Experiment-5

Three-phase Full and Semi-Controlled Rectifier

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Introduction

This experiment includes understanding the working principle of three-phase AC-DC semi-controlled and full-controlled converter. Various performance index of the converter needs to be analysed. Study the triggering circuit which consists of control circuit and driver circuit. These experiments will be performed in open loop control where student will generate the gate pulses as per the requirement of the experiment.

Single phase ac-to-dc converters are generally limited to a few kilowatts, and for higher levels of dc power output three-phase line commuted converters are used owing to restrictions on unbalanced loading, line harmonics, current surge and voltage dips. Increase in ripple frequency also reduces the filter size. Converter which can be operated both in rectifying and inverting modes are called fully controlled converters. When power flow can only occur from ac-to-dc, the converter is known as semi converter, or half controlled converter. Fully controlled three-phase converters find applications in high voltage dc power (HVDC) transmission, dc and ac motor drives with regenerative breaking capabilities.

Three phase full controlled rectifier

A. Circuit Description

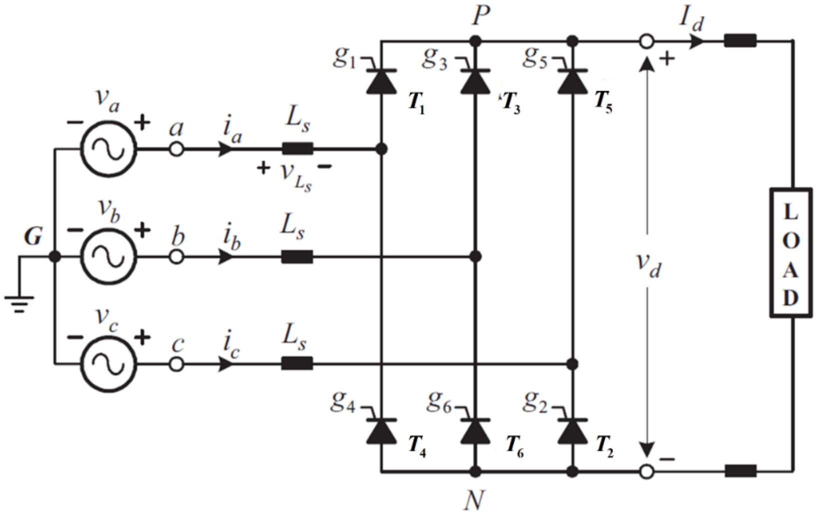


Fig.1 Power Circuit diagram of three phase full controlled rectifier

A three-phase fully-controlled bridge rectifier can be constructed using six thyristors. The bridge circuit has two halves, the positive half consisting of the thyristors T_1, T_3 and T_5 and the negative half consisting of the thyristors T_2, T_4 and T_6. At any instant of time, one thyristor from each half conducts when there is current flow.

The thyristors are triggered in the sequence T_1T_2, T_2T_3, T_3T_4, T_4T_5, T_5T_6, and T_6T_1 and so on. Triggering angle α, also called firing delay angle, is defined with respect to the cross over points of the phase voltages at which an equivalent diode would start to conduct. When the thyristors are fired at 0˚ firing angle, the output of the bridge rectifier would be the same as that of the circuit with diodes. Thyristor T_1 can start conducting only after $\theta = 30^\circ$, since it is reverse-biased before $\theta = 30^\circ$. For $\alpha = 0^\circ$, T_1 is triggered at $\theta = 30^\circ$, T_2 at 90˚, T_3 at 150˚ and so on. For $\alpha = 60^\circ$, T_1 is triggered at $\theta = 30^\circ + 60^\circ = 90^\circ$, T_2 at $\theta = 90^\circ + 60^\circ = 150^\circ$ and so on. Note that positive group of thyristors are fired at an interval of 120˚. Similarly, negative group of thyristors are fired with an interval of 120˚. But thyristors from both the groups are fired at an interval of 60˚. This means that commutation occurs every 60˚, alternatively in upper and lower group of thyristors.

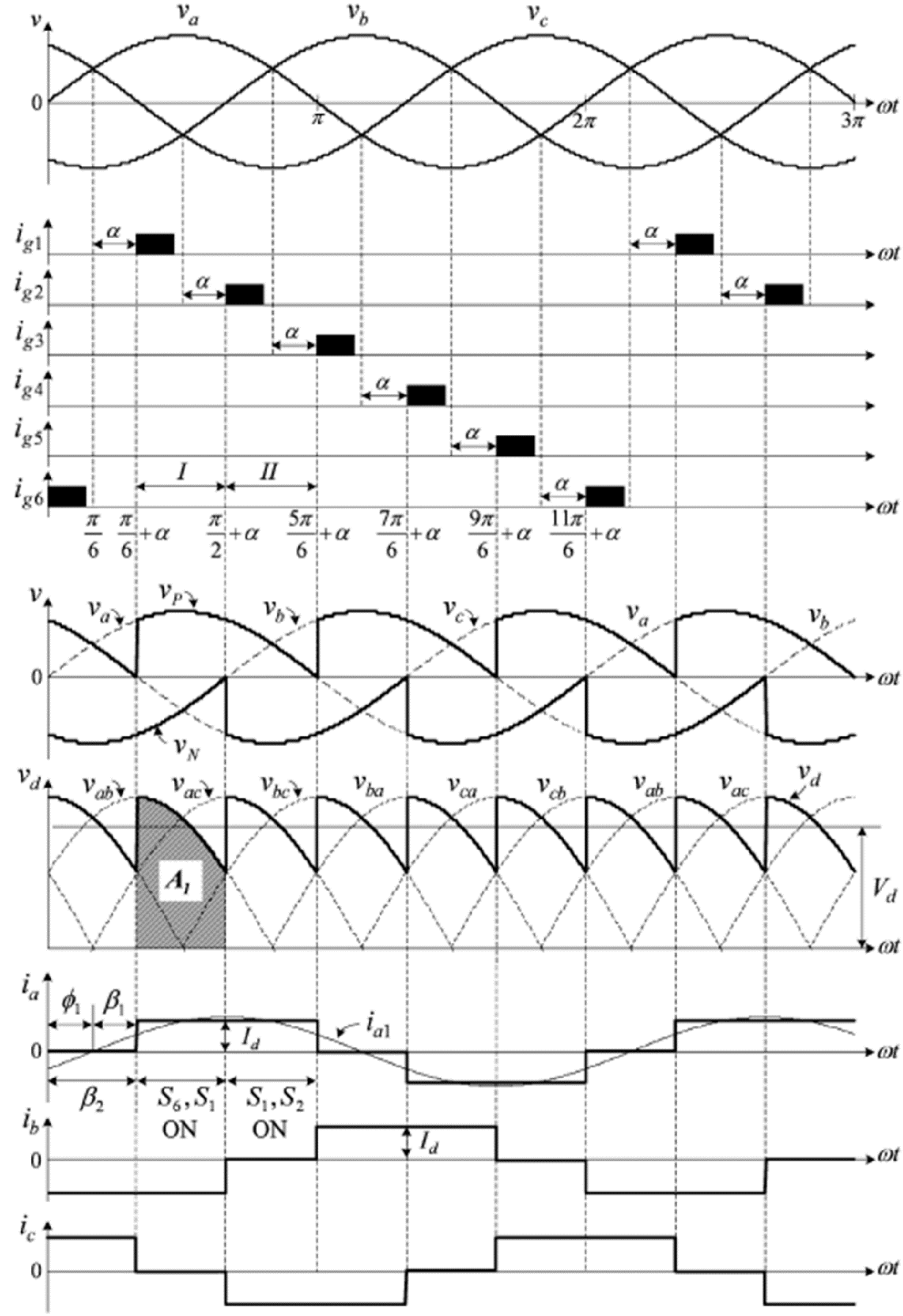


Fig.2 Waveforms of three phase full controlled rectifier operating at α = 30˚ for constant load current

When connected to the ac supply, firing gate pulses will be delivered to the thyristors in the correct sequence but, if only a single firing gate pulse is used, no current will flow, as the other thyristor in the current path will be in the off-state. Hence, in order to start the circuit functioning, two thyristors must be fired at the same time in order to commence current flow.

