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ELECTRICAL ENGINEERING DEPARTMENT

RECTIFIER

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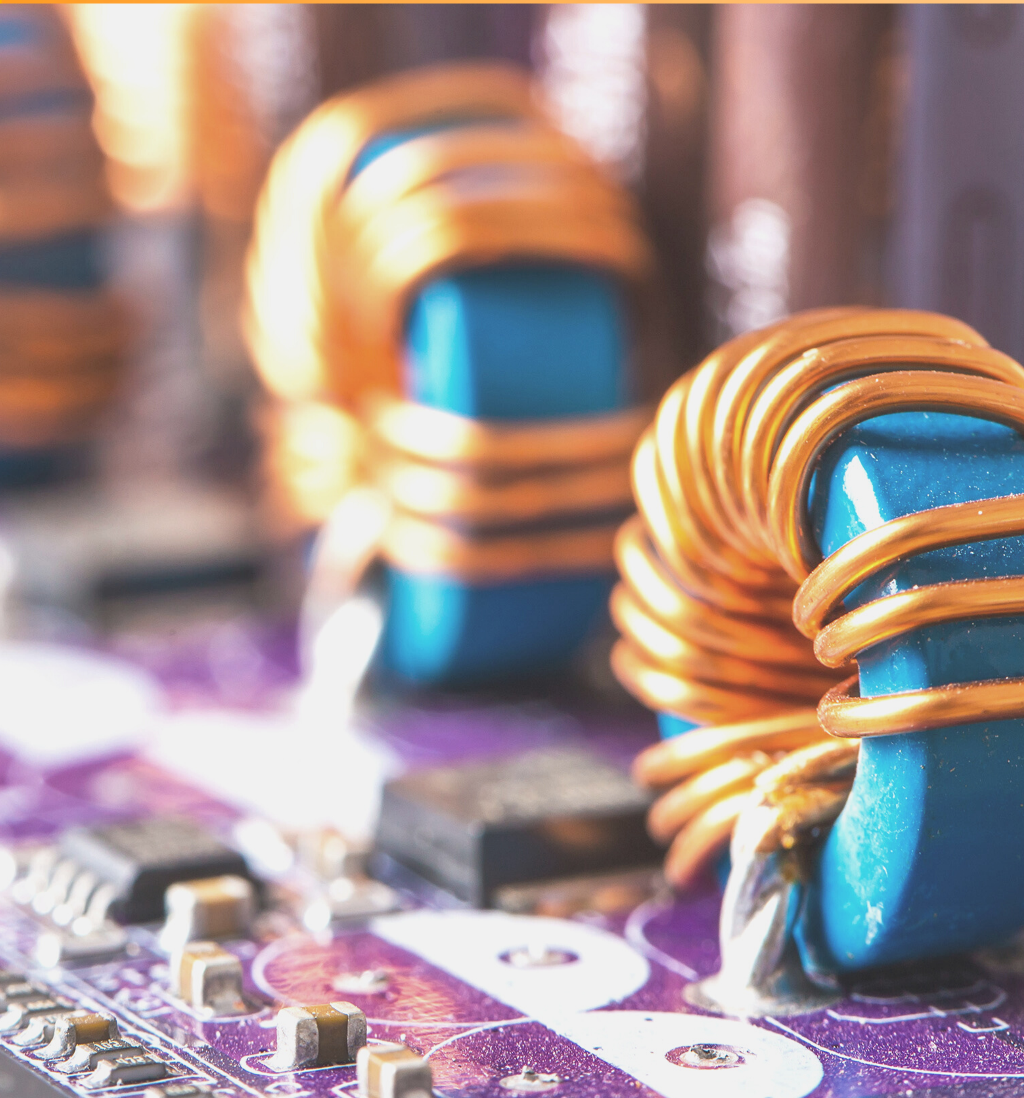

RECTIFIER

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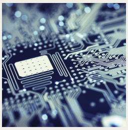
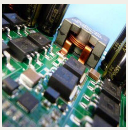
SYNOPSIS

POWER ELECTRONICS is aimed to equip students with the knowledge and skills related to power electronic devices and its application in power conversion. This e-book is written to provide the basic knowledge AC to DC converter. This e-book also will focus on the operational principle of AC to DC converter in clear and concise explanation of all the important concepts, support by figures and summary of equation. It’s also included the examples with worked solutions. This e-book consists the principle operation and application of single-phase and three-phase AC to DC converter. This e-book also Investigate the principle operation of single-phase half wave and full wave AC to DC converter Its also to enable quick revision of important concept and principle.

CONTENTS





1. Introduction To Rectifier

The most widely used application of power electronic devices has been in rectification. Rectification refers to the process of converting an AC voltage or current source to DC voltage and current. A rectifier is an electrical device that converts AC which periodically reverses direction, to DC which flows in only one direction. Rectifiers specifically refer to power electronic converters where the electrical power flows from the AC side to the DC side.

APPLICATIONS

A rectifier is an electrical component that converts alternating current (AC) to direct current (DC). A rectifier is analogous to a one-way valve that allows an electrical current to flow in only one direction. The process of converting AC current to DC current is known as rectification. Industrial rectifiers are used to convert AC power to DC power for many different applications. Typical applications of rectifier in industry are arc-furnace control, electro-winning, haulage truck assist, winder/elevator armature & field converters, electro-plating, soft starters, heater control, portable hand tool drives, dc motor drive(steel-rolling mills, paper mills, printing presses and textile mills), electrochemical and electrometallurgical processes, Magnet power supplies, High voltage dc transmission etc.

2. Uncontrolled Rectifier

In this type of rectifier, the produced DC output power is fixed with the converter used. They usually employ diodes as their power switches. The following subsections deal with the basic operation of some examples of uncontrolled rectifiers single-phase half-wave, center-tap and bridge rectifier loaded with resistive and series resistive inductive loads.

UNCONTROLLED HALF WAVE RECTIFIER WITH R LOAD

Single-Phase Half-Wave Uncontrolled Rectifier with Resistive Load Figure 2-1 shows the basic circuit for a single-phase, half-wave uncontrolled rectifier supplying a resistive load.

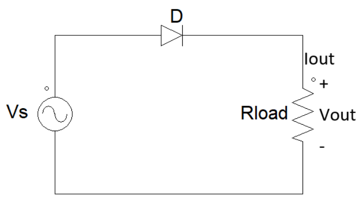


Figure 2 1: Uncontrolled Half -wave Rectifier with Resistive

The operation for the uncontrolled half-wave rectifier with resistive when the diode, D will be in the forward bias condition during the first half cycle and the output voltage will appear from 0 to π. The input voltage appears across the load as shown in Figure 2-2 below. For this configuration, the diode will conduct (becomes forward-biased) whenever the supply voltage Vs is positive. This means that, during the positive half cycle, ($0 < \omega t < \pi$), The diode conducts and behaves like a closed switch connecting the supply to the load. Current output will flow through the load and since the load is resistive, the load current waveform will be replica of the voltage waveform. The current wave form1is shown in Figure 2(d). Vo = Vs. then when during negative half cycle Diode D1 in blocking condition (reverse biased). The Output voltage is zero. Vo = 0V.

