Aalto University
School of Engineering

Power Electronics

ELEC-E8412 Power Electronics, 5 ECTS

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Chapter 1: Introduction

Learning Outcomes:

At the end of this session, you will be able to:

- describe different types of power electronics converters
- describe the role of power electronics in various applications
- calculate the different power calculations (instantaneous, average, and apparent power)
- calculate the average voltage, current, and power over different components
- calculate the RMS value of voltage and current
- calculate the power factor
- calculate the total harmonic distortion (THD)

Role of Power Electronics

Power conversions in power systems:

- The power electronics interface facilitates the transfer of power from the source to the load/grid by converting voltages and currents from one form to another, in which it is possible for the source and load to reverse roles.
- Typical applications of power electronics include conversion of AC to DC, conversion of DC to AC, conversion of an unregulated DC voltage to a regulated DC voltage, and conversion of an AC power source from one amplitude and frequency to another amplitude and frequency.
- The controller shown in Figure 1-1 allows management of the power transfer process in which the conversion of voltages and currents should be achieved with as high energy-efficiency and high power density as possible.

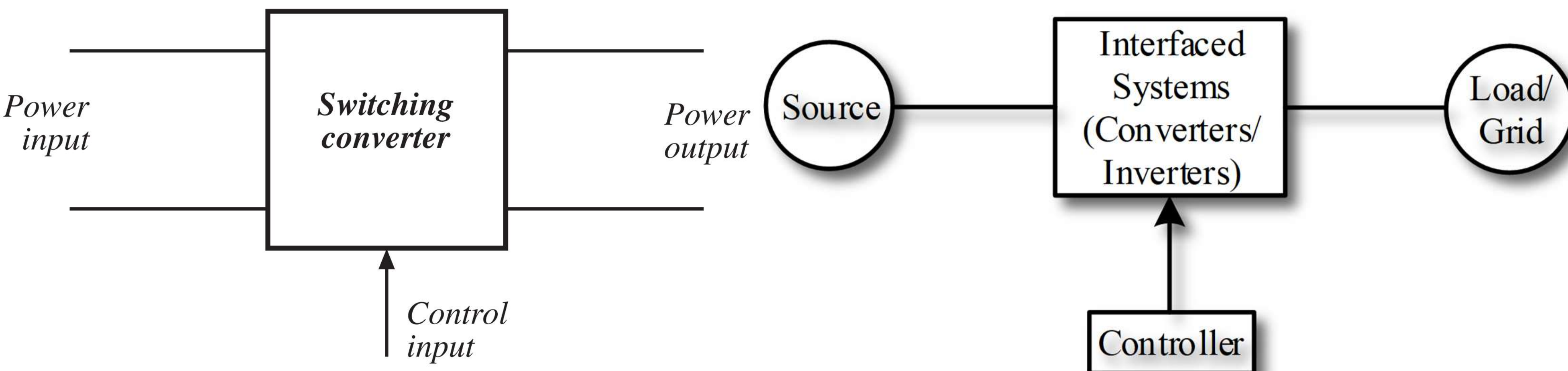


Figure 1-1: Power conversion between the source and the load by power electronics interfaces.

Power Electronics Applications

1. You want to charge your cellphone:

- They use lithium ion battery with 3.7 V (load side)
- Source is an AC power supply with 230 V (rms)
- They are 2 kinds of stiff voltages which you can not directly hook them up together; otherwise, you blow up your cellphone
- You need a conversion mechanism to convert AC power to a DC power

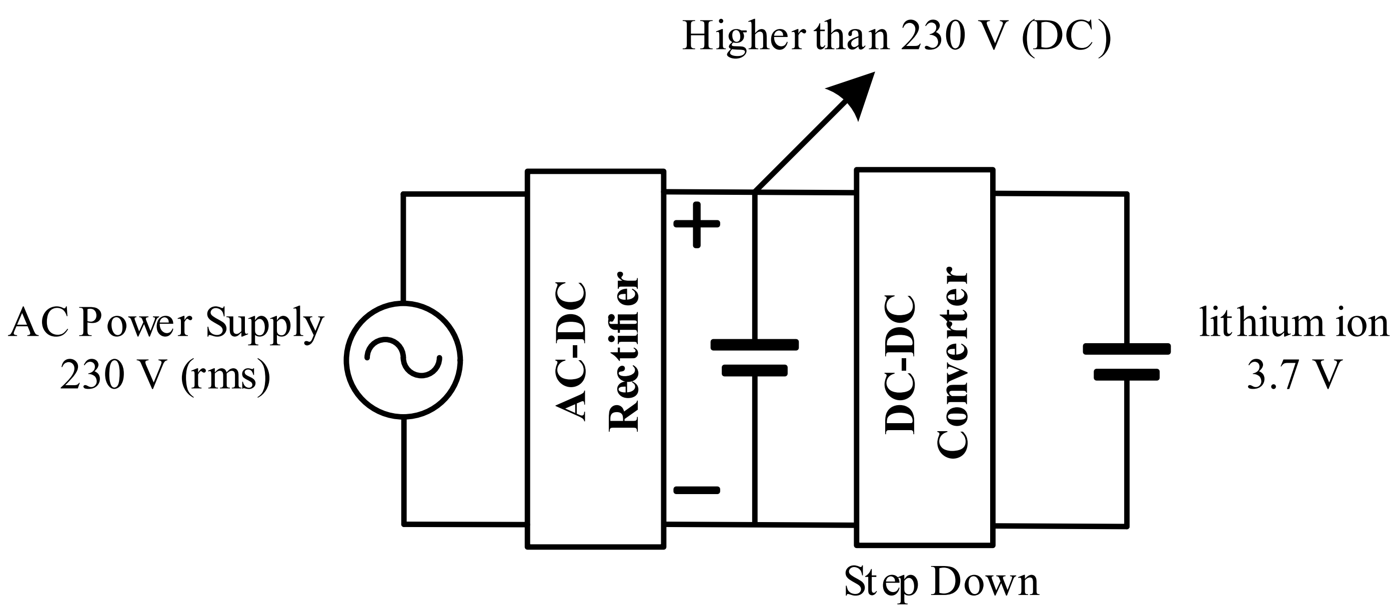


Figure 1-2: General model of conversion mechanism for charging a cellphone.

