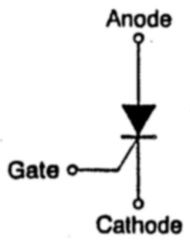
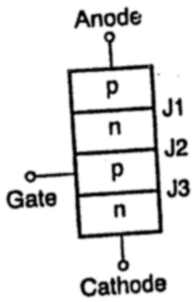
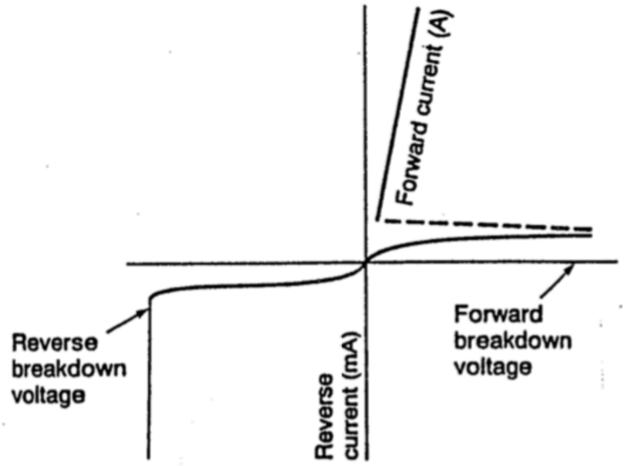
Silicon Controlled Rectifier (SCR / Thyristor)

A thyristor is a high speed switch that can handle up to 1000A







<u>When gate current OFF</u>

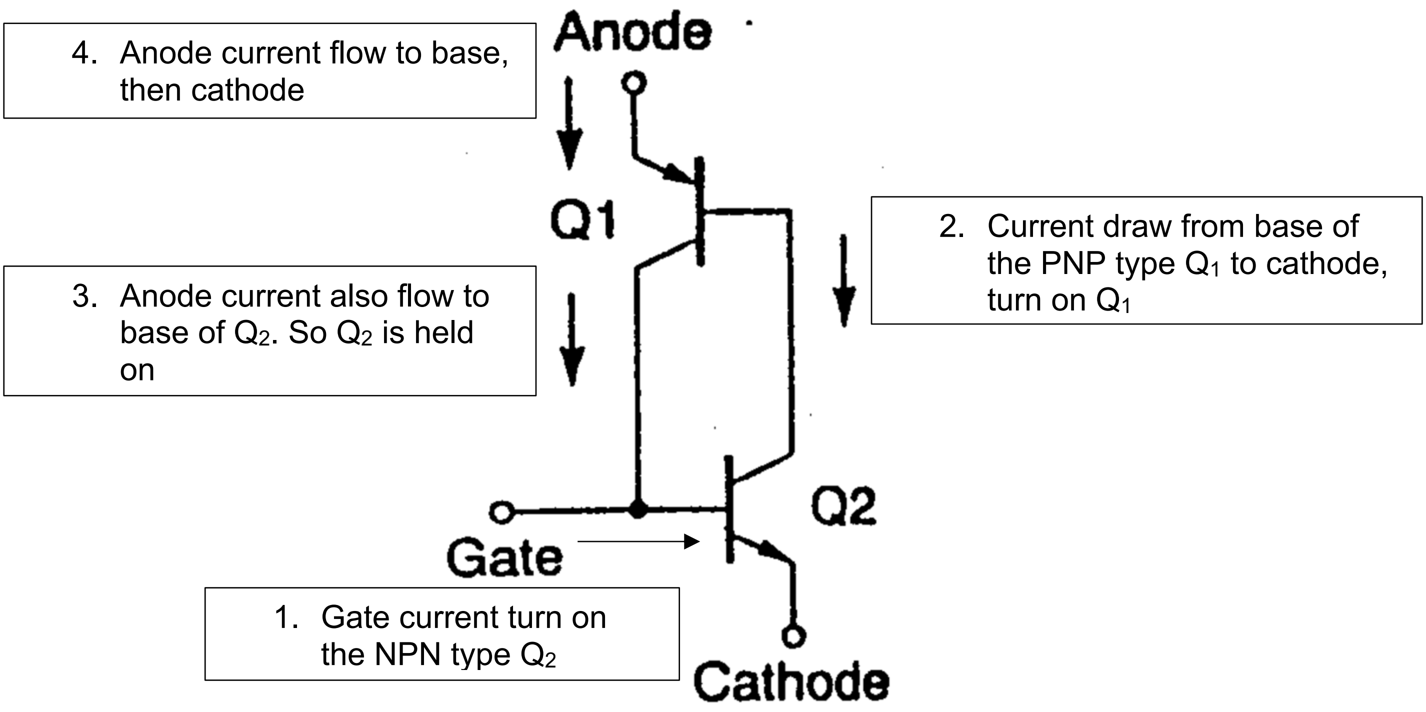
- If anode is relatively positive to cathode, the thyristor is forward biased. Since the gate is OFF, the device is in forward blocking state.
- If anode is relatively negative to cathode, the thyristor is reverse biased. If voltage increase to a large value, the junction will breaks down and the thyristor is in conducting state with large current under negligible resistance.

