# Design with Analog Multiplexers

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Dedicated to my loving wife
S. Latha (Late)

# CONTENTS

# PREFACE

The most popular analog multiplexer ICs CD4051, CD4052 and CD4053 are used for many electronic circuits. This book explains how they are used for (i) analog function circuits and (ii) digital circuits.

I am highly indebted to my

(i) Mentor Prof. Dr. V.G.K. Murti who taught me about Function Circuits
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# CHAPTER 1

# INTRODUCTION TO ANALOG MULTIPLEXER

An analog multiplexer (also known as a MUX or data selector) is a device used to select one of many input signals and connect that selected input to a single output/transmission line. A select line is used to control which input is connected to the output of the multiplexer. An analog multiplexer incorporates analog switches to select one signal from multiple analog inputs and forward it to a single output line. The analog multiplexer can also be used as a demultiplexer since analog switches can transfer a signal bidirectionally. The multiplexer offers the benefit of reducing the required number of transmission lines by switching various signals onto a single line.

## 1.1 TRANSISTOR MULTIPLEXERS

Figure 1.1 shows analog multiplexer using transistors. If the control input CON is HIGH ($+V_{CC}$), transistor $Q_1$ is ON, $Q_2$ is OFF and ($V_1$) will appear at $V_N$. If the control input CON is LOW ($-V_{CC}$), transistor $Q_1$ is OFF, $Q_2$ is ON and ($V_2$) will appear at $V_N$. The operation is illustrated in table I.

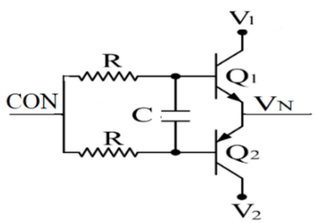



Fig. 1.1 Transistor multiplexer

Table I

| CON | $V_N$ |
|---|---|
| HIGH | $V_1$ |
| LOW | $V_2$ |

## 1.2 JFET MULTIPLEXERS

Figure 1.2 shows analogue multiplexers using FETs. If the control input CON is HIGH ($+V_{CC}$), FETs $Q_1$ is ON, $Q_2$ is OFF and ($V_1$) will appear at $V_N$. If control input CON is LOW ($-V_{CC}$), FETs $Q_1$ is OFF, $Q_2$ is ON and ($V_2$) will appear at $V_N$. The operation is illustrated in Table II.

## 1.3 MOSFET MULTIPLEXER

Figure 1.3 shows analogue multiplexer using MOSFETs. If the control input CON is HIGH ($+V_{CC}$), MOSFETs $Q_1$ is ON, $Q_2$ is OFF and ($V_1$) will appear at $V_N$. If control input CON is LOW ($-V_{CC}$), MOSFETs $Q_1$ is OFF, $Q_2$ is ON and ($V_2$) will appear at $V_N$. The operation is illustrated in table III.

## 1.4 ANALOGUE MULTIPLEXER IC CD 4053

Fig. 1.4 shows the symbol of analogue triple 2 to 1 multiplexer. Each multiplexer has four terminals. In case of multiplexer $M_1$, it has 'ay','ax', 'a' and 'A' terminals. In case of multiplexer $M_2$, it has 'by','bx','b' and 'B' terminals. In case of multiplexer $M_3$, it has 'cy','cx','c' and 'C' terminals.

