

Summary

The purpose of this assignment was to investigate, analyse and explain the operation of half wave and full wave, non-controlled, bridge rectifier circuits under a number of differing load conditions.

A series of current, voltage and waveform measurements were then carried out in order to calculate power into the load, ripple factor, transformer utilisation factor and rectifier efficiency for each type of circuit.

From the results obtained, it will be seen that the full wave rectifier circuit is a more efficient way to convert an ac supply to dc.

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Introduction

Background

Rectification is the process of converting an ac signal into a dc signal.

Rectification is carried out at all levels of electrical power, from a thousandth of a watt to detect an AM radio signal, to thousands of kilowatts to operate heavy electrical machinery.

["Rectification (electricity)," Microsoft® Encarta® Online Encyclopaedia 2000 <http://encarta.msn.com> © 1997-2000 Microsoft Corporation.]

We shall investigate power rectifiers in this report – rectifying an ac voltage supply into a dc voltage.

The rectifier is found in almost all of today's electrical appliances and anywhere that requires a constant dc level derived from the mains ac voltage supply. For example, the rectifier together with a transformer enable you to plug such items as mobile phones, VCR's, washing machines etc, and other items that require a dc supply, into the mains ac supply.

Electronic rectifiers are components that convert an ac input of voltage and current into a unidirectional or dc output. The output from these rectifiers however will not be a perfect dc level, and depending upon the configuration of the rectifying circuit, may contain a significant ac ripple component.

The ripple has a frequency that is the same as the supply frequency for half wave rectifier circuits, and twice the supply frequency for full wave circuits.

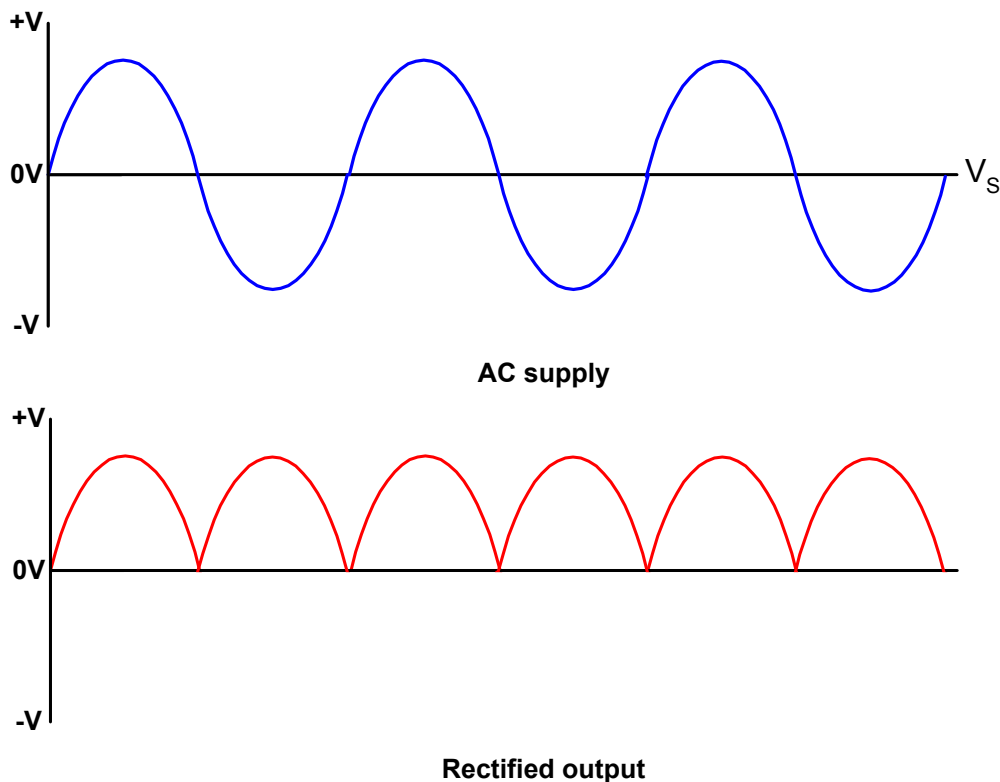


Fig.1 – Example of full wave uncontrolled rectifier output

This is illustrated in fig.1, the output from the rectifier is dc, but the waveform is far from being a perfect dc level and would require further smoothing to reduce the ac ripple content to somewhere approaching a level dc value.

What can also be deduced from the waveform is that the circuit is a full wave rectifier, as the dc output ripple is twice the frequency of the ac supply input.

As will be demonstrated later from our results, the configuration of the rectifier will also affect the efficiency of the rectifier circuit.

Objective

The objective of this assignment was to construct various types of rectifier circuits, measure and record the appropriate signals, and then in two cases compare the measured results with the theoretical calculated results. An explanation of the operation of each type of circuit was also to be provided.

Theory

Rectifiers are divided into two classes, *half wave* and *full wave*.

Half wave rectifiers

The simplest half wave rectifier can be made using a single diode as shown in Fig.2 (a/b) below.

