed, the vehicular direction is forward. With S_3 and S_4 closed, the direction is reversed. This type of chopper arrangement has a typical duty cycle from 20 to 80 percent. At the stopped condition, all four relay contacts (S_2,S_3,S_4,S_5) are open. With S_2 and S_5 closed and the chopper at low speed (rate), the motor voltage averages about 20 percent of the battery voltage. Increasing the duty cycle of the chopper may increase this voltage to 80 percent of the battery voltage to provide greater motor output. When the 80 percent point is reached, contact S_1 is closed to apply full battery voltage to the motor, and maximum torque will be obtained. Diode D is the freewheeling diode. Its purpose is to protect the motor from high voltage transients that can be produced when the thyristor is turned off. The chopper may use a pulse width modulation control if so desired.

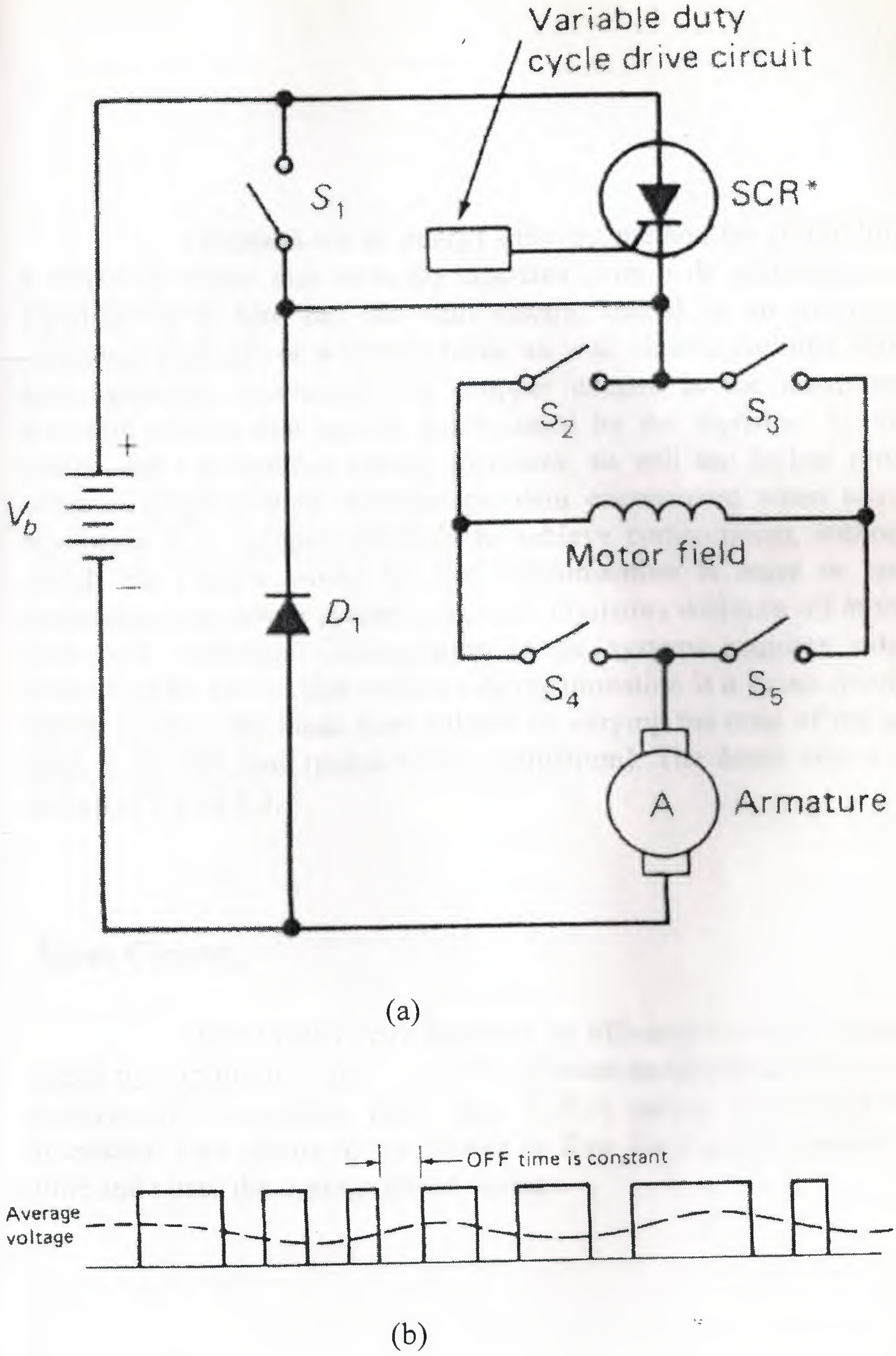


Figure 6.2
Chopper pulse width modulated waveform.

Choppers are an energy-efficient method for controlling a series dc motor that normally operates from a dc power source supplied by at hird rail (as with electric trains) or an overhead conductor (trolley) or a battery bank, as with electric forklifts. One basic problem encountered in chopper control is the maximum armature current that can be commutated by the thyristor. As the motor size (horsepower rating) inereases, so will the locked rotor armature requirements. Another problem encountered when using thyristors in a chopper circuit is to achieve commutation, without which the control would be lost. Commutation is more or less automatic in ac power systems since the thyristors will turn off at the line zero crossings. Commutation in dc systems requires extra circuitry. One circuit that achieves dc commutation is a Jones circuit, which controls the mean load voltage by varying the ratio of the **on** time to the **off** time (pulse width modulation). The Jones circuit is shown in figure 6.3.

Jones Circuit.

The Jones circuit provides an efficient control of motor speed by varying the duty cycle. To increase motor speed. The time between SCR_1's gating pulse and SCR_2's gating pulse will be increased. This allows motor current to flow for a greater period of time and raises the average motor voltage.

