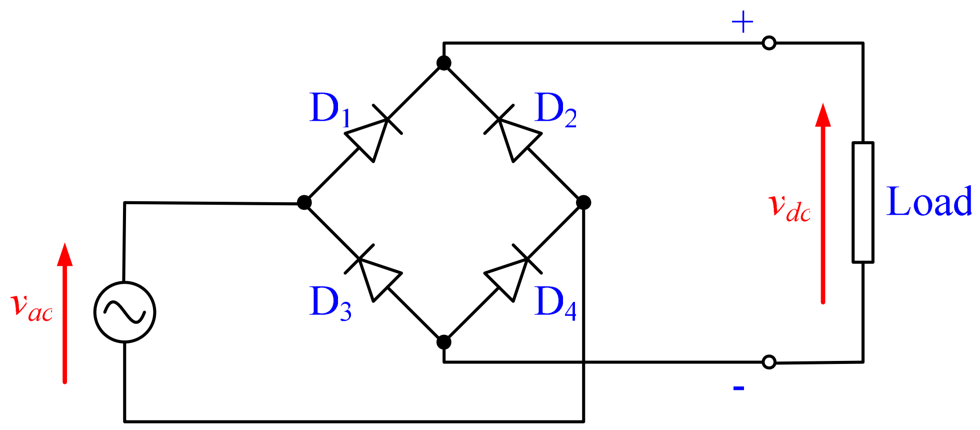
Electrical Power Engineering 3

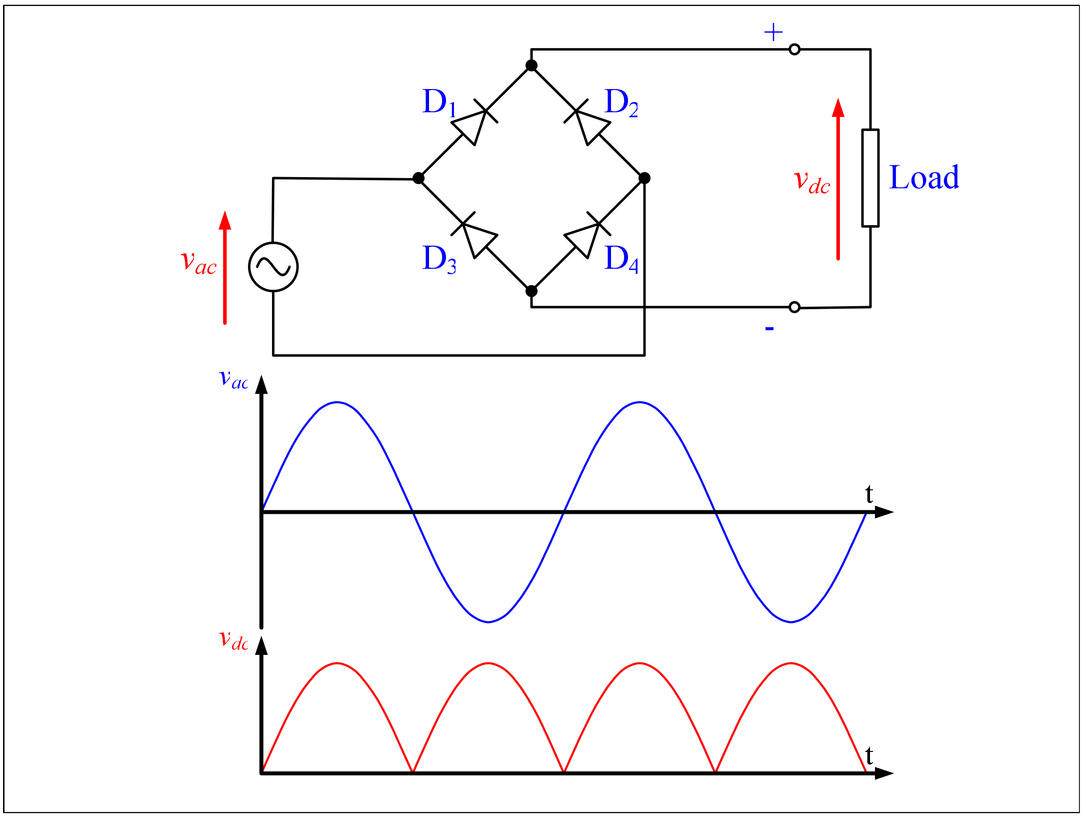
Power Electronics

Rectifier Circuits

Converts ac to dc.

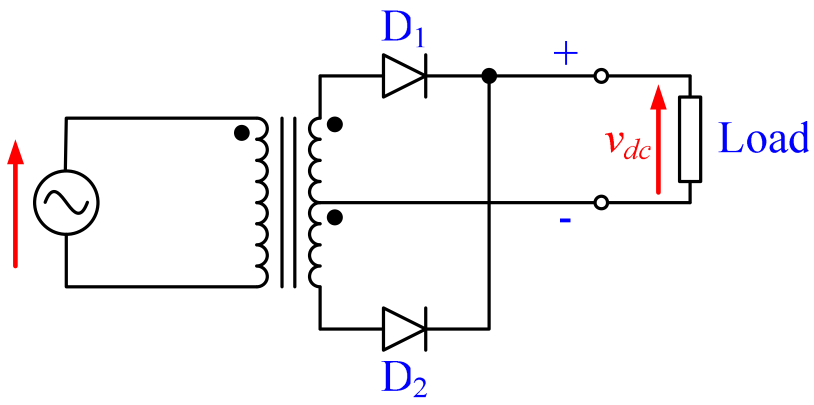
One Phase Bridge Rectifier



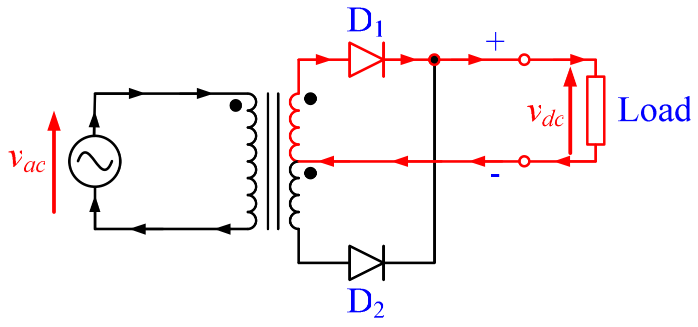


The single phase diode bridge is the most common circuit for converting ac to dc. Diodes D_1 and D_4 conduct in the positive ½ cycle of the input voltage, and diodes D_2 and D_3 in the negative ½ cycle. The output is a set of ½ sine waves.

Centre-Tapped Transformer Rectifier

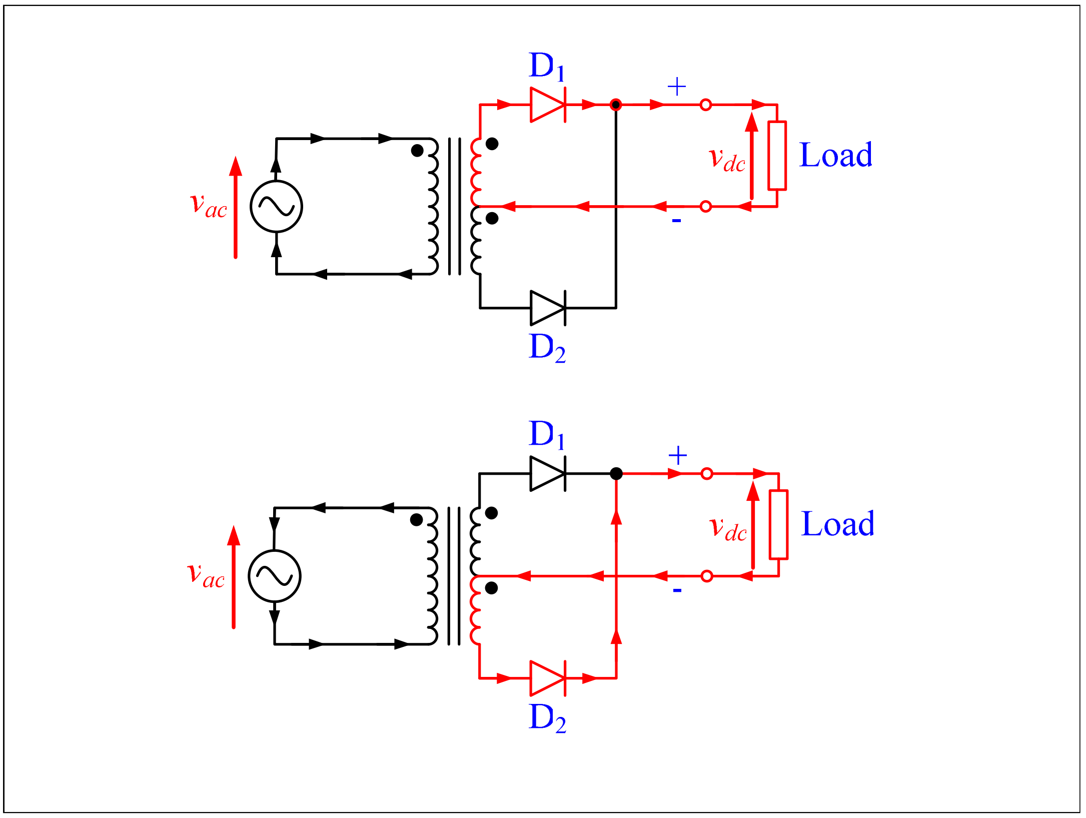


An alternative to the Bridge Rectifier is the Centre-Tapped Transformer Rectifier



During the positive ½ cycle, current flows *into the dot* on the transformer primary (remember the transformer dot notation), therefore it must flow *out of the dot* on the secondary.