B. Analysis

The ideal average output voltage V_d for continuous load current is given by

$$V_d = \frac{3\sqrt{2}}{\pi} V_{LL} \cos\alpha = V_{d0} \cos\alpha$$

Here, V_{LL} is the line-to-line rms voltage and α is the firing angle.

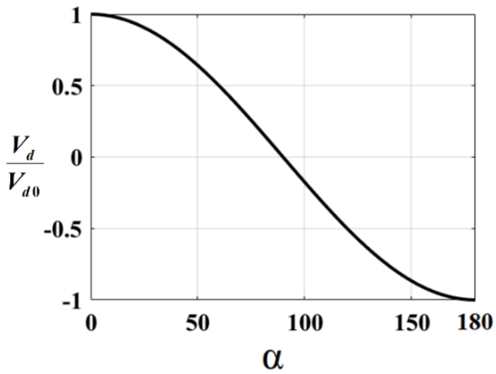


Fig.3 Variation of normalised voltage w.r.t. firing angle α

The ideal average of the converter output voltage, with resistive load, is given by

$$V_d = \frac{3\sqrt{2}}{\pi} V_{LL} \left[1 + \cos\left(\alpha + \frac{\pi}{3}\right)\right] \qquad \text{for } \frac{\pi}{3} \le \alpha \le \frac{2\pi}{3}$$

$$= \frac{3\sqrt{2}}{\pi} V_{LL} \cos\alpha \qquad \text{for } \alpha \le \frac{\pi}{3}$$

The rectifier dc output voltage V_d is positive when the firing angle α is less than 90˚and becomes negative for an α greater than 90˚. However, the dc current I_d is always positive, irrelevant to the polarity of the dc output voltage. V_d reaches its maximum negative value at α = 180°. In a practical rectifier where the line inductance L_s is present, the firing angle α should be less than 180° to prevent SCR commutation failure. When the rectifier produces a positive dc voltage, the power is delivered from the supply to the load. With a negative dc voltage, the rectifier operates in an inverting mode, and the power is fed from the load back to the supply.

In case of full-controlled converter, average and rms value of on-state switch current is same as average and rms load current respectively. The source current I_s for any phase (a, b, or c) flows for 120° out of every 180°. Therefore, the rms value of the source current for constant load current I_d is given by

$$I_{s(rms)} = \sqrt{\frac{2\pi}{3} \times \frac{1}{\pi} I_d^2} = \sqrt{\frac{2}{3}} I_d$$

Each thyristor conducts for 120° out of every 360°. So, the rms value of the thyristor current is

$$I_{T(rms)} = \sqrt{\frac{2\pi}{3} \times \frac{1}{2\pi} I_d^2} = \frac{I_d}{\sqrt{3}}$$

The average value of thyristor current is

$$I_{T(av)} = \frac{I_d}{3}$$

The instantaneous source current can be expressed in Fourier series as below:

$$i_s(t) = I_{a0} + \sum_{n=1}^{\infty} (I_{an} \cos n\omega t + I_{bn} \sin n\omega t)$$

$$I_{a0} = \frac{1}{\pi} \int_0^{2\pi} i_s(t) d\omega t$$

$$\Rightarrow I_{a0} = \frac{1}{\pi} \left[\int_{\frac{\pi}{6}+\alpha}^{\frac{5\pi}{6}+\alpha} I_d d\omega t - \int_{\frac{7\pi}{6}+\alpha}^{\frac{11\pi}{6}+\alpha} I_d d\omega t \right]$$

$$\Rightarrow I_{a0} = \frac{I_d}{\pi} \left[\left(\frac{5\pi}{6} + \alpha - \frac{\pi}{6} - \alpha \right) - \left(\frac{11\pi}{6} + \alpha - \frac{7\pi}{6} - \alpha \right) \right]$$

$$\Rightarrow I_{a0} = 0$$

$$I_{an} = \tfrac{1}{\pi} \int_0^{2\pi} i_s(t) \cos n\omega t \, d\omega t$$

$$\Rightarrow I_{an} = \frac{1}{\pi} \left[\int_{\frac{\pi}{6}+\alpha}^{\frac{5\pi}{6}+\alpha} I_d \cos n\omega t \, d\omega t - \int_{\frac{7\pi}{6}+\alpha}^{\frac{11\pi}{6}+\alpha} I_d \cos n\omega t \, d\omega t \right]$$

$$\Rightarrow I_{an} = \frac{I_d}{\pi} \left[\frac{\sin n\omega t}{n} \bigg|_{\frac{\pi}{6}+\alpha}^{\frac{5\pi}{6}+\alpha} - \frac{\sin n\omega t}{n} \bigg|_{\frac{7\pi}{6}+\alpha}^{\frac{11\pi}{6}+\alpha} \right]$$

$$\Rightarrow I_{an} = \frac{I_d}{n\pi} \left[\sin n\left(\frac{5\pi}{6} + \alpha\right) - \sin n\left(\frac{\pi}{6} + \alpha\right) + \sin n\left(\frac{7\pi}{6} + \alpha\right) \right.$$
$$\left. - \sin n\left(\frac{11\pi}{6} + \alpha\right) \right]$$

$$\Rightarrow I_{an} = \frac{2I_d}{n\pi}\left[\sin\frac{n\pi}{3}\cos n\left(\frac{\pi}{2}+\alpha\right) - \sin\frac{n\pi}{3}\cos n\left(\frac{3\pi}{2}+\alpha\right)\right]$$

$$\Rightarrow I_{an} = -\frac{4I_d}{n\pi}\sin n\alpha \sin\frac{n\pi}{3}$$

$$I_{bn} = \frac{1}{\pi}\int_0^{2\pi} i_s(t)\sin n\omega t\, d\omega t$$

$$\Rightarrow I_{bn} = \frac{1}{\pi}\left[\int_{\frac{\pi}{6}+\alpha}^{\frac{5\pi}{6}+\alpha} I_d \sin n\omega t\, d\omega t - \int_{\frac{7\pi}{6}+\alpha}^{\frac{11\pi}{6}+\alpha} I_d \sin n\omega t\, d\omega t\right]$$

$$\Rightarrow I_{bn} = \frac{I_d}{\pi}\left[\frac{\cos n\omega t}{n}\Bigg|_{\frac{5\pi}{6}+\alpha}^{\frac{\pi}{6}+\alpha} + \frac{\cos n\omega t}{n}\Bigg|_{\frac{7\pi}{6}+\alpha}^{\frac{11\pi}{6}+\alpha}\right]$$