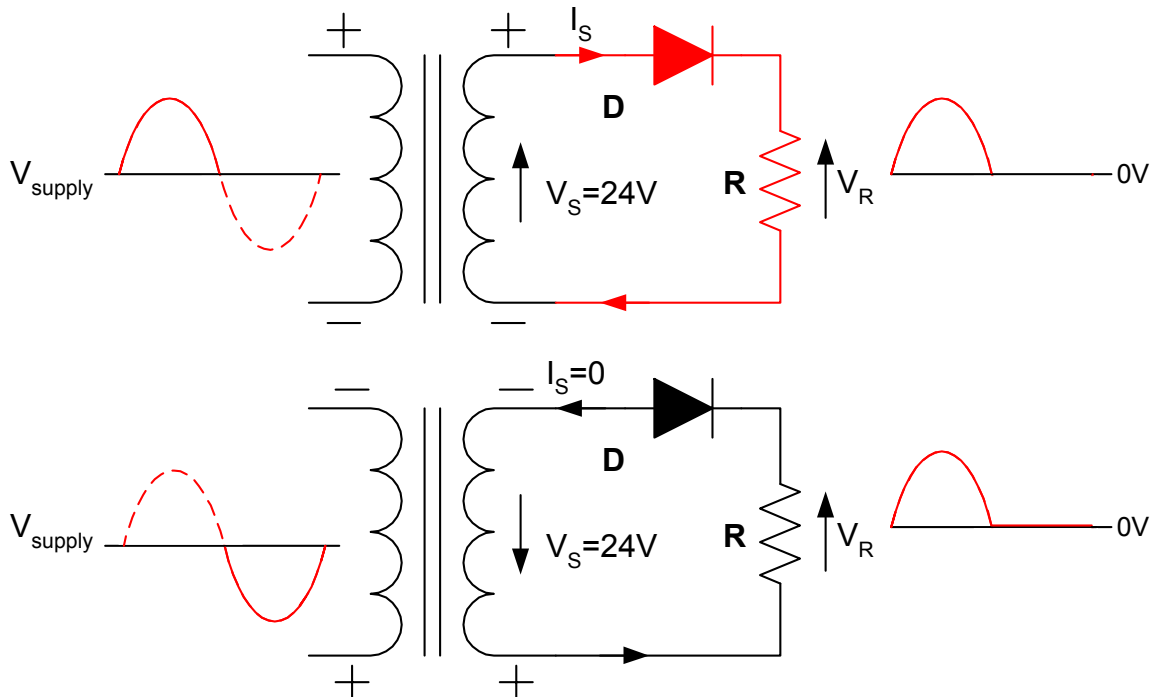


Fig.2 (a/b) – Half wave uncontrolled rectifier operation

In this circuit, the load is purely resistive and current can only flow in one direction because of the blocking action of the diode. During the positive half cycle of the ac supply the diode is forward biased and current is supplied to the load. Then, during the alternate negative half cycle of V_S , when the diode is reversed biased, the load current is blocked – hence the circuit is known as a half wave rectifier.

Note: the dc output ripple is at the same frequency as the ac supply.

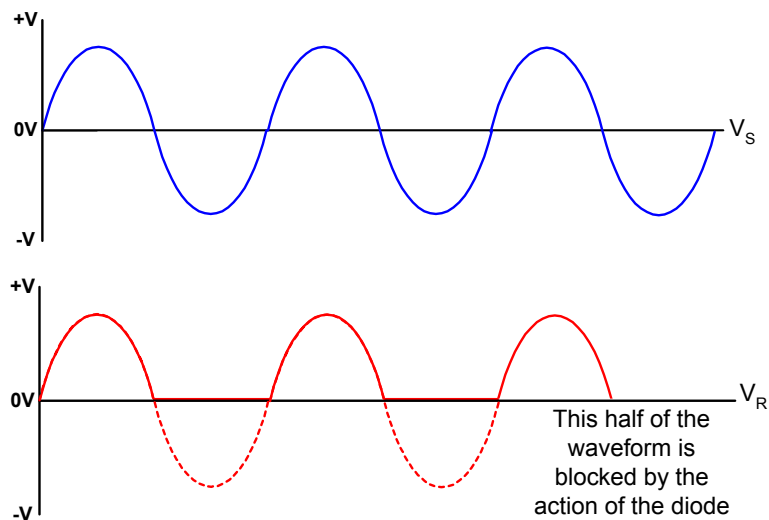


Fig. 3 – Half wave uncontrolled rectifier waveforms

Full wave rectifiers

A full wave rectifier uses four devices connected as a bridge – hence the term ‘bridge rectifier’.

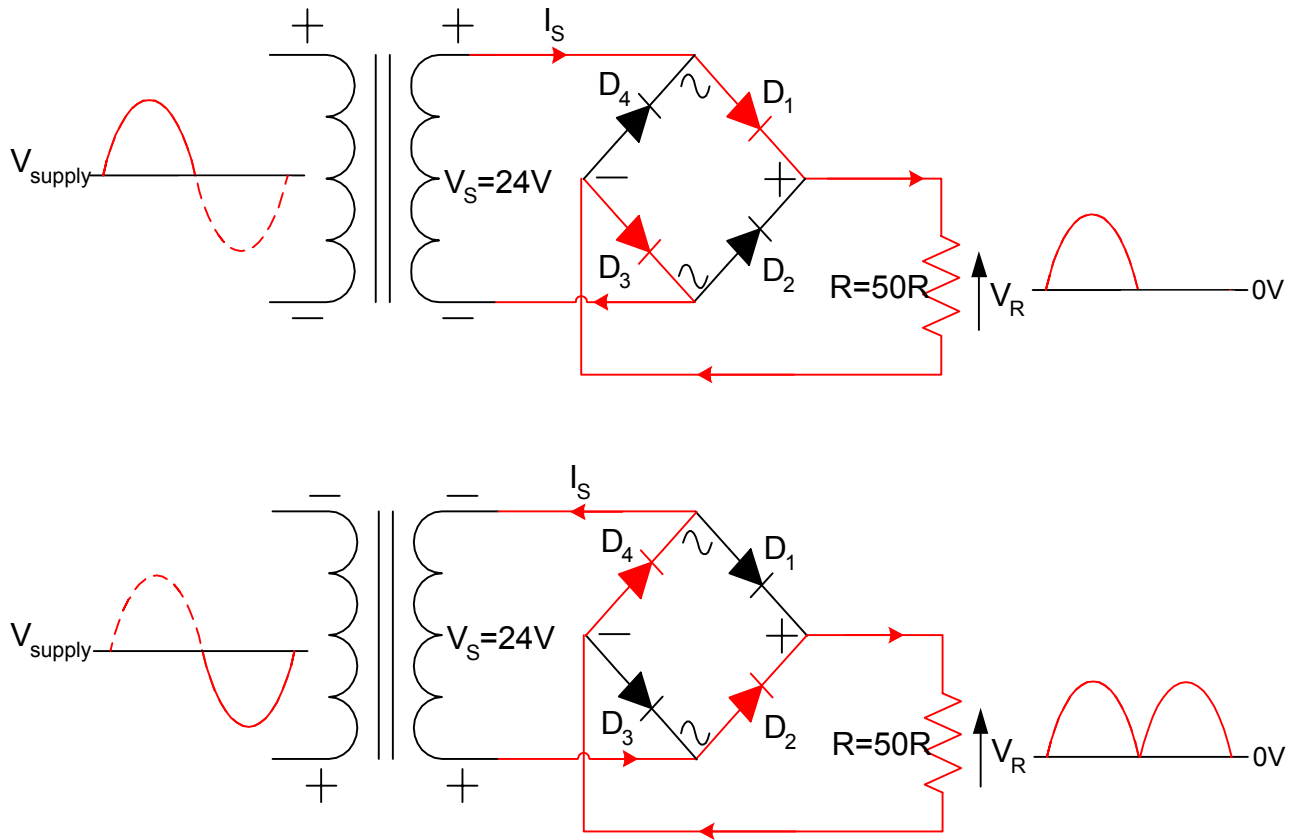


Fig.4 (a/b) – Operation of a full wave uncontrolled bridge

When the ac supply is in its positive half cycle as shown in fig.4a, the diodes D_1 and D_3 are forward biased and therefore supply power to the load and diodes D_2 and D_4 are reversed biased and do not conduct. As the ac supply enters its alternate negative half cycle (fig.4b), diodes D_1 and D_3 now become reversed biased and stop conducting, and diodes D_2 and D_4 become forward biased and supply power to the load.

What can be observed from this is that the load receives current in the same direction from both the positive and negative cycles of the supply voltage, and this gives rise to the increased efficiency of the full wave rectifier over the half wave rectifier.