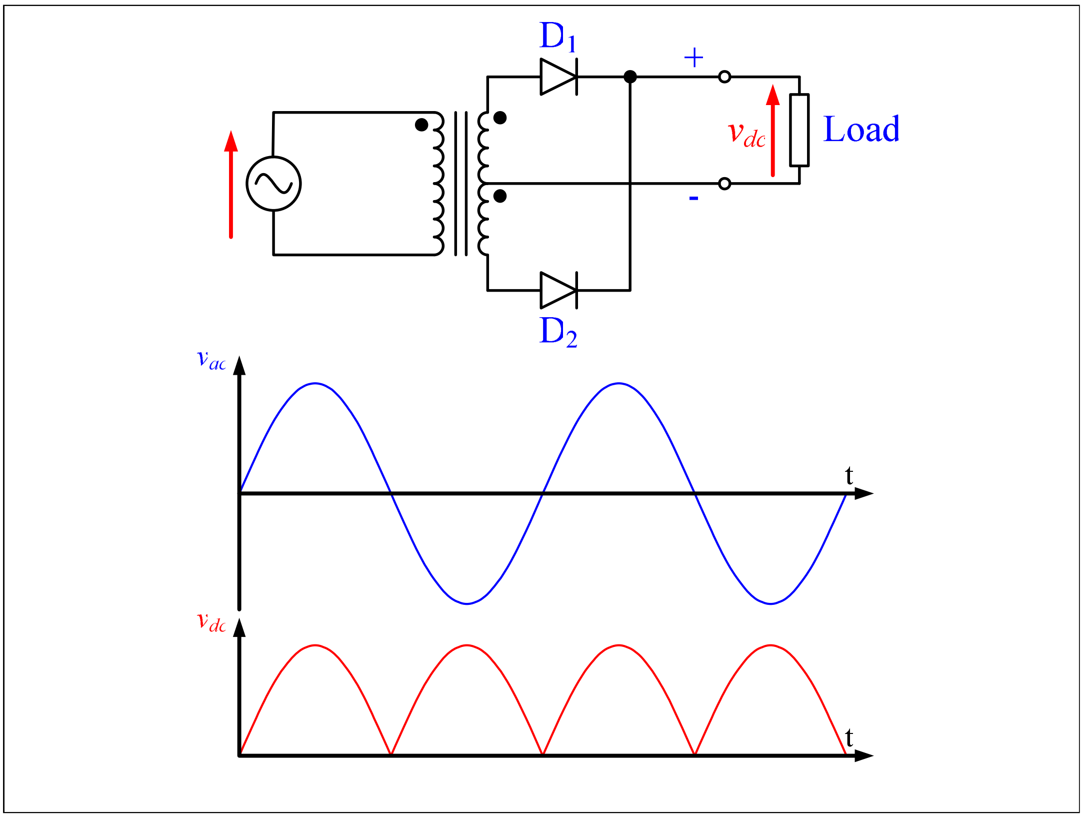
Thus current flows out of the dot of the top half, through D_1, down through the load and back to the centre tap on the transformer. Current cannot flow out of the dot on the lower half, as current would then be going backwards through diode D_2, therefore no current flows in the lower half of the transformer.



During the negative ½ cycle, current flows *out of the dot* on the transformer primary therefore it must flow *into the dot* on the secondary.

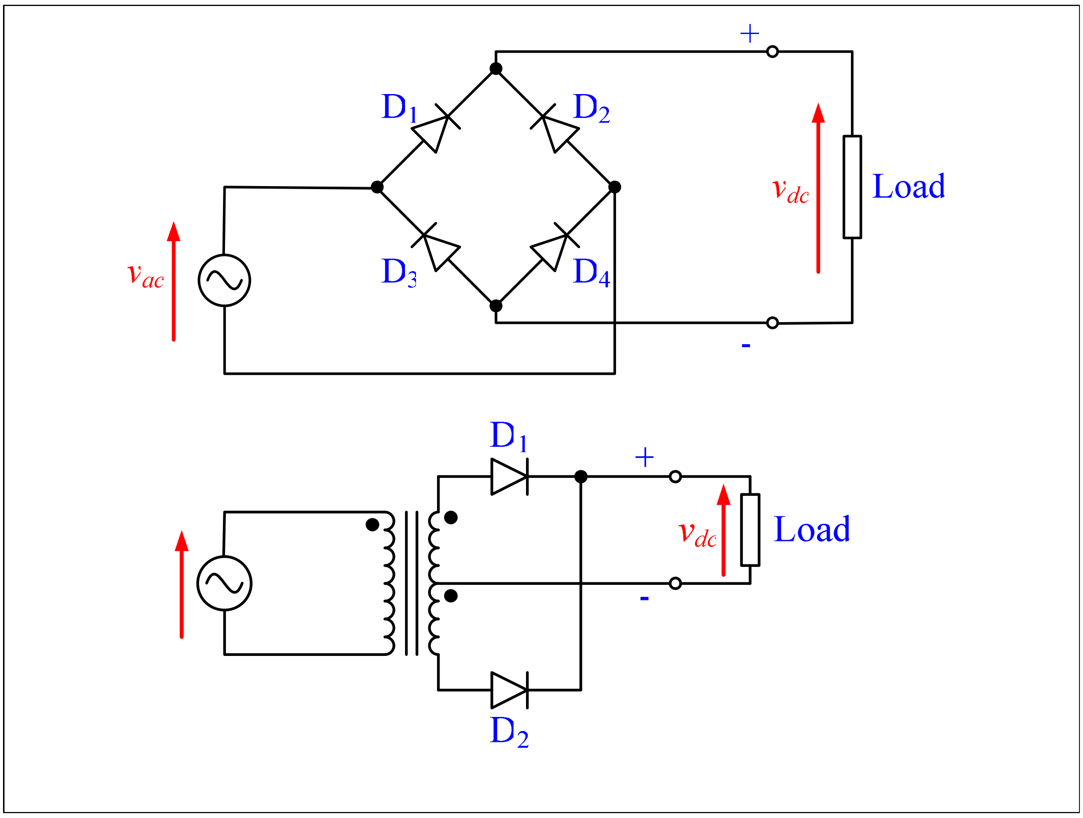
Current cannot flow into the dot on the upper half, as current would then be going backwards through diode D_1. However, current can flow into the dot on the lower half of the transformer secondary, forwards through D_2, up to the positive rail and down through the load and back to the centre tap.

Note that current is flowing down through the load in both half cycles, ie. rectification has taken place.



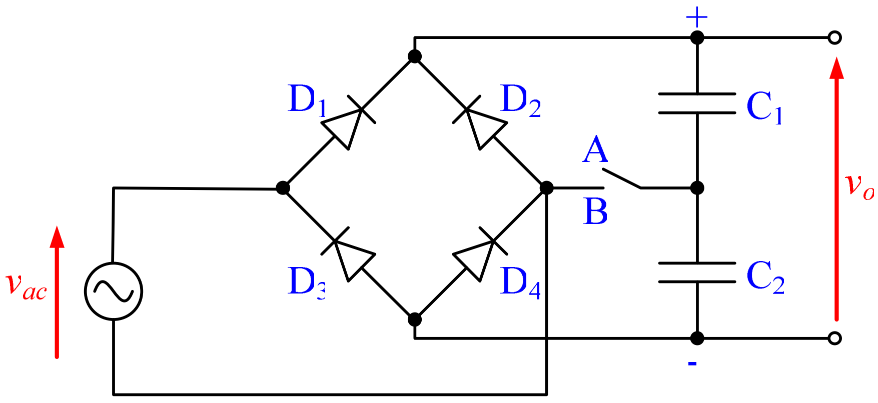
The output waveform is exactly the same as that of the diode bridge rectifier.

A transformer is required for this circuit, which can add to the size and weight considerably. However, a transformer may be required for other reasons (eg. for isolation, or to step-down the voltage), and the circuit uses only 2 diodes compared to 4 in the bridge rectifier.

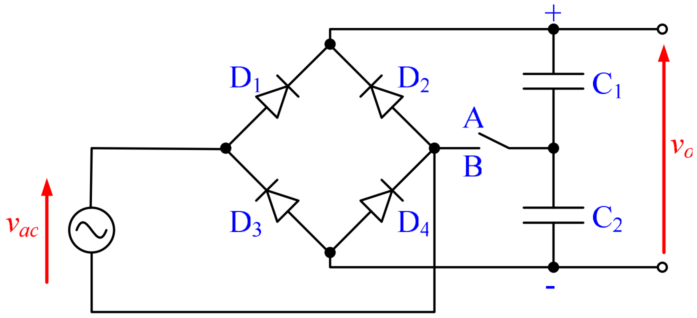


+
D1
D2
v_{dc}
Load
v_{ac}
D3
D4
-
D1
+
v_{dc}
Load
-
D2

Switchable 230/110 Volt Rectifier

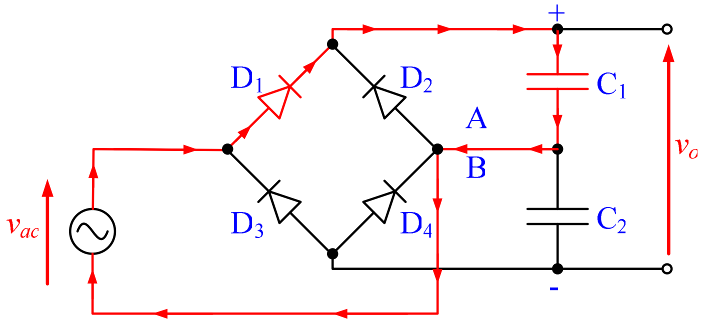


The inclusion of the switch and the centre-tapped capacitor network allows the power supply to operate either form a 230 volt input (eg in Europe) or 110 volt input (eg in the USA).



Position A:

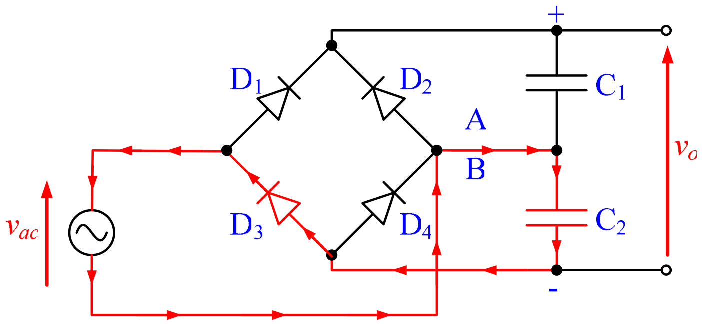
- Standard diode bridge
- $V_o \approx \sqrt{2}\ .\ 230 = 325$ V



Position B:

- Positive ½ cycle
  - C1 charged to peak ac volts

If a 110 (or 115) volt input is used, then the switch should be moved to position B. In this case the upper capacitor will be charged during the positive half cycle, and the lower capacitor during the negative half cycle.

