Rectifier circuits and filters

The circuits which convert alternating current (AC) into direct current (DC) are known as rectifiers. If such rectifiers rectify both the positive and negative half cycles of an input alternating waveform, the rectifiers are referred as full wave rectifiers. Alternatively, we can say, a rectifier is a device that converts alternating current (AC) to direct current (DC). It does it by using a diode or a group of diodes. We know that a diode permits current only in one direction and blocks the current in the other. We use this principle to construct various rectifiers.

We can classify rectifiers into two types:
1. Half Wave Rectifier
2. Full Wave Rectifier

A **half wave rectifier** is defined as a type of rectifier that only allows one half-cycle of an AC voltage waveform to pass, blocking the other half-cycle. Half-wave rectifiers are used to convert AC voltage to DC voltage, and only require a single diode to construct.

A rectifier is a device that converts alternating current (AC) to direct current (DC). It is done by using a diode or a group of diodes. Half wave rectifiers use one diode, while a full wave rectifier uses multiple diodes.

**Half Wave Rectifier Theory**

A half wave rectifier is the simplest form of rectifier available. We will look at a complete half wave rectifier circuit later – but let’s first understand exactly what this type of rectifier is doing.

The diagram below illustrates the basic principle of a half-wave rectifier. When a standard AC waveform is passed through a half-wave rectifier, only half of the AC waveform remains. Half-wave rectifiers only allow one half-cycle (positive or negative half-cycle) of the AC voltage through and will block the other half-cycle on the DC side, as seen below.

Only one diode is required to construct a half-wave rectifier. In essence, this is all that the half-wave rectifier is doing.

Since DC systems are designed to have current flowing in a single direction (and constant voltage – which we’ll describe later), putting an AC waveform with positive and negative cycles through a DC device can have destructive (and dangerous) consequences. So we use half-wave rectifiers to convert the AC input power into DC output power. But the diode is only part of it – a complete half-wave rectifier circuit consists of 3 main parts:

1. A transformer
2. A resistive load
3. A diode

A half wave rectifier circuit diagram looks like this:

![Half Wave Rectifier Circuit Diagram](image)

We’ll now go through the process of how a half-wave rectifier converts an AC voltage to a DC output.

First, a high AC voltage is applied to the primary side of the step-down transformer and we will get a low voltage at the secondary winding which will be applied to the diode.

![Half Wave Rectifier Operation Diagram](image)

During the positive half cycle of the AC voltage, the diode will be forward biased and the current flows through the diode. During the negative half cycle of the AC voltage, the diode will be reverse biased and the flow of current will be blocked. The final output voltage waveform on the secondary side (DC) is shown in figure 3 above.
This can be confusing on first glance – so let’s dig into the theory of this a bit more. We’ll focus on the secondary side of the circuit. If we replace the secondary transformer coils with a source voltage, we can simplify the circuit diagram of the half-wave rectifier as:

![Diagram of half-wave rectifier circuit with load and source voltage](image)

Now we don’t have the transformer part of the circuit distracting us. For the positive half cycle of the AC source voltage, the equivalent circuit effectively becomes:

![Diagram of positive half cycle of AC source voltage](image)

This is because the diode is forward biased, and is hence allowing current to pass through. So we have a closed circuit. But for the negative half cycle of the AC source voltage, the equivalent circuit becomes:

![Diagram of negative half cycle of AC source voltage](image)

Because the diode is now in reverse bias mode, no current is able to pass through it. As such, we now have an open circuit. Since current cannot flow through to the load during this time,
the output voltage is equal to zero. This all happens very quickly – since an AC waveform will oscillate between positive and negative many times each second (depending on the frequency). Here’s what the half wave rectifier waveform looks like on the input side ($V_{\text{in}}$), and what it looks like on the output side ($V_{\text{out}}$) after rectification (i.e. conversion from AC to DC):

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{half_wave_rectifier}
\caption{Half wave rectifier waveform.}
\end{figure}

The graph above actually shows a positive half wave rectifier. This is a half-wave rectifier which only allows the positive half-cycles through the diode, and blocks the negative half-cycle. The voltage waveform before and after a positive half wave rectifier is shown in figure 4 below.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{positive_half_wave_rectifier}
\caption{Positive half wave rectifier.}
\end{figure}
Half Wave Rectifier Formula
We will now derive the various formulas for a half wave rectifier based on the preceding theory and graphs above.