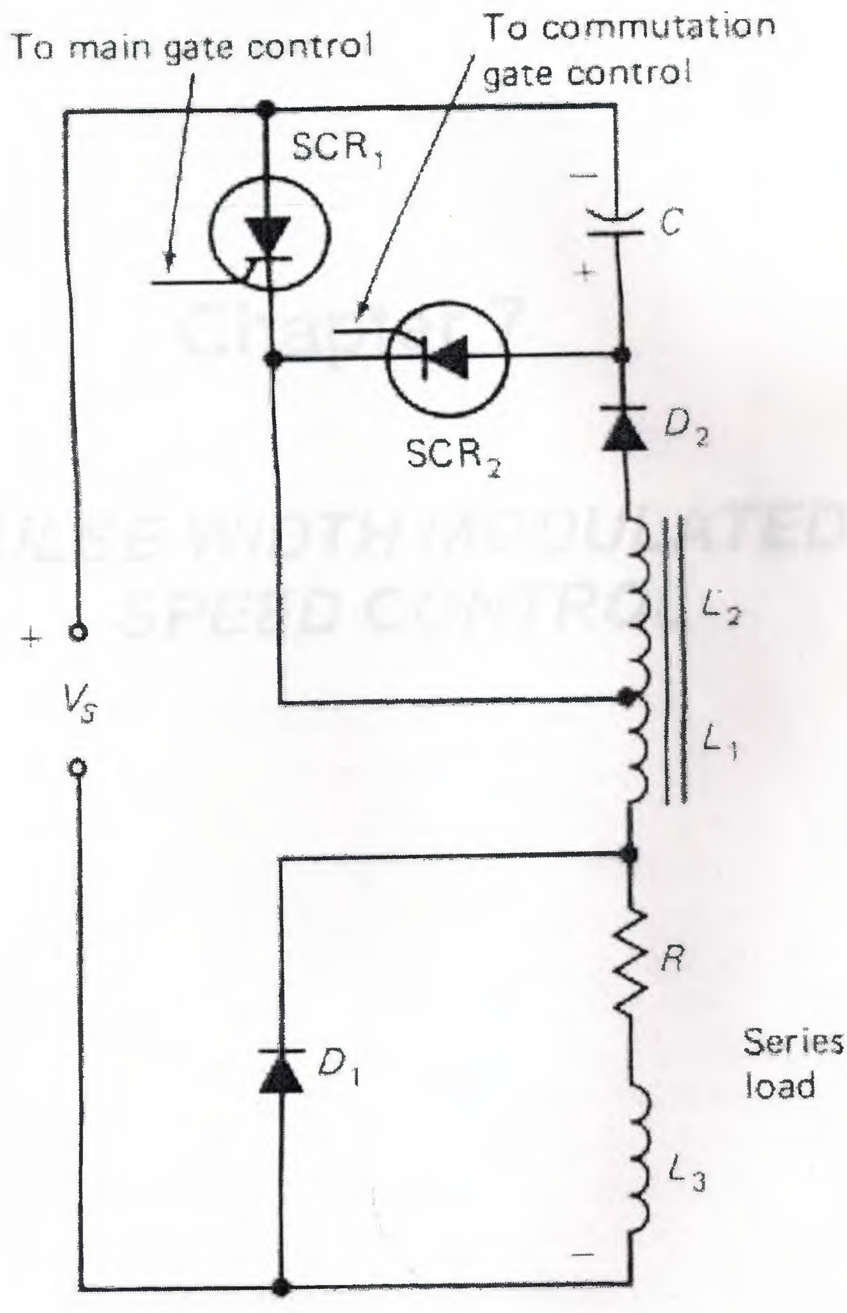


Figure 6..3
Jones pulse width modulated chopper circuit.

Chapter 7

PULSE WIDTH MODULATED SPEED CONTROL

Pulse width modulated motor speed control

There are various methods for controlling the speed of motors, but the pulse-width modulation technique is most popular. Generally sinusoidal pulse-width modulation is used to achieve a variable ac voltage at the inverter output by keeping the dc-input voltage constant. In this system the carrier is synchronized with the single and a multiple-of-three ratio is maintained to reduce the harmonic content. The fundamental output voltage is controlled by the variation of the modulation index. When the modulation index is less than unity, the voltage at fundamental frequency with carrier frequency harmonics and the related side bands appear at the output. Increasing the modulation index beyond unity and the voltage waveform approaches the square wave can increase the output voltage. Therefore, PWM control is suitable for both constant-torque and constant-power modes of operation.

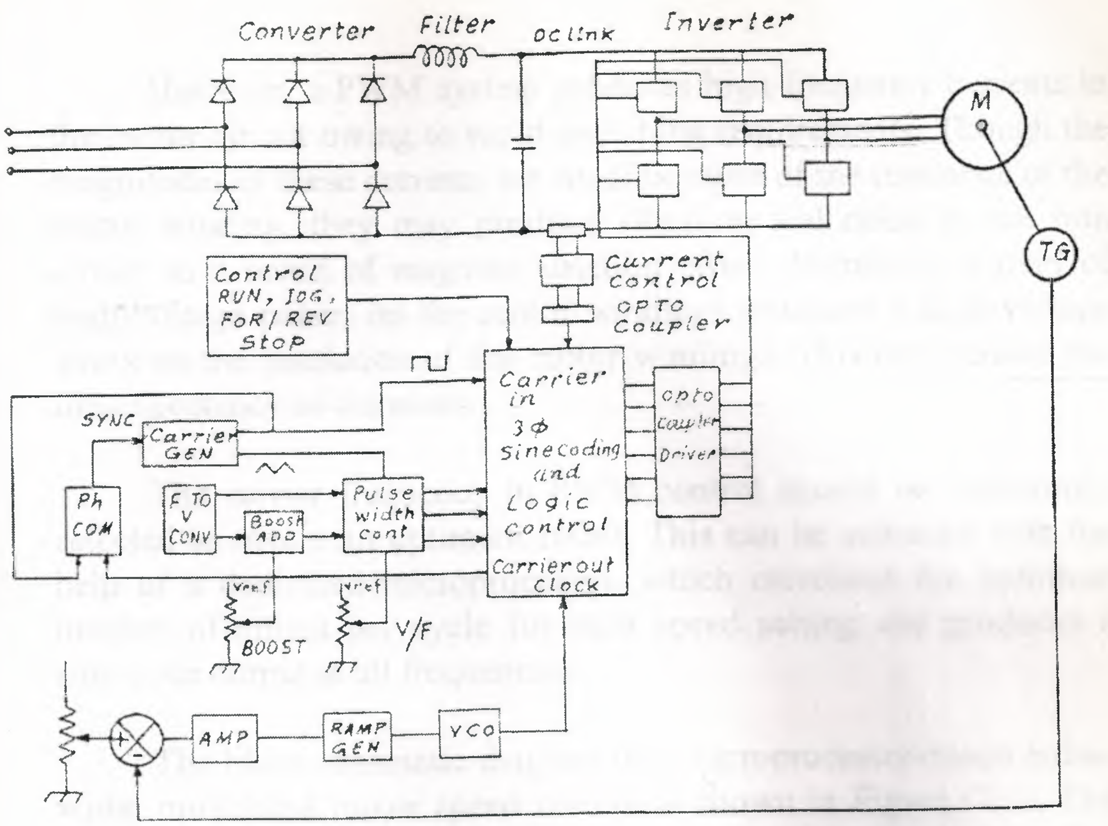


Figure 7.1
Microprocessor based Pulse Width Modulation Control System.

However, a PWM system produces high-frequency currents in the motor circuit owing to rapid-switching requirements. Though the magnitudes of these currents are small because of the reactance of the motor winding, they may produce vibration and noise in the iron circuit as a result of magneto striction effect. Moreover, a train of high-voltage pulses on the motor windings produces a high-voltage stress on the insulation of the motor windings. This may reduce the life expectancy of the motor.

The carrier frequency in PWM control should be judiciously selected to obtain an optimum result. This can be achieved with the help of a dedicated microprocessor, which calculates the optimum number of pulses per cycle for each speed setting and produces a sine-code output at all frequencies.

The block schematic diagram of a microprocessor-based pulse-width modulated motor speed control is shown in Figure (7.1). The logic section consists of a microprocessor based on Intel 8080. The input ac power is converted to dc by an uncontrolled bridge rectifier and sufficiently filtered to supply a smoothed dc. The dc voltage is applied to the three-phase inverter. The inverter consists of gate turn-off Thyristors.

In the scheme, the feed voltage of the techogenerator is compared with the set speed reference voltage. The error voltage is amplified and applied to a ramp generator. The ramp generator determines the maximum and minimum speed limits and also the acceleration and retardation. The output of the ramp generator is applied to a voltage-controlled oscillator, which produces a variable-frequency pulse output. This variable-frequency output pulse represents the set speed voltage signal suitably modified by the ramp generator. This signal is used for PWM control and as a clock signal by the microprocessor. The PW M control circuit maintains the V/f ratio and provides a boost in V/f whenever required. The microprocessor logic scheme is sine coded with double-edged modulation. The output of the microprocessor is fed to the inverter devices through the coupler driver. With this arrangement a very close sine wave output is produce to the motor load.