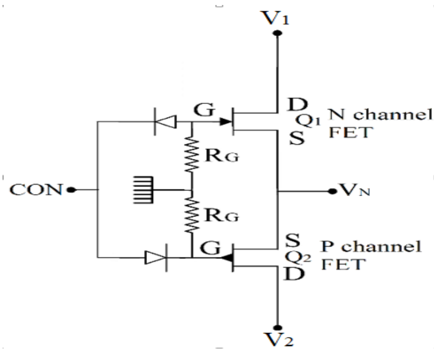



Fig.1.2 FET multiplexer

Table II

| CON | $V_N$ |
|---|---|
| HIGH | $V_1$ |
| LOW | $V_2$ |

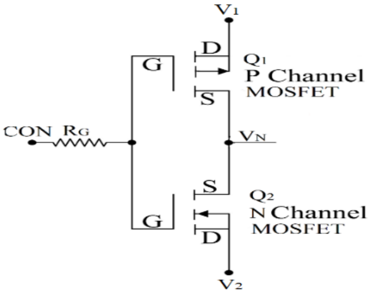



Fig. 1.3 MOSFET multiplexer

Table III

| CON | $V_N$ |
|---|---|
| HIGH | $V_1$ |
| LOW | $V_2$ |

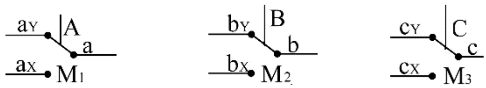



Fig. 1.4 Triple 2 to 1 multiplexers

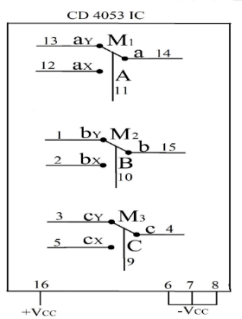


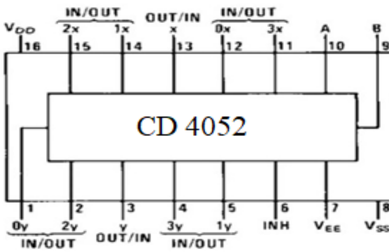

Fig. 1.5 Pin details of CD 4053 IC

In multiplexer $M_1$, if the pin ‘A’ is HIGH, then ‘ay’ is connected to ‘a’ and if the pin ‘A’ is LOW, then ‘ax’ is connected to ‘a’. In multiplexer $M_2$, if the pin ‘B’ is HIGH, then ‘by’ is connected to ‘b’ and if the pin ‘B’ is LOW, then ‘bx’ is connected to ‘b’. In multiplexer $M_3$, if the pin ‘C’ is HIGH, then ‘cy’ is connected to ‘c’ and if the pin ‘C’ is LOW, then ‘cx’ is connected to ‘c’.

All the three multiplexers $M_1$,$M_2$ and $M_3$ are available in one IC PACKAGE of CMOS CD4053 IC. The pin details of this CD4053 IC are given in the Fig. 1.5.

## 1.5 ANALOG MULTIPLEXERS CD4051 and CD4052

Fig. 1.6 shows pin details of analog multiplexer IC 4052. Fig. 1.7 shows pin details of analog multiplexer IC 4051.



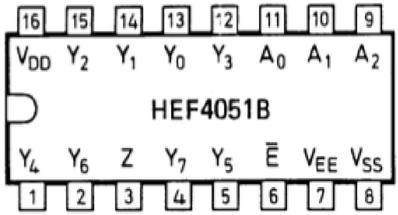




Fig. 1.7 pin details of IC 4051

Fig. 1.6 pin details of IC 4052

## 1.6 INTERNAL DIAGRAM OF 555 TIMER

Fig. 1.8 shows the internal diagram of 555 timer.

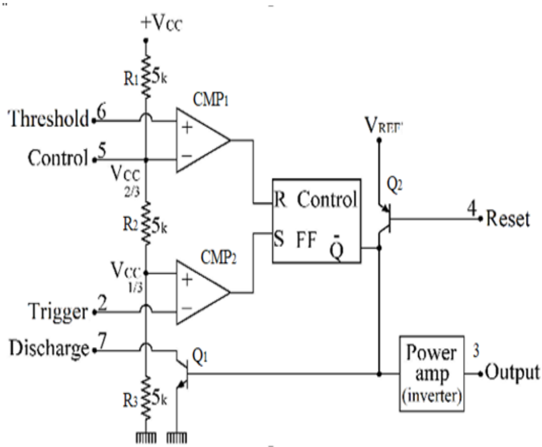



Fig. 1.8 Internal diagram of 555 timer

# CHAPTER 2

# WAVEFORM GENERATORS

The circuits which generate sine, square, pulse, saw tooth and triangular waveforms are discussed in this chapter. These waveforms are used in timing and control, signal carriers for information transmission and storage, sweep signals for information display, test signals for automatic test and measurement and audio signals for electronic music. The function of function generator is to produce a waveform of a particular frequency, amplitude, and shape and duty cycle. Sine wave oscillators are used to test the characteristics of low pass, high pass and band pass filters. Pulse waveforms are used to test digital circuits. Saw tooth and triangular waves are required to develop function circuits either internally or externally.

## 2.1 ASTABLE MULTIVIBRATOR

Fig. 2.1 shows an astable multivibrator using op-amp. Let us assume initially that the op-amp output is LOW (i.e., negative saturation). The voltage at the non-inverting terminal will be