Ripple Factor of Half Wave Rectifier
‘Ripple’ is the unwanted AC component remaining when converting the AC voltage waveform into a DC waveform. Even though we try our best to remove all AC components, there is still some small amount left on the output side which pulsates the DC waveform. This undesirable AC component is called ‘ripple’.

To quantify how well the half-wave rectifier can convert the AC voltage into DC voltage, we use what is known as the ripple factor (represented by γ or r). The ripple factor is the ratio between the RMS value of the AC voltage (on the input side) and the DC voltage (on the output side) of the rectifier.

The formula for ripple factor is:

\[
\gamma = \sqrt{\left(\frac{V_{\text{rms}}}{V_{\text{DC}}}\right)^2 - 1}
\]

Which can also be rearranged to equal:

\[
\text{Ripple factor}(r) = \frac{(I_{\text{rms}}^2 - I_{\text{dc}}^2)}{I_{\text{dc}}} = 1.21
\]

The ripple factor of half wave rectifier is equal to 1.21 (i.e. \(\gamma = 1.21\)).

Note that for us to construct a good rectifier, we want to keep the ripple factor as low as possible. This is why we use capacitors and inductors as filters to reduce the ripples in the circuit.

Efficiency of Half Wave Rectifier
Rectifier efficiency (\(\eta\)) is the ratio between the output DC power and the input AC power. The formula for the efficiency is equal to:

\[
\eta = \frac{P_{\text{dc}}}{P_{\text{ac}}}
\]

The efficiency of a half wave rectifier is equal to 40.6% (i.e. \(\eta_{\text{max}} = 40.6%\))

RMS value of Half Wave Rectifier
To derive the RMS value of half wave rectifier, we need to calculate the current across the load. If the instantaneous load current is equal to \(i_l = I_m \sin \omega t\), then the average of load current (\(I_{\text{dc}}\)) is equal to:

\[
I_{\text{dc}} = \frac{1}{2\pi} \int_0^\pi I_m \sin \omega t = \frac{I_m}{\pi}
\]
Where \( I_m \) is equal to the peak instantaneous current across the load (\( I_{\text{max}} \)). Hence the output DC current (\( I_{\text{DC}} \)) obtained across the load is:

\[
I_{\text{DC}} = \frac{I_{\text{max}}}{\pi}, \text{ where } I_{\text{max}} = \text{maximum amplitude of dc current}
\]

For a half-wave rectifier, the RMS load current (\( I_{\text{rms}} \)) is equal to the average current (\( I_{\text{DC}} \)) multiple by \( \pi/2 \). Hence the RMS value of the load current (\( I_{\text{rms}} \)) for a half wave rectifier is:

\[
I_{\text{rms}} = \frac{I_m}{2}
\]

Where \( I_m = I_{\text{max}} \) which is equal to the peak instantaneous current across the load.

**Peak Inverse Voltage of Half Wave Rectifier**

Peak Inverse Voltage (PIV) is the maximum voltage that the diode can withstand during reverse bias condition. If a voltage is applied more than the PIV, the diode will be destroyed.

**Form Factor of Half Wave Rectifier**

Form factor (F.F) is the ratio between RMS value and average value, as shown in the formula below:

\[
F.F = \frac{\text{RMS value}}{\text{Average value}}
\]

The form factor of a half wave rectifier is equal to 1.57 (i.e. F.F= 1.57).