<u>When gate current ON (Gate current ~10mA)</u>

- The forward current blocking traits is gone, while the reverse blocking traits remain.
- Anode current (Load current) can pass through and is controlled by external impedance.
- ~1V drop across the thyristor.
- Load current must > Latching current (I_L), the thyristor will revert to blocking state (thyristor will turn off) if the load current < holding current (I_H).
- What happen between IH and IL???

Therefore, once the thyristor is triggered, there is no control except turning the load current < I_H.

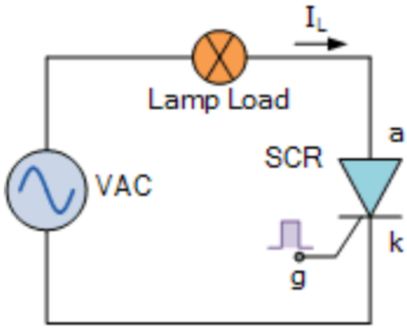
Thyristor Operation Principle



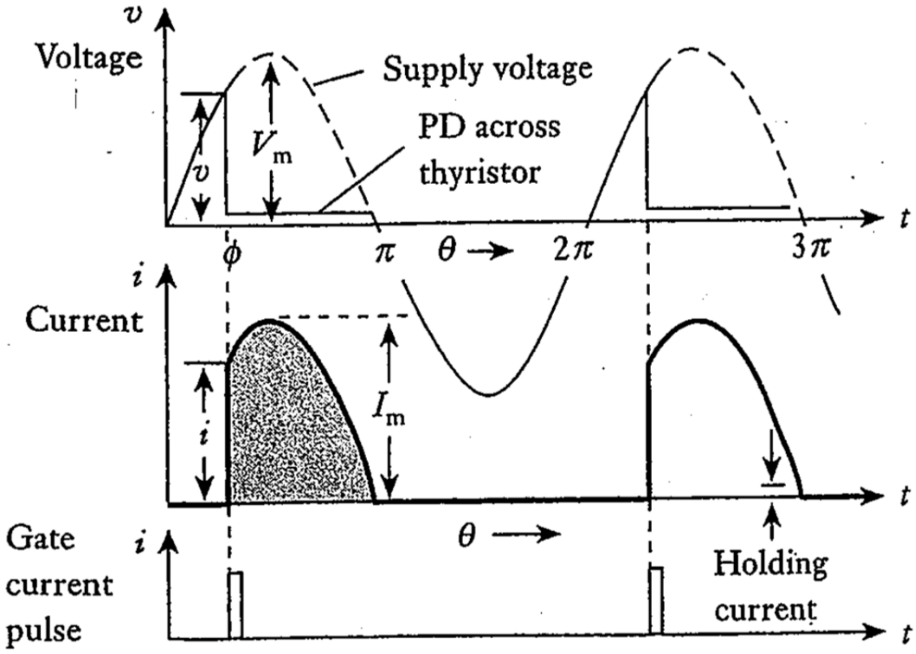
Therefore, once the gate is pulsed on, the SCR maintains its own gate current to lock the anode current

<u>Thyristor controlled rectifier</u>

When a thyristor connected as shown is supplied by a sinusoidal voltage and is triggered at an instant corresponding to an angle ϕ:



Waveforms:



The average current is (by Mean Value Theorem):

$$
\begin{aligned}
I_{avg} &= \frac{1}{2\pi - 0}\int_0^{2\pi} I_m \sin{(t)}\, dt \\
&= \frac{1}{2\pi}\left[\int_0^{\phi} I_m \sin(t)\, dt + \int_{\phi}^{\pi} I_m \sin(t)\, dt + \int_{\pi}^{2\pi} I_m \sin(t)\, dt\right] \\
&= \frac{1}{2\pi}\int_{\phi}^{2\pi} I_m \sin(t)\, dt \\
&= \frac{I_m}{2\pi}(1 + cos\phi)
\end{aligned}
$$

For fully controlled rectifier, the average current will be:

$$
I_{avg} = \frac{I_m}{\pi}(1 + cos\phi)
$$

For I_m, If V is AC:

$$V_m = I_m R$$
$$V\sqrt{2} = I_m R$$

Definition of Instantaneous Power (AC)

$$\begin{aligned} P_{inst} &= V(t)I(t) \\ &= I(t)^2 R \\ &= \frac{V(t)^2}{R} \end{aligned}$$