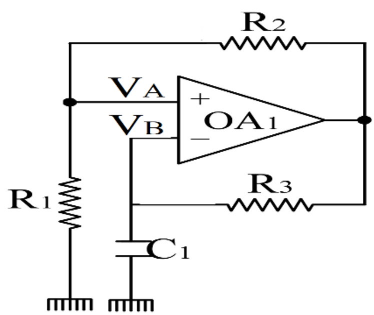



Fig. 2.4 astable multivibrator

$$V_A = \beta(-V_{SAT})$$

$$\beta = \frac{R_1}{R_1 + R_2} \qquad (2.1)$$

The voltage at inverting terminal $V_B$ will be positive w.r.t $V_A$ and its potential is decreasing i.e., $C_1$ charges down through $R_3$. When the potential difference between the two input terminals approaches zero, the op-amp comes out of saturation. The positive feedback from the output to terminal $V_A$ causes regenerative switching which drives the op-amp to positive saturation. Capacitor $C_1$ charges up through $R_3$ and $V_B$ potential rises exponentially; when it reaches $V_B = \beta(+Vcc)$ the circuit switches back to the state in which op-amp is in negative saturation. The sequence therefore repeats to produce square waveform of time period T at its output. The time period T is given as

$$T = 2R_3C_1 \ln(1 + 2\frac{R_1}{R_2}) \qquad (2.2)$$

Voltage to period converter: If in the astable multivibrator shown in Fig.2.1, the $R_2$ terminal is removed from the output terminal and an analog multiplexer is added between $R_2$ and output as shown in Fig. 2.2, then the circuit will work as voltage to time period converter. The time period T is given as

$$T = V_I K_1 \qquad (2.3)$$

Where $K_1$ is a constant depends on equation (2.2) and op-amp saturation voltage or supply voltage Vcc.

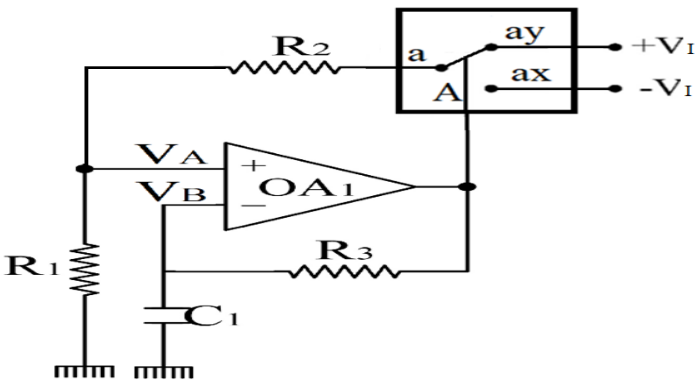



Fig. 2.2 voltage to period converter

Voltage to frequency converter: If in the astable multivibrator shown in Fig. 2.1, the $R_3$ terminal is removed from the output terminal and an analog multiplexer is added between $R_3$ and output as shown in Fig. 2.3, then the circuit will work as voltage to frequency converter. The frequency 'f' is given as

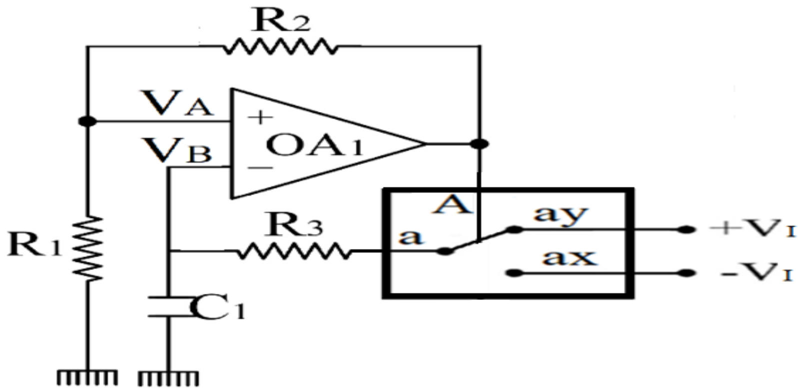



Fig. 2.3 voltage to frequency converter

$$f = V_I K_1 \qquad (2.4)$$

Where $K_1$ is a constant depends on equation (2.6) and op-amp saturation voltage or supply voltage $V_{CC}$.

## 2.2 SAW TOOTH WAVE GENERATORS

Two circuits for generation of saw tooth wave are shown in Figs. 2.4 and their associated waveforms in Fig. 2.5. A saw tooth wave $V_{S1}$ of peak value $V_R$ and time period T is generated by these circuits.