$$\Rightarrow I_{bn} = \frac{I_d}{n\pi}\left[\cos n\left(\frac{\pi}{6}+\alpha\right) - \cos n\left(\frac{5\pi}{6}+\alpha\right) + \cos n\left(\frac{11\pi}{6}+\alpha\right) - \cos n\left(\frac{7\pi}{6}+\alpha\right)\right]$$

$$\Rightarrow I_{bn} = \frac{4I_d}{n\pi}\sin\frac{n\pi}{3}\cos n\alpha$$

For fundamental component,

$$i_{s1}(t) = -\frac{4I_d}{\pi}\sin\frac{\pi}{3}\sin\alpha\cos\omega t + \frac{4I_d}{\pi}\sin\frac{\pi}{3}\cos\alpha\sin\omega t$$

$$\Rightarrow i_{s1}(t) = \frac{2\sqrt{3}I_d}{\pi}[\cos\alpha\sin\omega t - \sin\alpha\cos\omega t]$$

$$\Rightarrow i_{s1}(t) = \frac{2\sqrt{3}I_d}{\pi}\sin(\omega t - \alpha)$$

RMS value of the fundamental frequency component,

$$I_{s1} = \frac{4I_d}{\pi}\sin\frac{\pi}{3} = \frac{2\sqrt{3}I_d}{\pi}$$

Total Harmonic Distortion,

$$THD = \frac{\sqrt{I_s^2 - I_{s1}^2}}{I_{s1}} \times 100$$

Distortion factor, $DF = {}^{I_{s1}}/_{I_s}$

Displacement power factor, $DPF = \cos\alpha$

Input power factor, $IPF = DF \times DPF = {}^{I_{s1}}/_{I_s} \cos\alpha$

Fundamental active power input to the converter, $P = 3V_{ph}I_{s1}\cos(\alpha)$

Fundamental reactive power input to the converter, $Q = 3V_{ph}I_{s1}\sin(\alpha)$

C. Specification

Input voltage: V_{LL} (rms) = 440 V

Average load current: I_d =10 A.

Thyristor rms current rating,

$I_{T(rms)} = \frac{10}{\sqrt{3}} = 5.77A$

Thyristor average current rating,

$I_{T(av)} = \frac{10}{3} = 3.33\ A$

Peak working forward blocking voltage, $V_{DWM} = 440 \times \sqrt{\frac{2}{3}} = 359\ V$

Peak working reverse blocking voltage, $V_{RWM} = 440 \times \sqrt{\frac{2}{3}} = 359\ V$

Voltage Safety Factor, $V_{SF} = \frac{V_{RRM}}{\sqrt{2}\times V_{ph(rms)}} = 2$ (considered)

Peak repetitive forward voltage, $V_{DRM} = 2 \times 359 = 718\ V$

Peak repetitive reverse voltage, $V_{RRM} = 718\ V$

Peak non-repetitive reverse voltage, V_{RSM}=1.3 * V_{RRM}= 933.4 V

Maximum Peak repetitive forward voltage, V_{DRM} rating of SCR ≥ 718V

Peak non-repetitive forward voltage, V_{DSM}=1.3 * V_{RRM}= 933.4 V

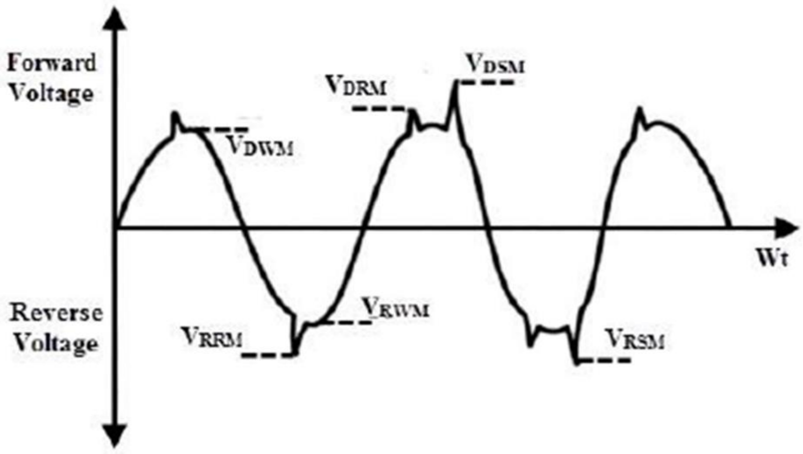


Fig.4 Voltage across thyristor and corresponding ratings

Voltage safety factor chosen ≈ 2; Current safety factor chosen ≈ 3.

Based on the above calculations and safety factor VS-16TTS12-M3 [1] is chosen. The specifications of VS-16TTS12-M3 are as follows:
On-state rms current = 16A at T_c=98°C
On-state average current = 10A at Tc=98°C
Repetitive peak off-state voltage, V_{DRM}=1200V

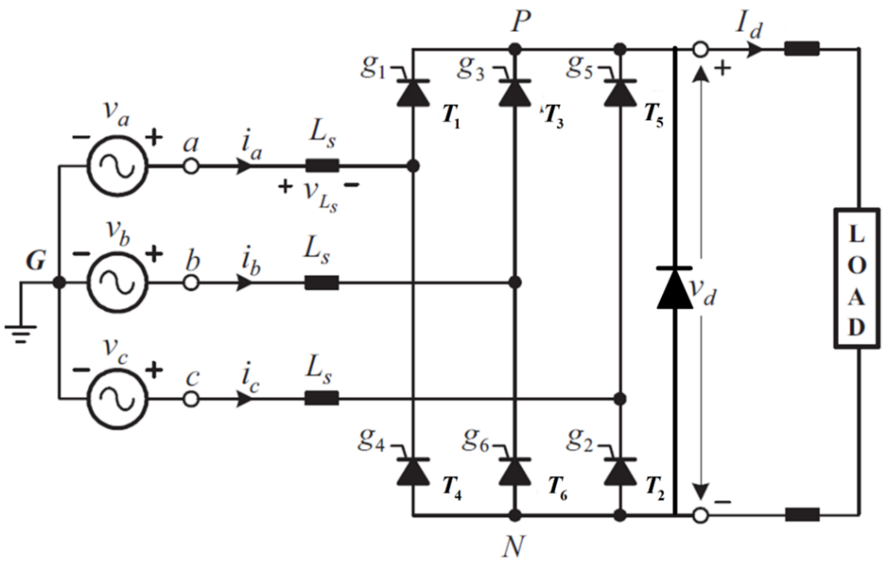
On-state power dissipation in thyristor,
$P_T = V_{T0} I_{T(av)} + R_T I_{T(rms)}^2 = 1.4 \times 3.33 + 24 \times 10^{-3} \times 5.77^2 = 5.46\ W$