The average output voltage Vo(ave) can be determined as;

$$
\begin{aligned}
V_{o(ave)} &= \frac{1}{2\pi}\int_0^{\pi} V_m \sin \omega t \, d\omega t \\
&= \frac{V_m}{2\pi}((-\cos\pi) - (-\cos(0)) \\
&= \frac{V_m}{\pi} \qquad (1)
\end{aligned}
$$

2. Uncontrolled Rectifier

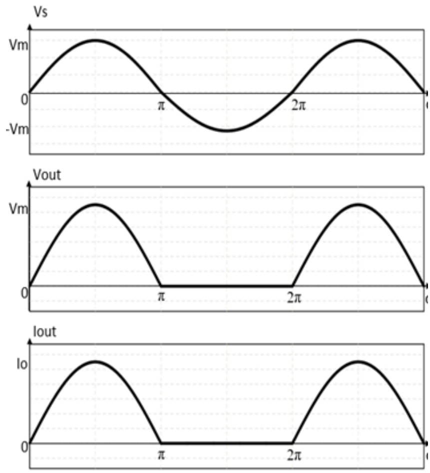


Figure 2-2: Output voltage and current waveform of half-wave uncontrolled rectifier with resistive load

The average output current is as follow;

$$I_{o(ave)} = \frac{V_{0(ave)}}{R} = \frac{V_m}{\pi R} \tag{2}$$

For the rms output voltage and current are as follow:

$$V_{o(rms)} = \sqrt{\frac{1}{2\pi}\int_0^{\pi} (v_m \sin \omega t)^2 \omega t}$$

$$= \frac{v_m}{2}\sqrt{\frac{1}{\pi}\left(\pi - \frac{\sin 2(\pi)}{2}\right)} \tag{3}$$

and

$$I_{o(rms)} = \frac{V_{0(rms)}}{R} = \frac{v_m}{2R}\sqrt{\frac{1}{\pi}\left(\pi - \frac{\sin 2(\pi)}{2}\right)} \tag{4}$$

EXAMPLE 1

The uncontrolled half-wave rectifier in Figure 2 is connected to a source voltage of 120V at a frequency of 60 Hz. The load resistor is 10ohm. Determine the average load voltage and current, and power absorbed by the load of the circuit

SOLUTION

From the eq. 1 the average output voltage is:

$$V_{o(ave)} = \frac{V_m}{\pi} = \frac{169.71}{\pi} = 54.02$$

$$V_m = \sqrt{2}V_{rms} = \sqrt{2}(120 = 169.71$$

The average output current can be calculated using eq. 2

$$I_{o(ave)} = \frac{V_{0(ave)}}{R} = \frac{54.02}{10} = 5.4\text{A}$$

The average power absorbed by the resistor is:

$$P_{dc} = V_{o(ave)} I_{o(ave)} = 54.02(5.4) = 291.7watt$$

UNCONTROLLED HALF-WAVE RECTIFIER WITH RESISTIVE AND INDUCTIVE LOAD

The uncontrolled half-wave rectifier with resistive and inductive load (RL) load is shown in Figure 2-3.

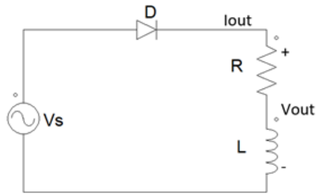


Figure 2 -3 : Uncontrolled Half -wave Rectifier with Resistive and Inductive Load

2. Uncontrolled Rectifier

The operation for the uncontrolled half-wave rectifier with resistive and inductive load is not much different from the basic resistive load that has been discuss before. The diode, D will be in the forward bias condition during the first half cycle and the output voltage will appear from 0 to π. However, during the second half cycle, the output continues until extinction angle, β as shown in figure 2-4 below. This happen due to inductor where energy store in magnetic field is discharge when there is no current flowing in the circuit.

With the additional inductor the output current will be lags to the output voltage. Output current gradually increase to maximum value during the positive cycle and will gradually decrease to zero during negative cycle. The current wave form is shown in figure 2-8.

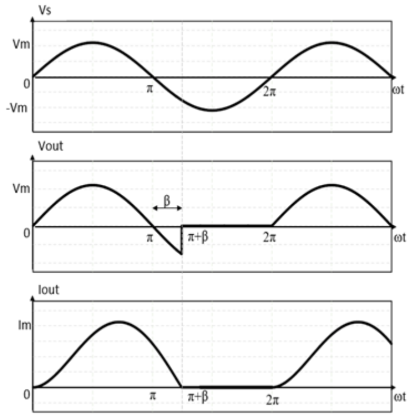


Figure 2 4: Output voltage and current waveform of uncontrolled half-wave rectifier with Resistive and Inductive Load

The average output voltage Vo(ave) can be determined as;

$$V_{o(ave)} = \frac{1}{2\pi}\int_0^{\pi+\beta} V_m \sin\omega t \, d\omega t$$

$$= \frac{V_m}{2\pi}(1 - cos(\pi + \beta)) \qquad (5)$$

The average output current is as follow;

$$I_{o(ave)} = \frac{V_{0(ave)}}{Z}$$

$$= \frac{V_m}{2\pi Z}(1 - \cos(\pi + \beta)) \qquad (6)$$

Where

$$Z = \sqrt{R^2 + X_L{}^2}$$

For the rms output voltage and current are as follow:

$$V_{o(rms)} = \sqrt{\frac{1}{2\pi}\int_0^{\pi+\beta} (v_m \sin\omega t)^2 \omega t}$$

$$= \frac{v_m}{2}\sqrt{\frac{1}{\pi}\left(\pi + \beta - \frac{\sin 2(\pi+\beta)}{2}\right)} \qquad (7)$$

and

$$I_{o(rms)} = \frac{V_{0(rms)}}{Z}$$

$$= \frac{v_m}{2Z}\sqrt{\frac{1}{\pi}\left(\pi + \beta - \frac{\sin 2(\pi+\beta)}{2}\right)} \qquad (8)$$

EXAMPLE 2:

A 50Hz single-phase half-wave rectifier with resistive and inductive load as shown in figure 2-3 is supplied to Vm = 120 V, resistive and inductive load R = 10Ω and L = 50mH respectively. With extinction angle, β = 45°, calculate the average output voltage and current.

SOLUTION

From the eq. 5 the average output voltage is:

$$V_{o(ave)} = \frac{V_m}{2\pi}(1 - cos(\pi + \beta))$$

$$= \frac{120}{2\pi}(1 - cos(\pi + 45°))$$

$$= 32.603V$$

The average output current can be calculated using eq. 6

$$I_{o(ave)} = \frac{V_{0(ave)}}{Z}$$

$$= \frac{32.303}{18.62}$$

$$= 1.73A$$

$$Z = \sqrt{R^2 + X_L{}^2}$$

$$= \sqrt{10^2 + 2\pi(50)(50m)^2}$$

$$= 18.62$$

UNCONTROLLED CENTER TAP RECTIFIER WITH RESISTIVE LOAD

Figure 2-5 presents the circuit connection for a single-phase center tap rectifier loaded with a resistive load. It is sometimes referred to as the full-wave bridge rectifier. The input voltage appears across the load as shown in Figure 2-6 below. For this configuration, the two diodes will alternately conduct during each interval to provide a closed loop for the current. D1 conduct whenever the supply voltage Vs is positive while D2 conduct whenever the supply voltage Vs is negative as illustrated by Figure 2-6. Since the load is a resistive load. Then, the load current will have the same waveform as the load voltage