In Fig. 2.4(a)

$$V_R = 2V_{BE} \qquad (2.5)$$

$$T = 1.4R_1C_1 \qquad (2.6)$$

In Fig. 2.4(b), if initially op amp $OA_2$ output is LOW, the multiplexer $M_1$ connects 'ax' to 'a' and the integrator formed by resister $R_1$, capacitor $C_1$ and op amp $OA_1$ integrates ($-V_R$) and its output is given as

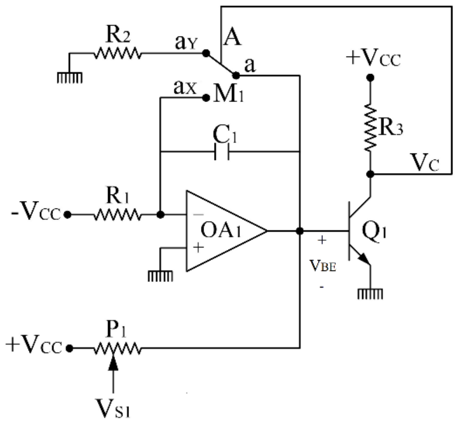



Fig. 2.4(a) Saw tooth wave generator – I

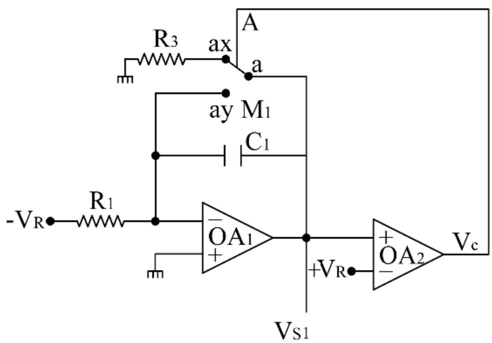



Fig. 2.4(b) Saw tooth wave generator – II

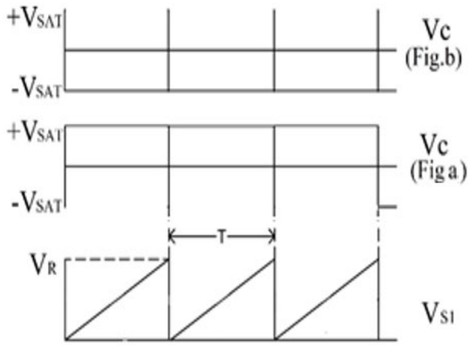



Fig. 2.5 associated waveforms of Fig. 2.4

$$V_{S1} = -\frac{1}{R_1C_1}\int -V_R dt$$

$$V_{S1} = \frac{V_R}{R_1C_1}t \qquad (2.7)$$

A positive going ramp is generated at the output of op amp $OA_1$ and when it reaches the value of reference voltage $+V_R$ the comparator $OA_2$ output becomes HIGH. The multiplexer $M_1$ now connects ‘ay’ to ‘a’ and shorts capacitor $C_1$ and hence the integrator output becomes zero. Then the comparator output is LOW and the sequence therefore repeats to give a perfect saw tooth wave $V_{S1}$ of peak value $V_R$ at the output of op – amp $OA_1$. From equation (2.7), Fig. 2.5 and fact that at t= T, $V_{S1} = V_R$.

$$V_R = \frac{V_R}{R_1C_1}T$$

## 2.3 FUNCTION GENERATOR – TYPE I

A triangular wave $V_{T1}$ with $\pm V_T$ peak to peak value and time period T is generated by the triangular wave generator shown in Figs. 2.6 and its associated waveforms are shown in Figs. 2.7.

The output of op amp $OA_1$ is a triangular wave $V_{T1}$ with $\pm V_T$ peak values and time period of T. Initially the comparator $OA_2$ output is LOW($-V_{SAT}$), the output of the integrator composed by op-amp $OA_1$, resistor $R_1$ and capacitor $C_1$, is given as

$$V_{T1} = -\frac{1}{R_1C_1}\int -V_{SAT}dt = \frac{V_{SAT}}{R_1C_1}t \qquad (2.9)$$

The integrator output is rising towards positive saturation and when it reaches a value $+V_T$, the comparator output becomes HIGH($+V_{SAT}$). The output of the integrator composed by op-amp $OA_1$, resistor $R_1$ and capacitor $C_1$, is given as

$$V_{T1} = -\frac{1}{R_1C_1}\int +V_{SAT}dt = -\frac{V_{SAT}}{R_1C_1}t$$

Now the output of the integrator is changing its slope from $+V_T$ towards ($-V_T$) and when it reaches a value '$-V_T$', the comparator output becomes LOW($-V_{SAT}$) and the sequence therefore repeats to give (i) a triangular waveform $V_{T1}$ with $\pm V_T$ peak to peak values at the output of op-amp $OA_1$ and (ii) a square waveform $V_C$ with $\pm V_{SAT}$ peak to peak values at the output of comparator $OA_2$.