PWM speed control for DC motor

The dc motor has long been known for the ease with which speed control can be implemented. All that needs be done is to vary the voltage applied to the armature. Traditionally, this has been accomplished by means of a rheostat. The shortcoming of this method is that the over all system is very in efficient because of the power dissipation in the rheostat. Note that the same drawback prevails when a solid-state rheostat, such as transistor replaces the variable-resistance rheostat. A more efficient approach is to chop the dc and obtain the variation in applied voltage by varying the duration of the **on** time of the chopper. The principle of operation for doing this with power transistors is old hat, for it is merely a relatively simple PWM speed control for dc motors is shown in figure 7.2. This circuit is simpler than might be assumed from first glance, for the four operational amplifiers all part of a single IC module. All that is needed is the IC, the power MOSFET, and a few passive components. Previous implementations of this control concept usually required a tachometer.

Speed sampling is accomplished by monitoring the counter EMF of the motor. This sensing is done by the lower right-hand operational amplifier through the 100 kΩ resistor connected to the motor armature. The upper right-hand operational amplifier is the PWM modulator. It delivers a rectangular wave to the motor, with a duty cycle determined by the dc voltage level applied to its non-inverting terminal by the previously described sense amplifier, the lower-right hand amplifier.

The inverting input terminal of the PWM receives a triangular waveform an oscillator comprising the tow left-hand op-amp. Thus, the circuit is straightforward the PWM is an op-amp fed by a variable dc voltage and a triangular wave.

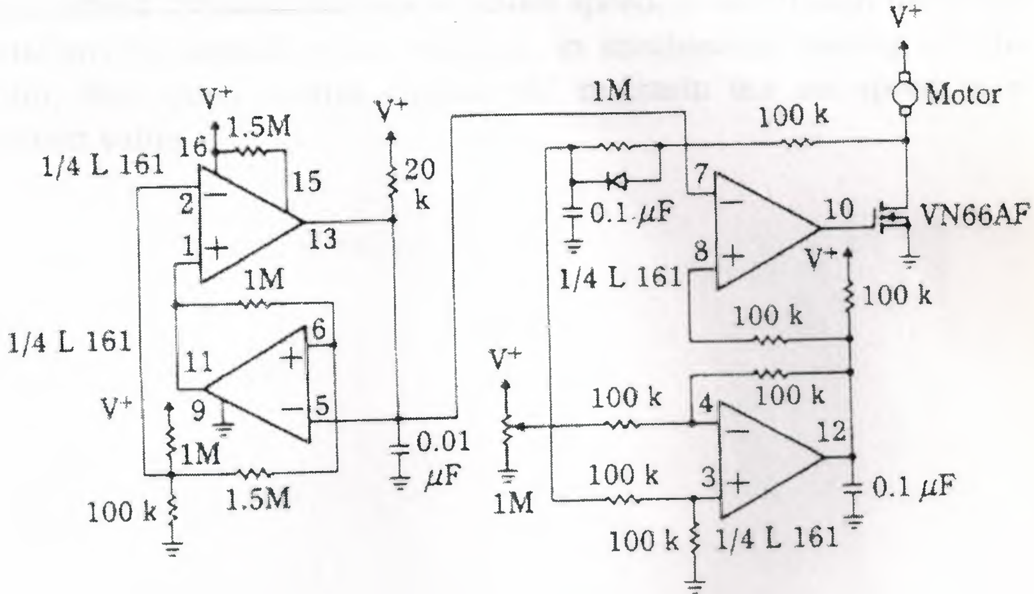


Figure 7.2
Pulse width modulated speed control of a DC motor.

Speed control occurs because of the change in the average value of armature current that can be brought about by adjusting the one megohm potentiometer associated with the sensing amplifier. Unlike some rheostatic speed controls, this circuit maintains the motor speed constant for any adjusted speed. Even though there are variations in applied motor voltage, in mechanical loading of the motor, this speed control circuit will maintain the set speed at a constant value.

PWM dc motor for electric vehicles

Direct-current motors have desirable characteristics for electric vehicles. Next to basic considerations of speed control, power, and torque, the all-important need is for high efficiency in order to extend battery capability between charging. One way of improving efficiency is to use pulse-width modulation in place of simple rheostatic (variable resistance) control of the armature current. Via pulse-width modulation technique, a great deal of I_2R dissipative loss can be eliminated.

An additional expedient for conserving battery drain is to use regenerative braking. The basic idea here is to use the drive motor as a generator during slow down. Not only is energy returned to the battery during such intervals, but the natural counter torque of the motor turned generator assists actual braking of the vehicle.

It happens that complementary-symmetry power MOSFET's can be arranged in a simple configuration to meet the needs of a PWM system with regenerative braking. Such power MOSFET's are easy to drive, easy to parallel, electrically rugged, and can have both minimal switching and conductive losses. Moreover, their intrinsic diodes can perform useful functions in the circuit, thereby reducing both parts count and cost. Viewed as a basic building block of an electric vehicle drive system, the representative circuit is shown in Figure 7.3. A nice feature of this arrangement is that there is no possibility of simultaneous conduction in the power MOSFET's both the N-channel unit and the P-channel unit cease conduction when the alternate unit is turned on.

The operation is as follows. In the motoring mode, the N-channel MOSFET Q_1 is chopped at a suitable pulse-repetition rate and duty cycle to give the vehicle desired motion. As long as acceleration or constant speed is desired, the P-channel power MOSFET Q_2 is kept in its non-conducting state. However, the intrinsic diode of Q_2 serves as the freewheeling diode to maintain steady current flow through the motor armature despite the chopping action of Q_1. Conversely, when it is desired to decelerate the vehicle, Q_2 is chopped at a suitable rate, and Q_1 is kept in its non-conducting state. The intrinsic diode of Q_1 then allows current from the generator to complete its path through the battery, thereby charging it. As alluded to before, this return of energy is accompanied by electromagnetic braking action in the armature. As can be seen, two accomplishments are realized through this circuit action enhanced braking is obtained for the vehicle, and