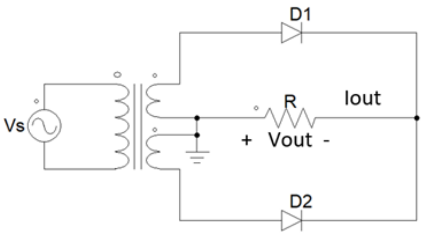


Figure 2 5 Uncontrolled Full-wave Centre-tap Rectifier with Resistive

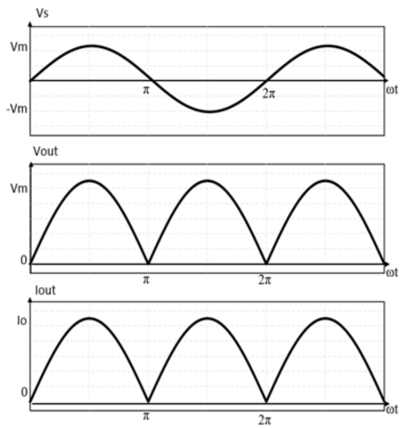


Figure 2 4: Output voltage and current waveform of uncontrolled half-wave rectifier with Resistive and Inductive Load

The average output voltage Vo(ave) can be determined as;

$$V_{o(ave)} = \frac{1}{\pi}\int_0^{\pi} V_m \sin \omega t \, d\omega t$$
$$= \frac{V_m}{\pi}((-\cos \pi) - (-\cos(0))$$
$$= \frac{2V_m}{\pi} \quad (9)$$

The average output current is as follow;

$$I_{o(ave)} = \frac{V_{0(ave)}}{R} = \frac{2V_m}{\pi R} \quad (10)$$

For the rms output voltage and current are as follow:

$$V_{o(rms)} = \sqrt{\frac{1}{\pi}\int_0^{\pi} (v_m \sin \omega t)^2 \omega t}$$
$$= \frac{v_m}{\sqrt{2}} \quad (11)$$

and

$$I_{o(rms)} = \frac{V_{0(rms)}}{R} = \frac{v_m}{\sqrt{2}R} \quad (12)$$

EXAMPLE 3:

The uncontrolled center tap rectifier in Figure 2-5 is connected to a source voltage of Vm=240 at a frequency of 60 Hz. The load resistor is 10Ω. Determine the average load voltage and current of the circuit.

SOLUTION

From the eq. 9 the average output voltage is:

$$V_{o(ave)} = \frac{2V_m}{\pi}$$
$$= \frac{(2)240}{\pi}$$
$$= 152.79V$$

The average output current can be calculated using eq. 10

$$I_{o(ave)} = \frac{V_{0(ave)}}{R}$$
$$= \frac{152.79}{10}$$
$$= 15.3A$$

UNCONTROLLED CENTER-TAP RECTIFIER WITH RESISTIVE AND INDUCTIVE LOAD

The circuit presents in Figure 2-7 is an uncontrolled center tap rectifier leaded with resistive load. Similar with the previous configuration, one diode will be conduct during each interval thus making the output continuous.

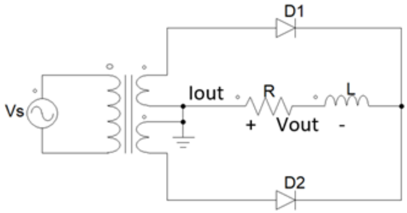


Figure 2 7: Uncontrolled full -wave center-tap Rectifier with Resistive and Inductive Load

During positive cycle from ($0 < \omega t < \pi$), D1 is in forward bias making close path for current to flow. Likewise, during negative cycle ranging between ($\pi < \omega t < 2\pi$), D2 is in forward bias and providing path for current to flow in the circuit. The output waveform for both voltage and current are shown in figure 2-8. Noticing the current waveform having less ripple compared to the voltage waveform. This due to the present of inductor in the load. The bigger value inductor, the smaller ripple in the current waveform.

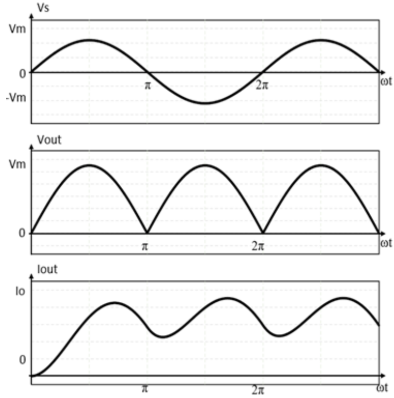


Figure 2-8: Output voltage and current waveform of uncontrolled full-wave center tap rectifier with Resistive and Inductive Load

The average output voltage Vo(ave) can be determined as;

$$V_{o(ave)} = \frac{1}{\pi}\int_0^{\pi} V_m \sin\omega t \, d\omega t$$
$$= \frac{2V_m}{\pi} \quad (13)$$

The average output current is as follow;

$$I_{o(ave)} = \frac{V_{0(ave)}}{Z} = \frac{2V_m}{\pi Z} \quad (14)$$

Where

$$Z = \sqrt{R^2 + {X_L}^2}$$

For the rms output voltage and current are as follow:

$$V_{o(rms)} = \sqrt{\frac{1}{\pi}\int_0^{\pi} (v_m \sin\omega t)^2 \omega t}$$
$$= \frac{V_{m,}}{\sqrt{2}} \quad (15)$$

and

$$I_{o(rms)} = \frac{V_{0(rms)}}{Z} = \frac{v_m}{Z\sqrt{2}} \quad (16)$$

EXAMPLE 4:

A 50Hz single-phase center tap rectifier with resistive and inductive load as shown in figure 2-7 is supplied to 240V, resistive and inductive load R = 50Ω and L = 50mH respectively. Calculate the average output voltage and current.

SOLUTION

From the eq. 13 the average output voltage is:

$$V_{o(ave)} = \frac{2V_m}{\pi}$$
$$= \frac{2(340)}{\pi}$$
$$= 216.08V$$

$$V_m = \sqrt{2}V_{rms}$$
$$= \sqrt{2}(240)$$
$$= 340$$

The average output current can be calculated using eq. 14

$$I_{o(ave)} = \frac{V_{0(ave)}}{Z}$$
$$= \frac{216.08}{52.41}$$
$$= 4.12A$$

$$Z = \sqrt{R^2 + {X_L}^2}$$
$$= \sqrt{50^2 + 2\pi(50)(50m)^2}$$
$$= 52.41$$

UNCONTROLLED BRIDGE RECTIFIER WITH RESISTIVE LOAD

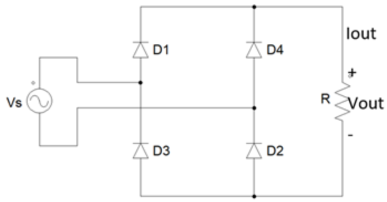


Figure 2 9: Uncontrolled Full-wave Bridge Rectifier with Resistive

Figure 2-9 presents the circuit connection for an uncontrolled bridge rectifier loaded with a resistive load. There are four diodes were used in this circuit. This bridge circuit is that it does not require a special centre-tapped transformer, thereby reducing its size and cost. It is commonly used in industrial application. The operation of this circuit during positive half cycle Diode D1 and D2 conducts, and the input voltage appear across the load for ($0 < \omega t < \pi$). The input voltage appears across the load as shown in Figure 2-10 below. During negative half cycle Diode D3 and D4 conducts, and the input voltage appear across the load for ($\pi < \omega t < 2\pi$).