The above also affects the frequency of the ac ripple, the result being that the output ac ripple is twice that of the input supply frequency, but half the amplitude.

Theoretical results

The results calculated in this section assume ideal components – please refer to the discussion of results section for more details on this subject.

For details of how the equations are derived and proofs of theory please see the appendix.

Half wave rectifier driving resistive load

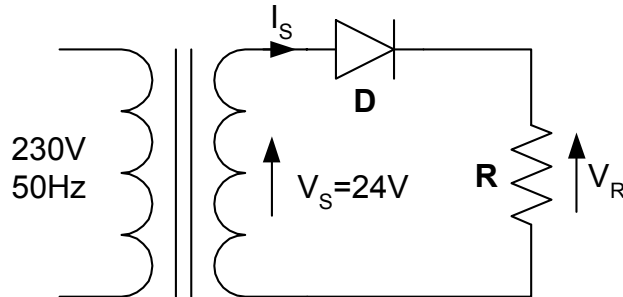


Fig.5 – Half wave uncontrolled rectifier driving resistive load

$$V_m = V_s \times \sqrt{2} = 24 \times \sqrt{2} = 33.941V$$

$$\therefore V_{dc} = \frac{\sqrt{2}V_s}{\pi} = \frac{\sqrt{2} \times 24}{\pi} = 10.804V$$

$$I_{dc} = \frac{V_{dc}}{R} = \frac{10.804}{50} = 0.216A$$

$$P_{dc} = V_{dc} \times I_{dc} = 10.804 \times 0.216 = 2.334W$$

$$V_{RMS} = \frac{V_m}{2} = \frac{33.941}{2} = 16.971V$$

$$I_{RMS} = \frac{V_m}{2R} = \frac{33.941}{100} = 0.339A$$

$$P_{ac} = \frac{V_s^2}{2R} = \frac{24^2}{100} = 5.760W$$

$$\text{Efficiency } \eta = \frac{P_{dc}}{P_{ac}} = \frac{2.334}{5.760} = 0.405$$

$$V_{ac} = \sqrt{V_{RMS}^2 - V_{dc}^2} = \sqrt{16.971^2 - 10.804^2} = 13.088V$$

$$\text{Form factor} = \frac{V_{RMS}}{V_{dc}} = \frac{16.971}{10.804} = 1.571$$

$$\text{Ripple factor} = \sqrt{\text{Form factor}^2 - 1} = \sqrt{1.571^2 - 1} = 1.211$$

(Cont.)

$$V_{\text{secRMS}} = \frac{V_m}{\sqrt{2}} \qquad I_{\text{secRMS}} = \frac{V_m}{2R}$$

$$V_{\text{secRMS}} = \frac{33.941}{\sqrt{2}} \qquad I_{\text{secRMS}} = \frac{33.941}{100}$$

$$V_{\text{secRMS}} = 24\text{V} \qquad I_{\text{secRMS}} = 0.339\text{A}$$

$$\text{T.U.F} = \frac{P_{\text{dc}}}{(V_{\text{secRMS}} \times I_{\text{secRMS}})} = \frac{2.334}{(24 \times 0.339)} = 0.287$$

Full wave rectifier driving resistive load

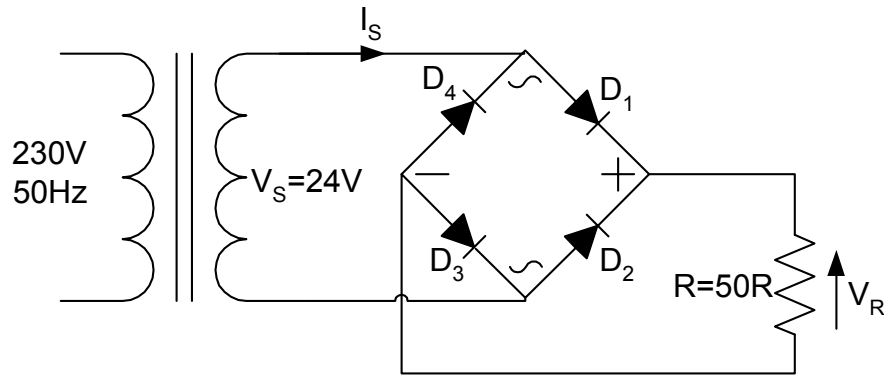


Fig.6 – Full wave uncontrolled rectifier driving resistive load

$$V_m = V_s \times \sqrt{2} = 24 \times \sqrt{2} = 33.941V$$

$$\therefore V_{dc} = \frac{2\sqrt{2}V_s}{\pi} = \frac{2 \times \sqrt{2} \times 24}{\pi} = 21.608V$$

$$I_{dc} = \frac{V_{dc}}{R} = \frac{21.608}{50} = 0.432A$$

$$P_{dc} = V_{dc} \times I_{dc} = 21.608 \times 0.432 = 9.335W$$

$$V_{RMS} = \frac{V_m}{\sqrt{2}} = \frac{33.941}{\sqrt{2}} = 24.0V$$

$$I_{RMS} = \frac{2V_m}{2R} = \frac{V_m}{R} = \frac{33.941}{50} = 0.679A$$

$$P_{ac} = \frac{2V_s^2}{2R} = \frac{V_s^2}{R} = \frac{24^2}{50} = 11.520W$$

$$\text{Efficiency } \eta = \frac{P_{dc}}{P_{ac}} = \frac{9.335}{11.520} = 0.810$$

$$V_{ac} = \sqrt{V_{RMS}^2 - V_{dc}^2} = \sqrt{24^2 - 21.608^2} = 10.445V$$

$$\text{Form factor} = \frac{V_{RMS}}{V_{dc}} = \frac{24}{21.608} = 1.111$$

$$\text{Ripple factor} = \sqrt{\text{Form factor}^2 - 1} = \sqrt{1.111^2 - 1} = 0.483$$

(Cont.)

$$V_{\text{secRMS}} = \frac{V_m}{\sqrt{2}} \quad I_{\text{secRMS}} = \frac{2V_m}{2R} = \frac{V_m}{R}$$

$$V_{\text{secRMS}} = \frac{33.941}{\sqrt{2}} \quad I_{\text{secRMS}} = \frac{33.941}{50}$$

$$V_{\text{secRMS}} = 24\text{V} \quad I_{\text{secRMS}} = 0.679\text{A}$$

$$\text{T.U.F} = \frac{P_{\text{dc}}}{(V_{\text{secRMS}} \times I_{\text{secRMS}})} = \frac{9.335}{(24 \times 0.679)} = 0.573$$

