Introduction to Rectifiers and their Performance Parameters

Rectification is the process of conversion of alternating input voltage to direct output voltage. **Rectifier** is a circuit that convert AC voltage to a DC voltage and permits the current to flow in one direction.

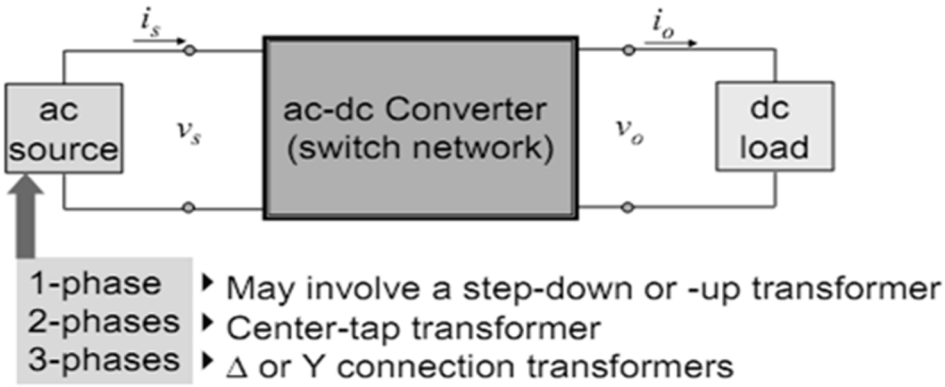
General Aspects

- AC to DC converters without control are known as **diode rectifiers**. They are designed using diodes, which convert input AC voltage into fixed AC output voltage at the same frequency.
- AC to DC controlled converters are designed using thyristors, such as SCR. which convert input AC voltage into variable AC output voltage at the same frequency.
- The rectifiers are required to supply ripple-free dc voltage or dc current to the load.
- The rectifiers usually draw highly non-sinusoidal current from the electric utility supply, giving rise to poor power factor and thus poor efficiency.

Rectifier Applications

- DC power supplies for computers and electronic equipments.
- Battery charging systems.
- High voltage dc (HVDC) transmission converters.
- DC motor control
- Reactor controls.
- Variable speed industrial drives.
- Uninterruptible power supply systems (UPS).
- Portable hand tool drives.
- Magnet power supplies.
- AC fed traction system using dc traction motor.
- Electro-chemical and electro-metallurgical processes.

Rectifier Topologies



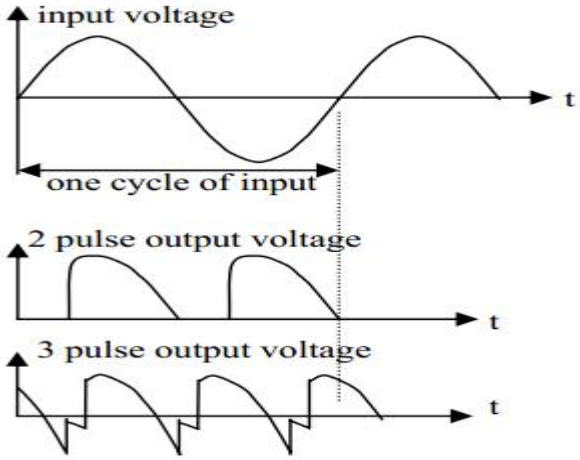
NOTE:

- Half-wave topology has less semiconductor switches but requires higher component stresses.
- Full-wave topology has more switches but is capable of handling high power with minimum component stresses.

NOTE:

The Pulse number in the output voltage waveform of the rectifier represent the rate of repetition in the output according to one cycle of input.

Rectifiers classified according to the output pulse numbers (2, 3, 4, 6, 12, etc.)