D. Effect of source inductance

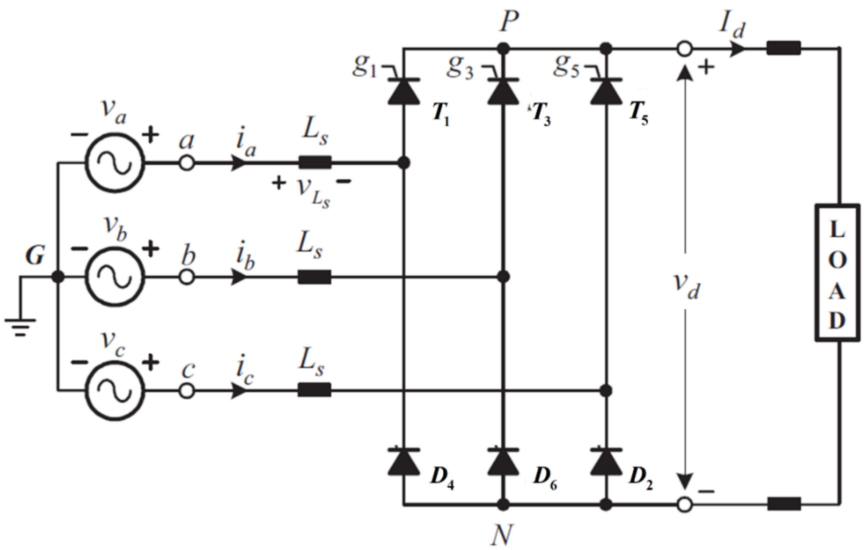
In a practical case, there will be always some source inductance L_s. Due to the source inductance, thyristor current will not reduce to zero instantly. For some commutation interval 'μ' two thyristors in a leg is in on-condition. There will be drop in the output voltage during commutation interval. This drop depends on the source inductance value and the load current.
The average output voltage V_d is given by
$$V_d = \frac{3\sqrt{2}}{\pi} V_{LL} \cos\alpha - \frac{3\omega L_s I_d}{\pi} = V_{d0} \cos\alpha - \frac{3\omega L_s I_d}{\pi}$$

Three phase semi-controlled rectifier

A. Circuit Description



(a)



(b)

Fig.5 Power Circuit diagram of three phase semi controlled rectifier

A fully controlled converter can be made a semi- converter by placing a freewheel diode across the load as shown in Fig.3 (a). This circuit has the same output voltage characteristic as that of the full converter with resistive load since the output voltage can never go negative because of the freewheel diode. Another configuration of a three-phase semi converter is a half-controlled Converter bridge, shown in Fig.3

(b), where half the devices are thyristors, the remaining being diodes. Thyristors get turned off either on the firing of another thyristor or by the action of the freewheeling diode. A semi-controlled converter, when compared to a fully controlled converter has higher harmonic content in the load voltage and the supply current waveforms.

B. Analysis

The average output voltage is given by

$V_d = \frac{3}{\sqrt{2}\pi} V_{LL}(1 + \cos\alpha)$ for $0 \leq \alpha \leq \pi$

For delay angle $\alpha < \frac{\pi}{3}$, output voltage wave is discontinuous.

Each thyristor conducts for 120° out of every 360°. So, the rms value of the thyristor current is

$$I_{T(rms)} = \sqrt{\frac{2\pi}{3} \times \frac{1}{2\pi} I_d^2} = \frac{I_d}{\sqrt{3}}$$

The average value of thyristor current is

$$I_{T(av)} = \frac{I_d}{3}$$

To find out the Fourier series of the input ac line current the load may be replaced by a constant current source having the same value as the average load current. This approximation will be valid provided the load current ripple is relatively small.

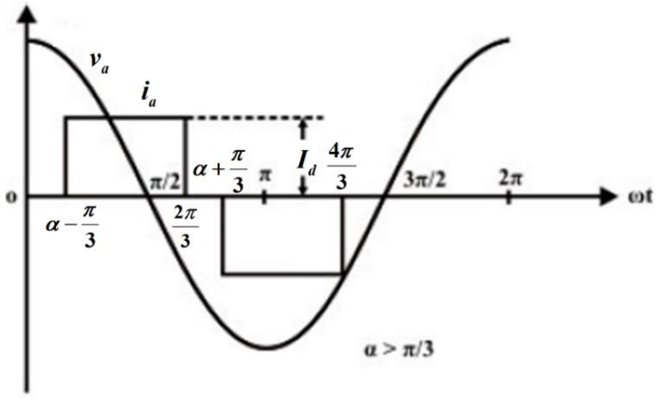


Fig.6 Phase voltage and current waveforms

The rms value of the source current for constant load current I_d is given by

$$I_{s(rms)} = \sqrt{\frac{\pi - \alpha}{\pi}} I_d$$

The instantaneous source current can be expressed in Fourier series as below:

$$i_s(t) = I_{a0} + \sum_{n=1}^{\infty} (I_{an} \cos n\omega t + I_{bn} \sin n\omega t)$$

$$I_{a0} = \frac{1}{\pi} \int_0^{2\pi} i_s(t) d\omega t$$

$$\Rightarrow I_{a0} = \frac{1}{\pi} \left[\int_{\alpha - \frac{\pi}{3}}^{2\pi/3} I_d d\omega t - \int_{\alpha + \frac{\pi}{3}}^{4\pi/3} I_d d\omega t \right]$$

$$\Rightarrow I_{a0} = \frac{I_d}{\pi} \left[\left(\frac{2\pi}{3} - \alpha + \frac{\pi}{3} \right) - \left(\frac{4\pi}{3} - \alpha - \frac{\pi}{3} \right) \right]$$

$$\Rightarrow I_{a0} = 0$$

$$I_{an} = \frac{1}{\pi} \int_0^{2\pi} i_s(t) \cos n\omega t \, d\omega t$$

$$\Rightarrow I_{an} = \frac{1}{\pi} \left[\int_{\alpha - \frac{\pi}{3}}^{2\pi/3} I_d \cos n\omega t \, d\omega t - \int_{\alpha + \frac{\pi}{3}}^{4\pi/3} I_d \cos n\omega t \, d\omega t \right]$$

$$\Rightarrow I_{an} = \frac{I_d}{\pi} \left[\frac{\sin n\omega t}{n} \bigg|_{\alpha - \frac{\pi}{3}}^{2\pi/3} - \frac{\sin n\omega t}{n} \bigg|_{\alpha + \frac{\pi}{3}}^{4\pi/3} \right]$$

$$\Rightarrow I_{an} = \frac{I_d}{n\pi} \left[\sin \frac{2n\pi}{3} - \sin n \left(\alpha - \frac{\pi}{3} \right) + \sin n \left(\alpha + \frac{\pi}{3} \right) - \sin \frac{4n\pi}{3} \right]$$

$$\Rightarrow I_{an} = \frac{2I_d}{n\pi} \left[\sin \frac{2n\pi}{3} + \cos n\alpha \sin \frac{n\pi}{3} \right]$$

$$\Rightarrow I_{an} = \frac{2I_d}{n\pi} [\cos n\alpha - (-1)^n] \sin \frac{n\pi}{3}$$

$$I_{bn} = \frac{1}{\pi} \int_0^{2\pi} i_s(t) \sin n\omega t \, d\omega t$$

$$\Rightarrow I_{bn} = \frac{1}{\pi} \left[\int_{\alpha - \frac{\pi}{3}}^{2\pi/3} I_d \sin n\omega t \, d\omega t - \int_{\alpha + \frac{\pi}{3}}^{4\pi/3} I_d \sin n\omega t \, d\omega t \right]$$