Results

Half wave uncontrolled rectifier driving resistive load

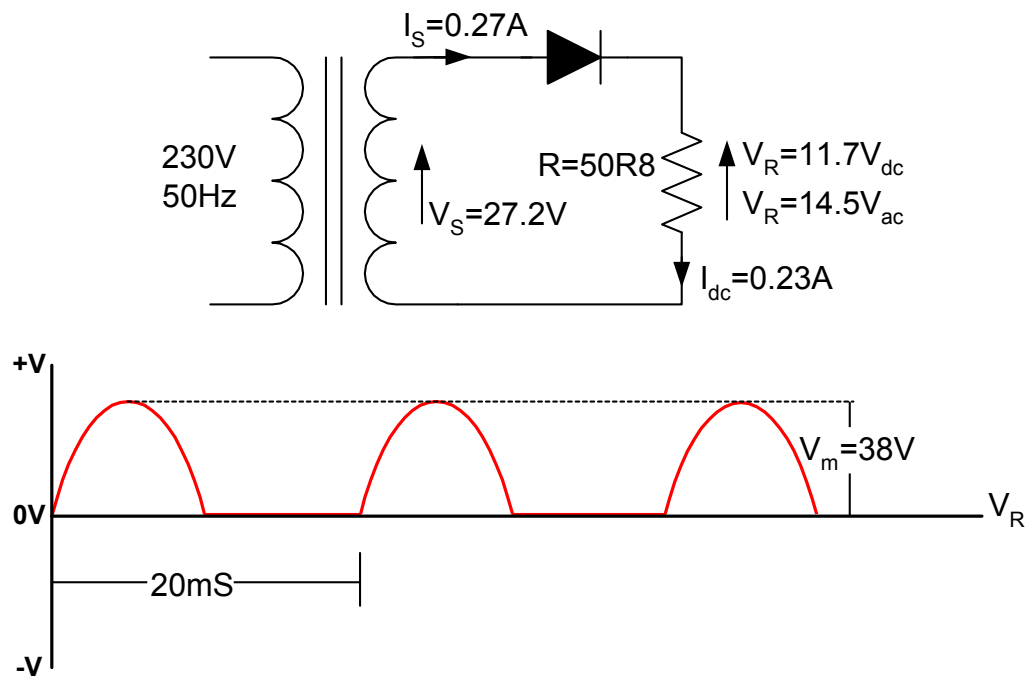


Fig.7 Half wave uncontrolled rectifier driving resistive load

The operation of the above circuit has been discussed in the section 'Theory'.

Half wave uncontrolled rectifier with resistive / inductive load

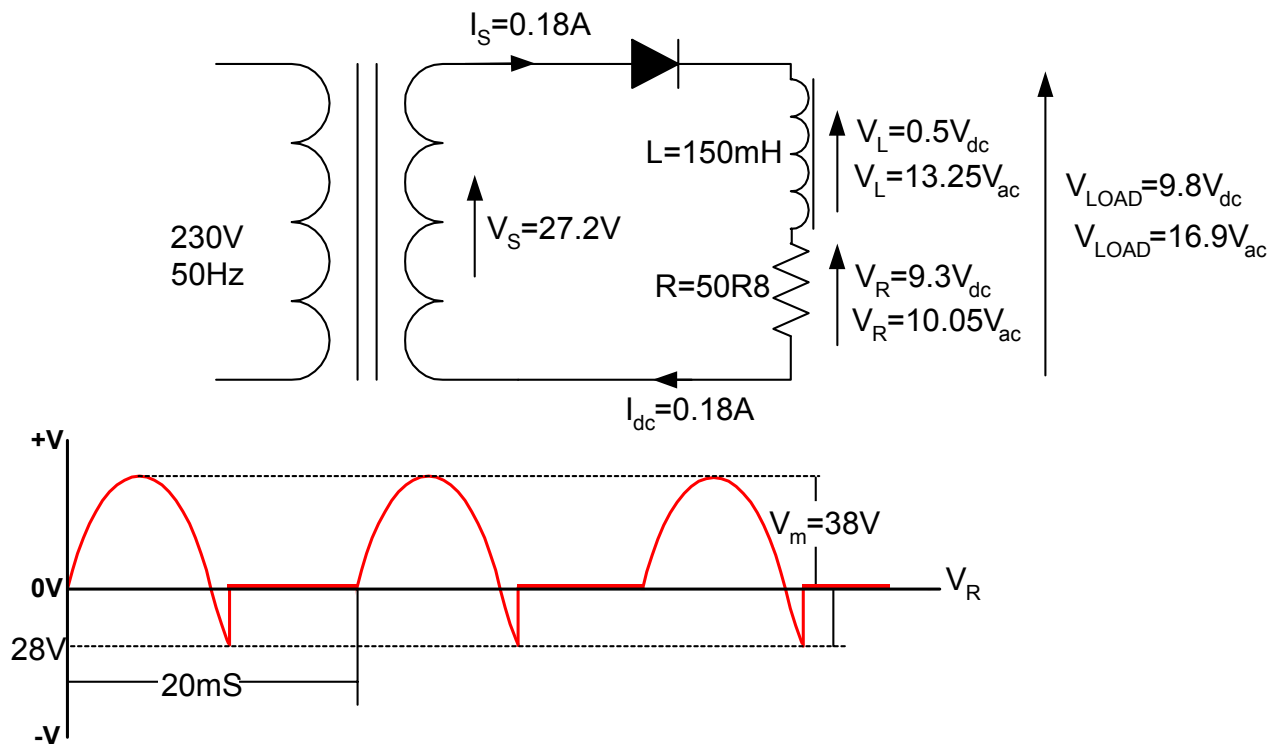


Fig.8 Half wave uncontrolled rectifier with resistive / inductive load

In this circuit we have an inductive load present. When the supply commences its positive cycle, the inductor will attempt to oppose the change of current through it so the current will rise slowly. When the negative half cycle commences the current in the inductor cannot dissipate immediately so the diode remains forward biased until the current coming from the supply is greater than the current in the inductor and the diode switches off. This is why the load sees part of the negative half cycle of the supply – the greater the inductance, more of the negative half cycle is seen by the load.