Types of Loads for Rectifier

- ► Resistive Load: (L=0, E=0)
- ► Inductive-Resistive: (medium L, low R and E=0) magnetic lift and relays.
- ► Inductive-Voltage Sink: (medium L, low R and E) DC motors, HVDC bus and battery charging circuit.
- ► Current Sink: (high L, low R and E) DC motors, heavy magnetic pick UPS and relays.
- ► Capacitive-Resistive :(L =0, R and E replaced by capacitor)

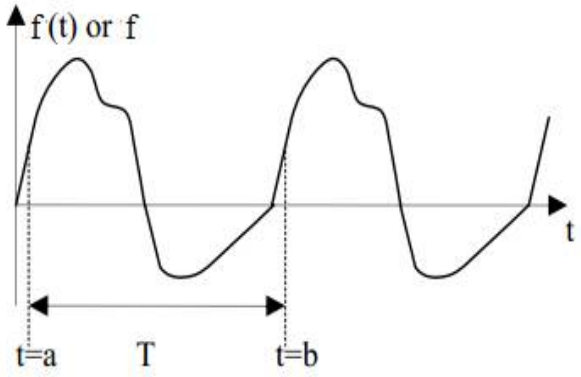
Performance parameters

Before starting to examine different topologies of single-phase or multi-phase rectifiers, we should be defined some rectifier parameters. These parameters are needed to compare the performances among the different structures.

1) Average, RMS, and form factor of the waveform

The root means square RMS or the effective value of the periodic function f(t) is given by:

$$F_{RMS} = F_{eff} = \sqrt{\frac{1}{b-a}\int_{t=a}^{b} f^2 dt}$$



The average value of the function or the DC value is given by:

$$F_{avg} = F_{dc} = \frac{1}{b-a}\int_{t=a}^{b} f dt$$

Form factor of f(t) is the ratio of the RMS value to the average value.

$$\boxed{FF = \frac{F_{RMS}}{F_{avg}}}$$

FF is a measure of the shape of the output voltage. If the output voltage is pure DC then $F_{RMS} = F_{avg} \rightarrow$ FF=1

2) Output dc power (average or dc output power delivered to the load)

$$P_{O(dc)} = V_{O(dc)} \times I_{O(dc)} \;\; ; \text{ i.e., } P_{dc} = V_{dc} \times I_{dc}$$

Where

$V_{O(dc)} = V_{dc}$ = average or dc value of output (load) voltage.

$I_{O(dc)} = I_{dc}$ = average or dc value of output (load) current.

3) Output Ac power

$$P_{O(ac)} = V_{O(RMS)} \times I_{O(RMS)}$$

4) Rectification efficiency

The rectification ratio (η), also known as rectification efficiency, is expressed by

$$\text{Efficiency } \eta = \frac{P_{O(dc)}}{P_{O(ac)}} \;; \qquad \%\text{ Efficiency } \eta = \frac{P_{O(dc)}}{P_{O(ac)}} \times 100$$

$$\eta = \frac{V_{o(dc)} I_{o(dc)}}{V_{o(rms)} I_{o(rms)}} = \frac{V^2{}_{o(dc)}}{V^2{}_{o(rms)}} = \left(\frac{1}{FF}\right)^2$$

We have assumed ideal switches, with no losses, that is $R_D = 0$.

5) AC component

The output voltage can be considered as being composed of two components

- The dc component $V_{O(dc)}$ = DC or average value of output voltage.
- The ac component or the ripple component $V_{ac} = V_{r(rms)}$= RMS value of all the ac ripple components.

The total RMS value of output voltage is given by

$$V_{O(RMS)} = \sqrt{V_{O(dc)}^2 + V_{r(rms)}^2}$$

Therefore

$$V_{ac} = V_{r(rms)} = \sqrt{V_{O(RMS)}^2 - V_{O(dc)}^2}$$

Hence: V_{ac}=0V for smooth DC voltage

6) Ripple Factor

The Ripple Factor (RF) which is a measure of the ac ripple content in the output voltage waveform. The output voltage ripple factor defined for the output voltage waveform is given by

$$r_v = RF = \frac{V_{r(rms)}}{V_{O(dc)}} = \frac{V_{ac}}{V_{dc}}$$

(***we have to keep in mind that our goal is to obtain a voltage and a current in the load as steady as possible***).

$$r_v = \frac{\sqrt{V_{O(RMS)}^2 - V_{O(dc)}^2}}{V_{O(dc)}} = \sqrt{\left[\frac{V_{O(RMS)}}{V_{O(dc)}}\right]^2 - 1}$$

Therefore

$$r_v = \sqrt{FF^2 - 1}$$

The RF is defined as the ratio of the effective AC component of the load voltage versus the DC voltage.