Power Electronics Applications

2. You want to charge your cellphone in your car:

- A 12 V lead acid battery is input
- The 3.7 V lithium ion battery is considered as a load
- The nature of these 2 voltages are the same (both DC), but their level are different and we can not directly hook them up
- You need a step down DC/DC convert

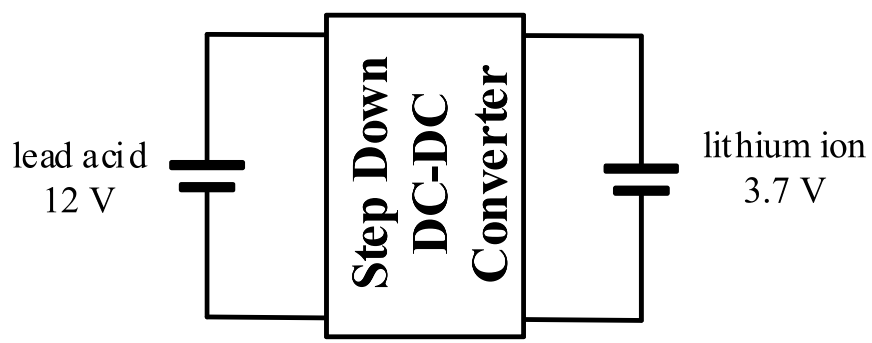


Figure 1-3: General model of conversion mechanism for charging a cellphone in a car.

Power Electronics Applications

3. You want to use flash in your camera:

- The battery of camera is 3.7 V lithium ion battery
- There is a capacitor which we need to charge it up to a certain amount of voltage
- You need a step up DC/DC convert to increase the voltage level

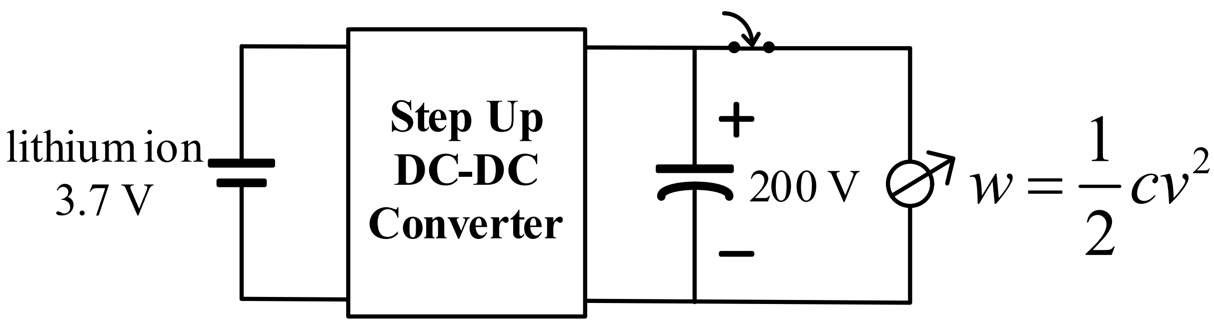


Figure 1-4: General model of conversion mechanism for providing required level of voltage to flash a camera.

Power Electronics Applications

4. You want to inject power from a solar panel to the power grid:

- The nature of these 2 voltages are not the same (DC-AC), as well as the level of voltages
- First, boost up the level of the voltage of PV panel by a DC-DC boost converter
- You need a DC/AC invert to invert DC signal to a sinusoidal AC signal and send some current back to the grid

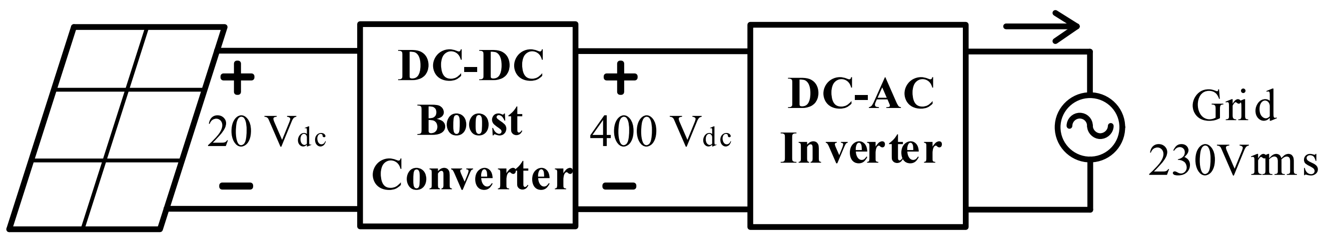


Figure 1-5: General model of conversion mechanism for power injection from a solar panel into the power grid.

Power Electronics Applications

5. You want to supply your electrical motor by a DC power supply:

- You have a battery bank 300 V as a source of power
- Load is a permanent magnet synchronous motors (PMSM) provides mechanical power to push the vehicle forward
- You need to have a 3phase DC-AC inverter (motor drive)

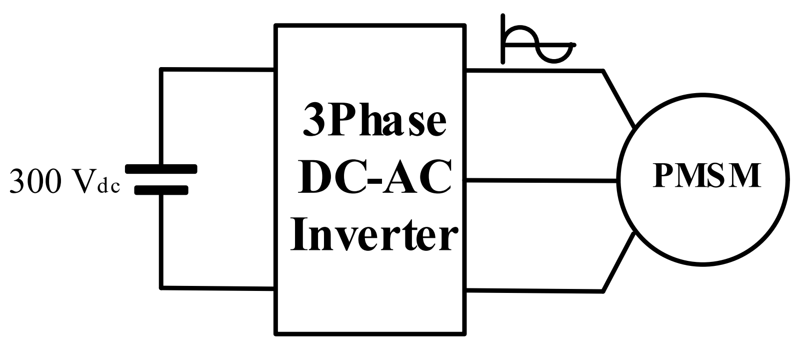


Figure 1-6: General model of conversion mechanism to supply electrical motor by a DC power supply.