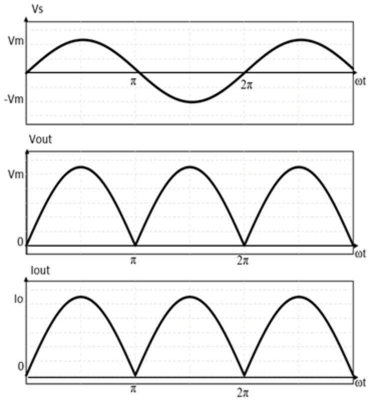


Figure 2-10 : Output voltage and current waveform of bridge uncontrolled rectifier with resistive load

The average output voltage Vo(ave) can be determined as;

$$V_{o(ave)} = \frac{1}{\pi}\int_0^{\pi} V_m \sin \omega t \, d\omega t$$

$$= \frac{V_m}{\pi}((-\cos \pi) - (-\cos(0))$$

$$= \frac{2V_m}{\pi} \qquad (17)$$

The average output current is as follow;

$$I_{o(ave)} = \frac{V_{0(ave)}}{R} = \frac{2V_m}{\pi R} \tag{18}$$

For the rms output voltage and current are as follow:

$$V_{o(rms)} = \sqrt{\frac{1}{\pi}\int_0^{\pi} (v_m \sin \omega t)^2 \omega t}$$

$$= \frac{v_m}{\sqrt{2}} \tag{19}$$

And

$$I_{o(rms)} = \frac{V_{0(rms)}}{R} = \frac{v_m}{\sqrt{2}R} \tag{20}$$

EXAMPLE 5:

A single phase uncontrolled bridge rectifier in Figure 2-9 is connected to a source voltage of 240V at a frequency of 60 Hz. The load resistor is 50Ω. Determine the rms load voltage and current of the circuit.

SOLUTION

From the eq. 19 the rms output voltage is:

$$V_{o(rms)} = \frac{V_m}{\sqrt{2}}$$

$$= \frac{340}{\sqrt{2}}$$

$$= 240V$$

$$V_m = \sqrt{2}V_{rms}$$

$$= \sqrt{2}(240)$$

$$= 340$$

The average output current can be calculated using eq. 20

$$I_{o(rms)} = \frac{V_{0(rms)}}{R}$$

$$= \frac{240}{50}$$

$$= 4.8A$$

UNCONTROLLED BRIDGE RECTIFIER WITH RESISTIVE AND INDUCTIVE LOAD

Figure 2-11 show an uncontrolled bridge rectifier with resistive and inductive load. During positive half cycle D1 and D2 are in forward bias condition. Current from the source voltage will flow through these diodes to reach the load and flow back to the source. During negative cycle, the conducting diodes will switch to D3 and D4 as the change the polarity in source will make these two diodes in forward bias.

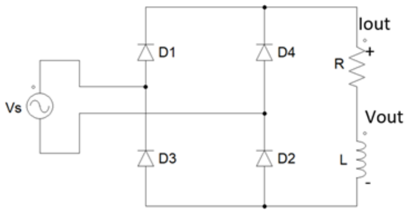


Figure 2-11: Uncontrolled Bridge Rectifier with Resistive and Inductive Load

The output voltage and output current are show in figure 2-12 below. Noticed that even with additional inductive load, the output voltage is similar with the Uncontrolled Bridge Rectifier with Resistive, where there is no extinction angle, β. This is due to continuation current flow in the circuit leaving no room for the inductor to discharge the energy stored. The output current is become continuous because the present of inductor. The larger inductor value, the less ripple will be seen in the output current waveform.

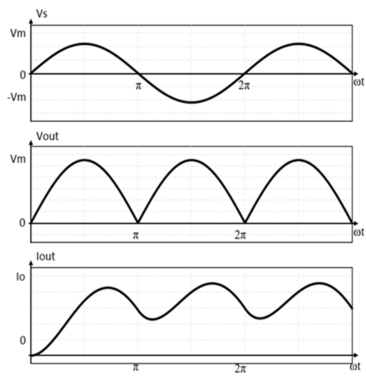


Figure 2-12: Output Voltage and Current Waveform of Uncontrolled Full-Wave Bridge Rectifier with Resistive And Inductive Load

The average output voltage Vo(ave) can be determined as;

$$V_{o(ave)} = \frac{1}{\pi}\int_0^{\pi} V_m \sin\omega t \, d\omega t$$
$$= \frac{2V_m}{\pi} \quad (21)$$

The average output current is as follow

$$I_{o(ave)} = \frac{V_{0(ave)}}{Z} = \frac{2V_m}{\pi Z} \quad (22)$$

Where

$$Z = \sqrt{R^2 + {X_L}^2}$$

For the rms output voltage and current are as follow:

$$V_{o(rms)} = \sqrt{\frac{1}{\pi}\int_0^{\pi} (v_m \sin\omega t)^2 \omega t}$$
$$= \frac{V_{m,}}{\sqrt{2}} \quad (23)$$

and

$$I_{o(rms)} = \frac{V_{0(rms)}}{Z} = \frac{v_m}{Z\sqrt{2}} \quad (24)$$

EXAMPLE 6:

A 50Hz single-phase bridge rectifier with resistive and inductive load as shown in figure 2-11 is supplied to 240V, resistive and inductive load R = 50Ω and L = 20mH respectively. Calculate the rms output voltage and current.

SOLUTION

From the eq. 23 the rms output voltage is:

$$V_{o(rms)} = \frac{V_m}{\sqrt{2}} = \frac{340}{\sqrt{2}} = 240V$$

$$V_m = \sqrt{2}V_{rms} = \sqrt{2}(240) = 340$$

The rms output current can be calculated using eq. 24

$$I_{o(rms)} = \frac{V_{0(rms)}}{Z} = \frac{240}{50.39} = 4.76A$$

$$Z = \sqrt{R^2 + {X_L}^2} = \sqrt{50^2 + 2\pi(50)(20m)^2} = 50.39$$

3. Controlled Rectifier

In this controlled rectifier, the switches used are change from diode to SCR. The circuit will not conduct until a forward current is apply to the gate. The following subsections discuss with the basic operation of some examples of controlled rectifiers single-phase half-wave, centre-tap and bridge rectifier loaded with resistive and series resistive inductive loads.

CONTROLLED HALF WAVE RECTIFIER WITH RESISTIVE LOAD

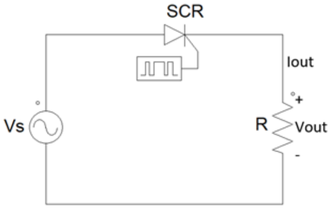


Figure 3-1: Controlled Half Wave Rectifier with Resistive Load

A circuit diagram showing in figure 3-1 is the controlled half-wave rectifier with resistive load. During the positive cycle SCR is in the forward blocking mode where no current will pass through the switch. When gate is applied to a forward current at ωt=α, the SCR will start to conduct and current are able to flow pass-through load. The output voltage, Vo become equal to supply voltage, Vs.

During negative cycle SCR is in reverse bias and will not conducting through the entire cycle. Current will not ably flow in the circuit thus making both output voltage and current Vo and Io become zero. The waveform for the controlled half-wave rectifier is shown in figure 3-2.