7) Current Ripple Factor

Defined for the output (load) current waveform is given by

$$r_i = \frac{I_{r(rms)}}{I_{O(dc)}} = \frac{I_{ac}}{I_{dc}}$$

Where $$I_{r(rms)} = I_{ac} = \sqrt{I_{O(RMS)}^2 - I_{O(dc)}^2}$$

The peak to peak ac ripple load current is the difference between the maximum and the minimum values of the output load current.

$$I_{r(pp)} = I_{O(\max)} - I_{O(\min)}$$

8) Transformer Utilization Factor (TUF)

A transformer is most often used both to introduce a galvanic isolation between the rectifier input and the AC mains and to adjust the rectifier AC input voltage to a level suitable for the required application. One of the parameters used to define the characteristics of the transformer is the Transformer Utilization Factor (TUF):

$$TUF = \frac{P_{DC}}{Effective\ Transformer\ VA\ Rating}$$

$$TUF = \frac{P_{O(dc)}}{V_S \times I_S}$$

Where

V_S = RMS value of transformer secondary output voltage (RMS supply voltage at the secondary)

I_S = RMS value of transformer secondary current (RMS line or supply current).

9) The Crest Factor (CF)

CF is a measure of a waveform AC output, showing the ratio of peak values to the average value. In other words, **crest factor** indicates how extreme the peaks are in an output waveform.

$$CF = \frac{I_{S(peak)}}{I_S} = \frac{\text{Peak input supply current}}{\text{RMS input supply current}}$$

10) Harmonic Factor (HF) or Total Harmonic Distortion Factor (THD)

The harmonic factor is a measure of the distortion in the output waveform and is also referred to as the total harmonic distortion (THD)

$$HF = \left[\frac{I_S^2 - I_{S1}^2}{I_{S1}^2}\right]^{\frac{1}{2}} = \left[\left(\frac{I_S}{I_{S1}}\right)^2 - 1\right]^{\frac{1}{2}}$$