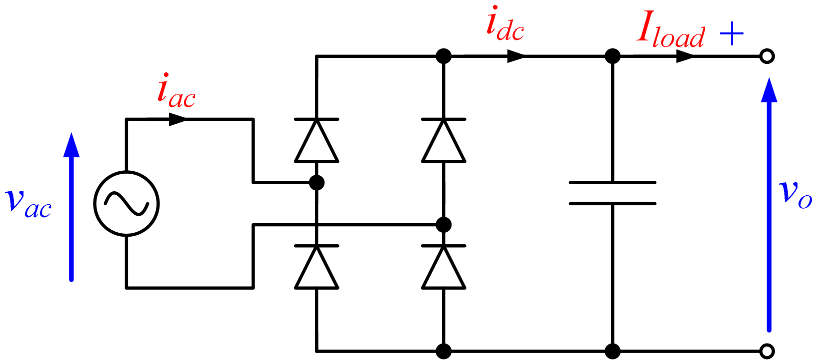


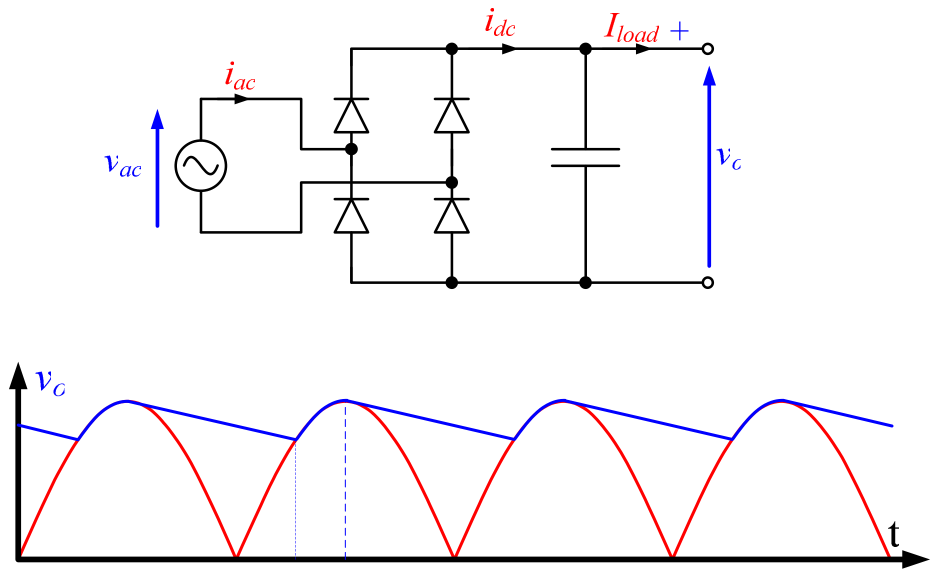
Position B:

- Positive ½ cycle
  - – C1 charged to peak ac volts
- Negative ½ cycle
  - – C2 charged to peak ac volts
- $V_o \approx 2 \times \sqrt{2} \times 110 = 311V$

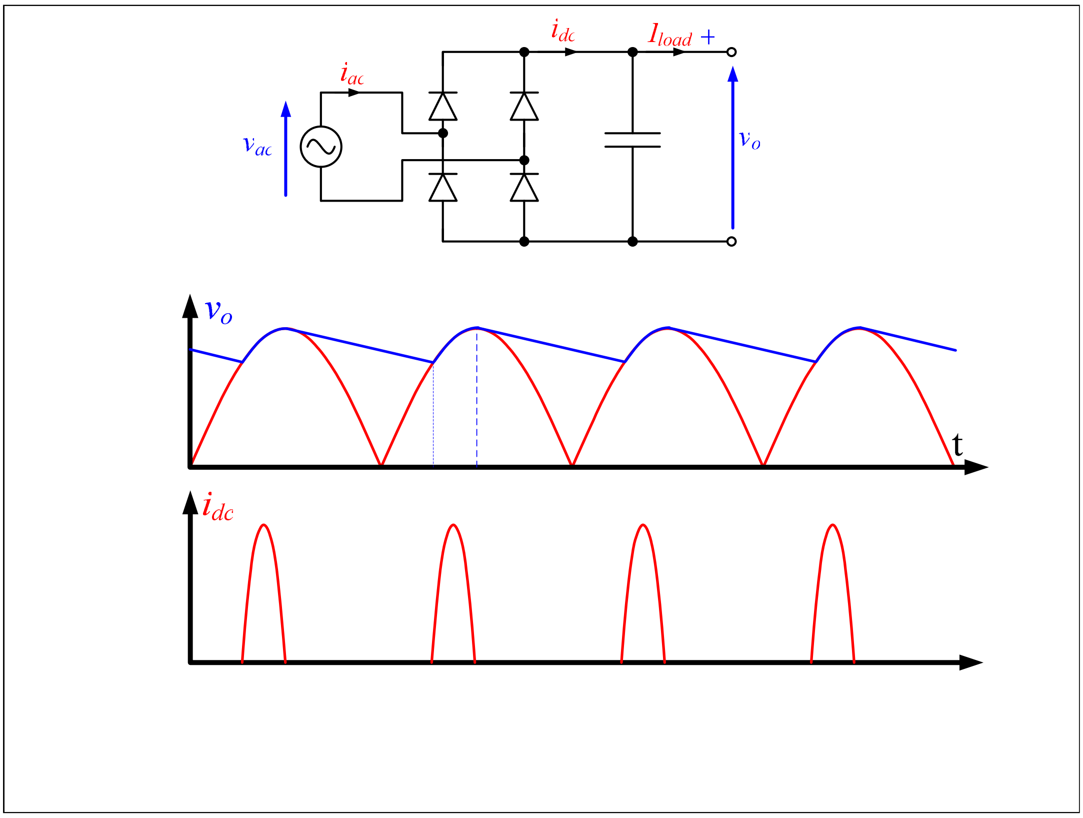
The total output voltage is approximately the same as for a 230 volt supply with the switch in position A, therefore any loading on the power supply can be identical.

1-Phase Rectifier with Capacitor Smoothing

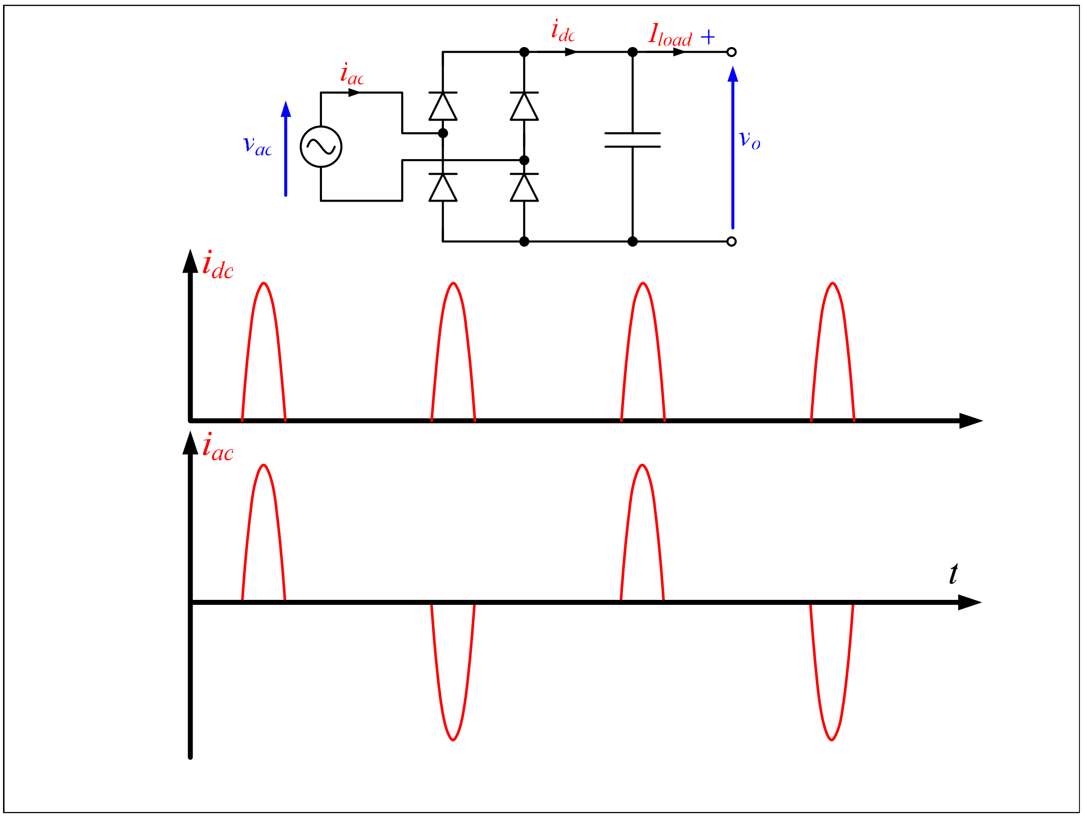




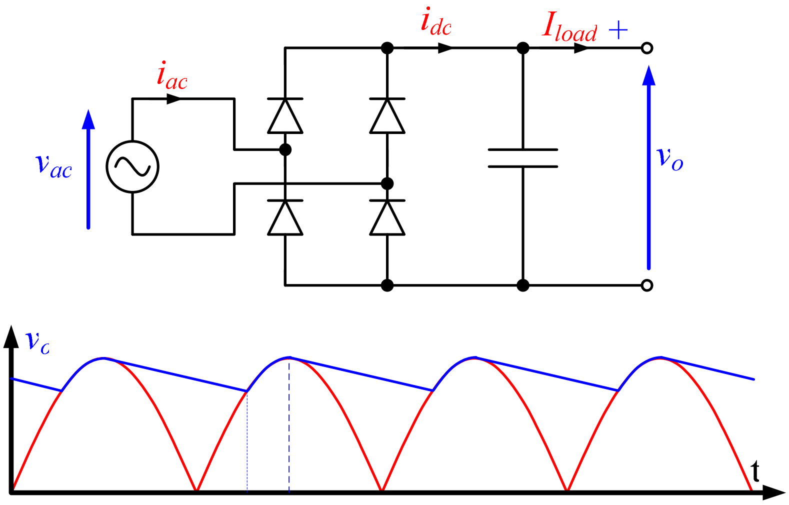
i_{ac}
v_{ac}
i_{dc}
I_{load} +
v_c
v_C
t



i_{dc}
I_{load} +
i_{ac}
v_{ac}
v_o
v_o
t
i_{dc}



The output voltage v_o, the charging current i_{dc} and the ac current i_{ac} are shown above. It can be seen that i_{dc} is a very narrow current spike. If a smoother dc supply is required, the capacitor C must be made larger. However, this also has the effect of making the current spike narrow, and hence taller (to pass the same energy.



$$C = \frac{power}{\left(v_{max}^2 - v_{min}^2\right)} \times \frac{1}{f}$$

The size of the capacitor depends on the level of smoothing required. The capacitor discharges from V_{max} to V_{min} through the load in approximately half an ac cycle, ie in time 1/(2*f*) where *f* is the supply frequency.