**Output DC Voltage**

The output voltage (\( V_{\text{DC}} \)) across the load resistor is denoted by:

\[
V_{\text{DC}} = \frac{V_{\text{Smax}}}{\pi}, \text{ where } V_{\text{Smax}} = \text{maximum amplitude of secondary voltage}
\]

**Applications of Half Wave Rectifier**

Half wave rectifiers are not as commonly used as full-wave rectifiers. Despite this, they still have some uses:

- For rectification applications
- For signal demodulation applications
- For signal peak applications

**Advantages of Half Wave Rectifier**

The main advantage of half-wave rectifiers is in their simplicity. As they don’t require as many components, they are simpler and cheaper to setup and construct.

As such, the main advantages of half-wave rectifiers are:

- Simple (lower number of components)
- Cheaper up front cost (as their is less equipment. Although there is a higher cost over time due to increased power losses)
We will discuss here **Full Wave Rectifier**. When we use a half-wave rectifier, a significant amount of power gets wasted as the only one half of each cycle passes through and the other the cycle gets blocked. Moreover, the half-wave rectifier is not efficient (40.6%) and we cannot use it for applications which need a smooth and steady DC output. For more efficient and steady DC, we will use a full wave rectifier.

A full wave rectifier converts both halves of each cycle of an alternating wave (AC signal) into pulsating DC signal.

We can further classify **full wave rectifiers** into
- Centre-tapped Full Wave Rectifier
- Full Wave Bridge Rectifier

**Construction of Centre-tapped Full Wave Rectifier**

A centre-tapped full wave rectifier system consists of:

1. Centre-tapped Transformer
2. Two Diodes
3. Resistive Load

Centre-tapped Transformer: – It is a normal transformer with one slight modification. It has an addition wire connected to the exact centre of the secondary winding. This type of construction divides the AC voltage into two equal and opposite voltages namely +Ve voltage ($V_a$) and -Ve voltage ($V_b$). The total output voltage is $V = V_a + V_b$
The circuit diagram is as follows

Working of Centre-tapped Full Wave Rectifier
We apply an AC voltage to the input transformer. During the positive half-cycle of the AC voltage, terminal 1 will be positive, centre-tap will be at zero potential and terminal 2 will be negative potential. This will lead to forward bias in diode $D_1$ and cause current to flow through it. During this time, diode $D_2$ is in reverse bias and will block current through it.

During the negative half-cycle of the input AC voltage, terminal 2 will become positive with relative to terminal 2 and centre-tap. This will lead to forward bias in diode $D_2$ and cause current to flow through it. During this time, diode $D_1$ is in reverse bias and will block current through it.
During the positive cycle, diode D₁ conducts and during negative cycle diode D₂ conducts and during positive cycle. As a result, both half-cycles are allowed to pass through. The average output DC voltage here is almost twice of the DC output voltage of a half-wave rectifier.

**Output Waveforms:**

During the positive cycle, diode D₁ conducts and during negative cycle diode D₂ conducts and during positive cycle. As a result, both half-cycles are allowed to pass through. The average output DC voltage here is almost twice of the DC output voltage of a half-wave rectifier.
**Full Wave Bridge Rectifier**

**Construction of Full Wave Bridge Rectifier**

A full wave bridge rectifier is a type of rectifier which will use four diodes or more than that in a bridge formation. A full wave bridge rectifier system consists of

1. Four Diodes
2. Resistive Load

We use the diodes namely A, B, C and D which form a bridge circuit. The circuit diagram is as follows

![Circuit Diagram](image)

**Figure - 1**

**Principle of Full Wave Bridge Rectifier**

We apply an AC across the bridge. During the positive half-cycle, the terminal 1 becomes positive, and terminal 2 becomes negative. This will cause the diodes A and C to become
forward-biased, and the current will flow through it. Meanwhile diodes B and D will become reverse-biased and block current through them. The current will flow from 1 to 4 to 3 to 2.