Power Electronics Applications

6. You want to supply your electrical motor by a 3 phase AC power supply:

- You have a 3phase AC source as input power
- Load is a permanent magnet synchronous motors (PMSM) provides mechanical power to push the vehicle forward
- Nature of voltage are the same (both AC). In source side, both amplitude and frequency are fixed. But in load side, both of the voltage's amplitude and frequency are variable
- You need to have a 3phase rectifier, and a DC-AC inverter to convert a DC input to an AC output

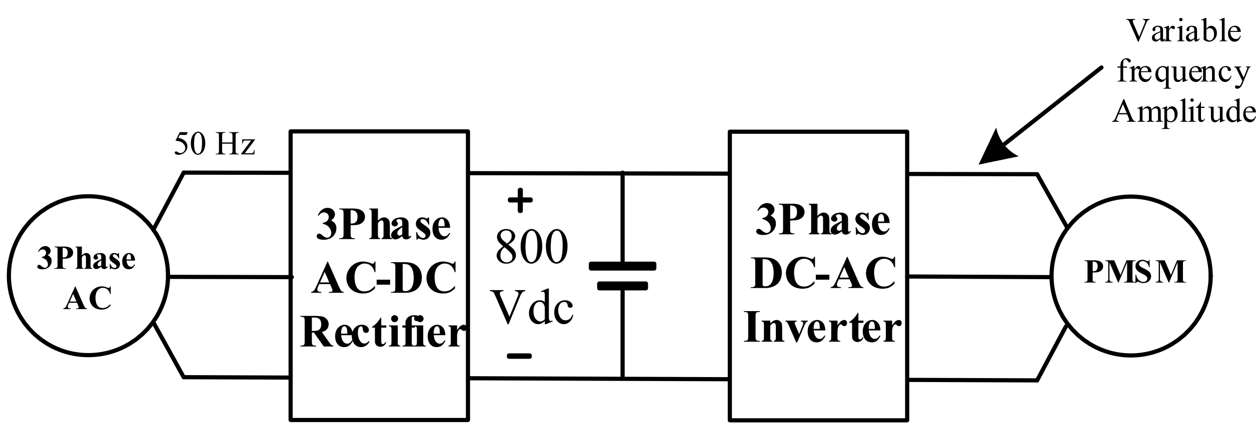


Figure 1-7: General model of conversion mechanism to supply electrical motor by a AC power supply.

Power Electronics Applications

7. You want to generate power from wind and inject it to power grid or local power source:

- You have a 3phase AC source as input power which is not very regulated in terms of frequency and amplitude
- You need to have a 3phase rectifier, and a DC-AC inverter to convert a DC input to an AC output

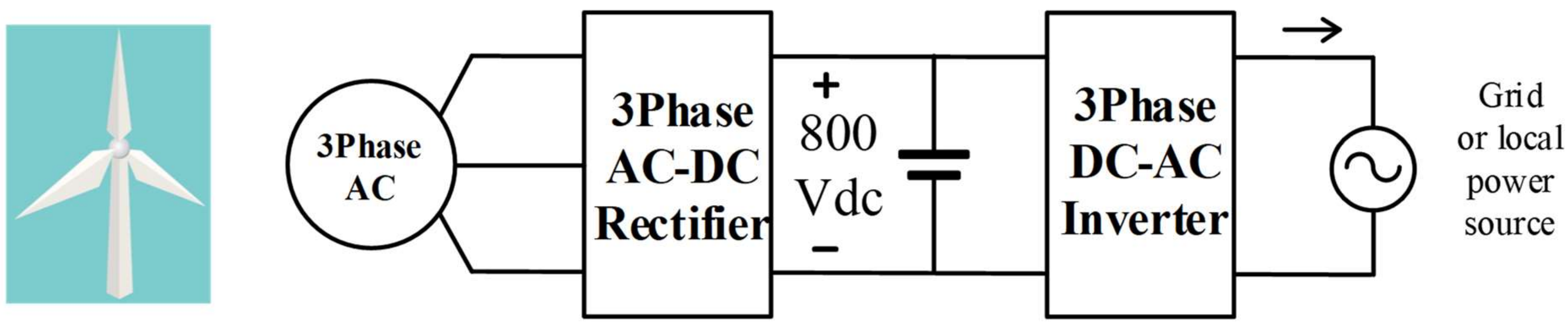


Figure 1-8: General model of conversion mechanism to inject power from wind turbine into the power grid or local power source.

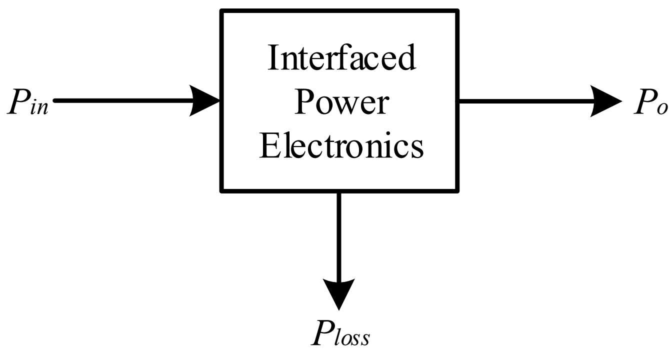
- As we can see, although the frequency and amplitude of input power were variable, the frequency and amplitude of output power is fixed.