From the waveforms shown in Fig. 2.7, from equation (2.9) and the fact that at $t = T/2$, $V_{T1} = 2V_T$

$$2V_T = \frac{V_{SAT}}{R_1C_1}\frac{T}{2}$$

$$T = \frac{4V_T R_1 C_1}{V_{SAT}} \qquad (2.10)$$

When the comparator $OA_2$ output is LOW ($-V_{SAT}$), the effective voltage at the non-inverting terminal of comparator $OA_2$ will be, by superposition principle,

$$\frac{(-V_{SAT})}{(R_2+R_3)}R_2 + \frac{(+V_T)}{(R_2+R_3)}R_3$$

When this effective voltage at the non-inverting terminal of comparator $OA_2$ becomes zero

$$\frac{(-V_{SAT})R_2 + (+V_T)R_3}{(R_2+R_3)} = 0$$

$$(+V_T) = (+V_{SAT})\frac{R_2}{R_3}$$

When the comparator $OA_2$ output is HIGH ($+V_{SAT}$), the effective voltage at the non-inverting terminal of comparator $OA_2$ will be by superposition principle

$$\frac{(+V_{SAT})}{(R_2+R_3)}R_2+\frac{(-V_T)}{(R_2+R_3)}R_3$$

When this effective voltage at non-inverting terminal of comparator $OA_2$ becomes zero

$$\frac{(+V_{SAT})R_2+(-V_T)R_3}{(R_2+R_3)}=0$$

$$(-V_T)=(-V_{SAT})\frac{R_2}{R_3}$$

$$\pm V_T=\pm V_{SAT}\frac{R_2}{R_3}\ \square\ 0.76(\pm V_{CC})\frac{R_2}{R_3} \qquad (2.11)$$

From equation (2.10) and (2.11), time period T of the generated triangular/square waveforms is given as

$$T=4R_1C_1\frac{R_2}{R_3} \qquad (2.12)$$

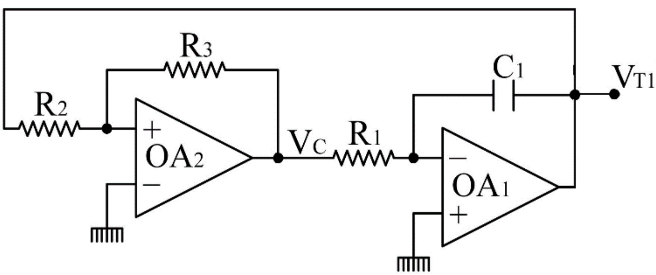



Fig. 2.6 triangular wave generator

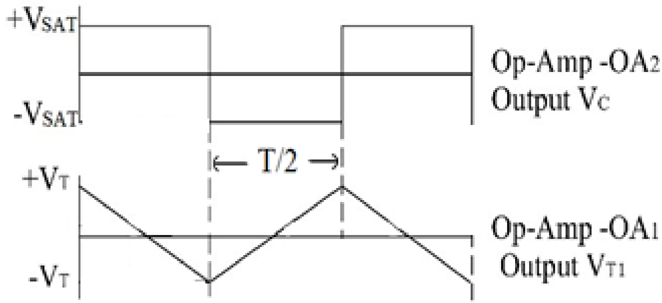



Fig. 2.7 associated waveforms of Fig. 2.6

The triangular wave generator shown in Fig. 2.6 can be converted in to a voltage-controlled function generator by adding an analog multiplexer between comparator and integrator as shown in Fig. 2.8.

$$T = \frac{4V_T R_1 C_1}{V_I} \tag{2.23}$$

$$T = \frac{4R_1 C_1}{V_I}\frac{R_2}{R_3} \tag{2.24}$$

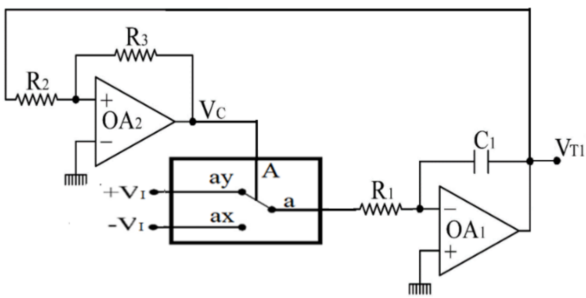



Fig. 2.8 function generator

## 2.4 FUNCTION GENERATOR – TYPE II

The circuit diagram of the function generator – type II is shown in Fig. 2.9 and its associated waveforms are shown in Fig. 2.10.