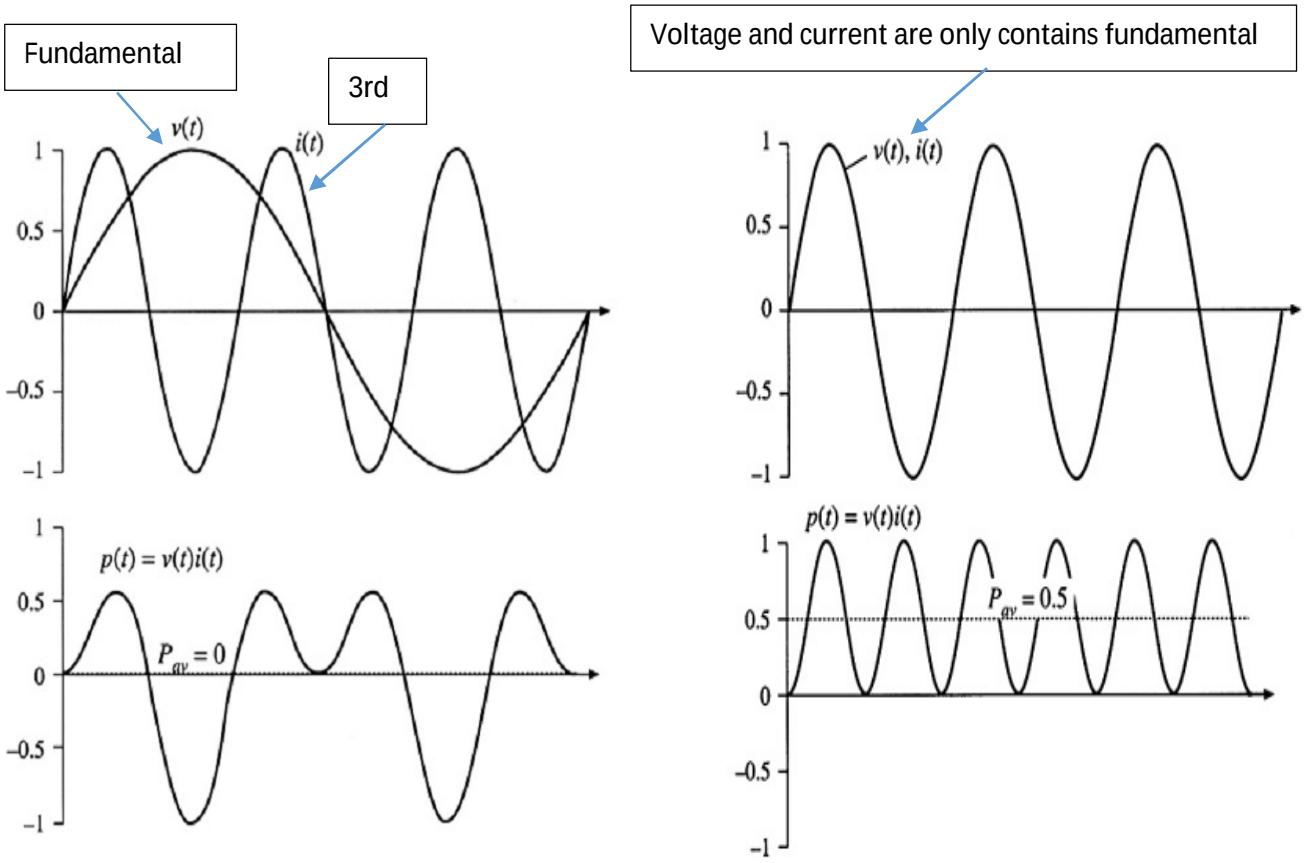
Where

I_S = RMS value of input supply current.

I_{S1} = RMS value of fundamental component of the input supply current.

Due to the power electronics converter operation the source current can be resolved into different harmonic components. The average input power is transfer from the source to the load only if the products of voltage and current harmonics of the same frequency:

At different voltage and current frequency **Energy circulates between the source and load**, But over one cycle the net energy transferred to the load is zero. Some examples of power flow in systems containing harmonics are illustrated figures below below:



It is useful to also take into consideration some parameters related to the switches—diodes or thyristors—like, for example, the Peak Inverse Voltage (PIV) during the blocking state of the device or the maximum current in the load. In practice, one has to choose devices with a peak

repetitive reverse voltage (V_{RRM} as reported on the data sheets) and a peak repetitive forward current (I_{FRM}) higher than the PIV and maximum load current.

For an Ideal Controlled Rectifier

$FF = 1$; which means that $V_{O(RMS)} = V_{O(dc)}$.

Efficiency $\eta = 100\%$; which means that $P_{O(dc)} = P_{O(ac)}$.

$V_{ac} = V_{r(rms)} = 0$; so that $RF = r_v = 0$; Ripple factor = 0 (ripple free converter).

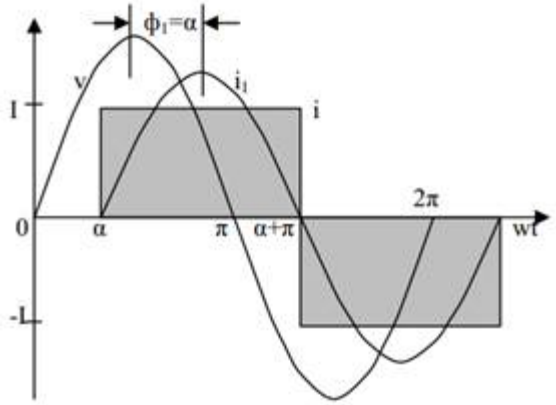
$TUF = 1$; which means that $P_{O(dc)} = V_S \times I_S$

$HF = THD = 0$; which means that $I_S = I_{S1}$

$PF = DPF = 1$; which means that $\phi = 0$

11) Input Power Factor (PF)

All PE converters draw non-sinusoidal current as shown below. Thus, this result in increased the RMS drawn current with increasing in transferred power, which is means more reactive power produced which results in increases the losses. Hence, for undistorted sinusoidal input voltage, the input power can be obtained only at fundamental component since no power transfer at different current and voltage frequencies:



Source Current and Voltage of a 2-Pulse Fully-Controlled Converter

$$P = V_{rms}\, I_{1rms} \cos\phi_1$$

$$\text{Then, } pf = \frac{V_{rms}\, I_{1rms} \cos\phi_1}{V_{rms}\, I_{rms}}$$

$$pf = \frac{I_{1rms}}{I_{rms}} \cos\phi_1$$

Where $\frac{I_{1rms}}{I_{rms}}$ the **distortion factor DF** and $\cos\varphi_1$ is the power factor of the fundamental components known as **Displacement factor DPF** because the fundamental current displaced by φ_1 of the voltage.