Half wave uncontrolled rectifier with resistive / inductive load and bypass diode

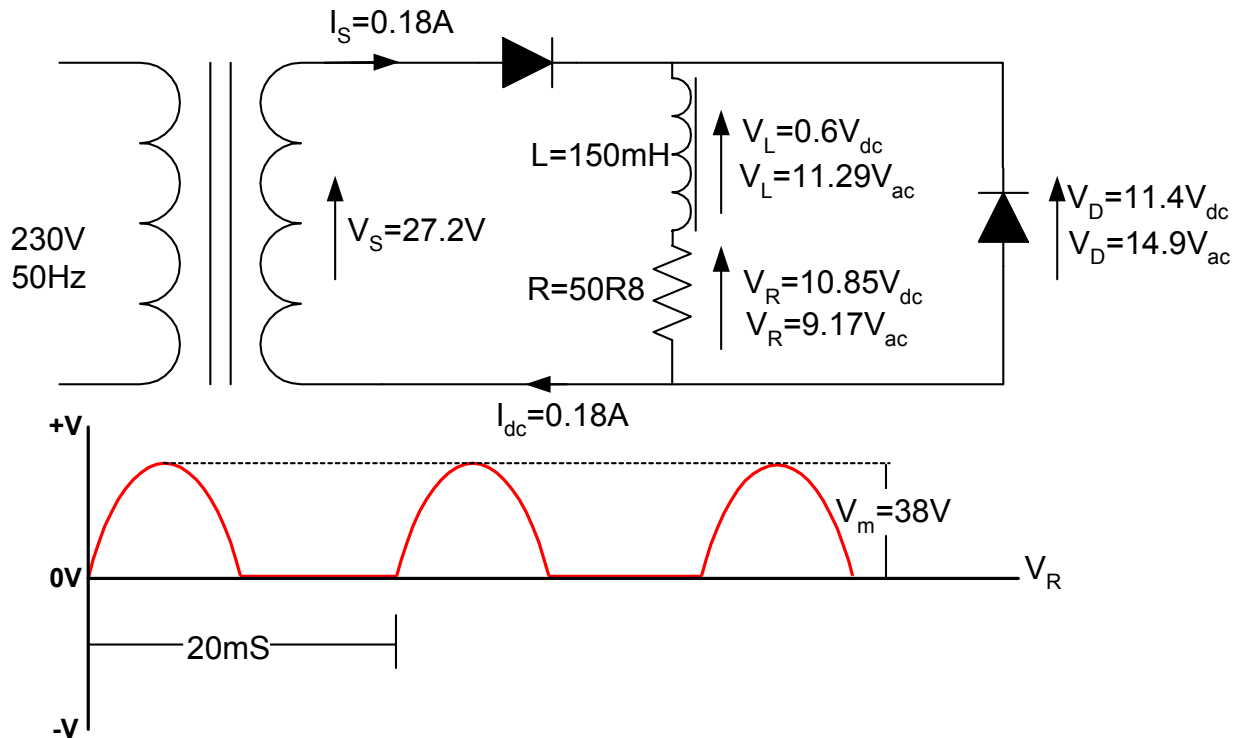


Fig.9 Half wave uncontrolled rectifier with resistive / inductive load and bypass diode

This circuit is similar to the previous circuit but with the addition of a freewheel or bypass diode connected across the output. This diode provides an alternate path for the current from the inductor to follow when the supply enters the negative half cycle. This diode enables the current to dissipate in the loop formed by L/R/D rather than fight against the negative going supply current.

Full wave uncontrolled rectifier with resistive load

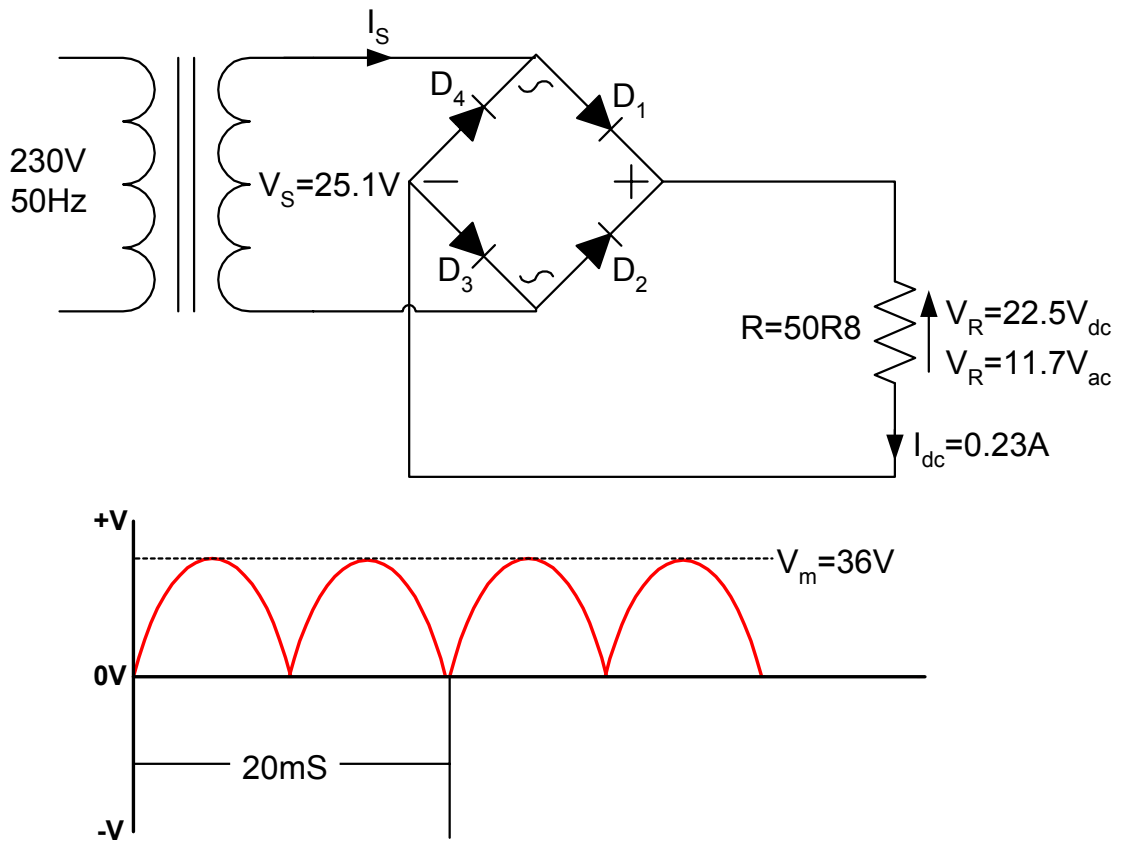


Fig.10 Full wave uncontrolled rectifier with resistive load

The operation of this circuit has been discussed in the 'Theory' section.