$$Power \approx \frac{\left(V_{max} - V_{min}\right)}{2} \times I_{load}$$

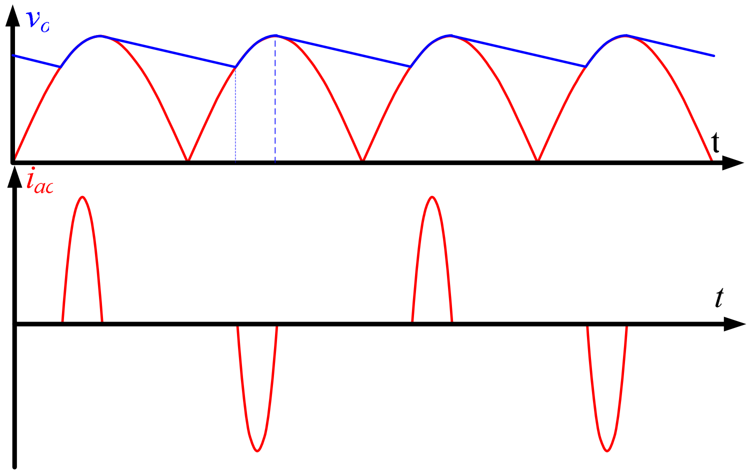
In a capacitor, *Q* = *CV,* therefore as the capacitor discharges:

$$\begin{aligned} \delta Q &= C.\delta V \\ &= C.\left(V_{max} - V_{min}\right) \\ &= \frac{I_{load}}{2f} \end{aligned}$$

(charge = current x time)

Combining the above:

$$\begin{aligned} C &= \frac{power}{\left(V_{max} - V_{min}\right) \times \left(V_{max} + V_{min}\right)} \times \frac{1}{f} \\ &= \frac{power}{\left(V_{max}^2 - V_{min}^2\right)} \times \frac{1}{f} \end{aligned}$$



- Smoother output requires bigger capacitor
  - – narrower, taller spike (for same energy)
- EC regulations limiting harmonic currents

New EC regulations have been introduced which severely limit the harmonic current equipment sold in the EU is allowed to draw from the mains supply.

This necessitates either large, expensive passive filters (L-C), or active filtering, which is far more complex.

Effect of Harmonic Currents

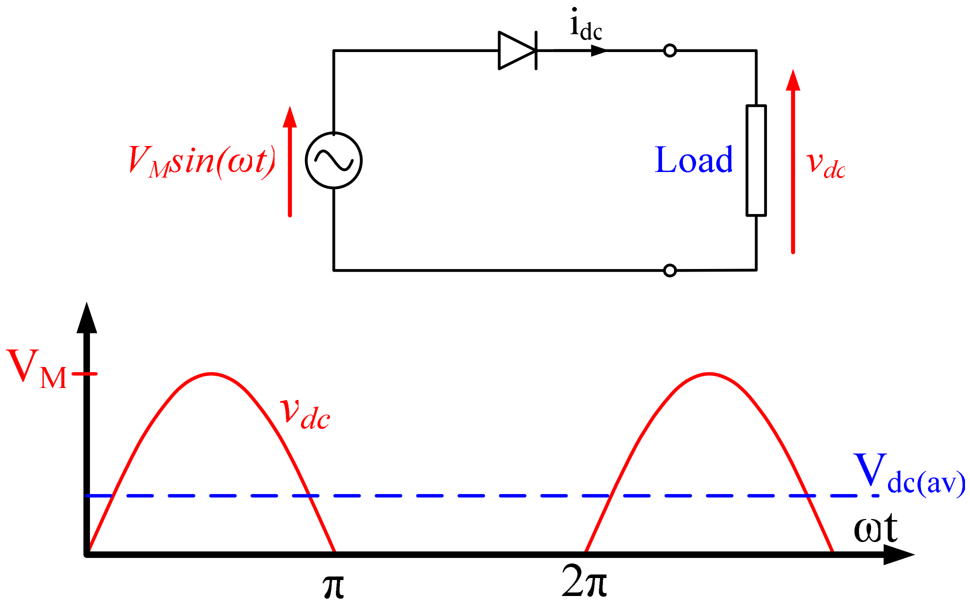
- Distortion of voltage waveform
- Harmonic heating of distribution transformers
- Production of EMI
- High neutral currents
- Nuisance tripping of circuit breakers

Electrical Power Engineering 3

Power Electronics

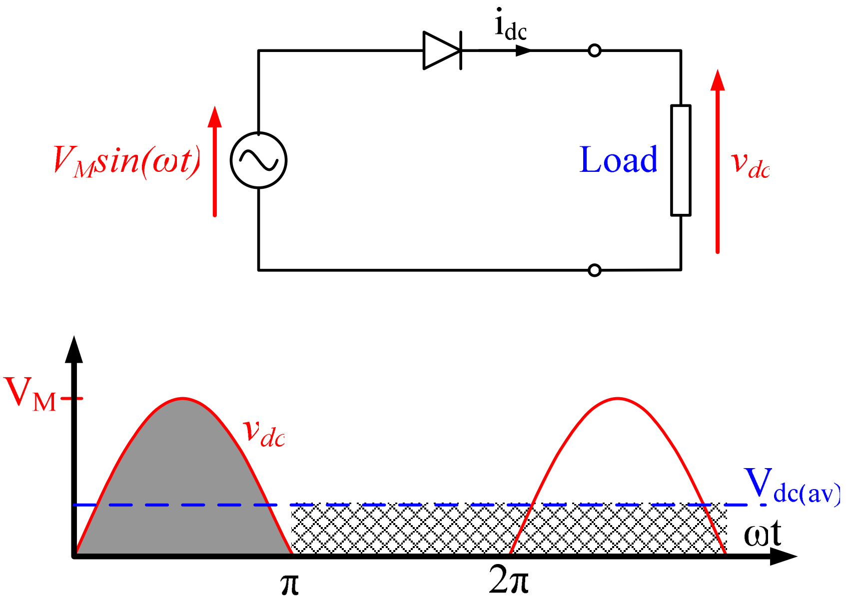
½ Wave Rectifiers

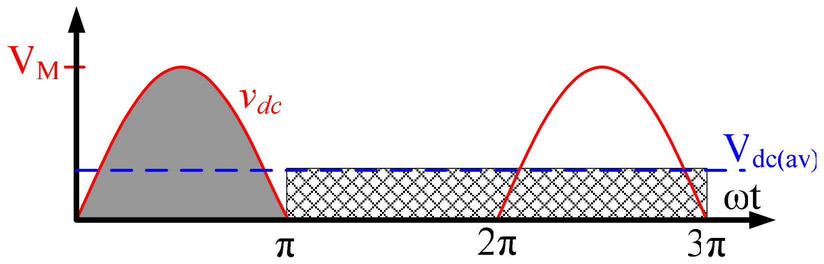
Single Diode with Resistive Load



The single diode ½-wave rectifier blocks the negative ½ cycle.

Single Diode with Resistive Load





$$V_{dc} \times 2\pi = area\ under\ curve$$

$$V_{dc} = \frac{1}{2\pi}\left(\int_0^{\pi} V_M . \sin \omega t . d(\omega t) + \int_{\pi}^{2\pi} 0 . d(\omega t)\right)$$

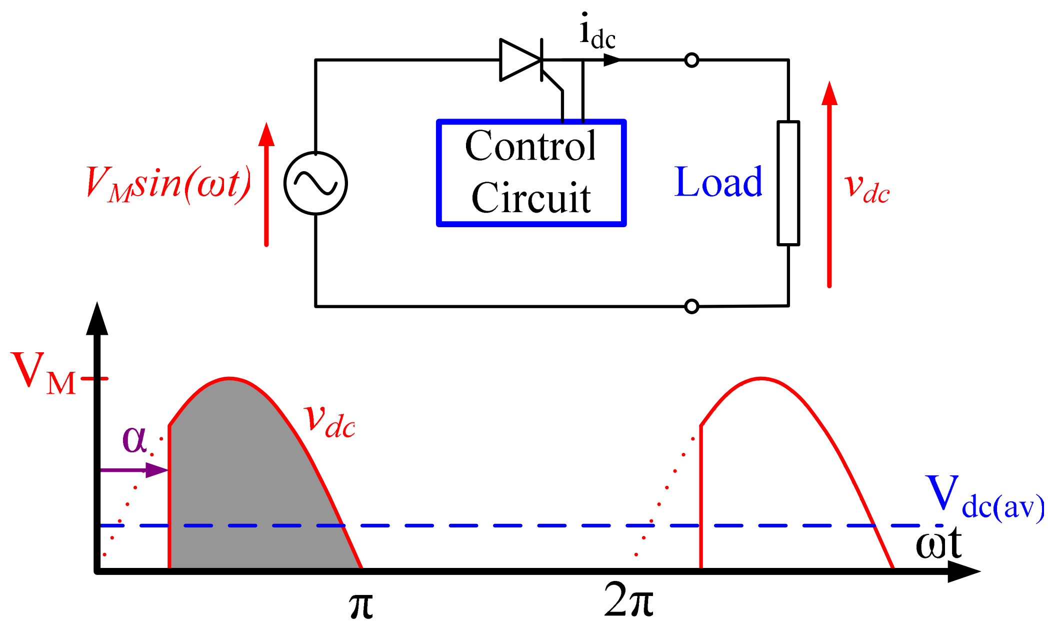
$$V_{dc} = \frac{V_M}{\pi}$$

The average dc voltage is such that the shaded area = the hatched area (ie. the area under the curve over one cycle = area under $V_{dc(av)}$ over one cycle).

$$V_{dc} \times 2\pi = area\ under\ curve$$

$$\begin{aligned}
V_{dc} &= \frac{1}{2\pi}\left(\int_0^{\pi} V_M . \sin \omega t . d(\omega t) + \int_{\pi}^{2\pi} 0 . d(\omega t)\right) \\
&= \frac{V_M}{2\pi} \times \left[-\cos t(\omega t)\right]_0^{\pi} + 0 \\
&= \frac{V_M}{2\pi} \times (1+1) \\
V_{dc} &= \frac{V_M}{\pi}
\end{aligned}$$