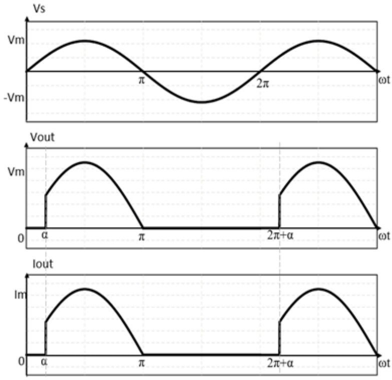


Figure 3-2: Output Voltage and Current Waveform of Controlled Half-Wave Rectifier with Resistive Load

The average output voltage Vo(ave) can be determined as;

$$V_{o(ave)} = \frac{1}{2\pi}\int_{\alpha}^{\pi} V_m \sin\omega t \, d\omega t$$
$$= \frac{V_m}{2\pi}(\cos\alpha + 1) \qquad (25)$$

The average output current is as follow

$$I_{o(ave)} = \frac{V_{0(ave)}}{R} = \frac{V_m(\cos\alpha + 1)}{2\pi R} \qquad (26)$$

For the rms output voltage and current are as follow:

$$V_{o(rms)} = \sqrt{\frac{1}{2\pi}\int_{\alpha}^{\pi} (v_m \sin\omega t)^2 \omega t}$$
$$= \frac{V_m}{2}\sqrt{\frac{1}{\pi}(\pi - \alpha + \frac{\sin 2\alpha}{2})} \qquad (27)$$

And

$$I_{o(rms)} = \frac{V_{0(rms)}}{R}$$
$$= \frac{V_m}{2R}\sqrt{\frac{1}{\pi}(\pi - \alpha + \frac{\sin 2\alpha}{2})} \qquad (28)$$

EXAMPLE 7:

A 50Hz single-phase half-wave rectifier with resistive load as shown in figure 3-1 is supplied to 240V, resistive load R = 20Ω. With firing angle, α = 30°, Determine the average load voltage and current, and power absorbed by the load of the circuit.

SOLUTION

From the eq. 25 the rms output voltage is:

$$V_{o(rms)} = \frac{V_m}{2\pi}(\cos\alpha + 1)$$
$$= \frac{340}{2\pi}(\cos 30° + 1)$$
$$= 100.98V$$

$$V_m = \sqrt{2}V_{rms}$$
$$= \sqrt{2}(240)$$
$$= 340$$

The rms output current can be calculated using eq. 26

$$I_{o(rms)} = \frac{V_{0(rms)}}{R}$$
$$= \frac{100.98}{20}$$
$$= 5.05A$$

The average power absorbed by the resistor is

$$P_{dc} = V_{o(ave)} I_{o(ave)}$$
$$= 100.98(5.05)$$
$$= 509.67 watt$$

CONTROLLED HALF WAVE RECTIFIERS WITH RESISTIVE AND INDUCTIVE LOAD

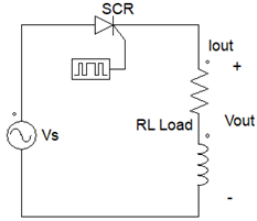


Figure 3-3: Halfwave Controlled Rectifier with Resistive and Inductive Load

A single phase halfwave controlled rectifier with inductive load is shown in Figure 3-3. Inductive load means the load consist of resistance and inductance. During positive half cycle of input voltage SCR is in forward biased condition but is not conduct. When a gating signal is applied to get terminal at ωt=α, SCR is turned on. The output voltage, Vo become equal to supply voltage, Vs. The inductor forces the output current, Io to increase gradually until it's reached the maximum value. After reached a maximum value then the output current will start to decrease. At ωt=2π , the output voltage, Vo become zero but the output current, Io is not zero due to inductor, L. The output current, Io forcing SCR to continue to conduct until the inductor is fully discharge at ωt= π+β. SCR will turn off until it is firing again on the next cycle. The output voltage and current waveform is shown in figure 3-4.

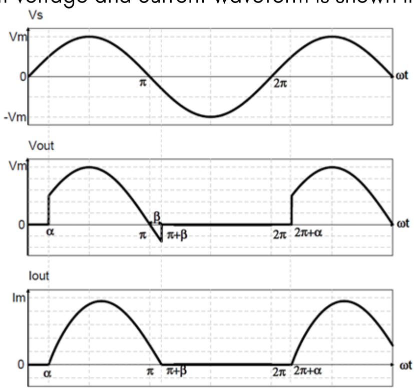


Figure 3-4: Output Voltage and Current Waveform of Single Phase Halfwave Controlled Rectifier with Resistive and Inductive Load

The average output voltage, Vo(ave) is given as

$$V_{o(ave)} = \frac{1}{T}\int_{\alpha}^{\pi+\beta} V_s\ Sin\omega t\ d\omega t$$
$$= \frac{V_m}{2\pi}(cos\alpha - \cos(\pi+\beta)) \qquad (29)$$

The average output current, Io(ave) is given by

$$I_{0(ave)} = \frac{V_{dc}}{Z}$$
$$= \frac{V_m}{2\pi Z}(cos\alpha - \cos(\pi+\beta)) \qquad (30)$$

The RMS value of load voltage, Vo(rms) is determine by

$$V_{o(rms)} = \sqrt{\frac{1}{T}\int_{\alpha}^{\pi+\beta}[V_s Sin\omega t]^2\ d\omega t}$$
$$= \sqrt{\frac{V_m{}^2}{4\pi}\left[(\pi+\beta) - \alpha - \frac{\sin(2(\pi+\beta))}{2} + \frac{\sin(2\alpha)}{2}\right]} \qquad (31)$$

The average output current, Io(rms) is given by

$$I_{o(rms)} = \frac{V_{oRMS}}{Z} \qquad (32)$$

where

$$Z = \sqrt{R^2 + X_L{}^2}$$

EXAMPLE 8:

A 50Hz single-phase controlled half-wave rectifier with resistive and inductive load as shown in figure 3-3 is supplied to Vm = 120V, resistive and inductive load R = 50Ω and L = 20mH respectively. Assuming the firing angle and extinction angle are equal α = β = 30°, calculate the rms output voltage and current.

SOLUTION

From the eq. 31 the rms output voltage is:

$$V_{o(rms)} = \sqrt{\frac{V_m{}^2}{4\pi}\left[(\pi+\beta) - \alpha - \frac{\sin(2(\pi+\beta))}{2} + \frac{\sin(2\alpha)}{2}\right]}$$
$$= \sqrt{\frac{120^2}{4\pi}\left[(\pi+30°) - 30° - \frac{\sin(2(\pi+30°))}{2} + \frac{\sin(2\ x\ 30°)}{2}\right]}$$
$$= 60V$$

The rms output current can be calculated using eq. 32

$$I_{o(rms)} = \frac{V_{0(rms)}}{Z} = \frac{60}{50.39} = 1.19A$$

$$Z = \sqrt{R^2 + {X_L}^2} = \sqrt{50^2 + 2\pi(50)(20m)^2} = 50.39$$

CONTROLLED CENTRE TAP RECTIFIERS WITH RESISTIVE LOAD

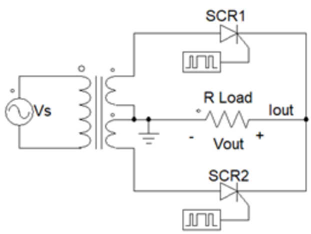


Figure 3-5: Controlled full wave centre tap rectifiers with resistive load

A circuit diagram of a full wave controlled rectifiers using centre tap with resistive load is shown in Figure 3-5. Terminal a is more positive with respect to terminal n, and terminal n is more positive with respect to terminal b.