Challenges with industry based on Power Electronics Converters

- Assuming you have a solar panel and you are going to harvest as much energy as you can from it. For this case **efficiency** of power electronics interfaces are highly important
- **Cost** is another important issue. For example, you need a converter for your TV. If the price for a normal TV is 1000 euros, the price of converter can not be 2000 euros
- **Size and volume** is important issues. For example, you have converter in your laptop. Everywhere you carry your laptop, this converter is with it
- **Dynamic response**. How quickly your power electronic converter reply to your request. For example, if we ask them to increase the speed of a drive from 1500 rpm to 2000 rpm, we should be able very quickly to do that
- **Reliability** is an important issue to guarantee a secure power for load/grid

Efficiency in Power Electronics Converters

$$\eta = \frac{P_0}{P_0 + P_{loss}} \longrightarrow P_0 = \frac{\eta}{1-\eta} P_{loss}$$



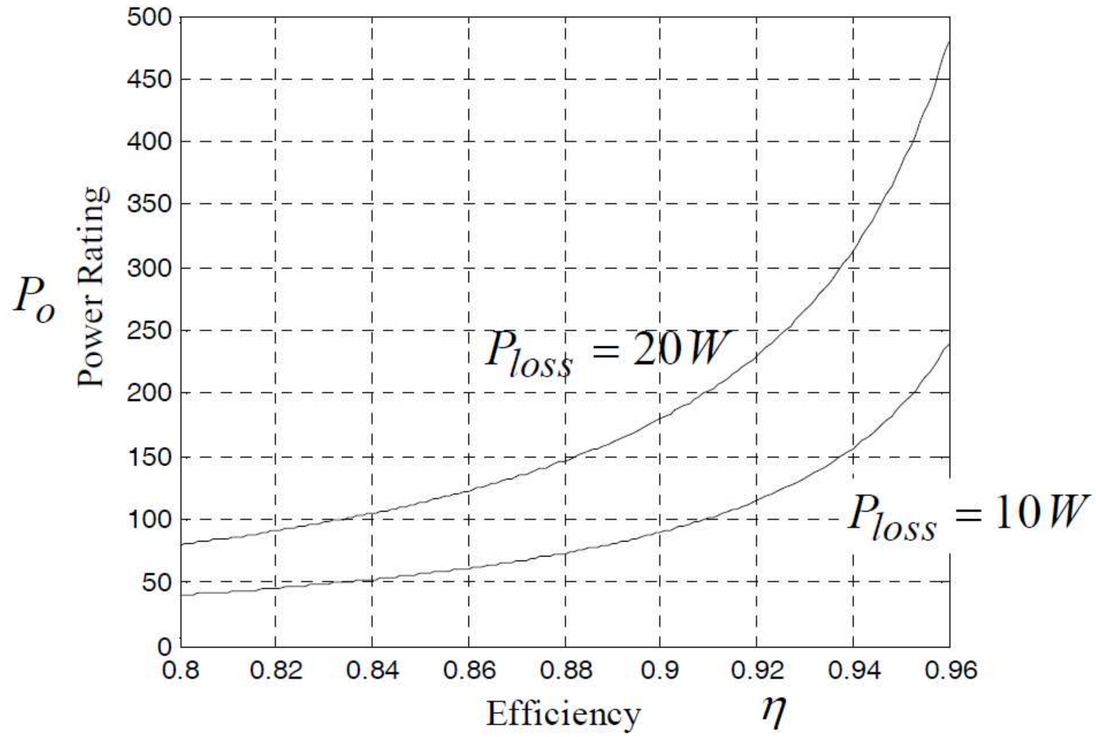
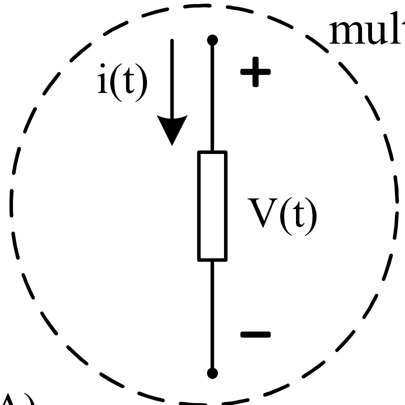


Figure 1-9: Power output capability as a function of efficiency.

Power Calculations

Instantaneous Power: The instantaneous power for any device is computed from the multiplication of the voltage across it and the current passing through it.



Time-varying quantity

$$p(t) = v(t).i(t) \qquad \text{(W)}$$

Passive Sign Convention

- $if \;\; p(t) > 0$ → Power is being absorbed (like a resistor)
- $if \;\; p(t) < 0$ → Power is being supplied (like battery)

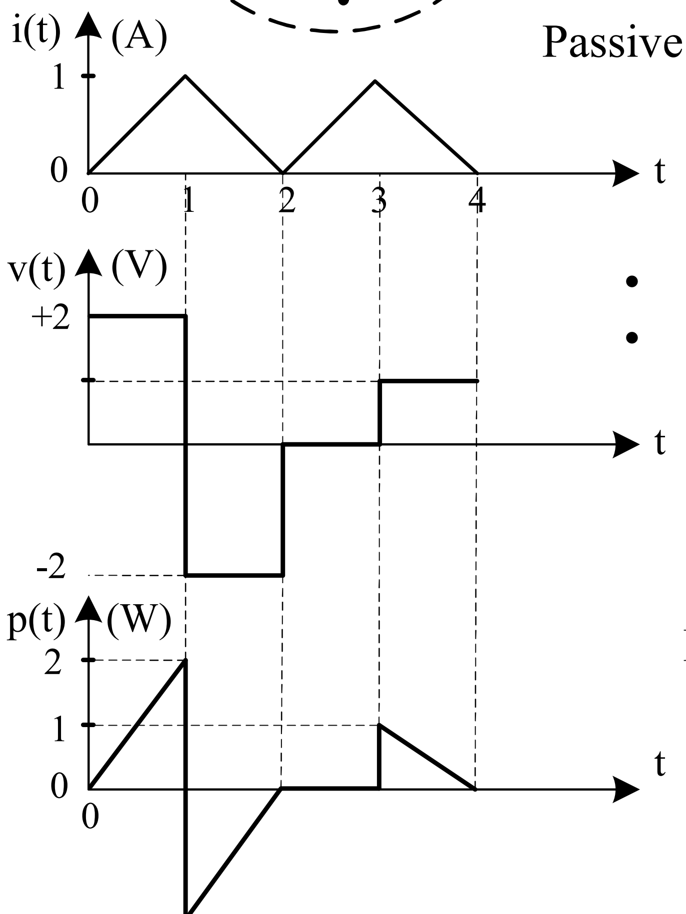


Figure 1-10

- **Energy** is the integral of instantaneous power.
- The energy absorbed by a component in the time interval from t_1 to t_2 is:

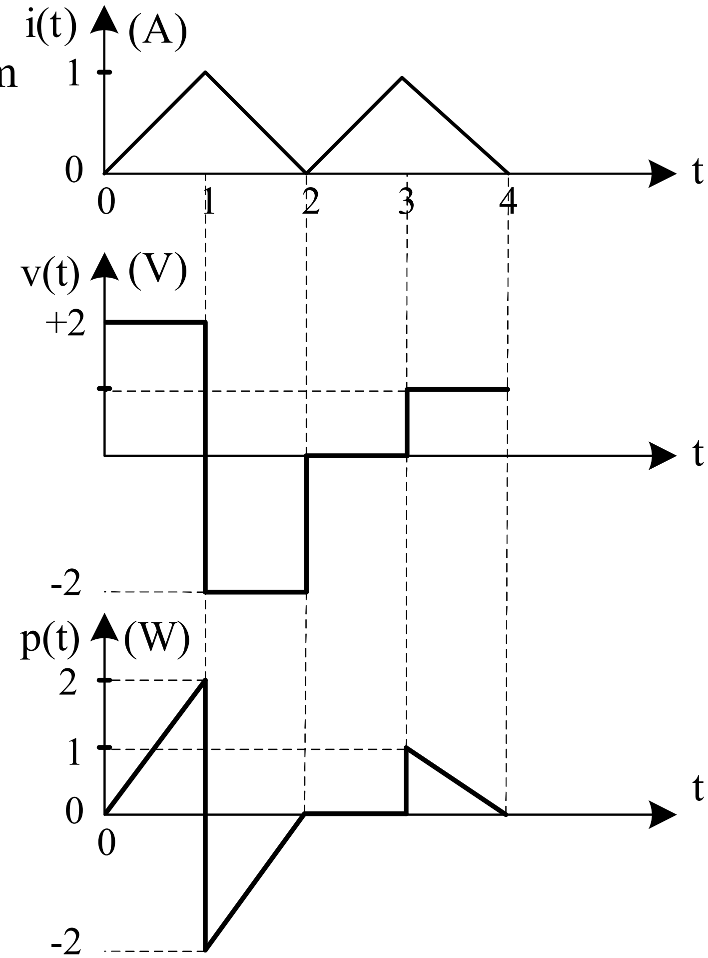
$$w = \int_{t_1}^{t_2} p(t)dt = \int_{t_1}^{t_2} v(t).i(t)dt \quad (J)$$

Example: for the above element energy absorbed from 0 to 1 is:

$$w = \int_{0}^{1} p(t)dt = 1 \quad (J)$$

Power Calculations

- **Average Power**: It is the average value of instantaneous power.



The **average power** absorbed by a component in the time interval from t_1 to t_2 is:

$$P = \frac{1}{t_2 - t_1}\int_{t_1}^{t_2} p(t)dt = \frac{1}{t_2 - t_1}\int_{t_1}^{t_2} v(t).i(t)dt$$

Example 1: The average power for the Figure 1-10 from 0 to 1 is:

$$P = \frac{1}{1-0}\int_0^1 p(t)dt = 1 \;\; \text{(W)}$$

Example 2: The average power for the Figure 1-10 from 1 to 2 is:

$$P = \frac{1}{2-1}\int_1^2 p(t)dt = -1 \;\; \text{(W)}$$

Example 3: The average power for the Figure 1-10 from 0 to 2 is:

$$P = \frac{1}{2-0}\int_0^2 p(t)dt = 0 \;\; \text{(W)}$$

- **Average Power in Periodic Signals**

If the **current** and **voltage** signals of a circuit element are **both** periodic and have the **same period**, the average power absorbed by that element over one period is:

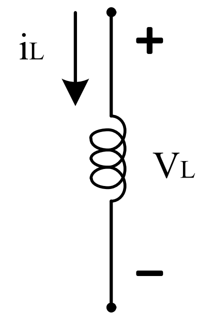
$$P = \frac{1}{T}\int_{t_0}^{t_0+T} p(t)dt = \frac{1}{T}\int_{t_0}^{t_0+T} v(t).i(t)dt$$

t_0 could be anytime instant, we just need to study the circuit element for a time interval of length T.

Calculation of Average Voltage and Current of Inductor

- **Inductor with Periodic Currents**

If iL is periodic ⟶ $i_L(t+T) = i_L(t)$



$$V_L = L\frac{di}{dt}$$

$$P_L = \frac{1}{T}\int_{t_0}^{t_0+T} p(t)dt = \frac{1}{T}\int_{t_0}^{t_0+T} v(t)i(t)dt = \frac{1}{T}\int_{t_0}^{t_0+T} L\frac{di}{dt}\times i(t)dt = \frac{L}{2T}\left[i_L(t)^2\right]_{t_0}^{t_0+T} = \frac{L}{2T}\left[i_L(t_0+T)^2 - i_L(t_0)^2\right] = 0$$

❖ The average power absorbed or supplied by an inductor is zero for periodic currents.