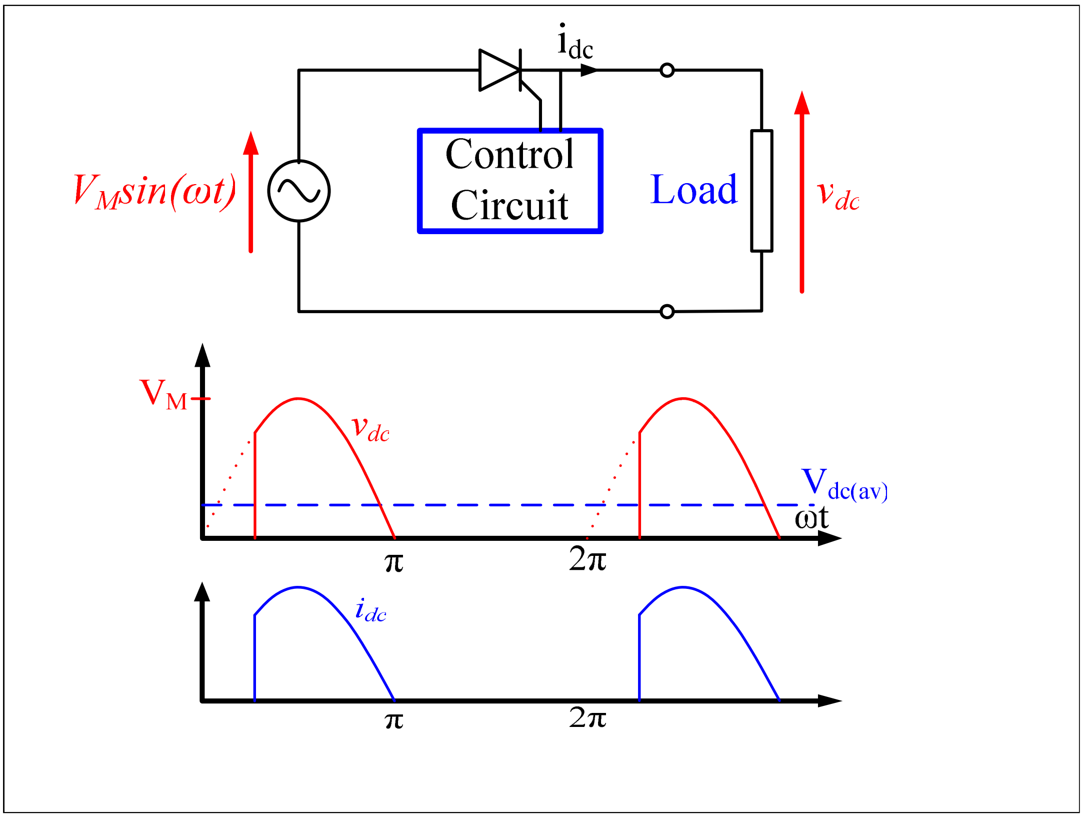
Single Thyristor with Resistive Load



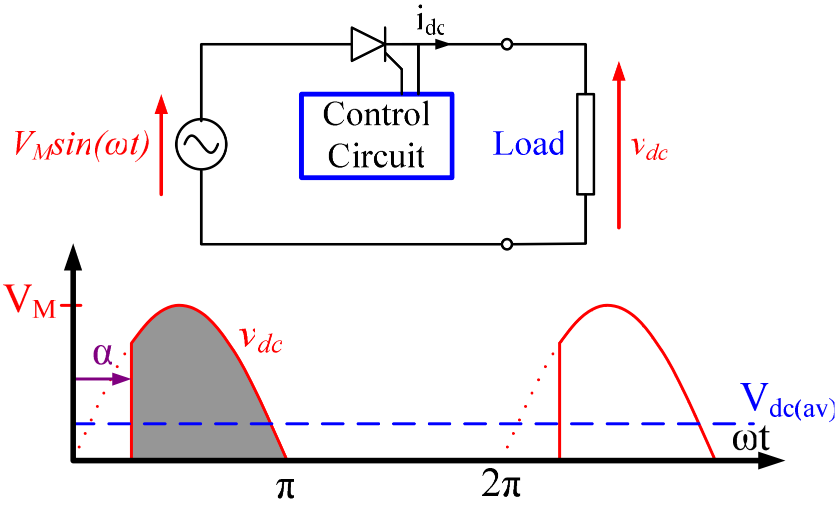
The diode can be replaced by a thyristor, which will block (even in the forward direction) until it is switched on at the appropriate time by the control circuit sending a pulse to the thyristor gate.

The delay angle α is the angle between when a diode would start to conduct and when the thyristor is fired.

Thus a diode is similar to a thyristor with α = 0.



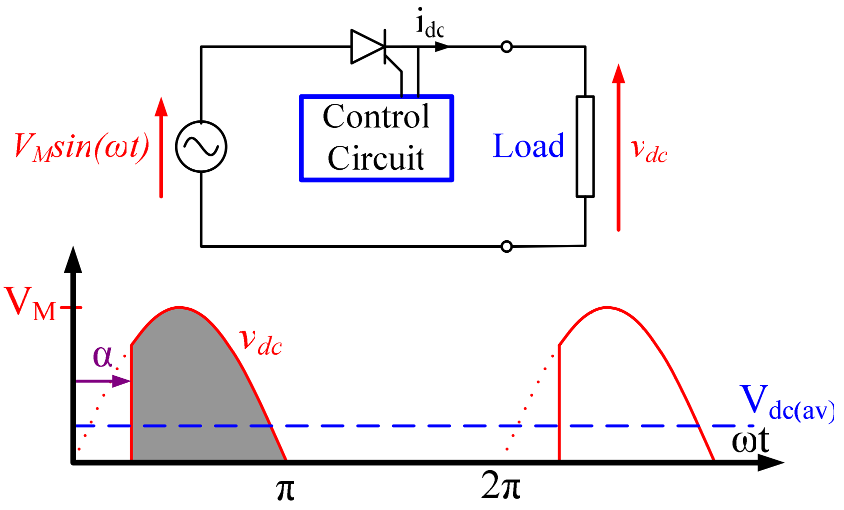
If the load is resistive, $V = IR$, therefore the current waveshape is the same as the voltage waveshape.



$$V_{dc} \times 2\pi = \int_{\alpha}^{\pi} V_M . \sin \omega t . d(\omega t)$$

$$V_{dc} = \frac{V_M}{2\pi}(1 + \cos \alpha)$$

As with the single diode, the average dc voltage is such that. the area under the curve over one cycle = area under $V_{dc(average)}$ over one cycle).



$$V_{dc} \times 2\pi = \int_{\alpha}^{\pi} V_M . \sin \omega t . d(\omega t)$$

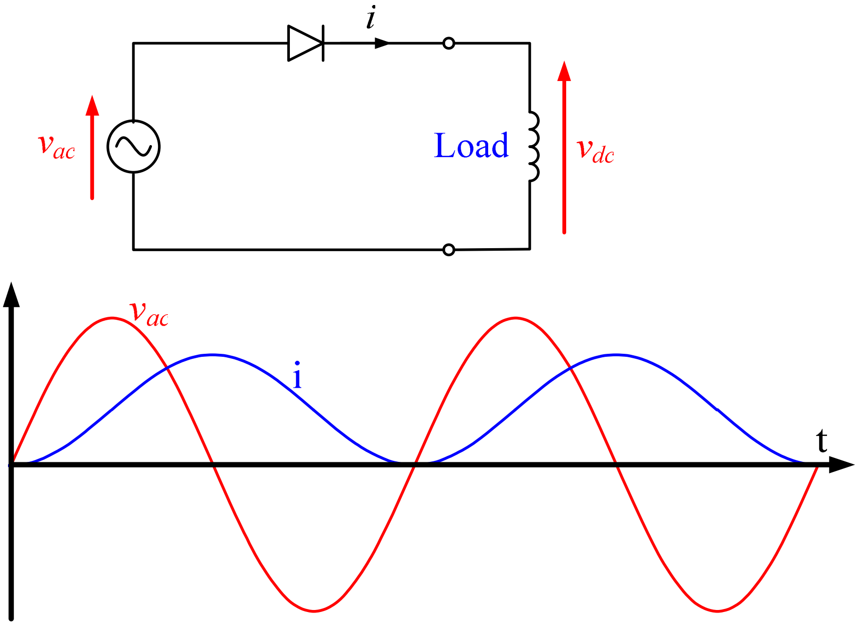
$$V_{dc} = \frac{V_M}{2\pi}(1 + \cos \alpha)$$

If $\alpha = 0$

$$V_{dc} = \frac{V_V}{\pi}$$

A diode is similar to a thyristor with α = 0: same average voltage.

Single Diode with Inductive Load



Voltage across inductor: $v_{dc} = v_L = L \cdot \frac{di}{dt}$

Supply voltage: $v_{ac} = V_M \cdot \sin(\omega t)$

When the diode is conducting, $v_{ac} = v_{dc}$

Therefore:

$$\frac{di}{dt} = \frac{V_M}{L} \cdot \sin(\omega t)$$

Integrating:

$$i = \frac{-V_M}{\omega L} \cdot \cos(\omega t) + C$$

At $t = 0$, $i = 0$, therefore:

$$C = \frac{V_M}{\omega L}$$

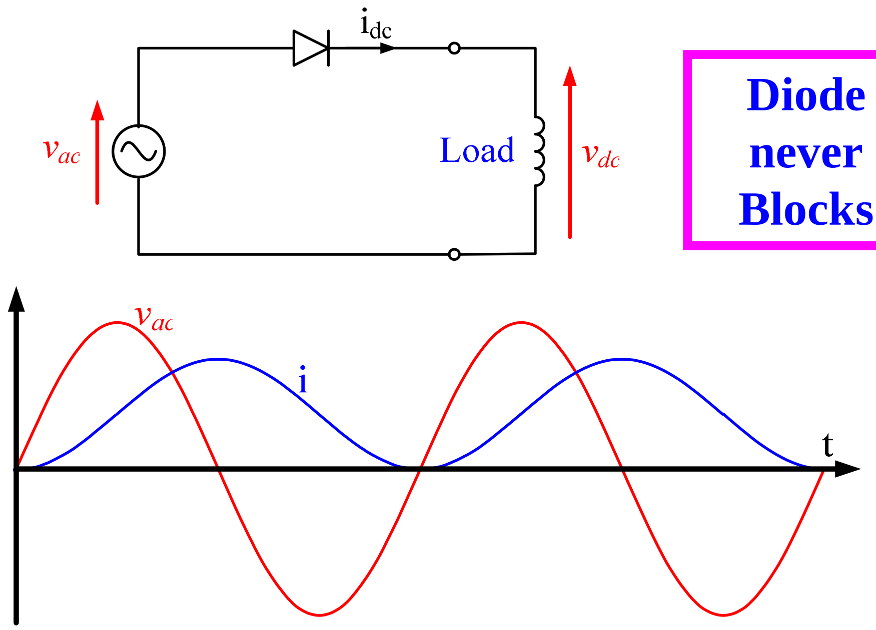
Thus:

$$i(t) = \frac{V_M}{\omega L} \cdot [1 - \cos(\omega t)]$$

Thus *i* never falls below zero, so the **DIODE IS NEVER BLOCKING!!**

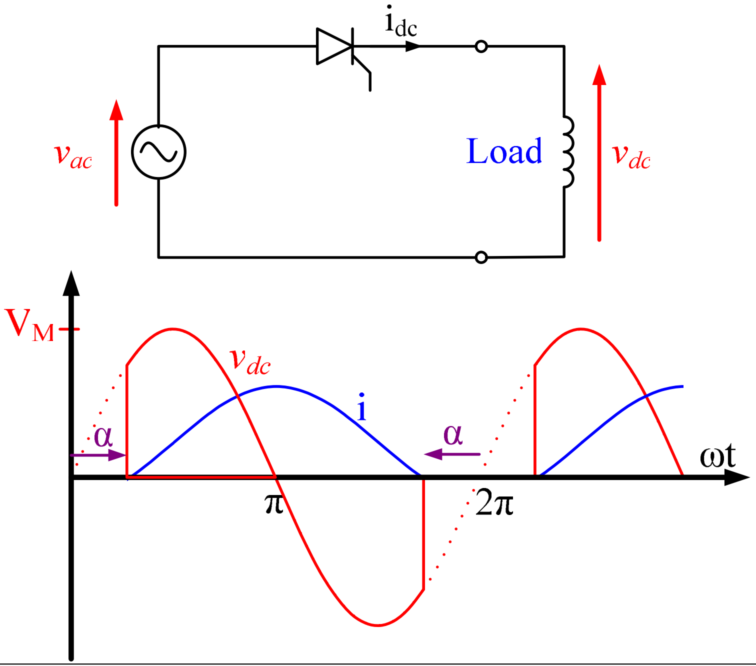
Therefore the inductor voltage $v_{dc} = V_M \cdot \sin(\omega t)$

Single Diode with Inductive Load



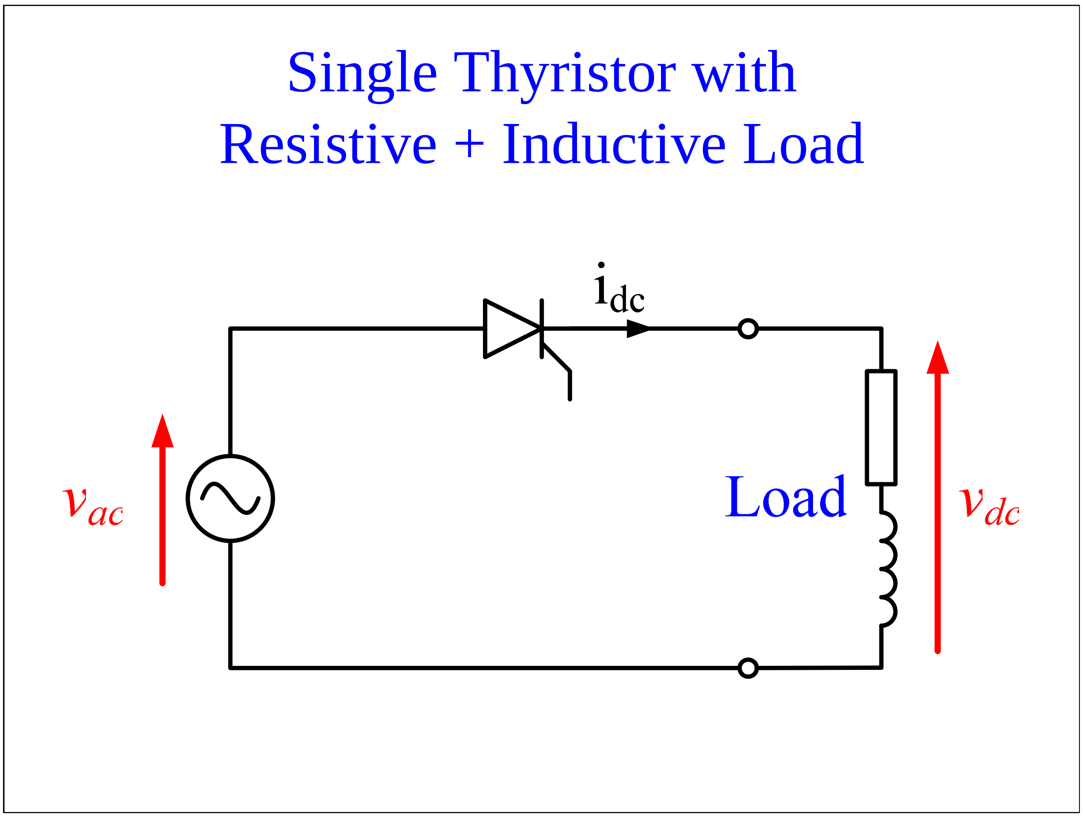
Diode never Blocks

Single Thyristor with Inductive Load

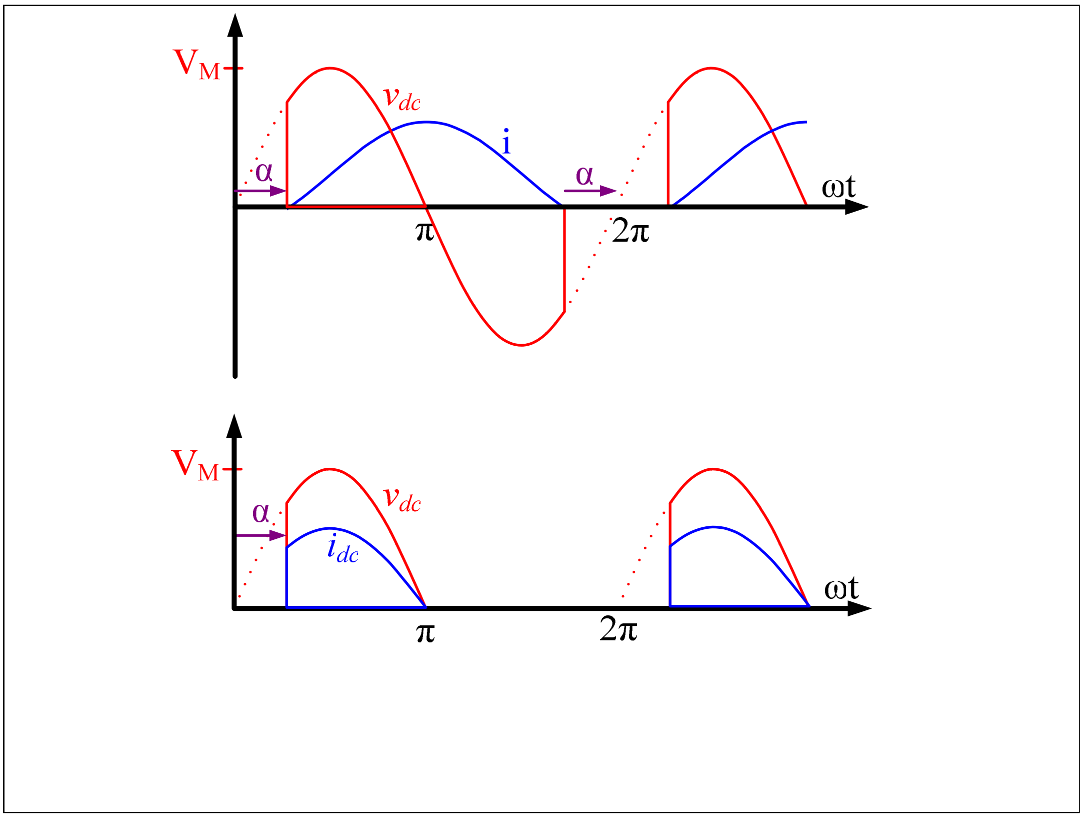


$$v_{dc} = v_L = L \cdot \frac{di}{dt}$$

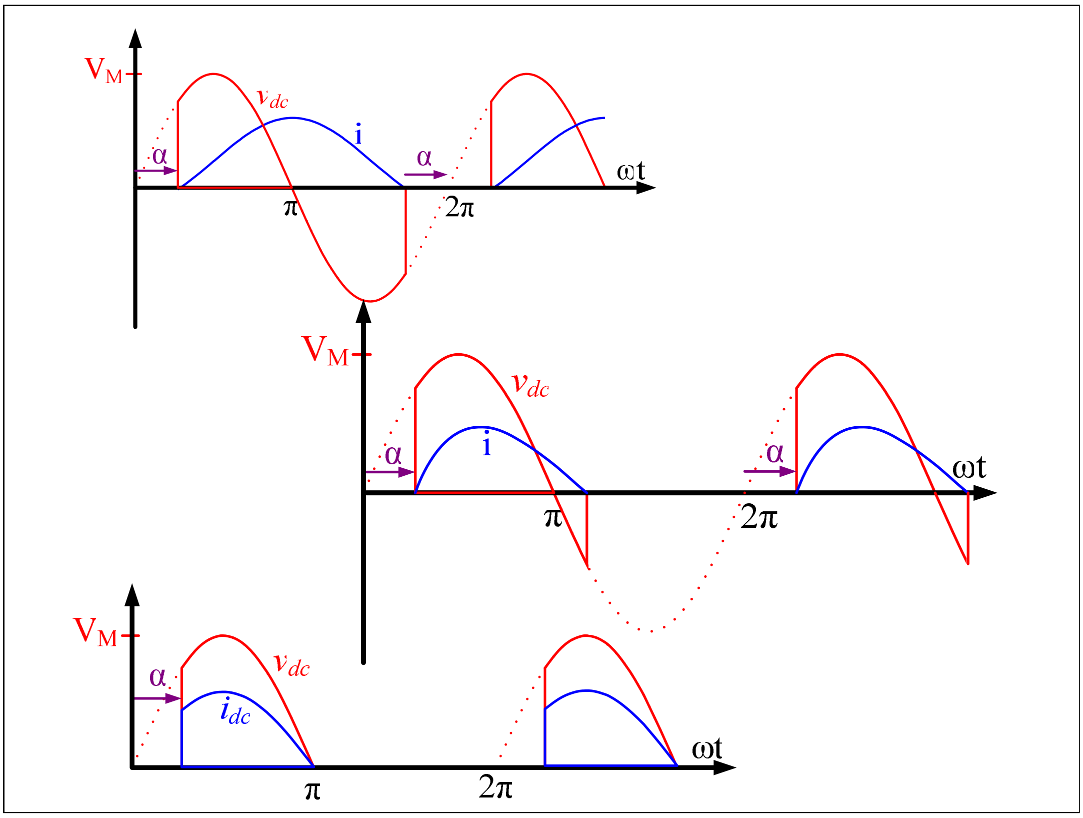
Thus when *v* is positive *I* increases, and when *v* is negative *I* decreases



Real loads always include some resistance.