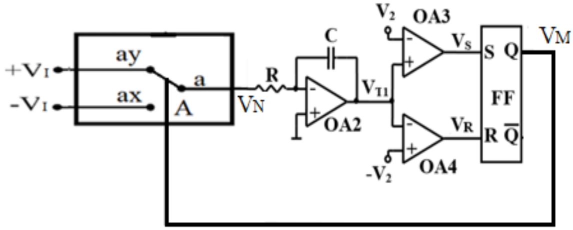



Fig. 2.9 Function generator – type II

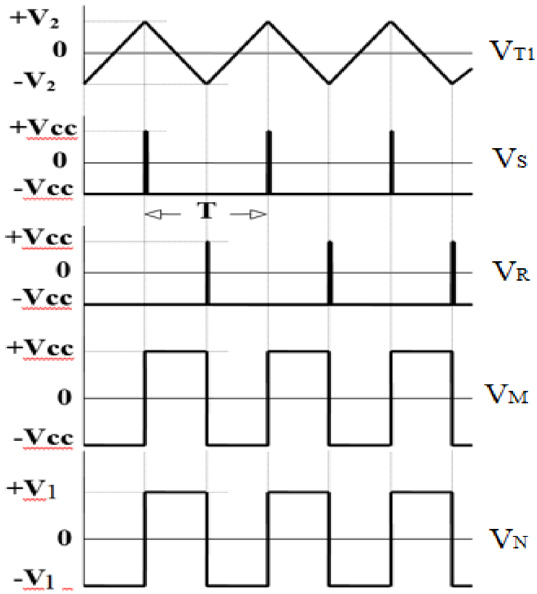



Fig. 2.10 Associated Waveforms of Fig. 2.9

Let initially the SR flip flop output Q be LOW. The multiplexer selects -$V_1$ ('ax' is connected to 'a'). –$V_1$ will be given to the integrator formed by $OA_2$, resistor R and capacitor C. Its output will be

$$V_{T1} = -\frac{1}{RC}\int -V_1 dt = \frac{V_1}{RC}t \qquad (2.25)$$

The output of integrator OA2 is a positive going ramp. When the output of the integrator exceeds the other input voltage $V_2$, SR Flip flop output Q is set to HIGH by the comparator $OA_3$. The multiplexer selects $+V_1$ ('ay' is connected to 'a') and $+V_1$ is given to the integrator $OA_2$. Now the integrator output will be

$$V_{T1} = -\frac{1}{RC}\int V_1 dt = -\frac{V_1}{RC}t \qquad (2.26)$$

The output of the integrator is changing its slope from positive to negative. When the output of the integrator exceeds the input voltage $-V_2$, SR flip flop output 'Q' will be reset to LOW by the comparator $OA_4$ and the cycle therefore repeats. From the equation (2.26) and from the waveforms shown in Fig. 2.10 at t = T/2, $V_T(t) = 2V_2$

$$2V_2 = \frac{V_1}{2RC}T \qquad (2.27)$$

$$T = \frac{V_2}{V_1}4RC \quad , \quad f = \frac{V_1}{V_2}\frac{1}{4RC} \qquad (2.28)$$

WORKED EXAMPLES:

2.1 Design a square wave generator for frequency of 1KHz. Power supply voltage of ±15V.

The square wave generator or astable multivibrator is given in Fig. 2.1. From equation (2.2)

$$T = 2R_3C_1 \ln(1 + 2\frac{R_1}{R_2})$$

Given; frequency = 1kHz

T = 1/f = 1mS

Let $R_2 = 1.16R_1$

Let $R_1$ = 10K, then $R_2$ = 11.6K

$T = 2R_3C_1 \ln 2.7241 = 2R_3C_1$

$$R_3 = \frac{T}{2C_1}$$

Let $C_1 = 0.05\mu F$,

$$R_3 = \frac{1X10^{-3}}{2X0.05X10^{-6}} = 10K$$

2.2 Design a saw tooth wave generator with peak value of 5V and time period of 1mS.

The saw tooth wave generator is shown in Fig. 2.5. Chose $V_R$ = 5V with LM3365V reference diode. Given: T = 1mS. Let $R_1$ = 1M.

From equation (2.8)

$$T = R_1 C_1\,,\quad C_1 = \frac{T}{R_1} = \frac{1X10^{-3}}{1X10^{6}} = 1nF$$

2.3 Design a triangular wave generator of time period 20mS with 10V peak volts. Power supply is ±15V.

The triangular wave generator circuit is shown in Fig. 2.6. Given: T = 20mS, $V_T$ = 10V, $V_{CC}$ = 15V

From equation (2.11)

$$\pm V_T = \pm V_{SAT}\frac{R_2}{R_3} \approx 0.76(\pm V_{CC})\frac{R_2}{R_3}$$

Let $R_2$ = 10K

$$R_3 = \frac{R_2\, 0.76 V_{CC}}{V_T} = 11.4K$$

From equation (2.12)

$$T = 4R_1C_1\frac{R_2}{R_3} = 3.5R_1C_1$$

Let $C_1$ = 0.1μF

$$R_1 = \frac{T}{3.5C_1} = \frac{20X10^{-3}}{3.5X0.1X10^{-6}} = 57.14K$$

2.4 Design a voltage controlled triangular wave generator of 1KHz frequency and 10V peak value. The given control voltage is (-1V). Power supply used is ±15V.