During the negative half-cycle, the terminal 1 will become negative, and terminal 2 will become positive. This will cause the diodes B and D to become forward-biased and will allow current through them. At the same time, diodes A and C will be reverse-biased and will block the current through them. The current will flow from 2 to 4 to 3 to 1.
**Bridge Rectifier Circuit Analysis**

The only difference in the analysis between full wave and centre tap rectifier is that

1. In a bridge rectifier circuit, two diodes conduct during each half cycle and the forward resistance becomes double (2RF).
2. In a bridge rectifier circuit, Vsmax is the maximum voltage across the transformer secondary winding whereas in a centre tap rectifier Vsmax represents the maximum voltage across each half of the secondary winding.

The different parameters are explained with equations below:

1. **Peak Current**

The instantaneous value of the voltage applied to the rectifier is given as

\[ vs = Vsmax \sin\ wt \]

If the diode is assumed to have a forward resistance of RF ohms and a reverse resistance equal to infinity, the current flowing through the load resistance is given as

\[ i1 = Imax \sin\ wt \] and \[ i2 = 0 \] for the first half cycle and \[ i1 = 0 \] and \[ i2 = Imax \sin\ wt \] for second half cycle The total current flowing through the load resistance RL, being the sum of currents \[ i1 \] and \[ i2 \] is given as:

\[ i = i1 + i2 = Imax \sin\ wt \] for the whole cycle.

Where the peak value of the current flowing through the load resistance RL is given as

\[ Imax = \frac{Vsmax}{2RF + RL} \]

2. **Output Current**

Since the current is the same through the load resistance RL in the two halves of the ac cycle, magnitude od dc current Idc, which is equal to the average value of ac current, can be obtained by integrating the current \[ i1 \] between 0 and \( \pi \) or current \[ i2 \] between \( \pi \) and 2\( \pi \).

\[ \text{So } I_{dc} = \frac{1}{\pi} \int_0^\pi i1 \, d(\omega t) = \frac{1}{\pi} \int_0^\pi Imax \sin\ wt \, d(\omega t) = \frac{2Imax}{\pi} \]

\[ \text{Output Current of Full Wave Rectifier} \]

3. **DC Output Voltage**

Average or dc value of voltage across the load is given as

\[ V_{dc} = Idc \times RL = 2/ \pi Imax \times RL \]

4. **Root Mean Square (RMS) Value of Current**

RMS or effective value of current flowing through the load resistance RL is given as

\[ I_{rms} = \frac{1}{\pi} \int_0^\pi i2^2 \, d(\omega t) = I_{max}^2/2 \text{ or } I_{rms} = Imax/\sqrt{2} \]
5. **Root Mean Square (RMS) Value of Output Voltage**

RMS value of voltage across the load is given as

\[ V_{\text{rms}} = I_{\text{rms}} R_L = \left(\frac{I_{\text{max}}}{\sqrt{2}}\right) R_L \]

6. **Rectification Efficiency**

Power delivered to load,

\[ P_{\text{dc}} = I^2 R_L = (2 \frac{I_{\text{max}}}{\pi})^2 R_L = \left(\frac{4}{\pi^2}\right) I^2_{\text{MAX}} R_L \]

AC power input to the transformer, \( P_{\text{ac}} = \) Power dissipated in diode junction + Power dissipated in load resistance \( R_L \)

\[ = I^2_{\text{rms}} R_F + I^2_{\text{rms}} R_L = \left(\frac{I^2_{\text{MAX}}}{2}\right) [R_F + R_L] \]

So, Rectification Efficiency, \( \eta = \frac{P_{\text{dc}}}{P_{\text{ac}}} = \frac{\left(\frac{4}{\pi^2}\right) I^2_{\text{MAX}} R_L}{\left(\frac{1}{2} I^2_{\text{MAX}}\right)} [R_F + R_L] \]

\[ = 0.812(1 + \frac{R_F}{R_L}) \]

In case of bridge rectifier, \( \eta = 0.812\left(1 + \frac{2R_F}{R_L}\right) \)

7. **Ripple Factor**

Form factor of the rectified output voltage of a full wave rectifier is given as

\[ K_f = \frac{I_{\text{rms}}}{I_{\text{avg}}} = \left(\frac{I_{\text{max}}}{\sqrt{2}}\right) / (2 \frac{I_{\text{max}}}{\pi}) = \frac{\pi}{2\sqrt{2}} = 1.11 \]