An R-L load is between a pure inductive load (top waveform) and a pure resistive load (bottom waveform)



Inductive load:

i peaks at π

i falls to zero at (2 π-α)

Resistive load:

i peaks at (π/2)

i falls to zero at π

Resistive+Inductive load:

i peaks between (π/2) and π

i falls to zero between π and (2 π-α)

Exactly where *i* peaks and *i* falls to zero depends on whether the load is mainly resistive or mainly inductive (ie. on the L/R time constant).

Don't try and calculate this – it's a messy calculation!

Electrical Power Engineering 3

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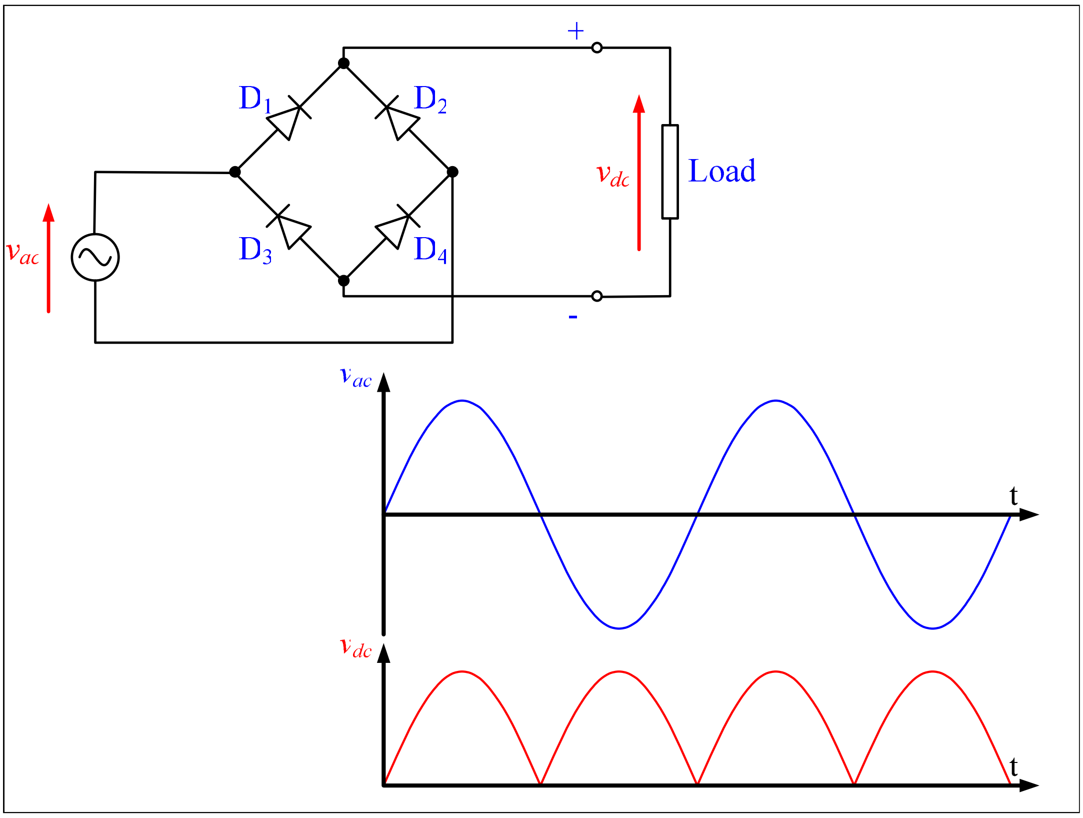
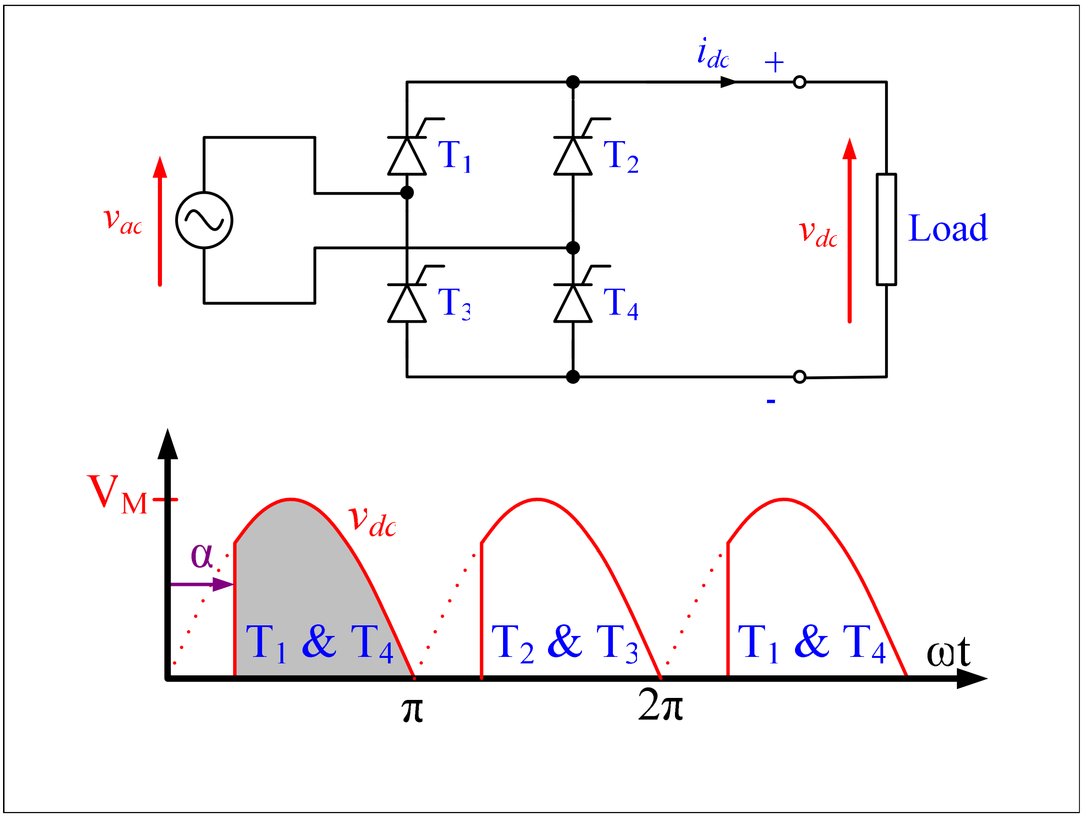
Single Phase Bridge Rectifiers



We’ve looked at this single phase diode bridge earlier in this module.



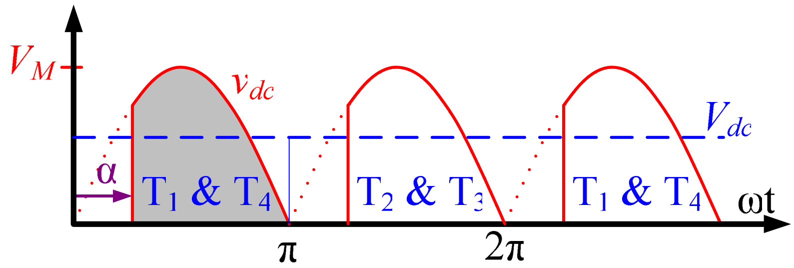
This is the same circuit (just drawn with vertical/horizontal lines rather than diamond-shaped), but with the diodes replaced by thyristors.

Now we can control when the device turns on (gate pulse applied at angle α), thus controlling the output voltage.

This is drawn for a pure resistive load, so $i = v/R$.

Thus $i = 0$ when $v = 0$

Thus the thyristor turns off at $v = 0$ (ie. when $\omega t = \pi$)



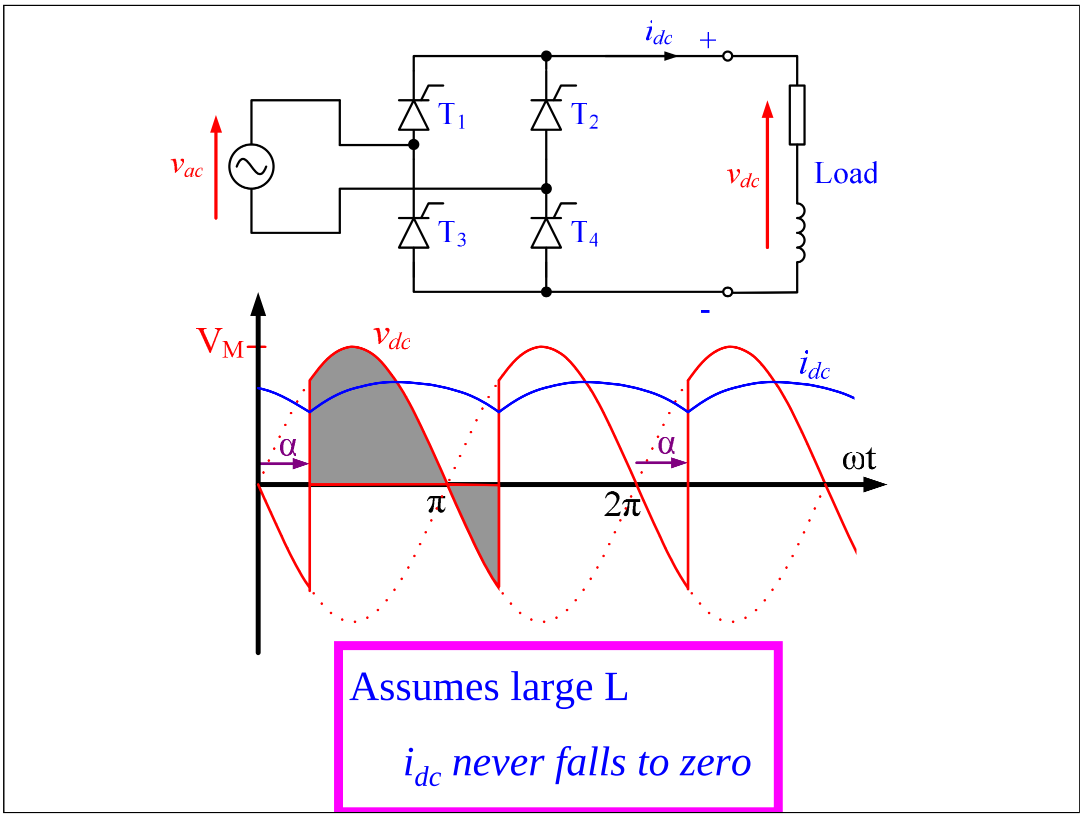
$$V_{dc} \times \pi = \int_{\alpha}^{\pi} V_M . \sin \omega t . d(\omega t)$$

$$V_{dc} = \frac{V_M}{\pi}(1 + \cos \alpha)$$

The average dc voltage across the load is calculated in the usual way,

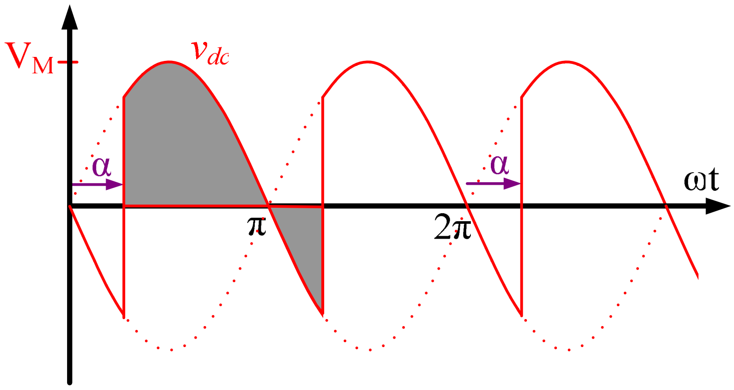
ie. the average dc voltage is such that. the area under the curve over half a cycle = area under $V_{dc(av)}$ over half a cycle.