Full wave uncontrolled rectifier with smoothing capacitor

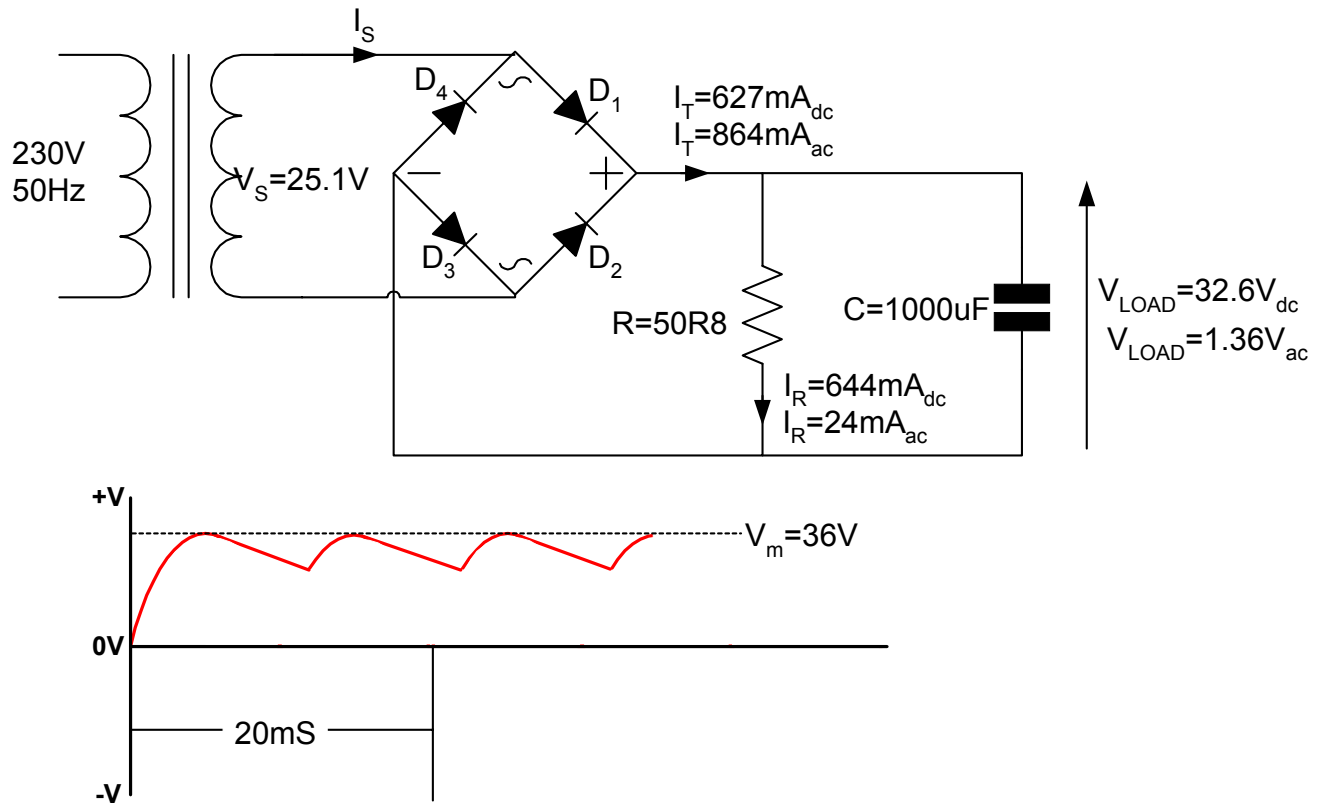


Fig.11 Full wave uncontrolled rectifier with smoothing capacitor

This circuit is similar to the previous circuit but with the addition of a smoothing capacitor. The capacitor becomes charged when the circuit is energised and when the input to it begins to decrease below its peak the capacitor discharges through the load resistor due to the diode becoming reversed biased (due to the capacitors charge). The capacitor discharges at a rate determined by R and C , which is normally much larger the period of input from the supply. During the next positive half cycle the diode becomes forward biased and the capacitor charges again.

Full wave rectifier with inductive / resistive load

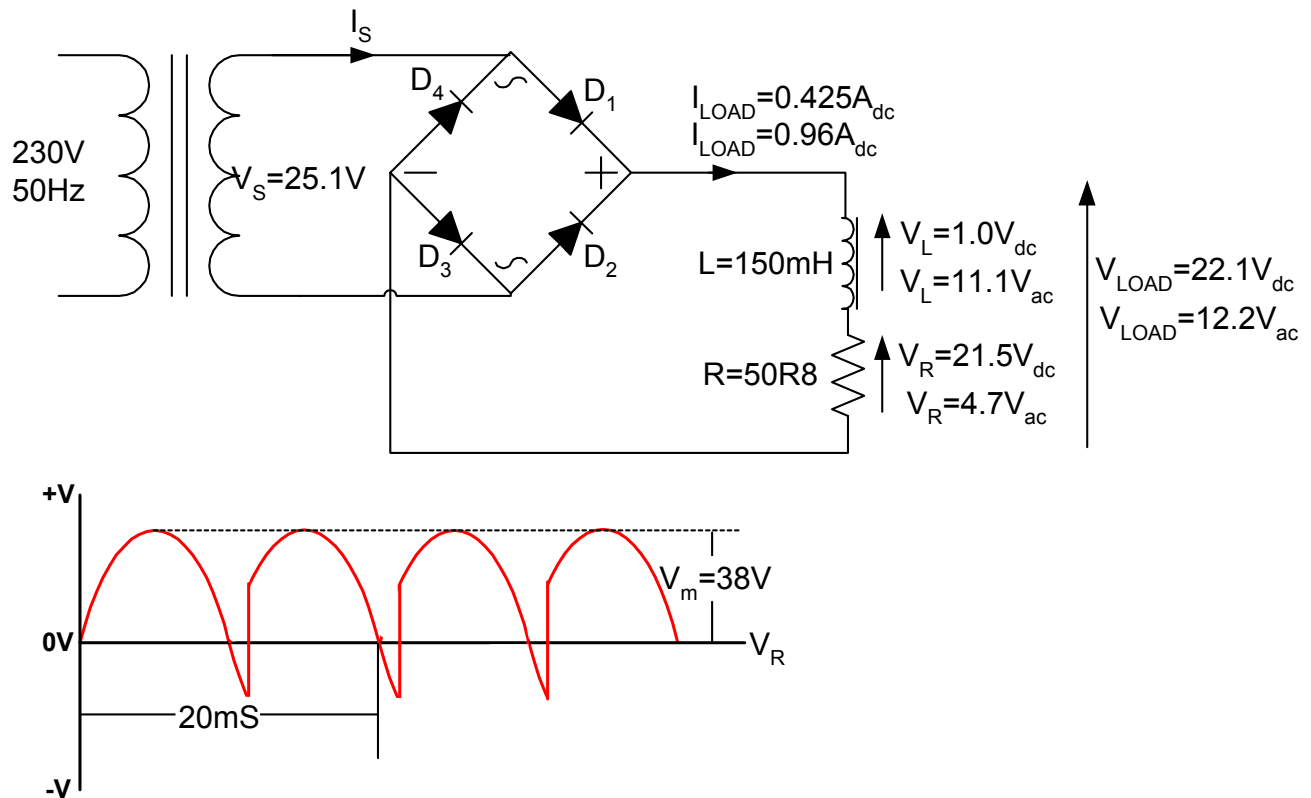


Fig.12 Full wave rectifier with inductive / resistive load

This circuit is similar in operation to the half wave rectifier with resistive / inductive load. When the supply commences its positive cycle, the inductor will attempt to oppose the change of current through it so the current will rise slowly. When the negative half cycle of the supply commences the current in the inductor cannot dissipate immediately so the diode remains forward biased and conducting until the current coming from the supply is greater than the current in the inductor at which point the diode switches off. Unlike the half wave rectifier when the load current had to return to zero during the missing half of the waveform, the rectifier now gives an additional pulse of current during this period. This leads to a small proportion of the positive going waveform being missing (as the inductive current is dissipated), so once the negative part of waveform has been dissipated, the current has to 'catch up' with the supply and therefore starts from a non zero value.