Given: f = 1KHz; T = 1/f = 1mS, $V_I$ = -1V, $V_T$ = 10V, $V_{CC}$ = 15V

The voltage controlled triangular wave generator is shown in Fig. 2.8

$$\pm V_T = \pm V_{SAT} \frac{R_3}{R_4} \approx 0.76(\pm V_{CC}) \frac{R_3}{R_4}$$

$$R_4 = 0.76(V_{CC}) \frac{R_3}{V_T}$$

Let $R_3$ = 10K

$$R_4 = 0.76X15X \frac{10X10^3}{10} = 11.4\text{ K}$$

From equation (2.28)

$$f = \frac{-V_I}{4RCV_T}$$

Let C = 0.1μF

$$R = \frac{-V_I}{4fCV_T} = \frac{1}{4X1X10^3X0.1X10^{-6}X10} = 250\Omega$$

# CHAPTER 3

# ANALOG MULTIPLIERS USING MULTIPLEXERS

If the width of a pulse train is made proportional to one voltage and the amplitude of the same pulse train to a second voltage, then the average value of this pulse train is proportional to the product of two voltages, and is called time division multiplier or pulse averaging multiplier or sigma delta multiplier. The time division multiplier can be implemented using (1) triangular wave (2) saw tooth wave and (3) without using any reference wave.

Peak responding multipliers are classified in to (i) peak detecting multipliers and (ii) peak sampling multipliers. A short pulse/saw tooth waveform whose time period 'T' is proportional to one voltage is generated. Another input voltage is integrated during the time period 'T'. The peak value of the integrated voltage is proportional to the product of the two input voltages. This is called double single slope peak responding multiplier. A square/triangular waveform whose time period 'T' is proportional to one voltage is generated. Another input voltage is integrated during the time period 'T'. The peak value of the integrated voltage is proportional to the product of the two input voltages. This is called double dual slope peak responding multiplier. A rectangular pulse waveform whose OFF time is proportional to one voltage is generated. Another voltage is integrated during this OFF time. The peak value of integrated output is proportional to the product of the two input voltages. This is called pulse width integrated peak responding multiplier. At the output stage of a peak responding multiplier, if peak detector is used, it is called peak detecting multiplier and if sample & hold is used, it is called peak sampling multiplier. The principles of peak responding multipliers are described in this chapter.

## 3.1 SAW TOOTH WAVE REFERENCED TIME DIVISION MULTIPLIER

The time division multiplier using saw tooth wave as reference is shown in Fig. 3.1 and its associated waveforms in Fig.3.2. A saw tooth wave $V_{S1}$ of peak value $V_R$ is compared with one input voltage $V_1$ by the op-amp OA and a rectangular wave $V_M$ is produced at the output of op-amp OA. The ON time '$\delta_T$' of the rectangular wave $V_M$, is given as