So, ripple factor, \( \gamma = 1.11^2 - 1 = 0.482 \)

8. **Regulation**

The dc output voltage is given as

\[ V_{\text{dc}} = 1_{dc} R_L = \frac{2}{\pi} I_{\text{max}} R_L \]

\[ = 2 V_{\text{MAX}} R_L / \pi [R_F + R_L] \]

\[ = [2 V_{\text{MAX}} / \pi] - 1_{dc} R_F \]

**If it is a bridge rectifier**, \( V_{\text{dc}} = [2 V_{\text{MAX}} / \pi] - 2_{dc} R_F \)
Filtered Output Of Half Wave Rectifier (Capacitor filter):
The output of the Half Wave rectifier is pulsating DC instead of steady-state. Where the electronic devices work on steady-state DC and some device may response unexpectedly for such type of pulsating DC. A filter circuit may be required to convert the pulsating DC to steady-state DC, where a simple filter circuit can be capacitor input filter. In the capacitor input filter circuit, the output of Half Wave rectifier is passed through a capacitor as the following circuit shows.

For the first quarter of the positive cycle of the input voltage, the capacitor will charge up to the supply maximum voltage $V_p$. For the second quarter of the positive cycle, the diode will become reverse bias because of the cathode at a higher potential than the anode. So, for the rest of the cycle, the capacitor will provide current to the load and discharge until the supply voltage becomes more than that of capacitor voltage. As the input voltage increased from the capacitor voltage the capacitor will again start charging and the chain will remain. **The discharging time of the capacitor depends upon the RC time constant.**

In the filtering action, the capacitor charges quickly and discharge slowly because of load resistance. That cause a change in voltage across the capacitor, which is undesirable and called ripple voltage.

$$V_{r(pp)} = V_p / f R L C$$

$$V_{DC} = (1 - (1 / (2 f R L C))) V_p$$

A measure of the effectiveness of the filter can be judged by the parameter called ripple factor. The formula of the ripple factor is the ratio between ripple voltage (peak to peak) and DC voltage.

$$r = V_r \text{ (peak to peak)}/V_{DC}$$
Conclusion:

▪ A rectifier converts AC voltage to DC voltage.
▪ Half wave Rectifier only passes current through load during the positive half cycle of sinusoidal.
▪ The output of half wave rectifier is pulsating DC voltage, to convert it to a steady state, a filter is used.
▪ The effectiveness of the filter can be measured by the ripple factor.

2.2 Full-wave Rectifier with Shunt Capacitor Filter
The circuit diagram of a full-wave rectifier with capacitor filter is shown below.

Full-wave Rectifier with Capacitor Filter

The filter capacitor C is placed across the resistance load RLoad. The whole working is pretty much similar to that of a half-wave rectifier with shunt capacitor explained above. The only difference is that two pulses of current will charge the capacitor during alternate positive (D1) and negative (D2) half cycles. Similarly capacitor C discharges twice through RLoad during one full cycle. This is shown in the waveform below.
The load current reduces by a smaller amount before the next pulse is received as there are 2 current pulses per cycle. This causes a good reduction in ripples and a further increase in the average dc load current.

**L-C Filters**

In the simple shunt capacitor filter circuit explained above, we have concluded that the capacitor will reduce the ripple voltage, but causes the diode current to increase. This large current may damage the diode and will further cause heating problem and decrease the efficiency of the filter. On the other hand, a simple series inductor reduces both the peak and effective values of the output current and output voltage. Then if we combine both the filter (L and C), a new filter called the L-C filter can be designed which will have a good efficiency, with restricted diode current and enough ripple removal factor. The voltage stabilizing action of shunt capacitor and the current smoothing action of series inductor filter can be combined to form a perfect practical filter circuit.