$$\Rightarrow I_{bn} = \frac{I_d}{\pi}\left[\frac{\cos n\omega t}{n}\Bigg|_{\frac{2\pi}{3}}^{\alpha-\frac{\pi}{3}} + \frac{\cos n\omega t}{n}\Bigg|_{\alpha+\frac{\pi}{3}}^{4\pi/3}\right]$$

$$\Rightarrow I_{bn} = \frac{I_d}{n\pi}\left[\cos n\left(\alpha - \frac{\pi}{3}\right) - \cos\frac{2n\pi}{3} + \cos\frac{4n\pi}{3} - \cos n\left(\alpha + \frac{\pi}{3}\right)\right]$$

$$\Rightarrow I_{bn} = \frac{2I_d}{n\pi}\sin n\alpha \sin\frac{n\pi}{3}$$

For fundamental component,

$$i_{s1}(t) = \frac{2I_d}{\pi}[\cos\alpha - (-1)^1]\sin\frac{\pi}{3}\cos\omega t + \frac{2I_d}{\pi}\sin\alpha\sin\frac{\pi}{3}\sin\omega t$$

$$\Rightarrow i_{s1}(t) = \frac{2I_d}{\pi}\left[(\cos\alpha - (-1)^1)\sin\frac{\pi}{3}\cos\omega t + \sin\alpha\sin\frac{\pi}{3}\sin\omega t\right]$$

$$\Rightarrow i_{s1}(t) = \frac{\sqrt{3}I_d}{\pi}[\cos\omega t + \cos\alpha\cos\omega t + \sin\alpha\sin\omega t]$$

$$\Rightarrow i_{s1}(t) = \frac{\sqrt{3}I_d}{\pi}[\cos\omega t + \cos(\omega t - \alpha)]$$

$$\Rightarrow i_{s1}(t) = \frac{2\sqrt{3}I_d}{\pi}\cos\frac{\alpha}{2}\cos\left(\omega t - \frac{\alpha}{2}\right)$$

RMS value of the fundamental frequency component,

$$I_{s1} = \frac{2\sqrt{3}I_d}{\pi}\cos\frac{\alpha}{2}$$

Total Harmonic Distortion,

$$THD = \frac{\sqrt{I_s^2 - I_{s1}^2}}{I_{s1}} \times 100$$

Distortion factor, $DF = {}^{I_{s1}}/_{I_s}$

Displacement power factor, $DPF = \cos\frac{\alpha}{2}$

Input power factor, $IPF = DF \times DPF = {}^{I_{s1}}/_{I_s}\cos\frac{\alpha}{2}$

Fundamental active power input to the converter, $P = 3V_{ph}I_{s1}\cos(\frac{\alpha}{2})$

Fundamental reactive power input to the converter, $Q = 3V_{ph}I_{s1}\sin(\frac{\alpha}{2})$

C. Specifications

Input voltage, $V_{LL} = 440V$
Load Current, $I_d = 10A$
Thyristor rms current rating,

$$I_{T(rms)} = \frac{10}{\sqrt{3}} = 5.77A$$

Thyristor average current rating,

$$I_{T(av)} = \frac{10}{3} = 3.33\ A$$

Diode rms current rating,

$$I_{D(rms)} = \frac{10}{\sqrt{3}} = 5.77A$$

Diode average current rating,

$$I_{D(av)} = \frac{10}{3} = 3.33\ A$$

Peak working forward blocking voltage, $V_{DWM} = 440 \times \sqrt{\frac{2}{3}} = 359\ V$

Peak working reverse blocking voltage, $V_{RWM} = 440 \times \sqrt{\frac{2}{3}} = 359\ V$

Voltage Safety Factor, $V_{SF} = \frac{V_{RRM}}{\sqrt{2} \times V_{ph(rms)}} = 2$ (considered)

Peak repetitive forward voltage, $V_{DRM} = 2 \times 359 = 718\ V$
Peak repetitive reverse voltage, $V_{RRM} = 718\ V$
Peak non-repetitive reverse voltage, V_{RSM}=1.3 * V_{RRM}= 933.4 V
Maximum Peak repetitive forward voltage, V_{DRM} rating of SCR ≥ 718V
Peak non-repetitive forward voltage, V_{DSM}=1.3 * V_{RRM}= 933.4 V
Voltage safety factor chosen ≈ 2; Current safety factor chosen ≈ 3.

Selection of thyristor:
Based on the above calculations and safety factor VS-16TTS12-M3 [1] is chosen. The specifications of VS-16TTS12-M3 are as follows:
On-state rms current = 16A at T_c=98°C
On-state average current = 10A at Tc=98°C
Repetitive peak off-state voltage, V_{DRM}=1200V

On-state power dissipation in thyristor,

$P_T = V_{T0} I_{T(av)} + R_T I_{T(rms)}^2 = 1.4 \times 3.33 + 24 \times 10^{-3} \times 5.77^2 = 5.46\ W$

Selection of diode:

Based on the above calculations and safety factor VS-HFA16PB120PbF [2] is chosen. The specifications of VS-HFA16PB120PbF are as follows:

On-state average current, I_{Fav} = 16A at Tc = 100°C

Repetitive peak off-state voltage, V_{RRM} = 1200V

Power loss calculation of diode,

$P_D = V_F I_{D(av)} + V_{RRM} Q_{rr} f_s = 2.3 \times 3.33 + 718 \times 260 \times 10^{-9} \times 50 = 7.67W$