- **Calculation of the Average Value of Voltage over the Inductor**

$$V_L = L\frac{di}{dt} \Rightarrow i_L(t_0+T) = \frac{1}{L}\int_{t_0}^{t_0+T} V_L(t)dt + i_L(t_0)$$

$$\frac{L}{T}\left(i_L(t_0+T) - i_L(t_0)\right) = \frac{1}{T}\int_{t_0}^{t_0+T} V_L(t)dt$$

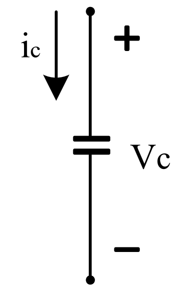
$$0 = \overline{V_L(t)}$$

$$0 = < V_L(t) >$$

$$0 = avg[V_L(t)]$$

❖ For periodic currents, the average voltage across an inductor is zero.

Capacitor with Periodic Voltage



$$i_c = c\frac{dv_c}{dt}$$

- The average power absorbed by a capacitor is zero for periodic voltages.

If Vc is periodic, the stored energy is the same at the end of a period as at the beginning. Therefore, the average power absorbed by the capacitor is zero for steady-state periodic operation; then, **Pc=0**

From the **voltage-current** relationship for the capacitor,

$$i_c = c\frac{dv_c}{dt} \;\rightarrow v(t_0+T) = \frac{1}{c}\int_{t_0}^{t_0+T} i_c(t)dt + v(t_0)$$

Rearranging the preceding equation and recognizing that the starting and ending values are the same for periodic voltages, we get

$$v(t_0+T) \text{ -} v(t_0) = \frac{1}{c}\int_{t_0}^{t_0+T} i_c(t)dt = 0$$

Multiplying by C/T yields an expression for average current in the capacitor over one period.

$$\overline{i_C(t)} = < i_C(t) > = avg[i_C(t)] = \frac{1}{T}\int_{t_0}^{t_0+T} i_c(t)dt = 0$$

- For periodic voltages, the average current in a capacitor is zero.

Root Mean Square (RMS) Value

RMS value of a periodic signal is:

$$X_{rms} = \sqrt{\frac{1}{T}\int_{t_0}^{t_0+T} x(t)^2\, dt}$$

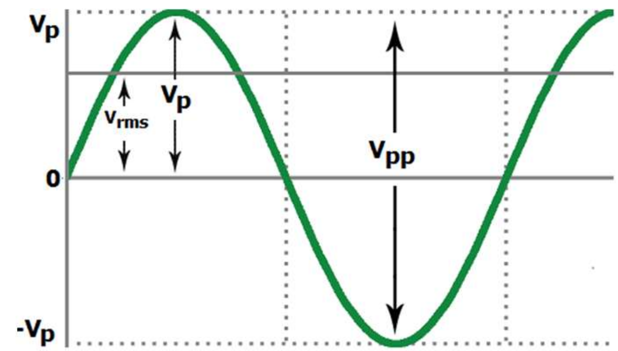
Not a function of time

Example: Find the RMS value for a periodic voltage waveform v(t) with period T.

$$V_{\text{rms}} = \sqrt{\frac{1}{T}\int_0^T [v(t)]^2 dt}.$$

For a sinusoidal voltage:

$$\begin{aligned} V_{\text{rms}} &= \sqrt{\frac{1}{T}\int_0^T [V_p \sin(\omega t + \phi)]^2 dt} \\ &= V_p \sqrt{\frac{1}{2T}\int_0^T [1 - \cos(2\omega t + 2\phi)] dt} \\ &= V_p \sqrt{\frac{1}{2T}\int_0^T dt} \\ &= \frac{V_p}{\sqrt{2}} \end{aligned}$$



$$V_{rms} = \frac{1}{\sqrt{2}} * V_p = 0.7071 * V_p$$

$$V_{rms} = \frac{1}{2\sqrt{2}} * V_{pp} = 0.35355 * V_{pp}$$

If a voltage is the sum of more than two periodic voltages, the rms value is

$$V_{\text{rms}} = \sqrt{V_{1,\text{rms}}^2 + V_{2,\text{rms}}^2 + V_{3,\text{rms}}^2 + \ \ldots} = \sqrt{\sum_{n=1}^{N} V_{n,\text{rms}}^2}$$

The rms value of $f(t)$ can be computed from the Fourier series:

$$V_{rms} = \sqrt{\sum_{n=0}^{\infty} V_{n,rms}^2} = \sqrt{V_0^2 + \sum_{n=1}^{\infty} (\frac{V_n}{\sqrt{2}})^2}$$

Example: Determine the RMS value of the current

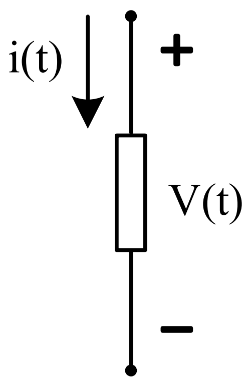
$$i(t)=8+15\cos(377t+30°)+6\cos[2(377)t+45°]+2\cos[3(377)t+60°]$$

Solution

$$I_{rms}=\sqrt{8^2+(\frac{15}{\sqrt{2}})^2+(\frac{6}{\sqrt{2}})^2+(\frac{2}{\sqrt{2}})^2}=14$$

Power Calculations

- **Apparent Power (S)**: It is the power which is not consumed exactly in the system.