L-C filters can be of two types: Choke Input L-section Filter and L-C Capacitor input filter

**Choke Input L-Section Filter**

An inductor filter increases the ripple factor with the increase in load current Rload. A capacitor filter has an inversely proportional ripple factor with respect to load resistance. Economically, both inductor filter and capacitor filter are not suitable for high end purpose.

L-C inductor input or L-section filter consists of an inductor ‘L’ connected in series with a half or full wave rectifier and a capacitor ‘C’ across the load. This arrangement is also called a choke input filter or L-section filter because it’s shape resembles and inverted L-shape. To increase the smoothing action using the filter circuit, just one L-C circuit will not be enough. Several L-section filters will be arranged to obtain a smooth filtered output. The circuit diagram and smoothened waveform of a Full wave rectifier output is shown below.

![L-C Filter - Inductor input L Section Filter](www.CircuitsToday.com)

**Section Filter**

As shown in the circuit diagram above, the inductor L allows the dc to pass but restricts the flow of ac components as its dc resistance is very small and ac impedance is large. After a signal passes through the choke, if there is any fluctuation remaining the current, it will be fully bypassed before it reaches the load by the shunt capacitor because the value of Xc is
much smaller than $R_{load}$. The number of ripples can be reduced to a great amount by making the value of $XL$ greater than $Xc$ at ripple frequency.

**Ripple Factor**

Ripple Factor $= \frac{Vac{rms}}{V_{dc}} = \frac{\sqrt{2}/3}{(Xc/XL)} = \frac{\sqrt{2}/3}{(1/[2wc])(1/[2wL])} = \frac{1}{6\sqrt{2}w^2LC}$

Though the $L$-$C$ filter has all these advantages, it has now become quite obsolete due to the huge size of inductors and its cost of manufacturing. Nowadays, IC voltage regulators are more commonly used along with active filters, that reduce the ripples and keeps the output dc voltage constant.

The diagram of $L$-$C$ Capacitor input filter and waveform is shown below.

**Π – Filter or Capacitance Input Filter**

The name pi – Filter implies to the resemblance of the circuit to a Π shape with two shunt capacitances (C1 and C2) and an inductance filter ‘L’. As the rectifier output is provided directly into the capacitor it also called a capacitor input filter.

The output from the rectifier is first given to the shunt capacitor $C$. The rectifier used can be half or full wave and the capacitors are usually electrolytic even though they large in size. In practical applications, the two capacitances are enclosed in a metal container which acts as a common ground for the two capacitors. Circuit diagram and the waveform are given below.

When compared to other type of filters, the Π – Filter has some advantages like higher dc voltage and smaller ripple factor. But it also has some disadvantages like poor voltage regulation, high peak diode current, and high peak inverse voltage.

This filter is divided into two – a capacitor filter and a L-section filter. The capacitor $C1$ does most of the filtering in the circuit and the remaining ripple os removed by the L-section filter (L-C2). $C1$ is selected to provide very low reactance to the ripple frequency. The voltage regulation is poor for this circuit as the output voltage falls off rapidly with the increase in load current.
**Ripple Factor**

Ripple Factor = \sqrt{\frac{2}{8w^3C1C2LR\text{load}}}

**R-C Filter**

We have already discussed about the drawbacks of using a pi-filter. The main reason for all these drawbacks is the use of inductor in the filter circuit. If we use a resistance in series, instead of the inductor as the filter, these drawbacks can be overcome. Thus the circuit is named as R-C filter. In this circuit, the ripples have to be made to drop across the resistance \( R \) instead of the load resistance \( RL \). For this, the value of \( RL \) is kept much larger than the value of reactance of capacitor \( C2 \) (\( XC2 \)). This means that each section reduces the ripple by a factor of at least 10.

Though the circuit nullifies certain drawbacks of the pi-filter, the circuit on its own has some problems as well. The filter has very poor voltage regulation. There is a large voltage drop in the resistance \( R \). The circuit also develops a lot of heat and this has to be dissipated through enough and adequate ventilation. Thus, the filter is only suitable for small load current or large load resistance circuits.