(The calculation is over just half a cycle, as that is the repeated period: clearly the average voltage over ½ a mains cycle is the same as over a full cycle in this case.)



If the load is inductive + resistive, then the current will still be positive after the voltage has fallen to zero.

Therefore the thyristors will remain on beyond $\omega t = \pi$, resulting in a negative voltage across the load between $\omega t = \pi$ and $\omega t = \pi + \alpha$

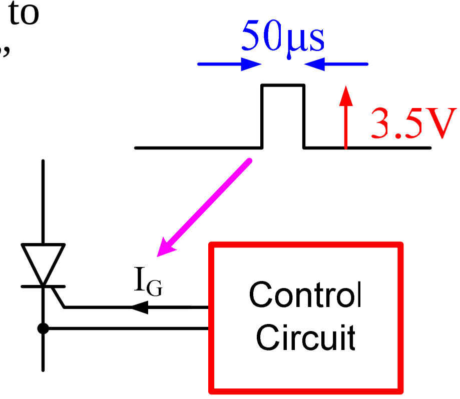


$$V_{dc} \times \pi = \int_{\alpha}^{\pi+\alpha} V_M .\sin \omega t.d(\omega t)$$

$$V_{dc} = \frac{2}{\pi}.V_M .\cos \alpha$$

Thyristor Gate Control Circuits

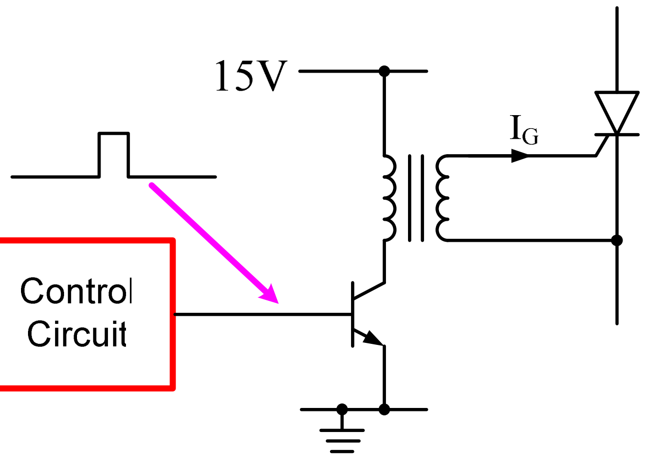
- Short pulses to reduce drive power
- Long enough for current to reach “Latching Current”
- Typically 50μs



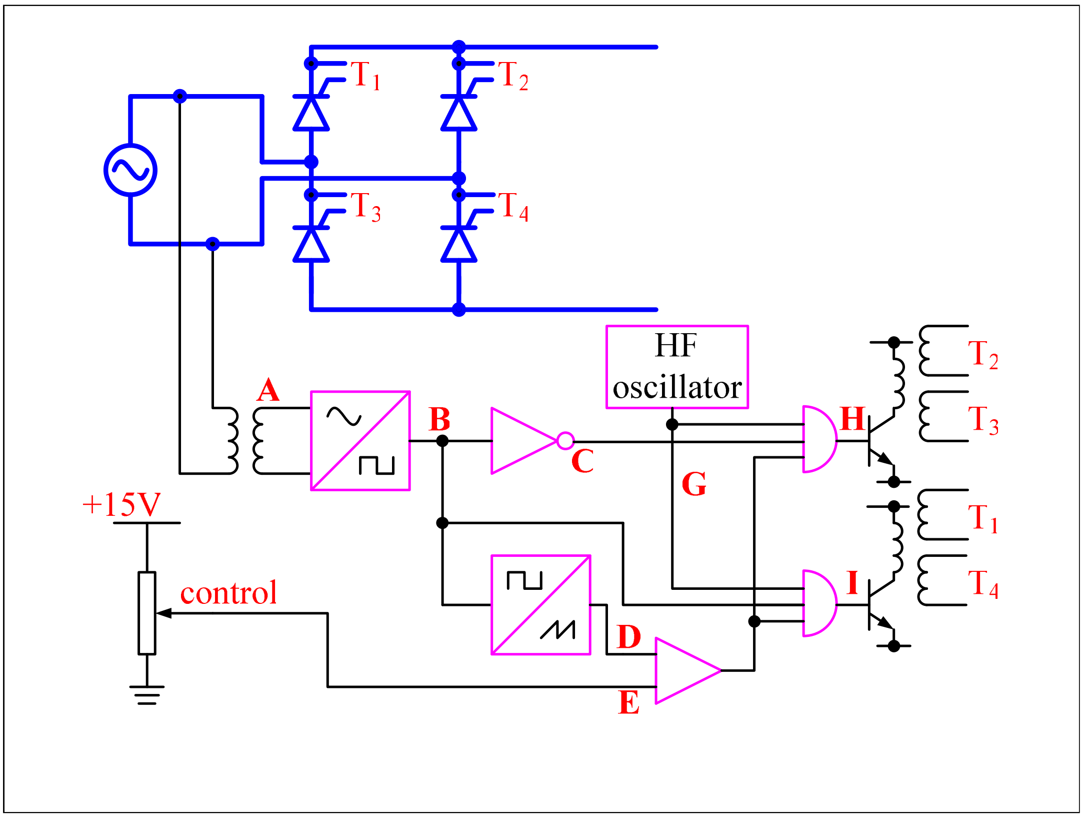
Once switched on (“fired” or “triggered”), the thyristor will stay on even if the gate signal is removed. Therefore short pulses can be used, reducing the gate power (the power drawn from the control circuit).

A thyristor will turn-on in about 1 μs, but if the load is inductive, a pulse of 50 μs is typically used to allow the current to reach the “latching current” (otherwise the thyristor will not latch-on).

Circuits with Isolation

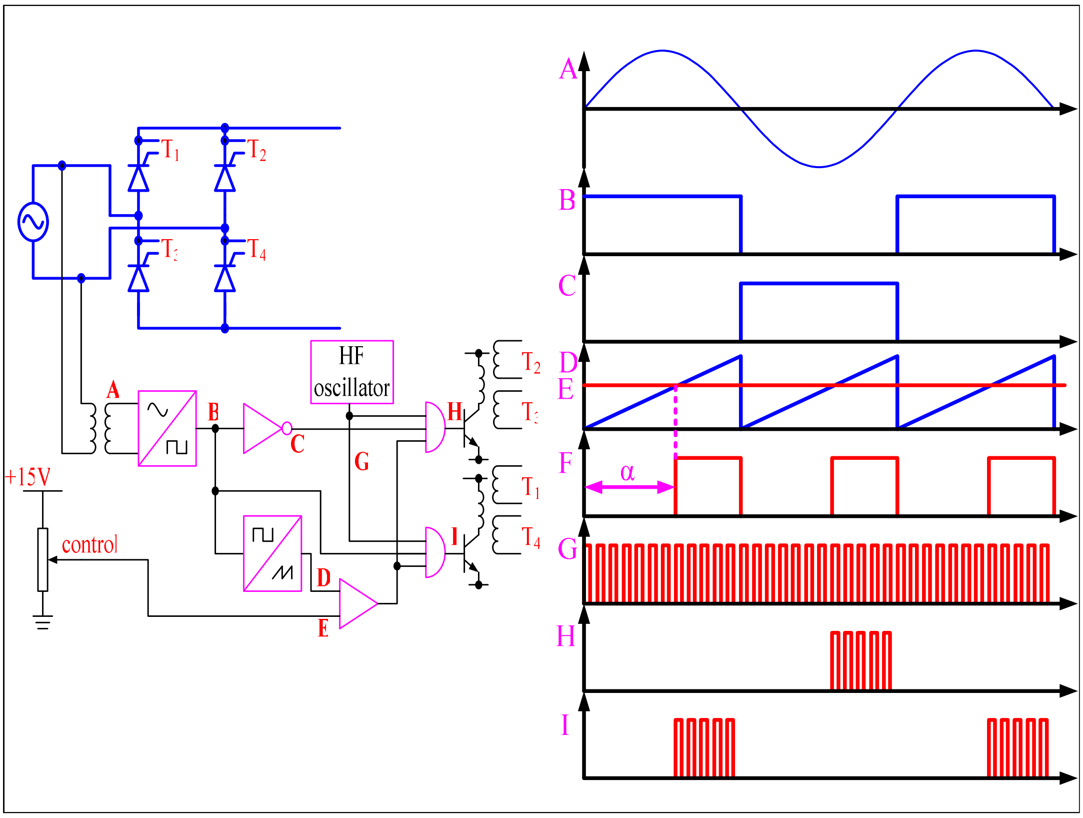


High frequency pulse transformers are often used to provide isolation between the high voltage power circuit and low voltage control circuit, to avoid damaging the latter.



Gate drive circuits tend to be specific to each manufacturer, and for the rest of this course will be omitted from the circuit diagrams. However, above is an example of a typical control circuit using discrete analogue/digital components.

Control could also be done using programmable components (eg. PIC, FPGA).



The waveforms at each node in the above circuit are shown on the right hand side.

A is controlled by moving the slider on the potentiometer (bottom left) up/down, hence moving the crossover point on the comparator inputs (D and E) left/right.

Waveform H is applied to thyristors T2 and T3 (via an isolating transformer), waveform I is applied to thyristors T1 and T4. Multiple pulses are applied, in case the thyristor doesn't switch on with the first one.