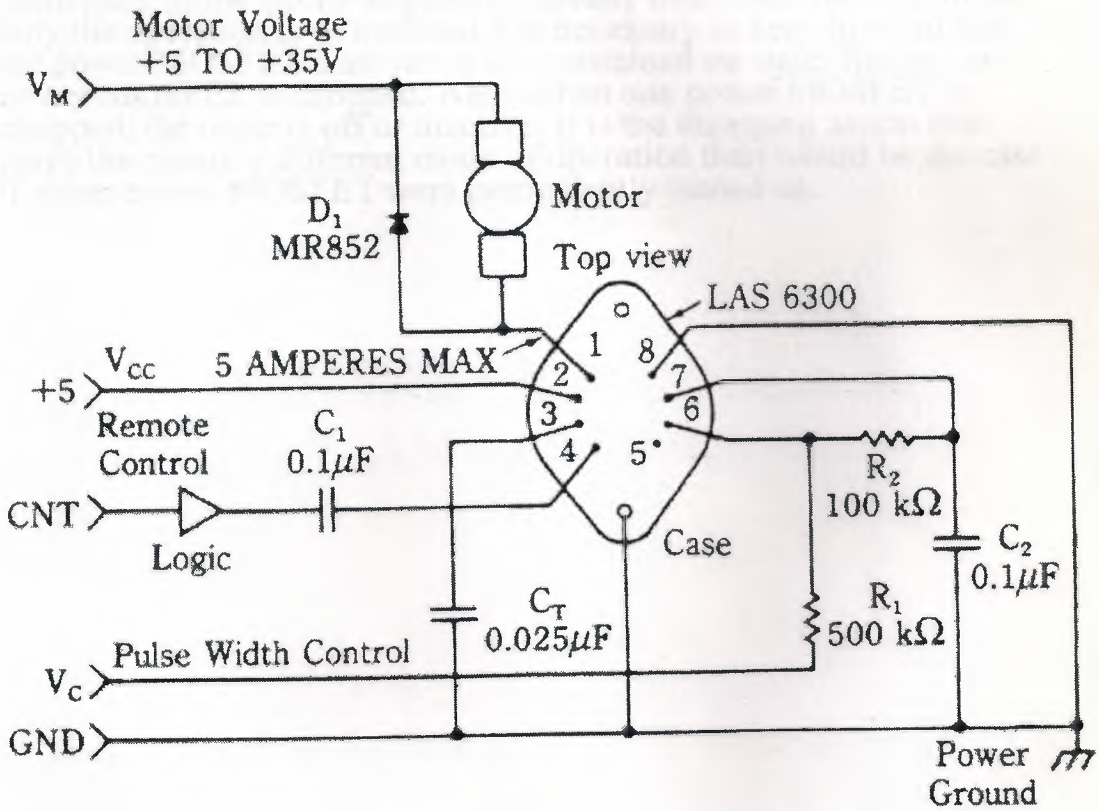


Figure 7.1
PWM Speed control of fractional-horse power DC motor.

charging current that would be otherwise wasted is returned to the battery.

Despite the topographic simplicity of this motor-driven circuit, its behavior is not readily obvious from inspection. Indeed, it might seem that the two freewheeling diodes are not properly polarized to participate in the circuit sequences already described. In order to see why the operation is as outlined it is necessary to keep in mind that the power MOSFET's are never in a sustained **on** state. Rather, each power MOSFET is chopped. Also, when one power MOSFET is chopped, the other is **off** or inactive. It is the chopping action that gives the circuit a different mode of operation than would be the case if either power MOSFET were permanently turned on.

Chapter 8

PULSE WIDTH MODULATED AMPLIFIERS

Pulse Width Modulated Amplifiers

The area between the wave and ground determines the average value (dc) of any wave. For a rectangular waveform, by changing the pulse width (t_{on}) while keeping the period (t_{period}) constant allows to control the signal's average value (V_{dc}) and can be calculated as

$$V_{dc} = [t_{on} / t_{period}]\, V_{peak}$$

Duty Cycle

Duty cycle may be defined as

= [Actual duration of the pulse / Duration of one half period]

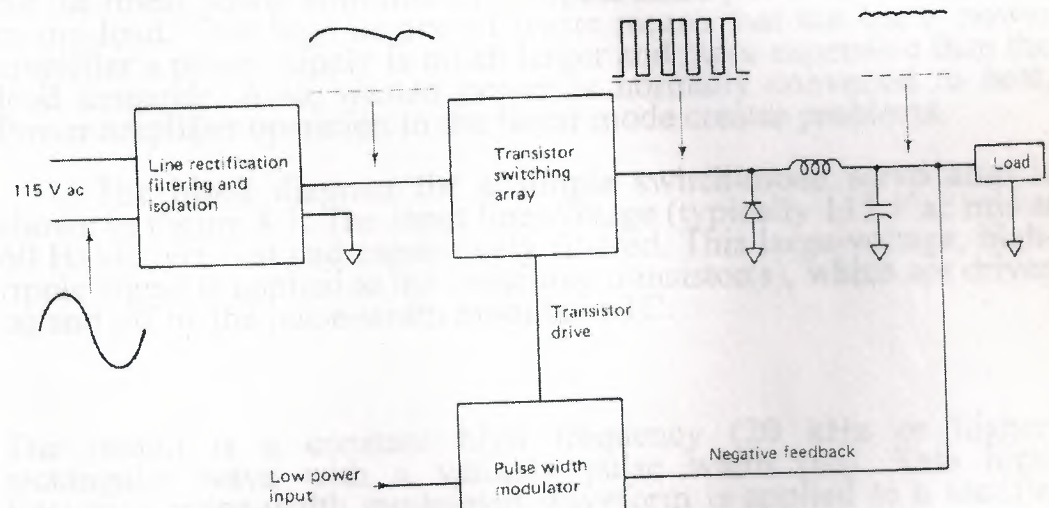


Figure 8.1
Block diagram of pulse width modulator amplifier.

Pulse width modulation waveform has narrow and wide width.

Switch- mode servo amplifier

The power operational amplifiers are required to dissipate a significant amount of power. This is because they are operated in their linear region, with considerable voltage across them, while providing many amperes of current to the load. Operation in this linear mode does impart minimum distortion to the signal. However, efficiency is very poor, often well below 50 %. It is not at all unusual for the linear power amplifier to dissipate more power than it delivers to the load. This high degree of waste means that the linear power amplifier's power supply is much larger and more expensive than the load demands. Also, wasted power is normally converted to heat. Power amplifier operation in the linear mode creates problems.

The block diagram for a simple switch-mode servo amp is shown in Figure 8.1. The input line voltage (typically 115 *V* ac rms at 60 Hz) is rectified and capacitively filtered. This large-voltage, high-ripple signal is applied to the switching transistor(s), which are driven on and off by the pulse-width modulator 1C.

The output is a constant high frequency (20 kHz or higher) rectangular wave with a variable pulse width (t_{on}). This high-frequency pulse-width modulated waveform is applied to a rectifier and LC filter, which smoothes out the variations, outputting a smooth dc voltage, equal to the average value of the pulse-width-modulated wave. Should some variation in the load cause the output to try to increase, the pulse-width-modulator 1C will sense this and reduce the pulse width to the switching transistors. This reduces the pulse width of the signal to the high-frequency Rectifier and filter, lowering the output voltage. Conversely, an increase in voltage at the low-power input will cause the pulse-width modulator to increase the pulse width out of the switching transistor array. This raises the voltage to the load. The load voltage tracks the low-power input voltage.

Pulse width modulated IC

A large variety of pulse-width modulation integrated circuits are available by different manufacturers. The choice to buy depends largely on the features of need, availability, and cost.

The LM-3524 PWM integrated circuit of National Semiconductor's represents a fair choice for switch-mode PWM integrated circuit available in the market. The block diagram of it is shown in figure 8.2. Several characteristics and features of this particular 1C should be pointed out The maximum input (supply) voltage is 40 volts. The output transistors are driven with complementary signals with a definite off period for each before either goes on. Each is capable of 100mA output. The on-chip oscillator's frequency is controlled by an external resistor and capacitor (pins 6 and 7). Maximum frequency is 350 kHz. The duty cycle is a function of the voltage at the compensation pin (pin9). The two output transistors are driven on alternately. On one cycle, the upper transistor is enabled through its NOR gate by a logic low at Q of the toggle flip-flop. Q is high, disabling the lower transistor. The next pulse from the oscillator flips the toggle flip-flop, setting Q to a logic high and Q to a logic low. These, in turn, enable the lower power transistor and disable the upper. This alternate action of the output transistors serves two purposes. First, each transistor rests for half the time, cooling down. Second, it allows push-pull operation if you should need to drive alternate halves of a power transformer primary. The key to the LM3524's performance is the comparator. To get one of the transistors on, its base must be driven high. This requires that all neither inputs to that NOR gate be at a logic low. The comparator's output goes low when the voltage on pin 9 (the compensation pin) is above the oscillator's ramp. Conversely, whenever the voltage on the oscillator's ramp rises above the voltage on the compensation pin, the comparator's output goes high, disables the NOR gate, and drives the transistors **off**.