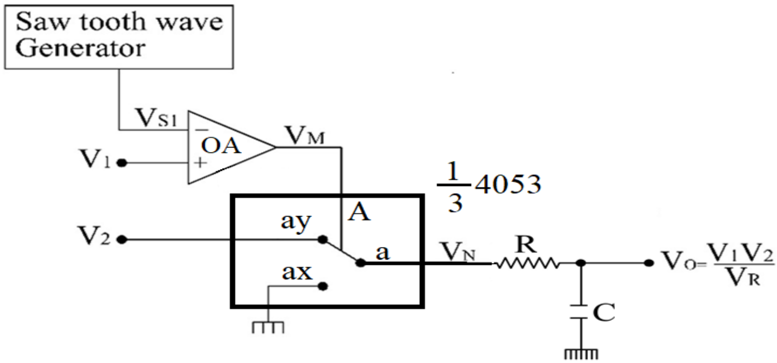



Fig. 3.1 Saw tooth wave referenced time division multiplier

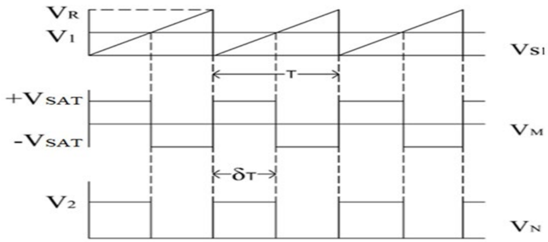



Fig.3.2 Associated Waveforms of Fig.3.1

$$\delta_T = \frac{V_1}{V_R} T \qquad (3.1)$$

This rectangular wave $V_M$ controls the analog multiplexer A. The analog multiplexer A is connecting (i) another input voltage $V_2$ during the ON time "$\delta_T$" of rectangular pulse $V_M$ ('ay' is connected to 'a') and (ii) zero volts during OFF time of rectangular pulse $V_M$ ('ax' is connected to 'a'), to the resistor (R) - capacitor (C) low pass filter (LPF). Another rectangular pulse waveform $V_N$ is generated at the output of analog multiplexer A with $V_2$ as peak value and time period of same 'T'. The resistor (R) - capacitor (C) low pass filter (LPF) at the output stage gives average value '$V_O$' of the pulse train '$V_N$'

$$V_O = \frac{1}{T}\int_{0}^{\delta_T} V_2 dt$$

$$V_O = \frac{1}{T}V_2\delta_T$$

$$V_O = \frac{V_1V_2}{V_R} \qquad (3.2)$$

## 3.2 TRIANGULAR WAVE REFERENCED TIME DIVISION MULTIPLIER

The time division multiplier using a triangular wave as a reference clock is shown in Fig 3.3 and its associated waveforms in Fig. 3.4.

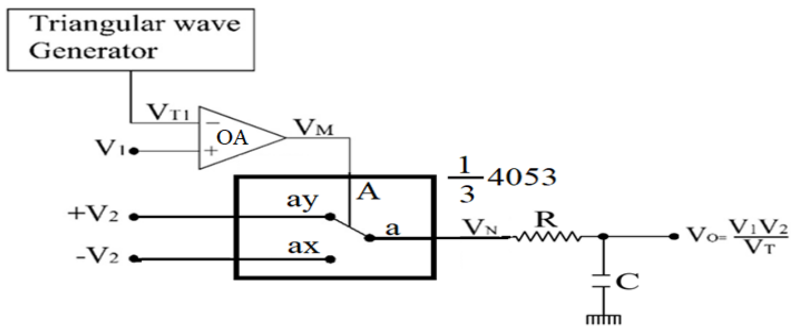



Fig. 3.3 Triangular wave referenced time division multiplier

A triangular wave $V_{T1}$ of $\pm V_T$ peak to peak value is compared with the input voltage $V_1$ by the op-amp OA and a asymmetrical wave $V_M$ is generated. The OFF time '$T_1$' of this rectangular wave $V_M$ is given as

$$T_1 = \frac{V_T - V_1}{2V_T}T \qquad (3.3)$$

The ON time '$T_2$' of this rectangular wave $V_M$ is given as

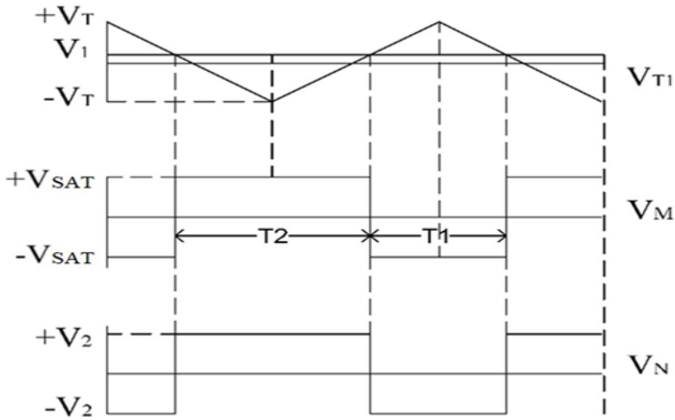



Fig. 3.4 Associated waveforms of Fig. 3.3

$$T_2 = \frac{V_T + V_1}{2V_T} T \tag{3.4}$$

The rectangular pulse $V_M$ controls analog multiplexer A. The analog multiplexer A connects the other input voltage ($+V_2$) during ON time $T_2$ ('ay' is connected to 'a') and ($-V_2$) during OFF time $T_1$ of the rectangular pulse $V_M$ ('ax' is connected to 'a') to the resistor (R) - capacitor (C) low pass filter (LPF). Another rectangular wave $V_N$ with $\pm V_2$ maximum values is generated at the output of analog multiplexer A. The resistor (R) - capacitor (C) low pass filter (LPF) gives average value ($V_O$) of this pulse train $V_N$ and is given as

$$V_O = \frac{1}{T}\left[\int_0^{T_2} (+V_2)dt + \int_{T_2}^{T_1+T_2} (-V_2)dt\right]$$

$$V_O = \frac{1}{T}(T_2 - T_1)V_2 \tag{3.5}$$

Equations (3.3) and (3.4) in (3.5) gives