As before, this is why the load sees part of the negative half cycle of the supply – the greater the inductance the more of the negative half cycle is seen by the load.

Specimen calculations

Half wave

Using the measurements obtained in fig. 7, the half wave rectifier with resistive load:

$$V_m = V_s \times \sqrt{2} = 27.2 \times \sqrt{2} = 38.467V$$

$$V_{dc} = \frac{\sqrt{2}V_s}{\pi} = \frac{\sqrt{2} \times 27.2}{\pi} = 12.244V$$

$$I_{dc} = \frac{V_{dc}}{R} = \frac{12.244}{50.8} = 0.241A$$

$$P_{dc} = V_{dc} \times I_{dc} = 12.244 \times 0.241 = 2.951W$$

$$V_{RMS} = \frac{V_m}{2} = \frac{38}{2} = 19V$$

$$I_{RMS} = \frac{V_m}{2R} = \frac{38}{101.6} = 0.374A$$

$$P_{ac} = \frac{V_s^2}{2R} = \frac{27.2^2}{100} = 7.282W$$

$$\text{Efficiency } \eta = \frac{P_{dc}}{P_{ac}} = \frac{2.951}{7.282} = 0.405$$

$$V_{ac} = \sqrt{V_{RMS}^2 - V_{dc}^2} = \sqrt{19^2 - 12.244^2} = 14.529V$$

$$\text{Form factor} = \frac{V_{RMS}}{V_{dc}} = \frac{14.529}{12.244} = 1.187$$

$$\text{Ripple factor} = \sqrt{\text{Form factor}^2 - 1} = \sqrt{1.187^2 - 1} = 0.640$$

$$V_{\text{secRMS}} = \frac{V_m}{\sqrt{2}} \quad I_{\text{secRMS}} = \frac{V_m}{2R}$$

$$V_{\text{secRMS}} = \frac{38}{\sqrt{2}} \quad I_{\text{secRMS}} = \frac{38}{101.6}$$

$$V_{\text{secRMS}} = 26.870V \quad I_{\text{secRMS}} = 0.374A$$

$$\text{T.U.F} = \frac{P_{dc}}{(V_{\text{secRMS}} \times I_{\text{secRMS}})} = \frac{2.951}{(26.870 \times 0.374)} = 0.294$$

Full wave

Using the measurements obtained in fig.10, the full wave rectifier with resistive load:

$$V_m = V_s \times \sqrt{2} = 25.1 \times \sqrt{2} = 35.497V$$

$$\therefore V_{dc} = \frac{2\sqrt{2}V_s}{\pi} = \frac{2 \times \sqrt{2} \times 24}{\pi} = 22.598V$$

$$I_{dc} = \frac{V_{dc}}{R} = \frac{22.598}{50.8} = 0.445A$$

$$P_{dc} = V_{dc} \times I_{dc} = 22.598 \times 0.445 = 10.056W$$

$$V_{RMS} = \frac{V_m}{\sqrt{2}} = \frac{36}{\sqrt{2}} = 25.456V$$

$$I_{RMS} = \frac{2V_m}{2R} = \frac{V_m}{R} = \frac{36}{50.8} = 0.709A$$

$$P_{ac} = \frac{2V_s^2}{2R} = \frac{V_s^2}{R} = \frac{25.1^2}{50.8} = 12.402W$$

$$\text{Efficiency } \eta = \frac{P_{dc}}{P_{ac}} = \frac{10.056}{12.402} = 0.811$$

$$V_{ac} = \sqrt{V_{RMS}^2 - V_{dc}^2} = \sqrt{25.456^2 - 22.598^2} = 11.719V$$

$$\text{Form factor} = \frac{V_{RMS}}{V_{dc}} = \frac{25.456}{22.598} = 1.126$$

$$\text{Ripple factor} = \sqrt{\text{Form factor}^2 - 1} = \sqrt{1.126^2 - 1} = 0.518$$

$$V_{\text{secRMS}} = \frac{V_m}{\sqrt{2}} \quad I_{\text{secRMS}} = \frac{2V_m}{2R} = \frac{V_m}{R}$$

$$V_{\text{secRMS}} = \frac{36}{\sqrt{2}} \quad I_{\text{secRMS}} = \frac{36}{50.8}$$

$$V_{\text{secRMS}} = 25.456V \quad I_{\text{secRMS}} = 0.709A$$

$$\text{T.U.F} = \frac{P_{dc}}{(V_{\text{secRMS}} \times I_{\text{secRMS}})} = \frac{10.056}{(25.456 \times 0.709)} = 0.557$$

Comparison of theoretical and measured results.

Half wave rectifier with resistive load			
<i>Quantity measured</i>	<i>Theoretical Value</i>	<i>Measured Value</i>	<i>Percentage Difference</i>
Dc power across the load	2.334W	2.951W	26.435%
Ac power across the load	5.760W	7.282W	26.424%
Rectifier efficiency	0.405	0.405	0%
Ripple factor	0.518	0.640	23.552%
Transformer utilisation factor	0.287	0.294	2.439%

Fig.13 Comparison of results – half wave rectifier

Full wave rectifier with resistive load			
<i>Quantity measured</i>	<i>Theoretical Value</i>	<i>Measured Value</i>	<i>Percentage Difference</i>
Dc power across the load	9.335W	10.056W	7.724%
Ac power across the load	11.520W	12.402W	7.656%
Rectifier efficiency	0.810	0.811	0.123%
Ripple factor	0.483	0.518	7.246%
Transformer utilisation factor	0.573	0.557	2.873%

Fig.14 Comparison of results – full wave rectifier

Discussion of results

With reference to the table of theoretical versus measured results it can be seen that there were some significant percentage differences in the two values.

As mentioned earlier, the theoretical results assume ideal components, but in reality, there may be some considerable losses when working with low voltages. The most significant error is to omit the voltage dropped across the diodes. In practice, the diode exhibits a barrier potential before the diode becomes forward biased. For silicon diodes as used in these experiments that value is approximately 0.7V. Therefore, a 10V peak input signal would become 9.3V peak output signal in a half wave rectifier. In some applications, the resultant voltage drop may become significant and the effect is more noticeable when using full wave rectifier circuits, as two diodes are conducting at any one time, giving a voltage drop of approximately 1.4V. Since this voltage drop is not taken into account in the theoretical calculations this will lead to an error being introduced, since the dc voltage and current will appear artificially high and since these values are then being used in further equations, the error will be compounded.