$V_{oscillator} < V_{comp}$ => Q **on**

$V_{oscillator} > V_{comp}$ => Q **off**

The higher the voltage on pin 9 is, the longer each cycle it exceeds the oscillator's ramp, and the longer each cycle one of the output transistors stays on. Driving V_{pin9} to 3 V should keep the output transistors **on** virtually the entire cycle. Conversely, pulling Vpin9 below 1 volt will force the transistors **off.**

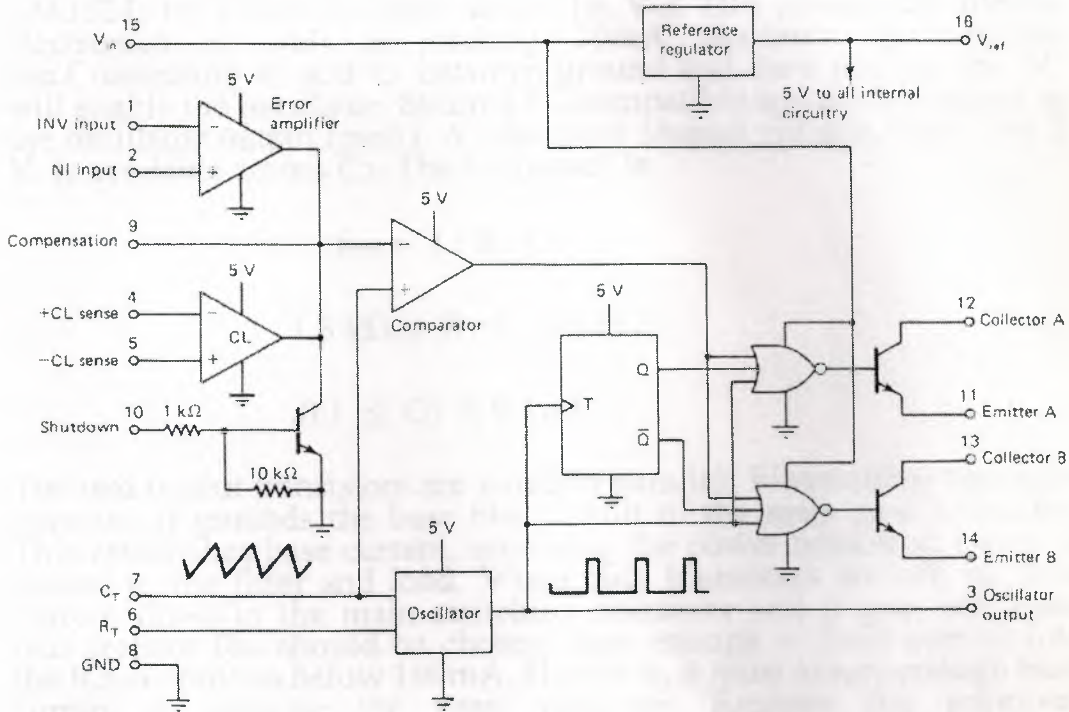


Figure 8.2
Block diagram of LM3524 pulse width modulator IC.

LM-3524 PWM as Forward Converter Amplifier

The LM3524 pulse-width modulator 1C in a simple forward converter amplifier is shown in Figure 8.3. Unregulated power is provided to both the switching transistor and the pulse-width modulator. This voltage must be at least 2 V greater than the largest output wanted. This provides saturation headroom for the transistor. However, the unregulated power must stay below 40 V, the chip's maximum supply voltage. With power and ground applied to the LM3524, +5 V dc will appear at pin 16, V_{ref}. This powers the internal electronics as well as making 20mA available for external use.Connecting R_T and C_T between ground and their pins on the 1C will enable the oscillator. Sharp TTL-compatible spikes will appear at the oscillator output (pin3). A saw-tooth shaped voltage, from 1 to 3 V, is available across C_T. The frequency is

$$f_{osc} \approx 1 / R_T C_T$$

$$1.8\ \mathrm{k}\Omega \leq R_T \leq 100\ \mathrm{k}\Omega$$

$$0.1 \leq C_T \leq 0.1\mu F$$

The two output transistors are wired in parallel. When either transistor goes on, it grounds the base bias circuit of the main pass transistor. This establishes base current, saturating the power transistor. Power is passed to the filter and load. When both transistors are off, no base current flows in the main switching transistor and it goes off. Base bias resistor R_{b1} should be chosen large enough to limit current into the ICs outputs to below 100mA. However, it must assure enough base current to saturate the pass transistor. Resistor R_{b2} improves performance by allowing the charge of parasitic capacitance and swamping out the effect of base leakage current. It is usually selected about 10 times larger than R_{b1}.

The switching signal from the transistor into a steady (more or less) dc signal for the load. The voltage at the load rectifier, inductor and capacitor convert the pulse-width-modulated is sampled by R_f and R_i and fed back to the inverting input of the error amplifier. Because of its high open-loop gain, this amplifier will drive its output to whatever voltage is necessary to minimize the difference in potential between its two inputs. The output voltage, at the load will be

$$V_L = V_{in} (1+R_f/R_i)$$

However, the error amp's common-mode input voltage is between 1.8 and 3.4 V. So you may need to add a zero and span circuit in front of V_{in}, to assure that the range of your control signal is converted to match these limits.

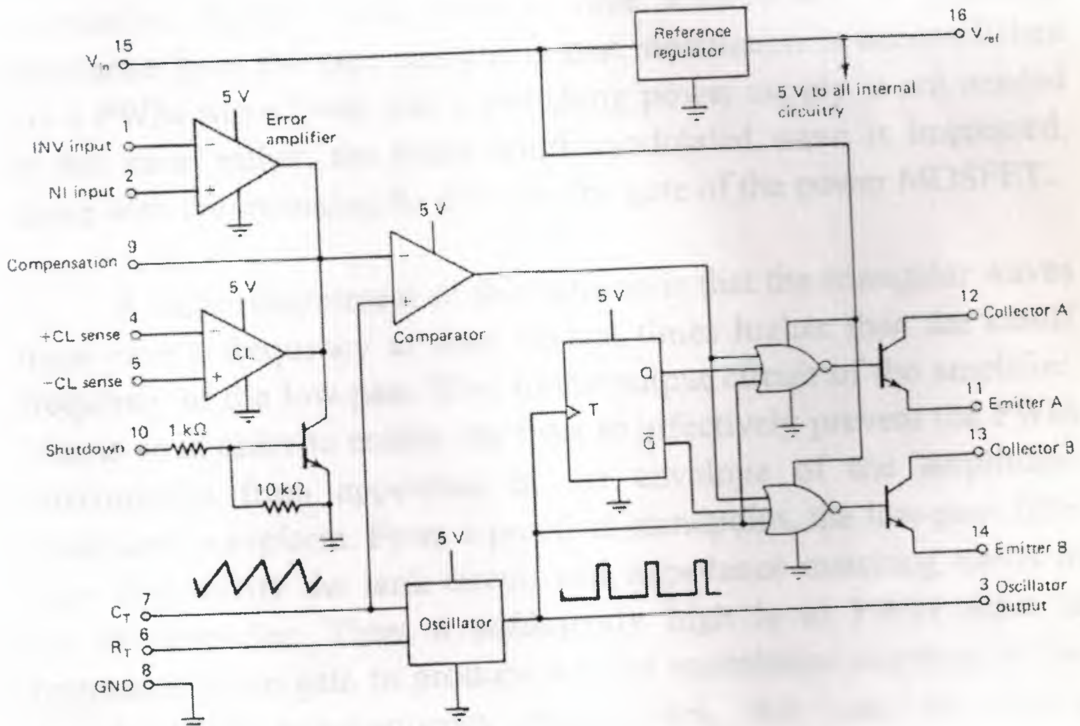


Figure 8.3
Block diagram of a sample forward converter amplifier.