If $i(t)\times v(t)$ are both periodic, apparent power will be:

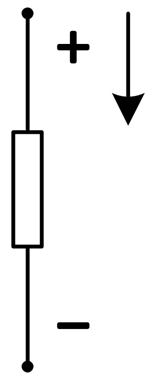
$$S=V_{rms}\times I_{rms}$$

- **Power Factor (PF)**:

$$PF=\frac{average\ power}{apparent\ power}=\frac{P}{V_{rms}.I_{rms}}=\frac{\frac{1}{T}\int_{t_0}^{t_0+T}v(t).i(t)dt}{V_{rms}.I_{rms}}$$

Power Calculations

- **Power Computations for Sinusoidal AC Circuit**



$$i(t) = I_m \cos(\omega t + \phi)$$

$$v(t) = V_m \cos(\omega t + \theta)$$

$$T = \frac{2\pi}{\omega}$$

$$I_{rms} = \frac{I_m}{\sqrt{2}}$$

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

$$\sin(A)\cos(B) = \frac{1}{2}\left[\sin(A+B) + \sin(A-B)\right]$$

$$\cos(A)\sin(B) = \frac{1}{2}\left[\sin(A+B) - \sin(A-B)\right]$$

$$\cos(A)\cos(B) = \frac{1}{2}\left[\cos(A+B) + \cos(A-B)\right]$$

$$\sin(A)\sin(B) = \frac{1}{2}\left[\cos(A-B) - \cos(A+B)\right]$$

Instantaneous power: $p(t) = v(t) \times i(t) = \frac{V_m I_m}{2}\left[\cos(2\omega t + \theta + \phi) + \cos(\theta - \phi)\right]$

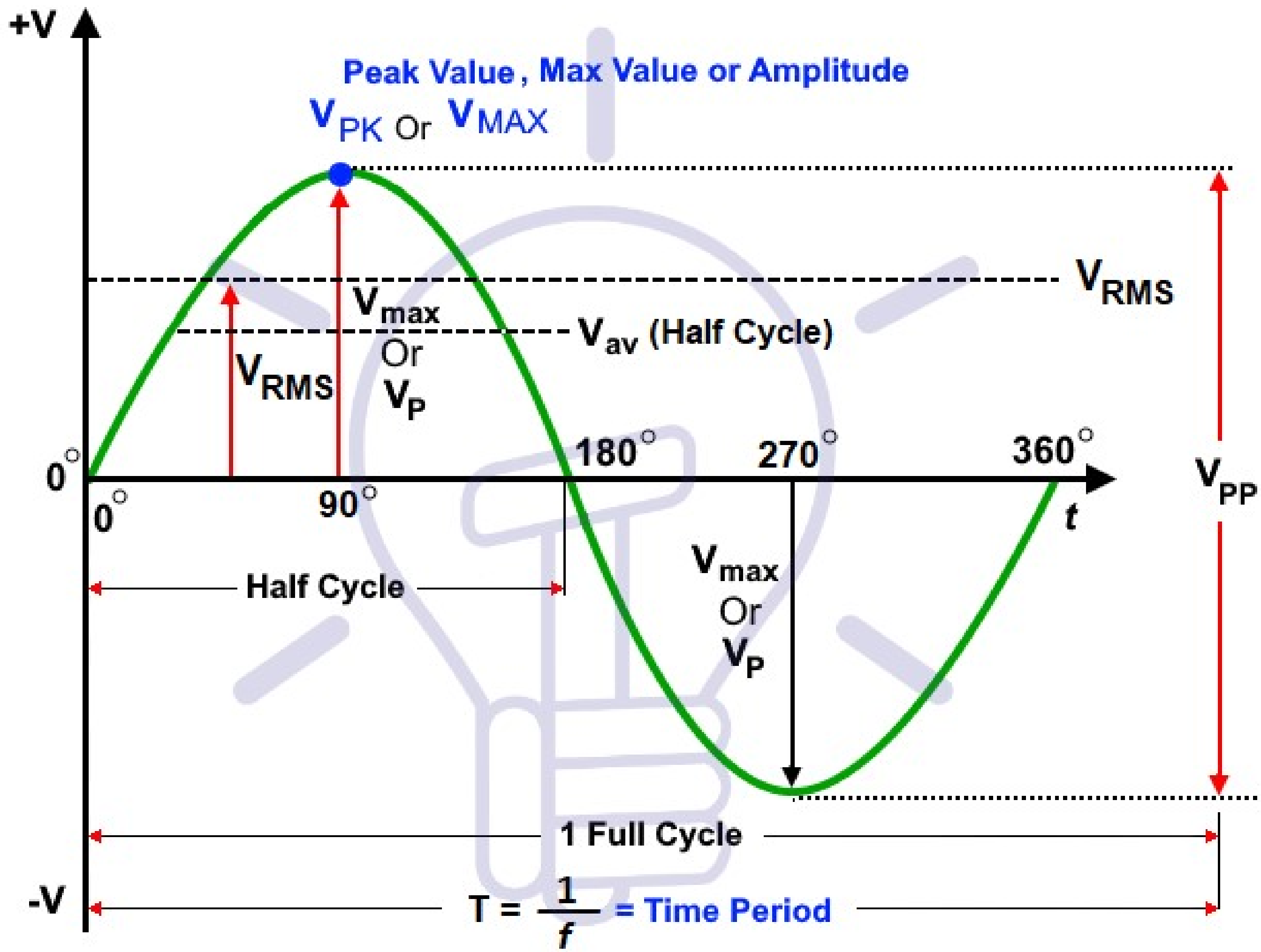
Average power:

$$P = \frac{1}{T}\int_0^T p(t)dt = \frac{V_m I_m}{2T}\int_0^T \left[\overbrace{\cos(2\omega t + \theta + \phi)}^{avrage\ \ value=0} + \cos(\theta - \phi)\right]dt$$

$$P = \frac{V_m I_m}{2}\cos(\theta - \phi) = \frac{V_m}{\sqrt{2}}\frac{I_m}{\sqrt{2}}\cos(\theta - \phi) = V_{rms} \times I_{rms} \times \cos(\theta - \phi)$$

$$PF = \frac{average\ power}{apparent\ power} = \frac{P}{V_{rms}.I_{rms}} = \frac{V_{rms} \times I_{rms} \times \cos(\theta - \phi)}{V_{rms}.I_{rms}} = \cos(\theta - \phi)$$

Power Calculations



Total harmonic distortion (THD)

(THD): is a term used to quantify the **nonsinusoidal** property of a waveform.