Additional sources of errors may occur from the following factors:

- The transformer is considered to be ideal and give precisely the rated voltage out.
- The resistor is considered ideal but it will have a tolerance value.
- The inductor is considered ideal but will have resistance within its windings
- Calibration and resolution of the equipment used to make the measurements
- The temperature coefficients of the components – the characteristics of the components will change the longer the circuit is energised.
- Ambient conditions – temperature and humidity can affect the instruments and the circuit itself
- Connections to the circuit itself – the way the components were connected may increase the overall resistance of the circuit.
- Human error when taking readings from instruments.
- The digital meter was found to be defective on all but the 10A current range so readings taken had a lower resolution.
- Mathematical errors due to 'rounding up' in calculations – these errors are further compounded if the figure is used to calculate further values.

Some or all of these errors may occur and as with mathematical errors will compound to give increased errors.

Conclusions

It is clear to see that the full wave rectifier offers better efficiency since the full ac supply cycle is used to supply power to the load although this is at the cost of an additional three diodes. However, if a relatively smooth dc level is required the full wave rectifier offers a dc output with much less ac ripple superimposed upon it, this means that smaller and therefore cheaper smoothing capacitors could be used to make the waveform much closer to a dc value.

The half wave rectifier is most suitable for low power and low voltage applications where a smooth dc level is not necessary and the costs of the components is a concern.

Sources of reference material

The following were used as sources of reference material within this report:

- Lecture notes – Dr.M.Lewis, University of Huddersfield
- Hughes Electrical Technology 7th Edition, McKenzie Smith, Longman
- Electronic Devices 4th Edition, Floyd, Prentice Hall
- Introduction To Power Electronics, Hart, Prentice Hall
- Power Electronics 3rd Edition, C.W.Lander, McGraw-Hill
- Power Supply Projects, R.A.Penfold, Babani Electronic Books
- Electronics Sourcebook For Engineers, G.Loveday, Pitman
- "Rectification (electricity)," Microsoft® Encarta® Online Encyclopaedia 2000
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Appendix

Proofs of theory.

The dc output voltage of a half wave rectifier can be calculated by finding the area under the curve over a full cycle and then dividing by the period, T.

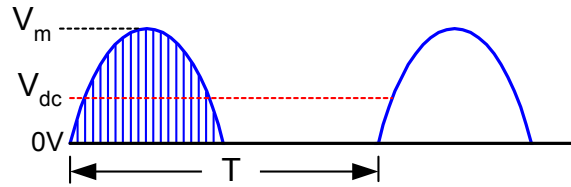


Fig 15 - Average value of half wave rectified signal

Note: The quantities in these equations refer to figures 2 / X.

$$V_{dc} = \frac{V_m}{\Pi}$$

[Source: Electronic Devices, 4th Edition. Pg56, Chap.2. Floyd. Published by Prentice Hall, 1996]

$$\text{But } V_m = \sqrt{2}V_s$$

$$\therefore V_{dc} = \frac{\sqrt{2}V_s}{\Pi}$$

DC current through the load:

$$I_{dc} = \frac{V_{dc}}{R}$$

DC power in the load:

$$\begin{aligned} P_{dc} &= V_{dc} \times I_{dc} = \frac{V_{dc}^2}{R} \\ &= \left(\frac{\sqrt{2}V_s}{\Pi} \right)^2 \frac{1}{R} = \frac{2V_s^2}{\Pi^2 R} \end{aligned}$$

RMS load voltage:

$$\begin{aligned} V_{RMS} &= \sqrt{\frac{1}{2\Pi} \int_0^{\Pi} V_m^2 \sin^2 \omega t \, d(\omega t)} \\ &= \sqrt{\frac{V_m^2}{2\Pi} \int_0^{\Pi} \frac{1}{2}(1 - \cos 2\omega t) \, d(\omega t)} \\ &= \sqrt{\frac{V_m^2}{2\Pi} \times \frac{1}{2} \left[\omega t + \frac{1}{2} \sin 2\omega t \right]_0^{\Pi}} \\ &= \sqrt{\frac{V_m^2}{4\Pi} [\Pi]} \end{aligned}$$

[Source: Hughes Electrical Technology, 7th edition. Pg380, Chap.21. McKenzie Smith. Published by Longman, 1995]

$$\therefore V_{RMS} = \frac{V_m}{2}$$

RMS Current in the load:

$$I_{\text{RMS}} = \frac{V_{\text{R}}}{R} = \frac{V_{\text{m}}}{2R}$$

AC Power:

$$P_{\text{ac}} = \frac{V_{\text{m}}^2}{4R} = \frac{V_{\text{s}}^2}{2R}$$

Rectifier efficiency:

$$\text{Efficiency } \eta = \frac{P_{\text{dc}}}{P_{\text{ac}}} = \frac{\frac{2V_{\text{s}}^2}{\pi^2 R}}{\frac{V_{\text{s}}^2}{2R}} = \frac{4}{\pi^2}$$

The output may be thought of as a combination of a dc value with an ac ripple component:

$$V_{\text{RMS}} = \sqrt{V_{\text{ac}}^2 + V_{\text{dc}}^2}$$
$$\therefore V_{\text{ac}} = \sqrt{V_{\text{RMS}}^2 - V_{\text{dc}}^2}$$

Form Factor:

$$\text{Form factor} = \frac{V_{\text{RMS}}}{V_{\text{dc}}} = \frac{V_{\text{m}}/\sqrt{2}}{V_{\text{m}}/\pi} = \frac{\pi}{2}$$

Ripple Factor:

$$\text{Ripple factor} = \frac{V_{\text{ac}}}{V_{\text{dc}}} = \frac{\sqrt{V_{\text{RMS}}^2 - V_{\text{dc}}^2}}{V_{\text{dc}}} = \sqrt{\frac{V_{\text{RMS}}^2}{V_{\text{dc}}^2} - 1}$$

$$\therefore \text{Ripple factor} = \sqrt{\text{Form factor}^2 - 1}$$

Transformer utilisation factor:

$$\text{T.U.F} = \frac{P_{\text{dc}}}{(V_{\text{secRMS}} \times I_{\text{secRMS}})}$$

$$V_{\text{secRMS}} = \frac{V_{\text{m}}}{\sqrt{2}} \quad I_{\text{secRMS}} = \frac{V_{\text{m}}}{2R} \quad P_{\text{dc}} = \frac{V_{\text{m}}^2}{\pi^2 R}$$

$$\therefore \text{T.U.F} = \frac{\frac{V_{\text{m}}^2}{\pi^2 R}}{\frac{V_{\text{m}}}{\sqrt{2}} \times \frac{V_{\text{m}}}{2R}} = \frac{2\sqrt{2}}{\pi^2}$$

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