Pulse width modulated RF amplifier

Modulation scheme for power-MOSFET RF output amplifiers another unique method of modulating power MOSFETs is shown in Fig 8.4. It is Probably more experimental in nature than the high-level modulation scheme. This approach is analogous to the grid modulation formats long used in tube transmitters. A profound difference from the tube designs is that modulation is accomplished via a PWM wave. Note that a switching power supply is not needed in this case; rather, the pulse width modulated wave is impressed, along with the incoming RF drive, at the gate of the power MOSFET.

A basic requirement of this scheme is that the triangular waves must have a frequency at least several times higher than the cutoff frequency of the low-pass filter in the output circuit of the amplifier. This is so in order to enable the filter to effectively prevent the PWM interruptions from appearing in the envelope of the amplitude-modulated waveform. From a practical standpoint, the low-pass filter must first satisfy the tank circuit and impedance-matching needs of the RF amplifier. Then, a sufficiently high level PWM wave is impressed at the gate to produce a clean modulation envelope at the output. With low-frequency transmitters, this can be readily accomplished, but it becomes increasingly more difficult to do so beyond transmitter frequencies of several megahertz or so. It then becomes more difficult to produce the requisite high-frequency PWM format, and contradictions in the design of the low-pass filter tend to become more aggravated.

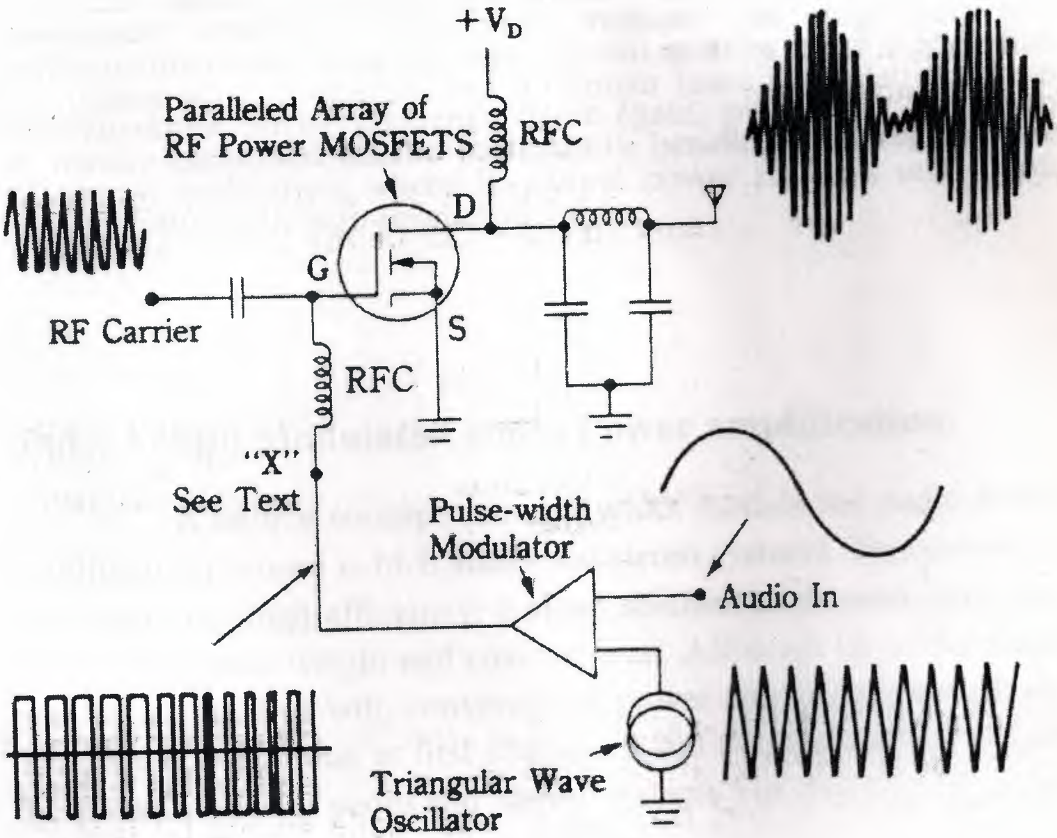


Figure 8.4
AM modulation technique for MOSFET transmitter.

A modification to the arrangement shown in Fig 8.4 can resolve difficulties. By inserting, at point X, a separate low-pass filter with a cutoff frequency just above the audio spectrum of interest, the gate will be impressed with an audio signal rather than the chopped PWM wave. The situation will then simulate the grid-modulation technique used in tube transmitters. The output low-pass filter or pi-network, in the drain circuit of the power MOSFET can then be optimized entirely for maximum performance as a tank circuit and impedance matcher. This also relaxes the high-frequency requirements of the triangular wave; it still must be much higher than the highest audio frequency, but no longer bears any relationship to the transmitter carrier frequency. Here again, power MOSFETs can be readily paralleled; this is particularly beneficial in low-level, or efficiency modulation, where RF output power is about one fourth that attainable with high-level modulation.

Pulse Width Modulated audio Power amplification

A unique concept of pulse width modulation audio power amplification is used in hi-fi audio and stereo systems. This technique promised very high efficiency, a clean solution to thermal problems, reduce the space, weight and cost per watt. Although its performance was not as good as with conventional power amplification methods. This is the reason that at first attempt, it did not successfully invade the domain of hi-fi audio and stereo systems but this technique has enjoyed wide spread use in other systems.

Pulse width modulated audio amplifier

The principle of the PWM audio amplifier is surprisingly simple. As seen in Fig.8.5, a pulse-width-modulated format is generated when an overdriven summing amplifier is simultaneously impressed with the audio signal and a high-frequency triangular wave, known as the carrier. The class D amplifiers are then turned on and off by the pulse-width modulated wave train. Here is where efficiency enters the picture; because the class D amplifiers are either on or off but never in an in-between state, their theoretical efficiency is 100 percent. The output of the class D amplifiers is passed through an integrator in the form of a low-pass filter with a cutoff frequency above the audio range, but much lower than the carrier frequency. What emerges is the restored audio wave, stripped of the interfering carrier frequency.

In Fig 8.5, The Schmitt trigger reproduces the PWM wave, but with steeper edges than when it emerges from the summing amplifier. It does this by delivering an essentially regenerated version of its input. The basic idea is that more rapid switching transitions make the class D amplifier operate more efficiently there is less power dissipated during rise and fall times. A driver stage is included to ascertain that the power MOSFETs in the class D amplifier are turned on hard during their on periods. The low-pass filter which is inserted between the class D amplifier and the speaker load has a cutoff frequency higher than the audio spectrum, but much lower than the carrier frequency (the triangular wave). The wave finally impressed across the speaker is a near replica of the original audio-input signal. Also shown in this diagram is an input amplifier for the audio signal. Whether this is needed for the sake of gain will depend upon the circumstances of an individual system, but it does provide an electrically convenient point to return negative feedback.

It is necessary that a very high-frequency triangular wave (carrier) be used. This contributes to the ability of a simple low-pass filter to strain out the PWM wave so that the recovered audio wave is nearly free of high-frequency contamination.