During positive half cycle of input voltage SCR1 is in forward biased and SCR2 is in reverse biased. SCR1 will not conduct until a triggering pulse applied to terminal get at ωt=α. SCR1 start to conduct. Output voltages appear across the load. When supply voltage cross zero at ωt= , SCR1 will reverse biased and turn off.

During negative half cycle of input voltage SCR1 is reverse biased and SCR2 is forward biased. SCR2 will not conduct until a triggering pulse applied to terminal get at ωt= +α. SCR2 start to conduct. Output voltages appear across the load. When supply voltage cross zero at ωt=2 , SCR2 reverse biased and turn off. This process of SCR turns off when supply voltage cross zero is called natural commutation or line commutation. Output voltage and current waveform of full wave controlled centre tap rectifier with resistive load is shown in figure 3-6.

The average output voltage, Vo(ave) is given as

$$V_{o(ave)} = \frac{2}{T}\int_{\alpha}^{\pi} V_s \; Sin\omega t \; d\omega t$$
$$= \frac{V_m}{\pi}(1 + cos\alpha) \qquad (33)$$

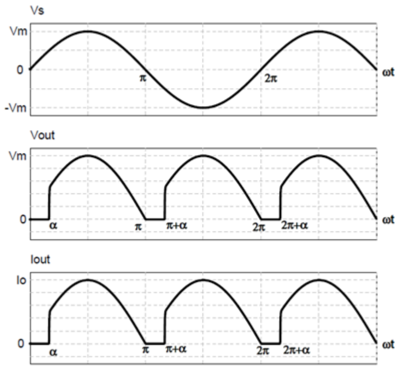


Figure 3-6: Output Voltage and Current Waveform of Single Phase Full wave Controlled Centre Tap Rectifier with Resistive Load

The average output current, Io(ave) is given by

$$I_{o(ave)} = \frac{V_{dc}}{R} \tag{34}$$

The RMS value of load voltage, Vo(rms) is determine by

$$V_{o(rms)} = \sqrt{\frac{2}{T}\int_{\alpha}^{\pi} [V_s Sin\omega t]^{2} \; d\omega t}$$

$$= \sqrt{\frac{{V_m}^2}{2\pi}\left[\pi - \alpha + \frac{1}{2} sin\, \alpha\right]} \tag{35}$$

The average output current, Io(rms) is given by

$$I_{o(rms)} = \frac{V_{oRMS}}{R} \tag{36}$$

CONTROLLED BRIDGE RECTIFIERS WITH RESISTIVE LOAD

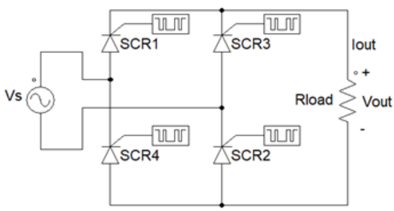


Figure 3-7: Controlled Full Wave Bridge Rectifier with Resistive Load

Figure 3-7 shows the circuit diagram of a single phase full wave controlled bridge rectifier with resistive load. It consists of four SCR. A pair of SCR is turn on and off simultaneously.

During positive half cycle of input voltage, SCR1 & SCR2 are in forward biased condition while SCR3 & SCR4 are in reverse biased. When SCR1 & SCR2 are triggered at ωt=α, SCR's start to conduct. The current flow through the circuit and output voltage appears across the load. When supply voltage cross zero at ωt=π, SCR will turn to reverse biased and commutated.

During negative half cycle SCR3 & SCR4 are triggered at ωt=π+α. SCR's start to conduct until the supply voltage reach zero at ωt=2π. SCR will turn off due to natural commutation. The process will repeat on the next cycle. The out waveform is shown in Figure 3-8.

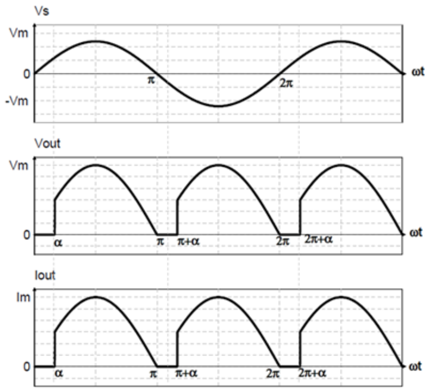


Figure 3-8: Output voltage and current waveform of single phase full wave controlled bridge rectifier with resistive load

The average output voltage, Vo(ave) is given as

$$V_{o(ave)} = \frac{2}{T}\int_{\alpha}^{\pi} V_s\ Sin\omega t\ d\omega t$$
$$= \frac{V_m}{\pi}(1 + cos\alpha) \qquad (37)$$

The average output current, Io(ave) is given by

$$I_{o(ave)} = \frac{V_{dc}}{R} \qquad (38)$$

The RMS value of load voltage, Vo(rms) is determined by

$$V_{o(rms)} = \sqrt{\frac{2}{T}\int_{\alpha}^{\pi} [V_s Sin\omega t]^{2} \; d\omega t}$$

$$= \sqrt{\frac{V_m^{\,2}}{2\pi}\left[\pi - \alpha + \frac{1}{2} sin\, \alpha\right]} \qquad (39)$$

The average output current, Io(rms) is given by

$$I_{o(rms)} = \frac{V_{oRMS}}{R} \qquad (40)$$

EXAMPLE 9:

A 50Hz single-phase controlled full-wave rectifier with resistive load is supplied to 200V, resistive load R = 20Ω. With firing angle, α = 45°, Determine the average load voltage and current, and power absorbed by the load of the circuit.

SOLUTION

From the eq. 25 the rms output voltage is:

$$V_{o(rms)} = \frac{V_m}{\pi}(\cos\alpha + 1)$$

$$= \frac{282.84}{\pi}(\cos 45° + 1)$$

$$= 153.69V$$

$$V_m = \sqrt{2}V_{rms}$$

$$= \sqrt{2}(200)$$

$$= 282.84$$

The rms output current can be calculated using eq. 26

$$I_{o(rms)} = \frac{V_{0(rms)}}{R}$$

$$= \frac{153.69}{20}$$

$$= 7.68A$$

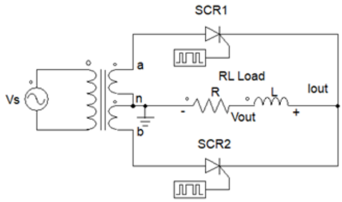
The average power absorbed by the resistor is

$$P_{dc} = V_{o(ave)} I_{o(ave)}$$

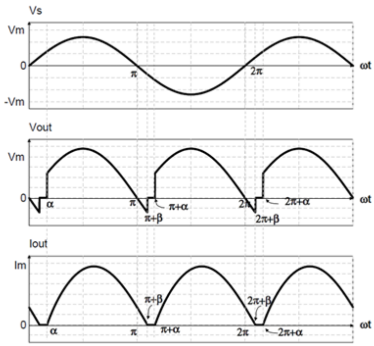
$$= 153.69(7.68)$$

$$= 1.15Kwatt$$

CONTROLLED CENTRE TAP RECTIFIERS WITH RESISTIVE INDUCTIVE LOAD



(a) Circuit diagram



(b) Output voltage and current for discontinuous load current mode (α>β).