THD is the ratio of the rms value of all the nonfundamental frequency terms to the rms value of the fundamental frequency term.

$$\mathrm{THD} = \sqrt{\frac{\sum_{n\neq 1} I^2_{n,\,\mathrm{rms}}}{I^2_{1,\,\mathrm{rms}}}} = \frac{\sqrt{\sum_{n\neq 1} I^2_{n,\,\mathrm{rms}}}}{I_{1,\,\mathrm{rms}}}$$

THD is equivalently expressed as:

$$\mathrm{THD} = \sqrt{\frac{I^2_{\mathrm{rms}} - I^2_{1,\,\mathrm{rms}}}{I^2_{1,\,\mathrm{rms}}}}$$

Example: A sinusoidal voltage source of $v(t)$=100 cos(314t) V is applied to a nonlinear load, resulting in a nonsinusoidal current which is expressed in Fourier series form as:

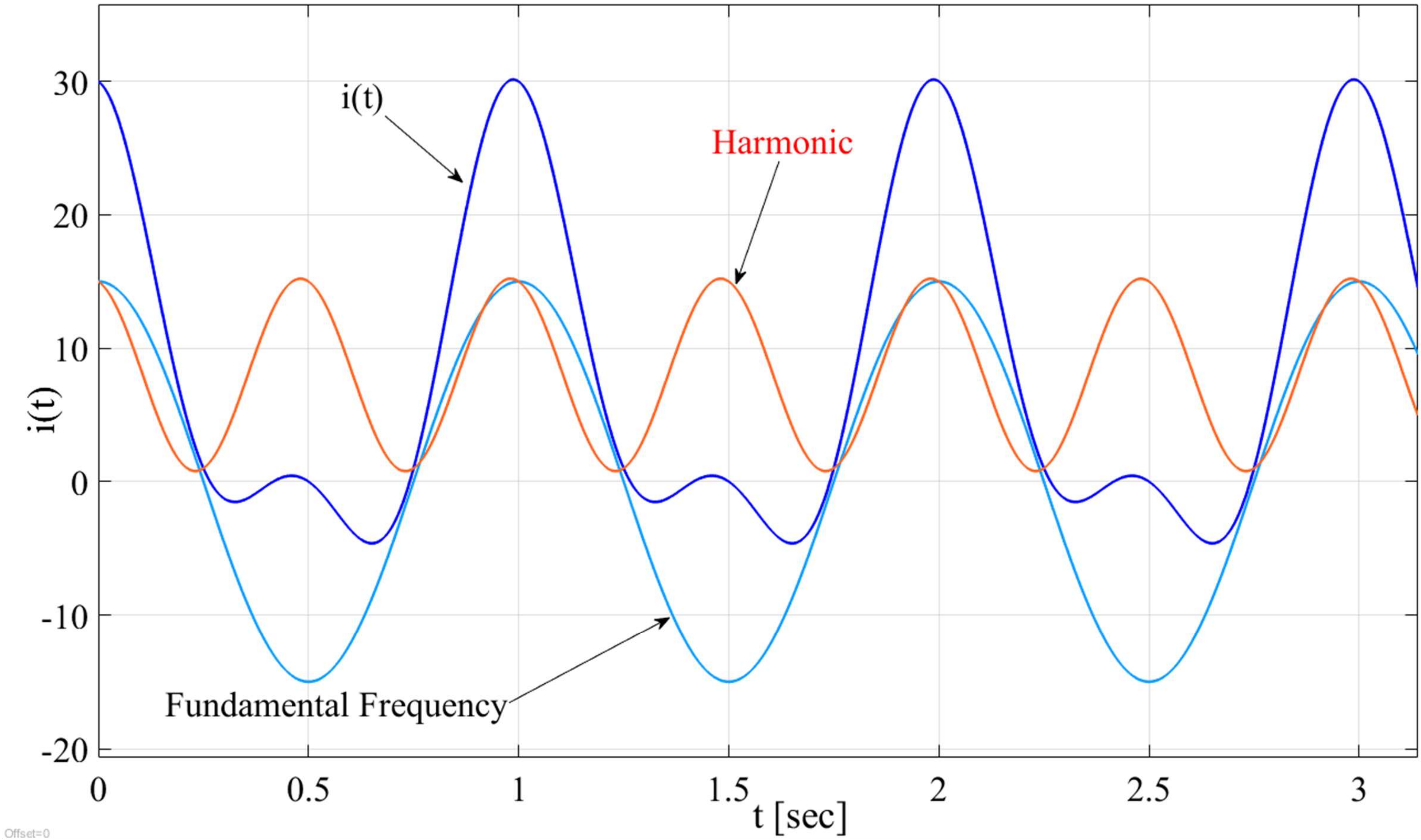
$$i(t) = 8 + 15\cos(314t + 30°) + 6\cos[2(314)t + 45°] + 2\cos[3(314)t + 60°]$$

Determine the total harmonic distortion of the load current.

Solution

$$I_{rms} = \sqrt{8^2 + \left(\frac{15}{\sqrt{2}}\right)^2 + \left(\frac{6}{\sqrt{2}}\right)^2 + \left(\frac{2}{\sqrt{2}}\right)^2} = 14$$

$$THD = \sqrt{\frac{I^2_{rms} - I^2_{1,rms}}{I^2_{1,rms}}} = \sqrt{\frac{14^2 - \left(\frac{15}{\sqrt{2}}\right)^2}{\left(\frac{15}{\sqrt{2}}\right)^2}} = 0.86 = 86\%$$



i(t)
Harmonic
Fundamental Frequency
30
20
10
0
-10
-20
0
0.5
1
1.5
2
2.5
3
t [sec]
i(t)
Offset=0

Questions and comments are most welcome!