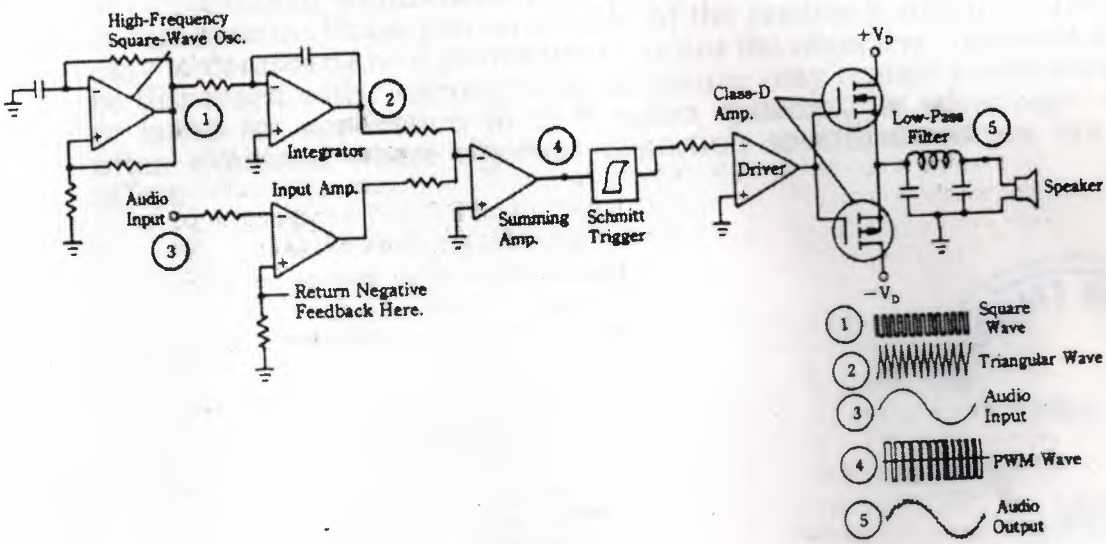


Figure 8.5
Audio amplification by pulse width modulation.

Another reason the carrier frequency must be high is that the effective negative feedback decreases with rising audio frequency to the extent that it is difficult to obtain reasonable feedback at higher audio frequencies. Negative feedback is needed for analogous reasons to its need in conventional amplifiers, the wave processing departs somewhat from ideal performance, so negative feedback is needed to cancel the inadvertent distortion.

A feedback network has the same demands made on it as in conventional amplifiers, but they are more difficult to comply with in this system. Phase and amplitude of the feedback signal are not so easy to control. If hi-fi performance is not the objective, feedback can be dispensed with. Although this technique may remain controversial or latent for application to hi-fi audio systems., its advantages are often exploited where rigorous distortion specifications are not in effect.

Chapter 9

PULSE WIDTH MODULATED POWER SUPPLIES

Pulse width modulated power supplies

The Power supply unit an is essential circuit block in practically all electronic equipment (computer and instruments etc.) Such equipment generally works from the ac power mains.The power supply unit is the power interface between the ac mains and the rest of the functional circuits of the equipment. The functional circuits of the equipment usually need power at one or more fixed dc voltages, which have to be maintained within close limits to ensure reliable working of the equipment.

The power supply unit is often required to meet certain terminal specifications such as

Isolation between the source and the load.

The permissible limits of output voltage variation (regulation) when the load current or ac mains voltage vary.

High power density for reduction of size and weight.

Controlled direction of power flow.

Automatic current limiting under fault or overload conditions.

Input and output waveforms with a low total harmonic distortion for small filters.

High conversion efficiency.

Controlled power factor if the source is an ac voltage.

Ripple voltage components.

The class of power supply systems most widely used in electronic equipment use the switching technique, and is known as pulse-width modulated power supplies. They are also called switch-mode power supplies or switching regulators. Pulse width modulated or switch-mode power supplies have advantages over linear regulators. There are two types of control ICs for the switch-mode power supplies and were commonly known as pulse width modulated control IC's.

Voltage-mode pulse width modulation control IC's.

Current-mode pulse width modulation control IC's.

Basically, they sample a portion of the regulated dc output voltage and varied the duty cycle of the switching waveform in such a way that the dc output voltage remained very nearly constant. Such servo action, of course, constitutes regulation. In as much as the power switch is either on or off, but never in a between state, efficiency is necessarily better than its linear counterparts. In both IC's dc-voltage regulation takes place via pulse width modulation that is, variation of the duty cycle of the switching wave.

Voltage-mode Switching Power Supply

The general idea of the voltage-mode switching supply is depicted in the block diagram of Figure 9a. In the voltage-mode control technique, a voltage comparator working from a dc error signal and a sawtooth or triangular voltage generates the PWM wave. The sawtooth is derived from the same internal oscillator that produces the switching.

In the voltage-mode control technique, the amount of usable gain in the error amplifier is generally less than desired because of the phase shift in the LC filter; high loop gain can lead to instability. Because of the varying conditions of power supply operation, compensating methods cannot be relied upon to extend gain beyond a certain point. The voltage-mode controller has limited ability to perform good line-voltage regulation.

Current-mode Switching Power Supply

The basic idea of current-mod switching power supply is depicted in figure 9b. In the current-mode control technique, the comparator also sees a dc error voltage and a sawtooth voltage at its inputs. In this case, however, the sawtooth is obtained from the current ramp through the switching device. Therefore, there are now two variables controlling the duty cycle of the PWM wave one is the **dc** error signal, the other is the amplitude of the voltage representing the current ramp through the switching device. In the current-mode controller, the effect of the filter phase shift is appreciably less. This enables higher gain to be deployed in the feedback paths so that tighter regulation can be achieved.

The current-mode control IC has however an additional feature. It samples not only a portion of the **dc** output voltage, but also a voltage representing the current through the switching device. The current-mode IC contains two feedback loops, one of these senses output voltage, as in the simpler voltage-mode control technique. The other feedback loop senses the current ramp through the switching device. The current-mode controller responds quickly and produces superior line-voltage regulation.

The practical implementation of current-mode control is easy because the dedicated control ICs can be associated with the power switch and the handful of circuit components in much the same way as the long-used voltage-mode control IC.