Hence the power factor (pf) is : pf= Distortion factor × Displacement factor

For heavy inductive load the output current of the rectifier is pure DC, thus the input current is square wave.

By using Fourier series for square waveform,

$$i = \frac{4I}{\pi}(\sin\theta + 1/3\sin 3\theta + 1/5\sin 5\theta + 1/7\sin 7\theta + \ldots..)$$

And hence $$I_{1rms} = \frac{1}{\sqrt{2}}\frac{4I}{\pi}$$

Then the distortion factor is:

$$\frac{I_{1rms}}{I_{rms}} = \frac{2\sqrt{2}}{\pi}$$

Harmonics Effect Reduction

The current of line-commutated (not PWM) rectifiers are suffers from non-sinusoidal shape. The harmonic orders reduced with increasing the number of rectifier output pulses:

Conv. Pulse Number	Harmonic Orders
2	3, 5, 7, 9, 11, 13, …
3	2, 4, 5, 7, 8, 10, 11, ...
6	5, 7, 11, 13, 17, 19, …
12	11, 13, 23, 25, …

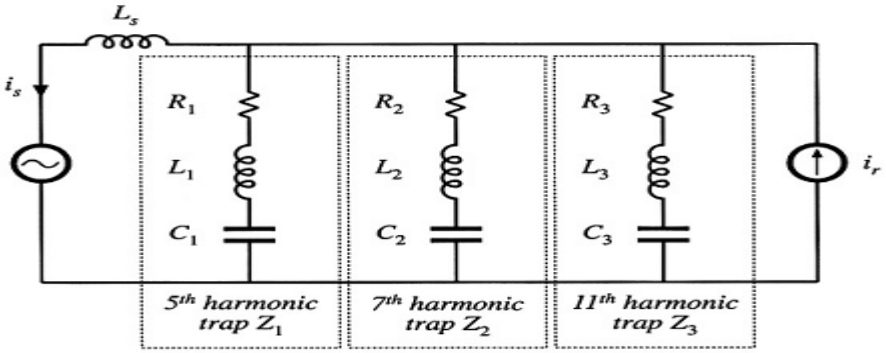
The harmonic order magnitude reduces with increasing the harmonic order. Thus, the closest order to the fundamental component, which are at low frequency, has the major effect on the current and must eliminate.

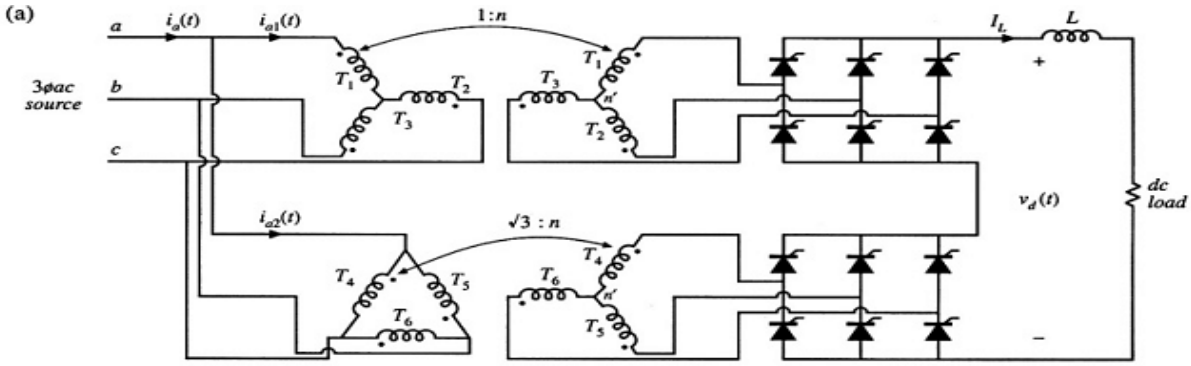
Harmonics Effect:

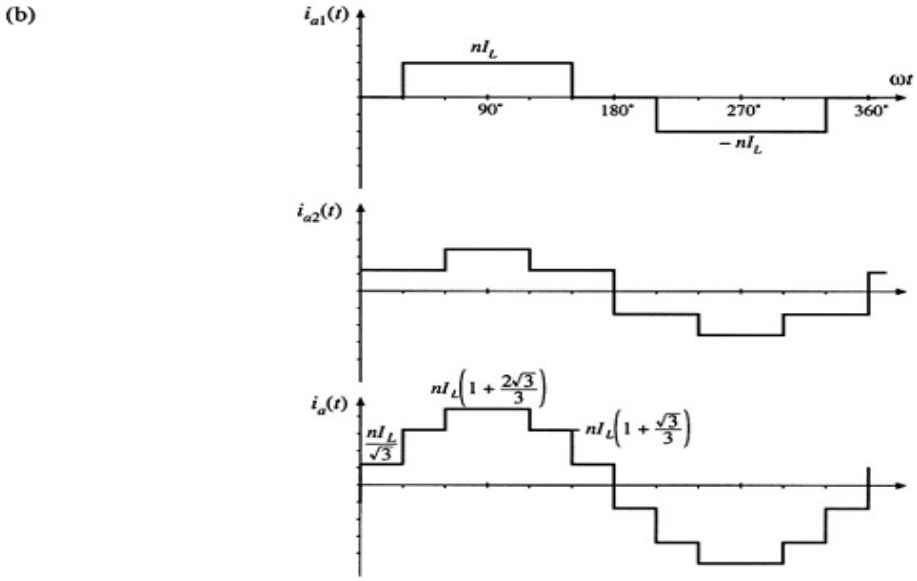
- Reduces the input power factor,
- Reduces the net energy transfer to the load which results in increasing ohmic loss and increasing magnetic losses,
- Interfering with communication circuit due to EMI effect,
- Lead to resonance in AC system if the harmonics frequency matching the natural frequency of ac system.
- The harmonics increase the rms value of the current while leaving the average power unchanged.

Harmonics Reduction:

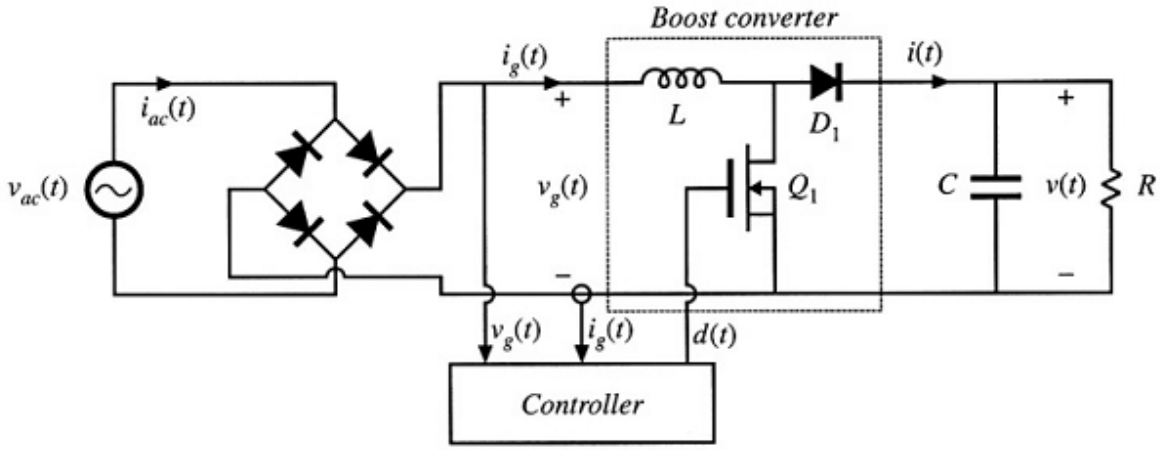
- Using converter with high output pulse numbers.
- Use Delta connection for the transformer.
- Connecting passive filter at the input of the rectifier.
- Using PWM rectifier.







Twelve-pulse rectifier: (a) circuit, (b) input phase *a* current waveforms.


Boost converter
$i_g(t)$
$i(t)$
$i_{ac}(t)$
L
D_1
$v_{ac}(t)$
$v_g(t)$
Q_1
C
$v(t)$
R
+
–
$v_g(t)$
$i_g(t)$
$d(t)$
Controller