Triggering Circuit

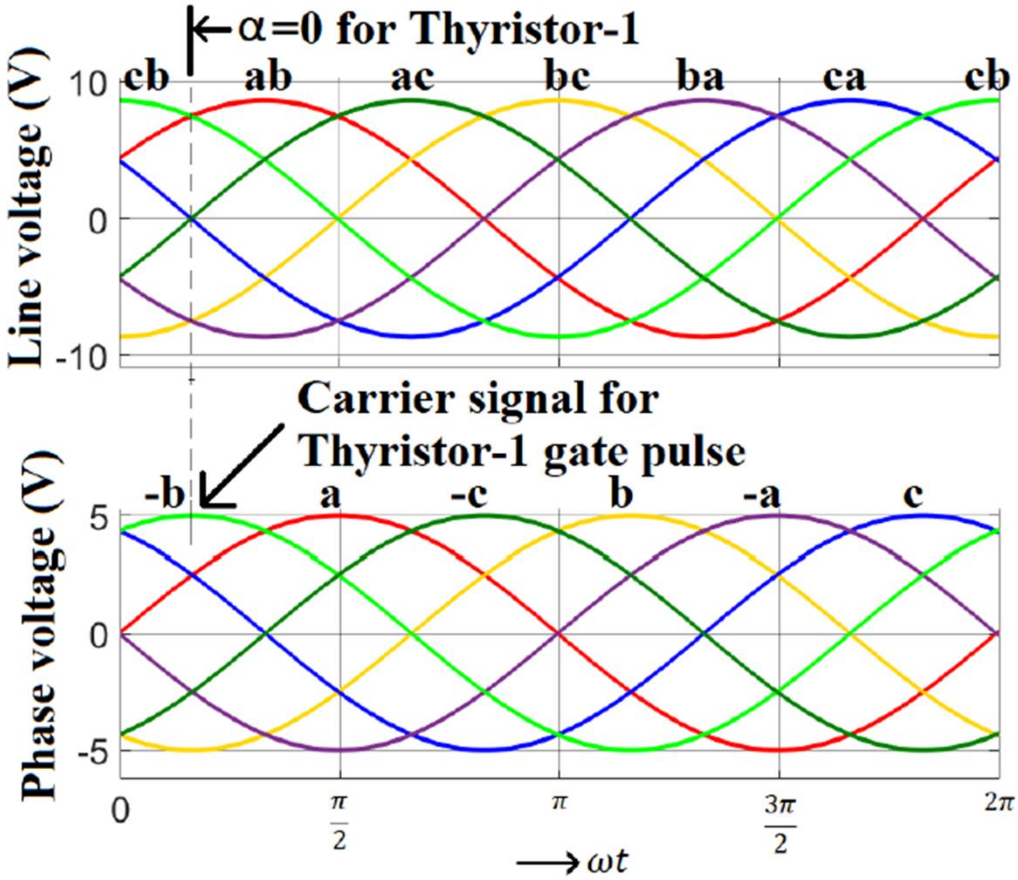


Fig.7 Line voltage and phase voltage waveforms

A. Linear triggering

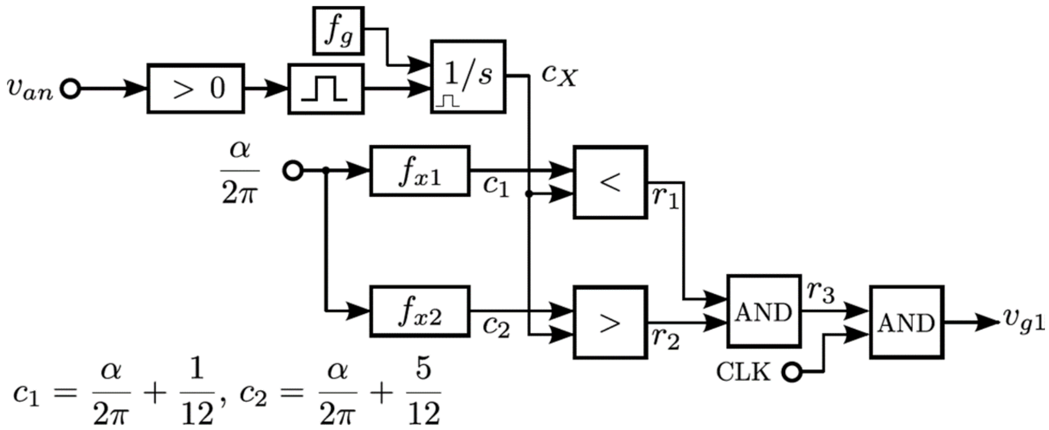


Fig.8 Linear triggering circuit

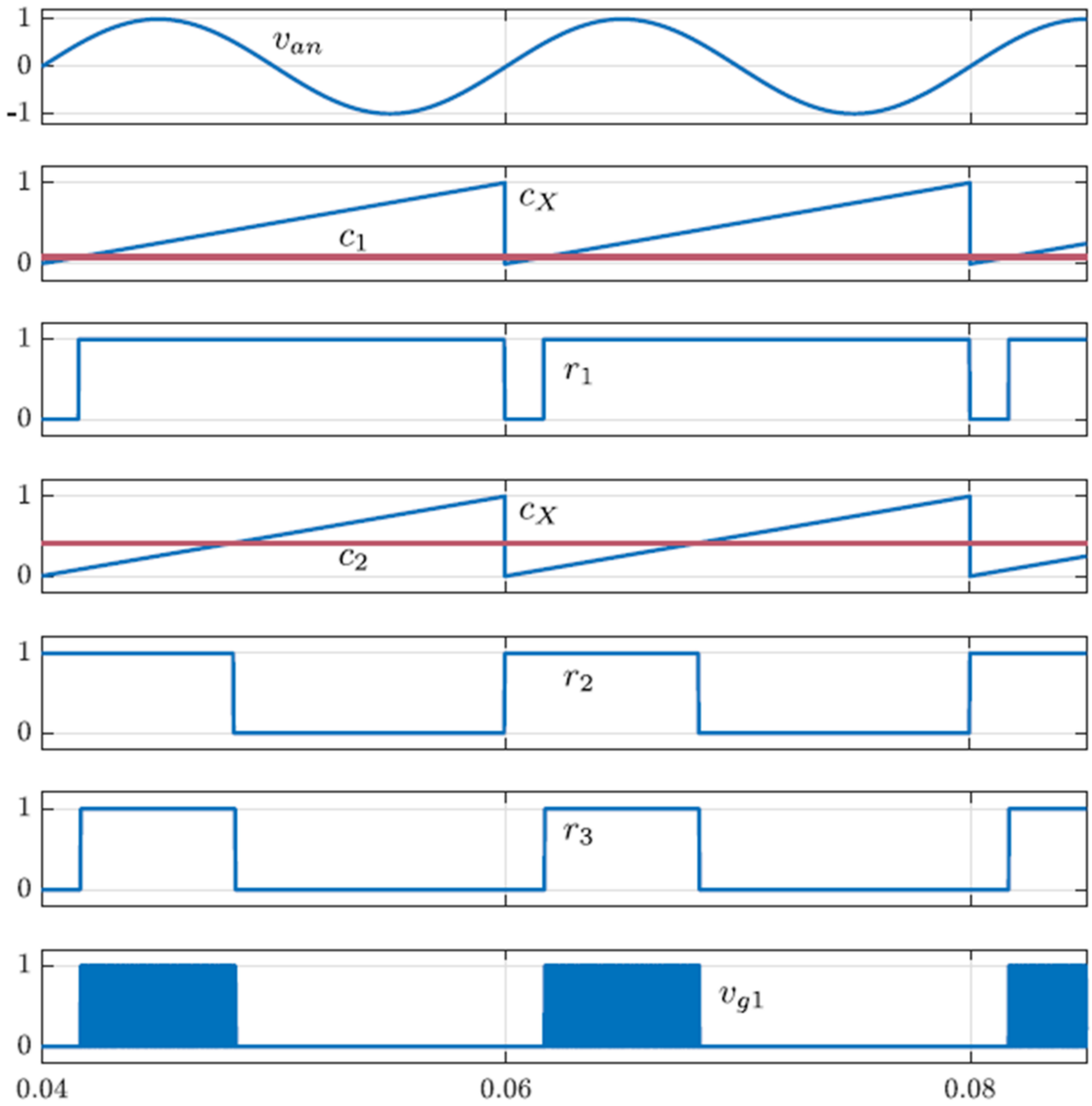


Fig.9 Relevant waveforms for generating gate pulses for 0° firing angle

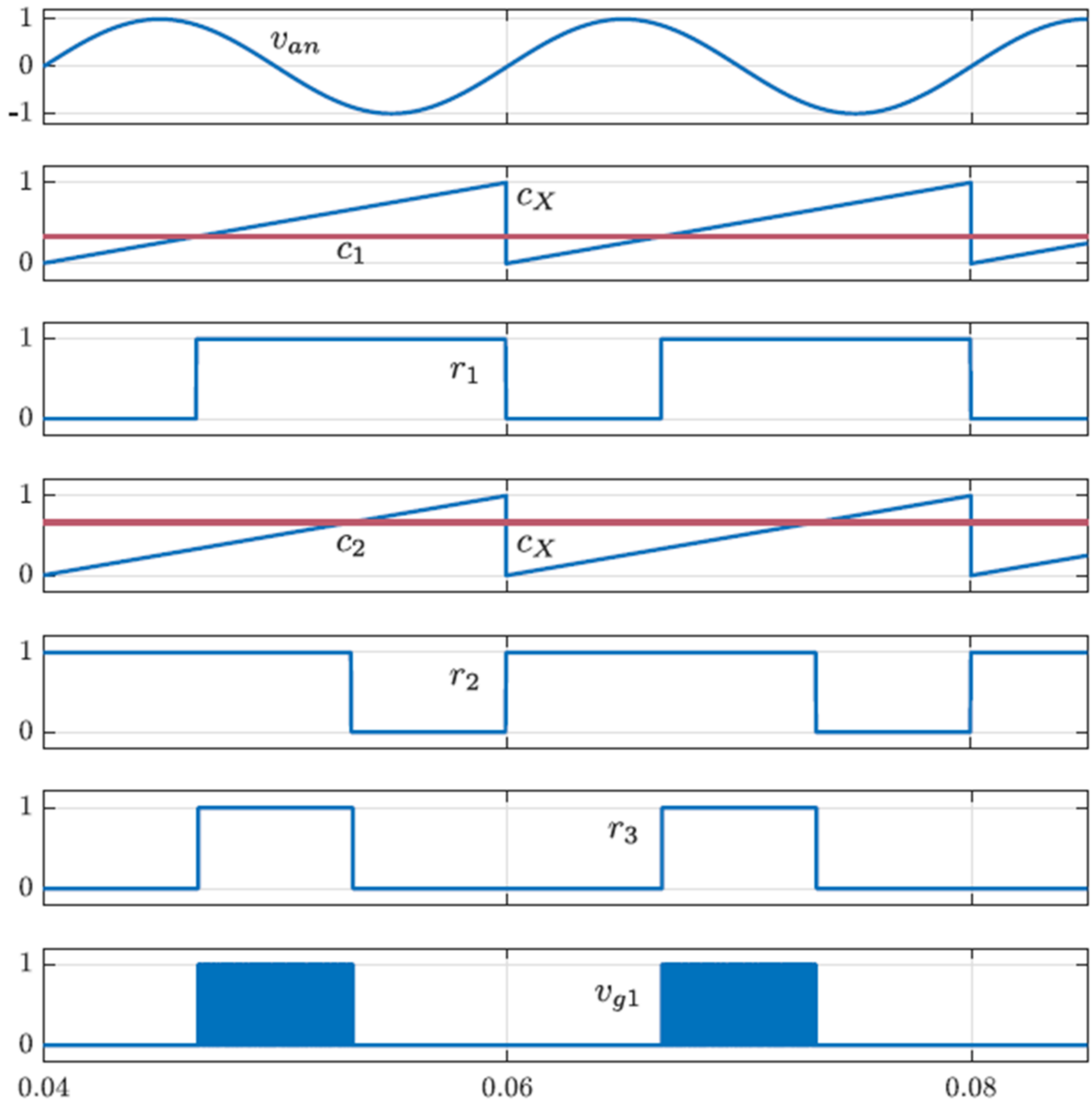