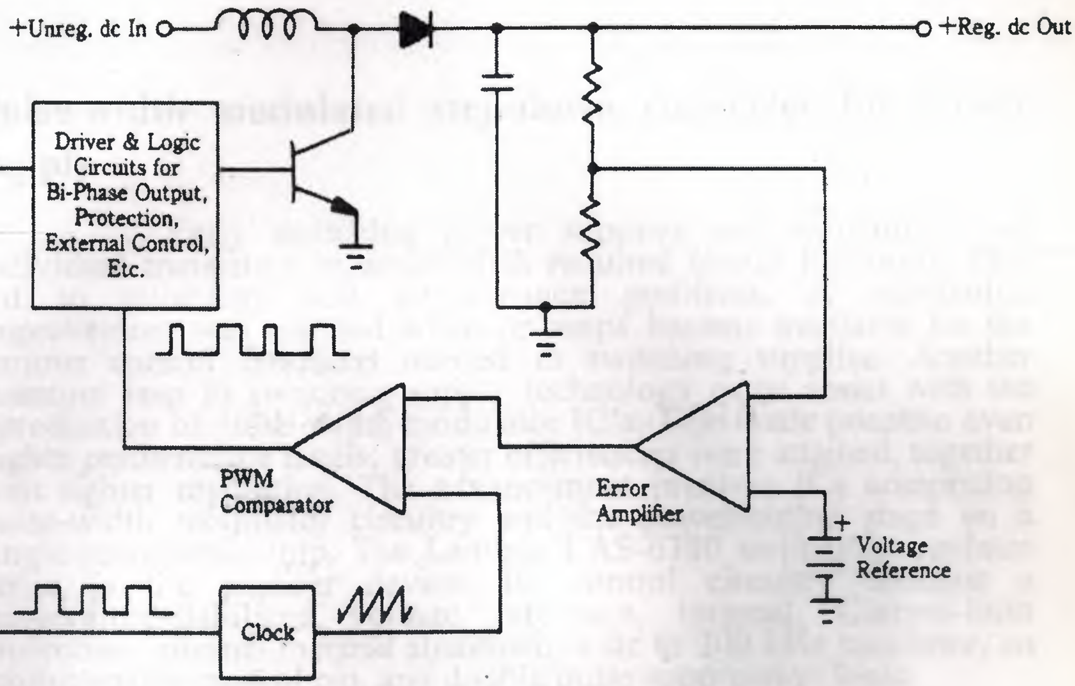


Figure 9a: Voltage–mode control technique

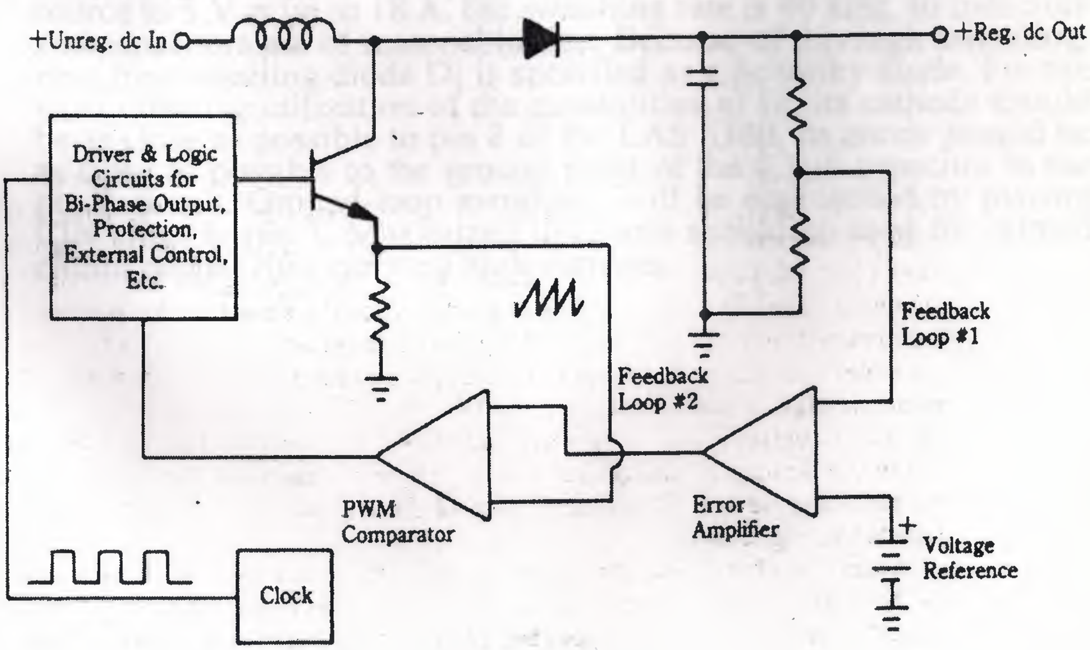


Figure 9b: Current-mode control technique.

Pulse-width modulated step-down converter for power supply

Early switching power supplies and regulators used individual transistors to accomplish required circuit functions. This led to reliability and performance problems. A substantial improvement was realized when op amps became available for the various control functions needed in switching supplies. Another quantum leap in switching-supply technology came about with the introduction of pulse-width modulator IC's. This made possible even higher performance levels; greater efficiencies were attained, together with tighter regulation. The advancement involves ICs comprising pulse-width modulator circuitry and the power-output stage on a single monolithic chip. The Lambda LAS-6380 switching regulator series is the pioneer device. Its control circuitry contains a temperature-stabilized voltage reference, internal, Current-limit protection, internal thermal shutdown, a **dc** to 200 kHz oscillator, an inhibit/enable control pin, and double pulse suppression logic.

A step-down converter circuit using the LAS 6380 is the unique regulating power supply is intended to convert a nominal 20 V source to 5 V at up to 18 A. the switching rate is 40 kHz, so inductors and capacitors are of reasonable size. Because of this high switching, rate, free wheeling diode Dl is specified as a Schottky diode. For the most effective utilization of the capabilities of D_1, its cathode should be as close as possible to pin 8 of the LAS 6380, its anode should be as close as possible to the ground point of the 0.1μF capacitor in the pin 4 circuit. Ground-loop avoidance will be approached by placing CIN close to pin 1. Maximized thickness should be used for printed circuit copper runs carrying high currents.

Chapter 10

CONCLUSION

Conclusion

From the above discussion, it becomes obvious that the pulse width modulation technique is most efficiently used in single and three phase converters and inverters circuits. There is no need for the controlled rectifiers. Since these converters and inverters generate harmonics into the supply. These problems can be minimized by forced commutations, which can improve the input power factor and reduce the harmonic levels. The forced commutation for ac-dc conversion can be implemented in practical systems using pulse width modulation. The sinusoidal and modified sinusoidal pulse width modulation can be applied to vary the load currentand to improve the quality of its waveforms. Sinusoidal pulse width modulation is most widely used but it suffers from drawbacks for example low fundamental output voltage. There are some other methods that offer improved performance are trapezoidal, staircase, stepped, delta, and harmonic injection modulation.

The pulse width modulation frequency is typically of the order of 100 kHz. The solid state semiconductor switching devices in converters and in inverters with pulse width modulation control can be gated to synthesize the desired shape of the output voltage and current. However, the devices are turned ON and OFF at load current with high di/dt value. The switches are subjected to a high voltage stress and the switching power loss of a device increases linearly with the switching frequency.

In pulse width modulation, long pulses expand considerable power during the pulse while bearing no additional information.Since the width is not constant, the power of the waveform is also not constant.Thus as the signal amplitude increases, transmitted power also increases. This means that the transmitter must be powerful enough to handle the maximum width pulses, although the average power transmitted is perhaps only one half of the peak power.Pulse width modulation still work if synchronization between transmitter and receiver fails.

To use pulse width modulation in time division multiplexing, we have to ensure that full-scale modulation will not cause a pulse from one message signal to enter a time slot belonging to another message signal. This restriction results in a wasteful use of time space in telephone systems that are characterized by high peak factors, which is one reason for not using pulse width modulation in telephony. It fall short of the ideal system for exchanging transmission bandwidth for noise performance.

The pulse width modulated transformer are used for the same general reasons that they appear in the more conventional electronic circuits to change the amplitude of the pulse, to couple successive stages of pulse amplifiers, to change impedance levels, to isolate direct current from a circuit element, etc. Pulse width modulated transformers are of small physical size and have relatively few turns in order to minimize leakage inductance. Since the time interval between pulses is long compared with the pulse duration, the load-carrying duty on the transformer is light.

The pulse width modulated chopper is used in variable-speed dc drives to supply the armature voltage for speed control of separately excited dc motors.The can also be used to provide a variable-supply voltage for series dc motor-speed control. The pulse width modulated chopper offers the advantage of higher efficiency than that of traditional electromechanical devices. The improved efficiency is due to the elimination of the wasted energy when using starting and control resistances for these motors.

The pulse width modulated amplifiers are drastically changing the field of power electronics. By using high-frequency digital switching methods, amplifiers are being built which are much smaller, lighter, and which consume (waste) considerable less power than the traditional linear amplifiers.

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