Figure 3 9: Single phase full wave controlled rectifiers using centre tap with inductive load. (a) Circuit diagram (b) output voltage and current for discontinuous load current mode (α⩾β).

A circuit diagram in Figure 3-9 shows a single phase full wave controlled rectifiers using centre tap with inductive load. Inductive load means the load consist of resistance and inductance. During positive half cycle of input voltage SCR1 is in forward biased and SCR2 is in reverse biased. SCR1 will not conduct until a triggering pulse applied to terminal get at ωt=α. SCR1 start to conduct. The current increase gradually due to inductive load. The current will increase until it reached a maximum value and start to decrease. The output voltage appears across the load. When supply voltage reached zero at ωt=π, SCR1 continue to conduct due to discharging of inductor current. SCR1 is forced to conduct until inductor is fully discharge at ωt=π+β.

During negative half cycle of input voltage SCR2 is forward biased. SCR2 will not conduct until a triggering pulse applied to terminal get at ωt= +α. Output voltages appear across the load. When supply voltage cross zero at ωt=2 , SCR2 will force to conduct until inductor is fully discharge at ωt=2π+β.

3. Controlled Rectifier

In this case the circuit is conduct in discontinuous load current mode (α⩾β). In this mode of conduction, the value of load current will reach zero. Figure 3-9 (a) show the output voltage and current for discontinuous load current mode (α>β).

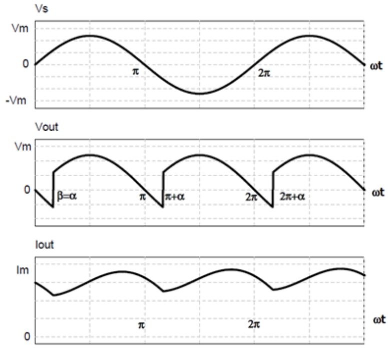


Figure 3 10: output voltage and current for continuous load current mode (β⩾α).

For β⩾α, the circuit will conduct in continuous load current mode. The output voltage and current are shown in Figure 3-10. If the load inductor value is large will produce a load current with small ripple and can be neglect. The output voltage will be like a dc voltage.

The average output voltage, Vo(ave) is given as

$$V_{o(ave)} = \frac{2}{T}\int_{\alpha}^{(\pi+\beta)} V_s\ Sin\omega t\ d\omega t$$
$$= \frac{V_m}{\pi}(cos\alpha - \cos(\pi+\beta)) \tag{41}$$

The average output current, Io(ave) is given by

$$I_{o(ave)} = \frac{V_{dc}}{R} \tag{42}$$

The RMS value of load voltage, Vo(rms) is determined by

$$V_{o(rms)} = \sqrt{\frac{2}{T}\int_{\alpha}^{(\pi+\beta)} [V_m Sin\omega t]^2\ d\omega t}$$
$$= \sqrt{\frac{V_m{}^2}{2\pi}\left[(\pi+\beta) - \alpha - \frac{\sin(2(\pi+\beta))}{2} + \frac{\sin(2\alpha)}{2}\right]} \tag{43}$$

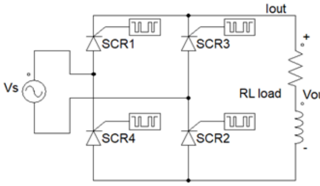
The average output current, Io(rms) is given by

$$I_{o(rms)} = \frac{V_{oRMS}}{Z} \tag{44}$$

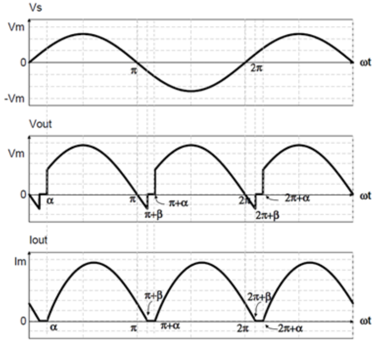
where

$$Z = \sqrt{R^2 + X_L{}^2}$$

CONTROLLED BRIDGE RECTIFIERS WITH RESISTIVE INDUCTIVE LOAD



(a) Circuit diagram



(b) Output voltage and current for discontinuous load current mode (α>β).

Figure 3-11: Single phase full wave controlled rectifiers using bridge with inductive load. (a) Circuit diagram (b) output voltage and current for discontinuous load current mode (α⩾β).

Circuit diagram of a single phase full wave controlled bridge rectifier with inductive load is shown in Figure 3-11.

During positive half cycle of input voltage, SCR1 & SCR2 are in forward biased condition while SCR3 & SCR4 are in reverse biased. When SCR1 & SCR2 are triggered at firing angle α, SCR start to conduct. The current flow through the circuit and output voltage appears across the load. The load current is gradually increase due to inductor load until it reaches maximum value, then it will start to decrease. When supply voltage cross zero at ωt=π, inductor current is continuing to discharge force SCR to continue to conduct until inductor is fully discharge at ωt= +β. There will be a negative output voltage appear across the load.

During negative half cycle of input voltage SCR3 & SCR4 turn to forward biased while SCR1 & SCR2 are reverse biased. When triggered at $\omega t=\pi+\alpha$, SCR3 & SCR4 start to conduct. Inductor current gradually increase to maximum and start to decrease. As explain earlier, when input voltage reaches zero at 2 , SCR continue to conduct until inductor current is fully discharge at $\omega t=2 +\beta$. There will be part of negative voltage appear across the load. Figure 3-11 show the output voltage and current for discontinuous load current mode ($\alpha>\beta$).

For $\beta \geqslant \alpha$ the circuit will conduct in continuous load current mode. The small ripple current can be neglected. The output voltage will be like a dc voltage. The output voltage and load current are shown in figure 3-12.

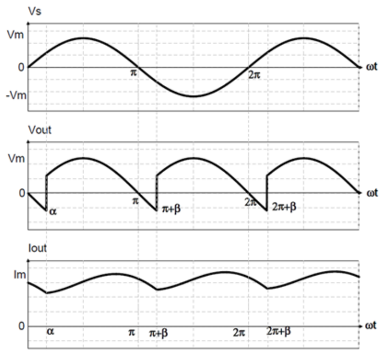


Figure 3-12: Single phase full wave controlled bridge rectifiers output voltage and current for continuous load current mode (β⩾α).

The average output voltage, Vo(ave) is given as

$$V_{o(ave)} = \frac{2}{T}\int_{\alpha}^{(\pi+\beta)} V_s\ Sin\omega t\ d\omega t$$
$$= \frac{V_m}{\pi}(cos\alpha - \cos(\pi+\beta)) \qquad (45)$$

The average output current, Io(ave) is given by

$$I_{o(ave)} = \frac{V_{o(ave)}}{R} \qquad (46)$$

The RMS value of load voltage, Vo(rms) is determined by

$$V_{o(rms)} = \sqrt{\frac{2}{T}\int_{\alpha}^{(\pi+\beta)} [V_m Sin\omega t]^2\ d\omega t}$$
$$= \sqrt{\frac{V_m{}^2}{2\pi}\left[(\pi+\beta) - \alpha - \frac{\sin(2(\pi+\beta))}{2} + \frac{\sin(2\alpha)}{2}\right]} \qquad (47)$$

The average output current, Io(rms) is given by

$$I_{o(rms)} = \frac{V_{oRMS}}{Z} \tag{48}$$

where

$$Z = \sqrt{R^2 + {X_L}^2}$$

EXAMPLE 10:

A 50Hz single-phase controlled half-wave rectifier with resistive and inductive load as shown in figure 3-3 is supplied to Vm = 120V, resistive and inductive load R = 50Ω and L = 20mH respectively. Assuming the firing angle and extinction angle are α =45° and β = 30° respectively, calculate the rms output voltage and current.