Fig.10 Relevant waveforms for generating gate pulses for 90° firing angle

B. Cosine Triggering

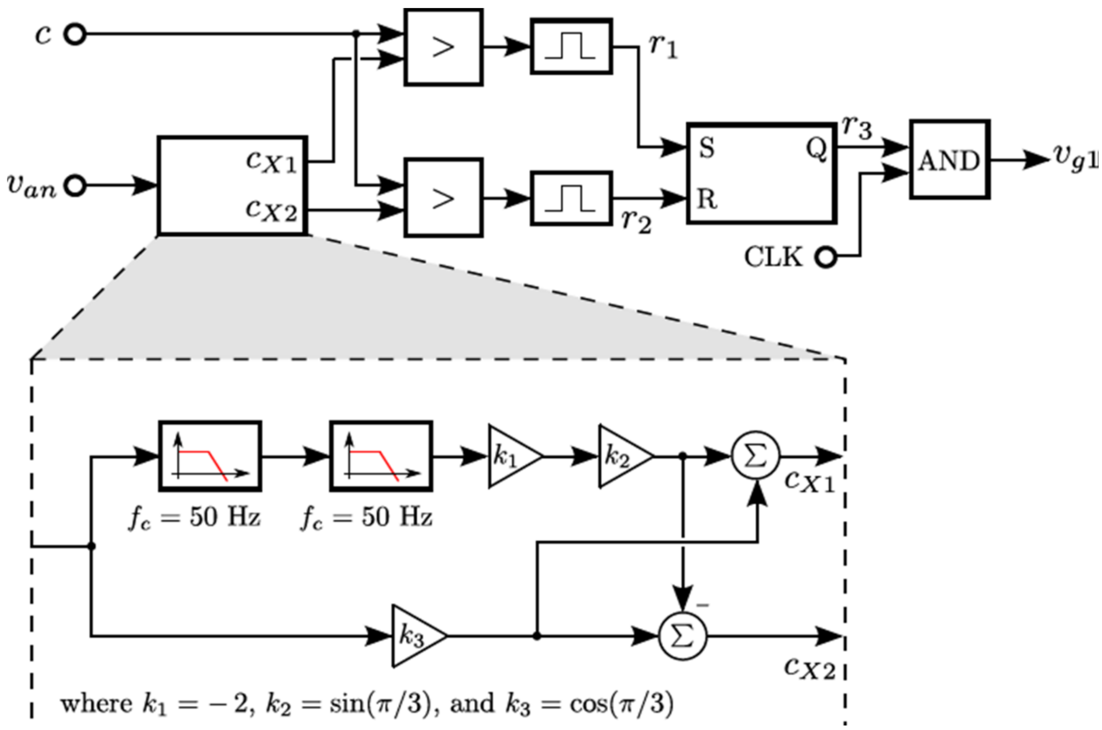


Fig.11 Cosine triggering circuit

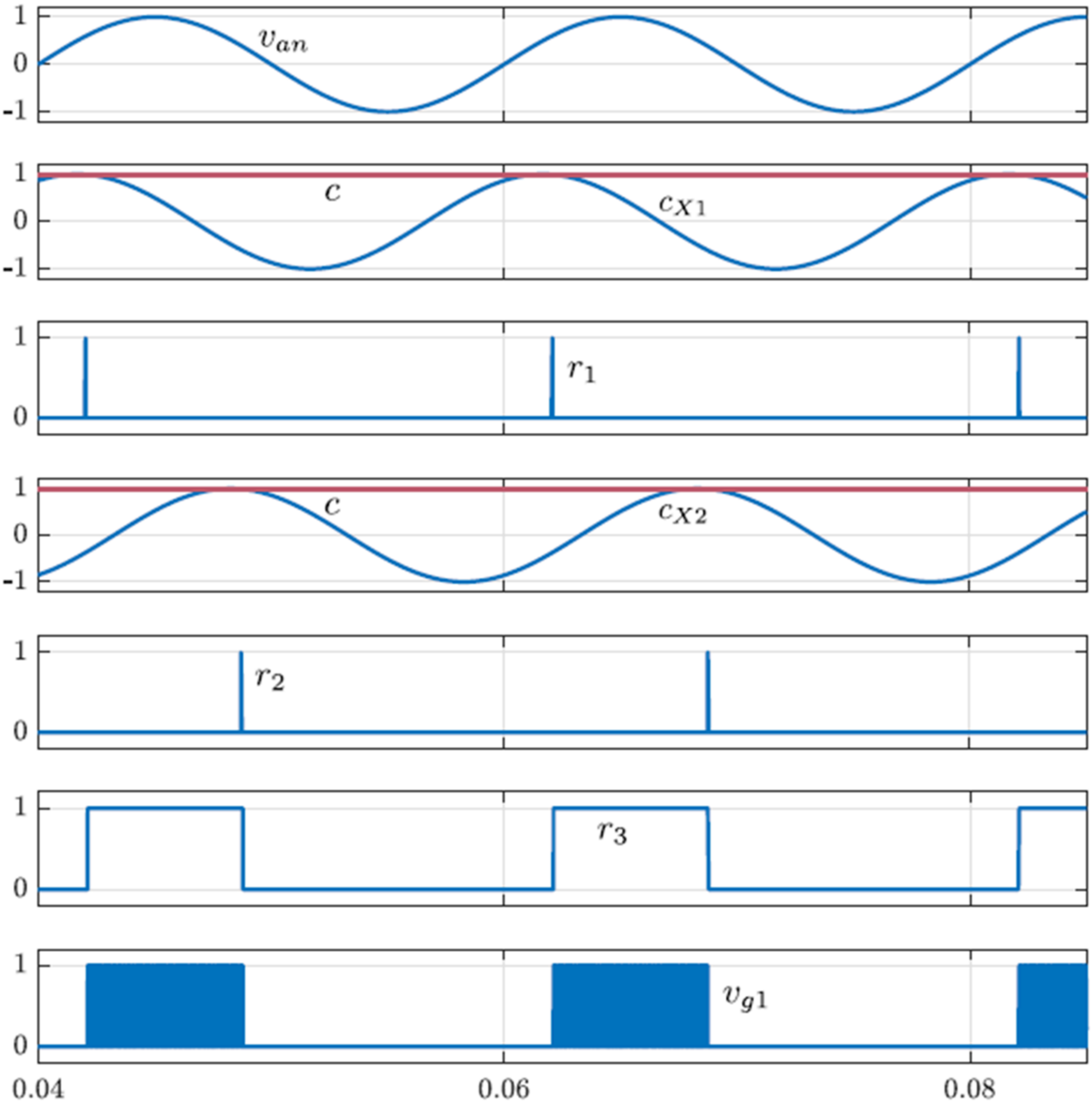


Fig.12 Relevant waveforms for generating gate pulses for 0° firing angle

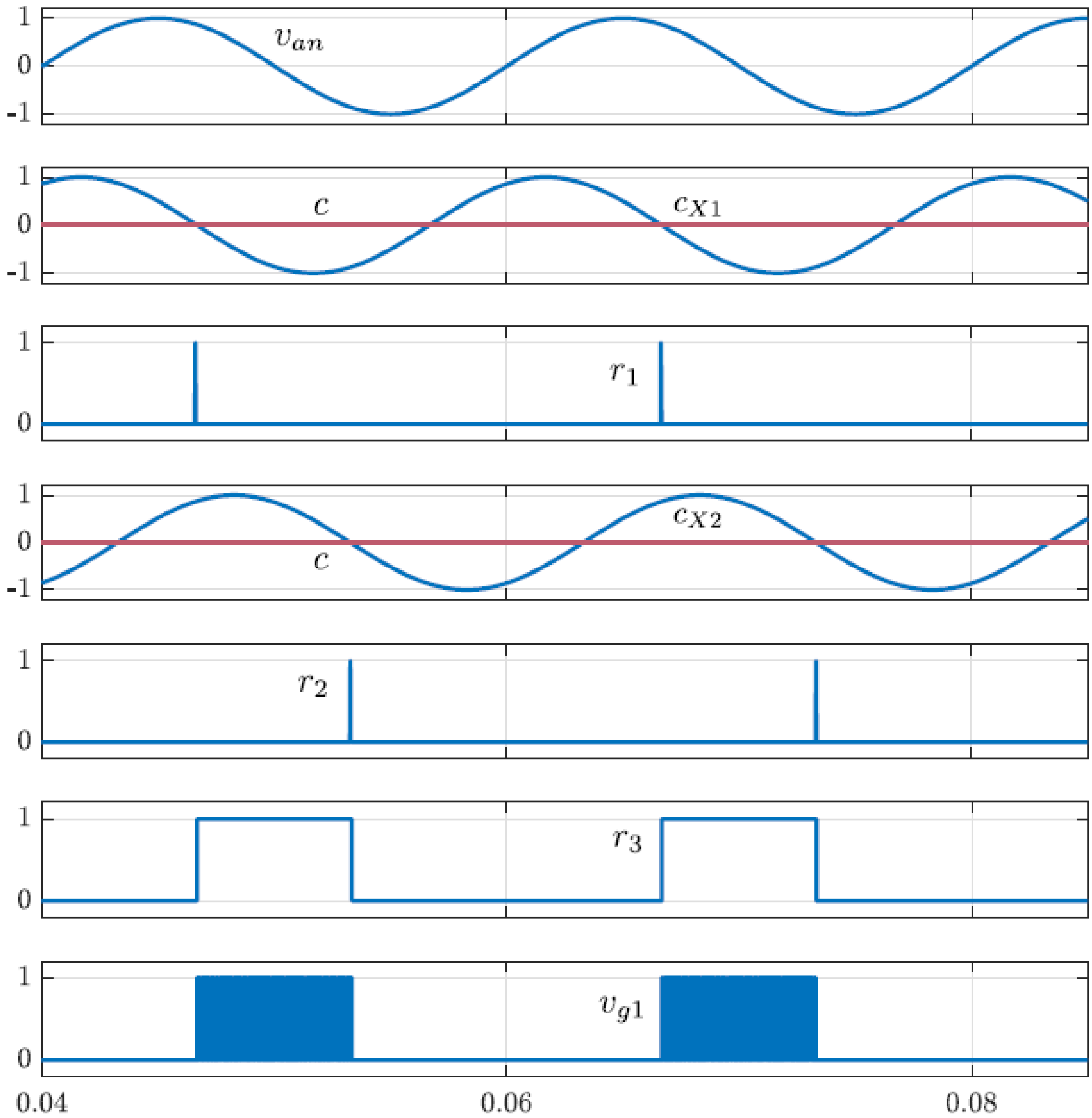


Fig.13 Relevant waveforms for generating gate pulses for 90° firing angle

References

[1] https://www.vishay.com/docs/96287/vs-16tts08_12-m3.pdf

[2] https://www.vishay.com/docs/94057/vs-hfa16pb1.pdf

[3] N. Mohan, T. M. Undeland, and W. P. Robbins, *Power Electronics. Converters, Applications and Design*, 3rd ed. John Wiley and Sons, Inc, 2003.