SOLUTION

From the eq. 47 the rms output voltage is:

$$V_{o(rms)} = \sqrt{\frac{{V_m}^2}{2\pi}\left[(\pi+\beta) - \alpha - \frac{\sin\big(2(\pi+\beta)\big)}{2} + \frac{\sin(2\alpha)}{2}\right]}$$

$$= \sqrt{\frac{120^2}{2\pi}\left[(\pi+30°) - 45° - \frac{\sin\big(2(\pi+30°)\big)}{2} + \frac{\sin(2\,x\,45°)}{2}\right]}$$

$$= 82.19\text{V}$$

The rms output current can be calculated using eq. 48

$$I_{o(rms)} = \frac{V_{0(rms)}}{Z} = \frac{82.19}{50.39} = 1.63A$$

$$Z = \sqrt{R^2 + {X_L}^2} = \sqrt{50^2 + 2\pi(50)(20m)^2} = 50.39$$

TUTORIAL

1) With the aid diagram of circuit and waveform explain the operation for single-phase half-wave uncontrolled rectifier with resistive load.

2) With the aid diagram of circuit and waveform explain the operation for center-tap controlled rectifier with resistive load.

3) With the aid diagram of circuit and waveform explain the operation for controlled bridge rectifier with resistive and inductive load for discontinuous load.

4) A rectifier using two SCR as a switch. Calculate the average voltage and current if the input voltage is 240V, R=20Ω, and $\alpha=30°$.

5) A half wave-diode rectifier is used to control a moto load. Calculate the voltage output average. Given the input voltage was 120V and $\beta=45°$.

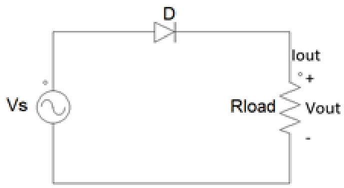
6) Calculate the average output voltage for the controlled half-wave rectifier with Resistive load if the input voltage is 300V and the firing angle is 60°.

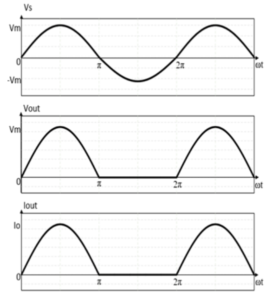
7) Calculate the triggering angle (α) if a rectifier has an input of 240V, 50Hz feed to a full-wave controlled rectifier with a 10Ω load and the average output DC is 45V.

8)A single-phase, half-wave controlled rectifier is connected to a voltage source of $V(t)= 170 \sin 2\pi ft$. The frequency of the supply is 50Hz. If the output voltage is 38.73V, calculate the firing angle, α to a load 10Ω load

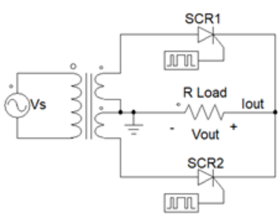
ANSWER

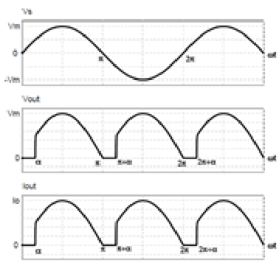
1) During the positive cycle, D is forward bias and will be conducting. The output will appear during the interval (0 < ωt < π). During the negative cycle D is reverse bias and will not be conducting. The output will become zero during the interval (0 < ωt < π). The circuit and output wave is show in figure below.





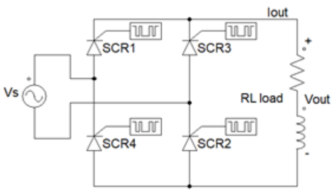
2) During positive half cycle of input voltage SCR1 is in forward biased and SCR2 is in reverse biased. SCR1 will not conduct until a triggering pulse applied to terminal get at ωt=α. SCR1 start to conduct. Output voltages appear across the load. When supply voltage cross zero at ωt=π, SCR1 will reverse biased and turn off. During negative half cycle of input voltage SCR1 is reverse biased and SCR2 is forward biased. SCR2 will not conduct until a triggering pulse applied to terminal get at ωt=π+α. SCR2 start to conduct. Output voltages appear across the load. When supply voltage cross zero at ωt=2π, SCR2 reverse biased and turn off. The circuit and output wave is show in figure below.

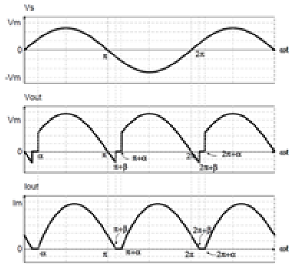




ANSWER

3) During positive half cycle of input voltage, SCR1 & SCR2 are in forward biased condition while SCR3 & SCR4 are in reverse biased. When SCR1 & SCR2 are triggered at firing angle α, SCR start to conduct. The current flow through the circuit and output voltage appears across the load. The load current is gradually increase due to inductor load until it reaches maximum value, then it will start to decrease. When supply voltage cross zero at ωt=π, inductor current is continuing to discharge force SCR to continue to conduct until inductor is fully discharge at ωt=π+β. There will be a negative output voltage appear across the load. During negative half cycle of input voltage SCR3 & SCR4 turn to forward biased while SCR1 & SCR2 are reverse biased. When triggered at ωt=π+α, SCR3 & SCR4 start to conduct. Inductor current gradually increase to maximum and start to decrease. As explain earlier, when input voltage reaches zero at 2π, SCR continue to conduct until inductor current is fully discharge at ωt=2π+β. There will be part of negative voltage appear across the load. The circuit and output wave is show in figure below.





4)

$$V_{o(ave)} = \frac{V_m}{\pi}(1+cos\alpha)$$

$$= \frac{240\sqrt{2}}{\pi}(1+\cos 30^\circ)$$

$$= 201.6V$$

$$I_{o(ave)} = \frac{V_{o(ave)}}{R}$$

$$= \frac{201.6}{20}$$

$$= 10.08A$$

ANSWER

5)

$$V_{o(ave)} = \frac{V_m}{2\pi}(1 - cos(\pi + \beta))$$

$$= \frac{120\sqrt{2}}{2\pi}(1 - cos(\pi + 45°))$$

$$= 46.11V$$

6)

$$V_{o(ave)} = \frac{V_m}{2\pi}(\cos\alpha + 1)$$

$$= \frac{300\sqrt{2}}{2\pi}(\cos 60° + 1)$$

$$= 71.62V$$

7)

$$V_{o(ave)} = \frac{V_m}{\pi}(\cos\alpha + 1)$$

$$45 = \frac{240\sqrt{2}}{2\pi}(\cos\alpha + 1)$$

$$\alpha = 125.69°$$

8)

$$V_{o(ave)} = \frac{V_m}{2\pi}(\cos\alpha + 1)$$

$$37.73 = \frac{170}{2\pi}(\cos\alpha + 1)$$

$$\alpha = 64.44°$$

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