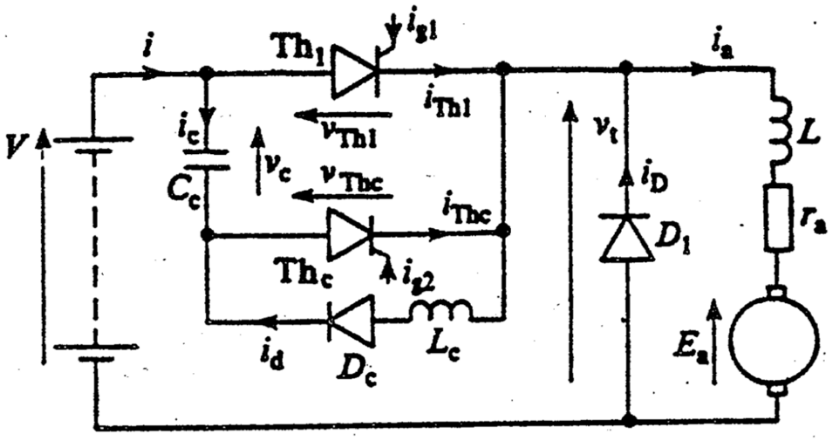
Definition of Average Power (AC)

$$P_{avg} = \frac{1}{t_2 - t_1}\int_{t_1}^{t_2} P_{inst}\, dt$$

DC / DC Chopper

A device that can control the input D.C. voltage by varying the on and off time of a converter.

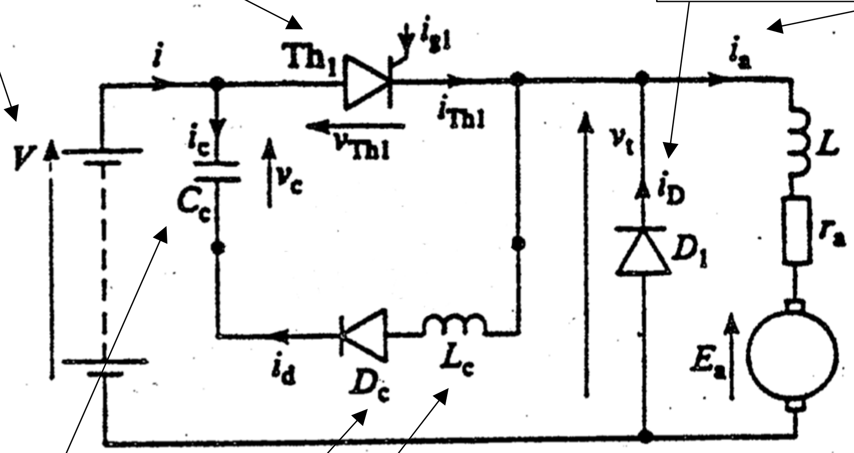
This chopper circuit provides a variable armature current I_a for torque pulsations and subsequently, speed perturbations (擾動) about a mean value, which cause rotor acceleration and deceleration. The full circuit is:



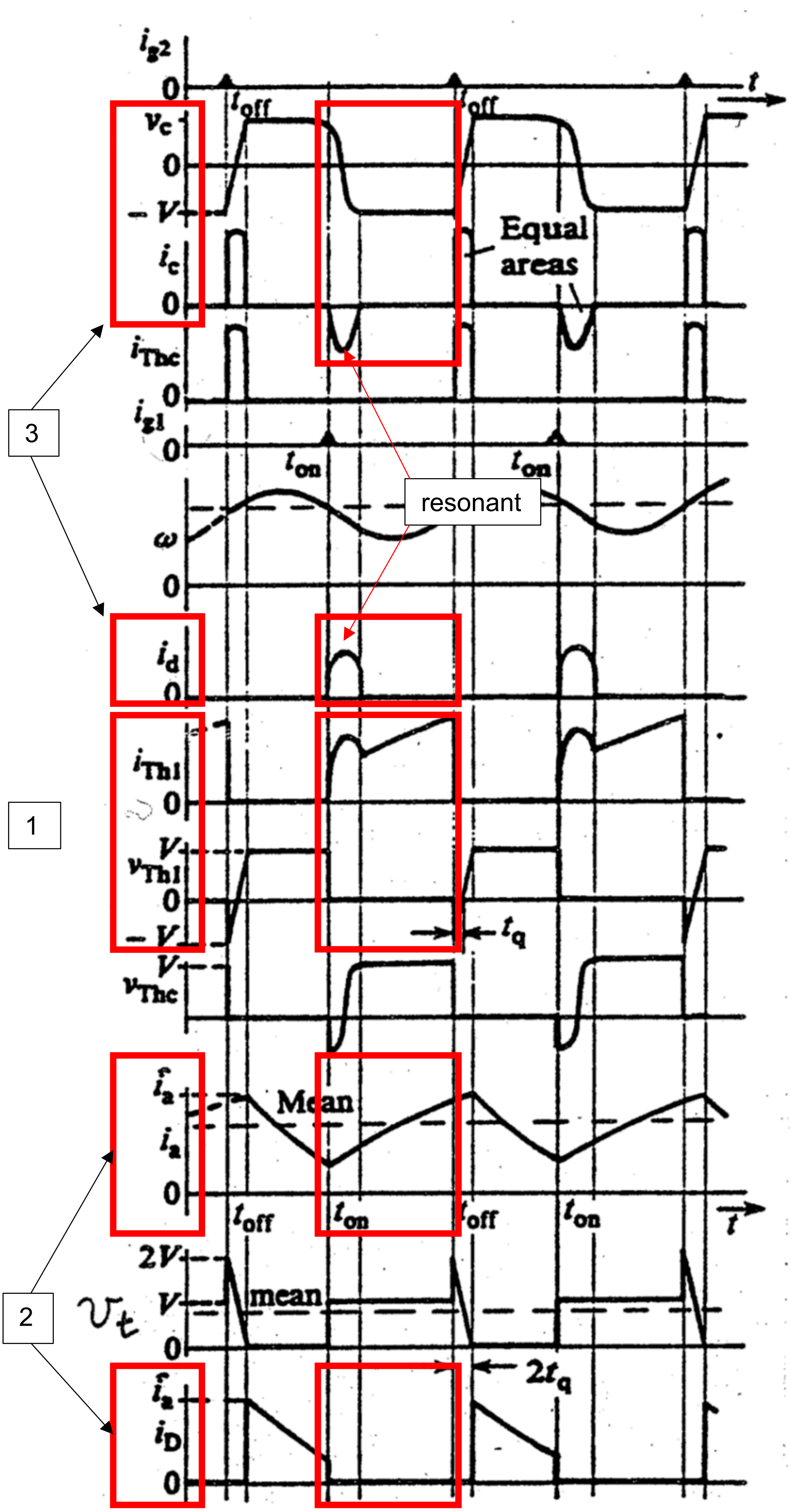
The operation details are as follows:
At time $t = t_{ON}$:

1. Th_1 receive an impulse i_{g1}, become forward biased. Supplying the armature with the voltage source V

2. i_a then increase exponentially, while i_D plunge to 0, because D_1 is now reverse biased

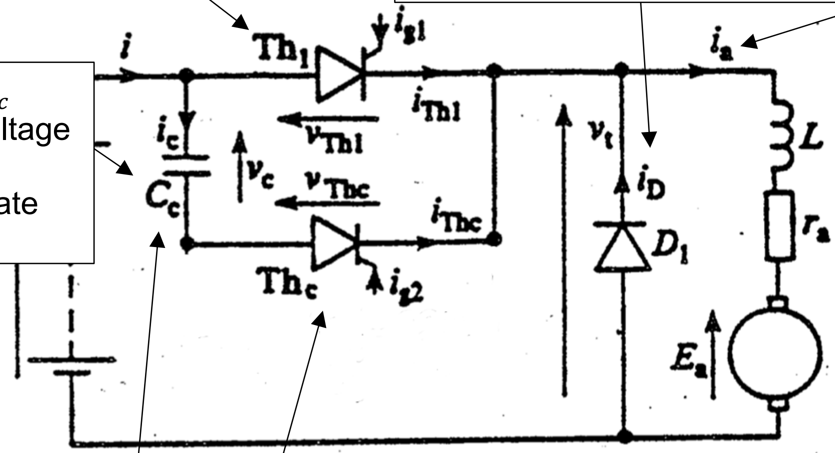


3. Current also pass through this path, and C_c resonant (oscillate) for half a period with L_c with relation $i_d = -i_c$ as v_c falls to 0. Energy transfer between them during oscillation and $v_c = -V$ when the oscillation is finished. The diode D_c here prevent further oscillatory interchange.



i_{g2}
0
t_{off}
t_{off}
t
v_c
0
$-V$
Equal
areas
i_c
0
i_{Thc}
0
i_{g1}
0
t_{on}
t_{on}
resonant
ω
0
3
i_d
0
i_{Th1}
0
1
V
v_{Th1}
0
$-V$
t_q
V
v_{Thc}
$\hat{i}_a$
Mean
i_a
0
t_{off}
t_{on}
t_{off}
t_{on}
t
$2V$
V
mean
v_t
2
0
$2t_q$
$\hat{i}_a$
i_D
0

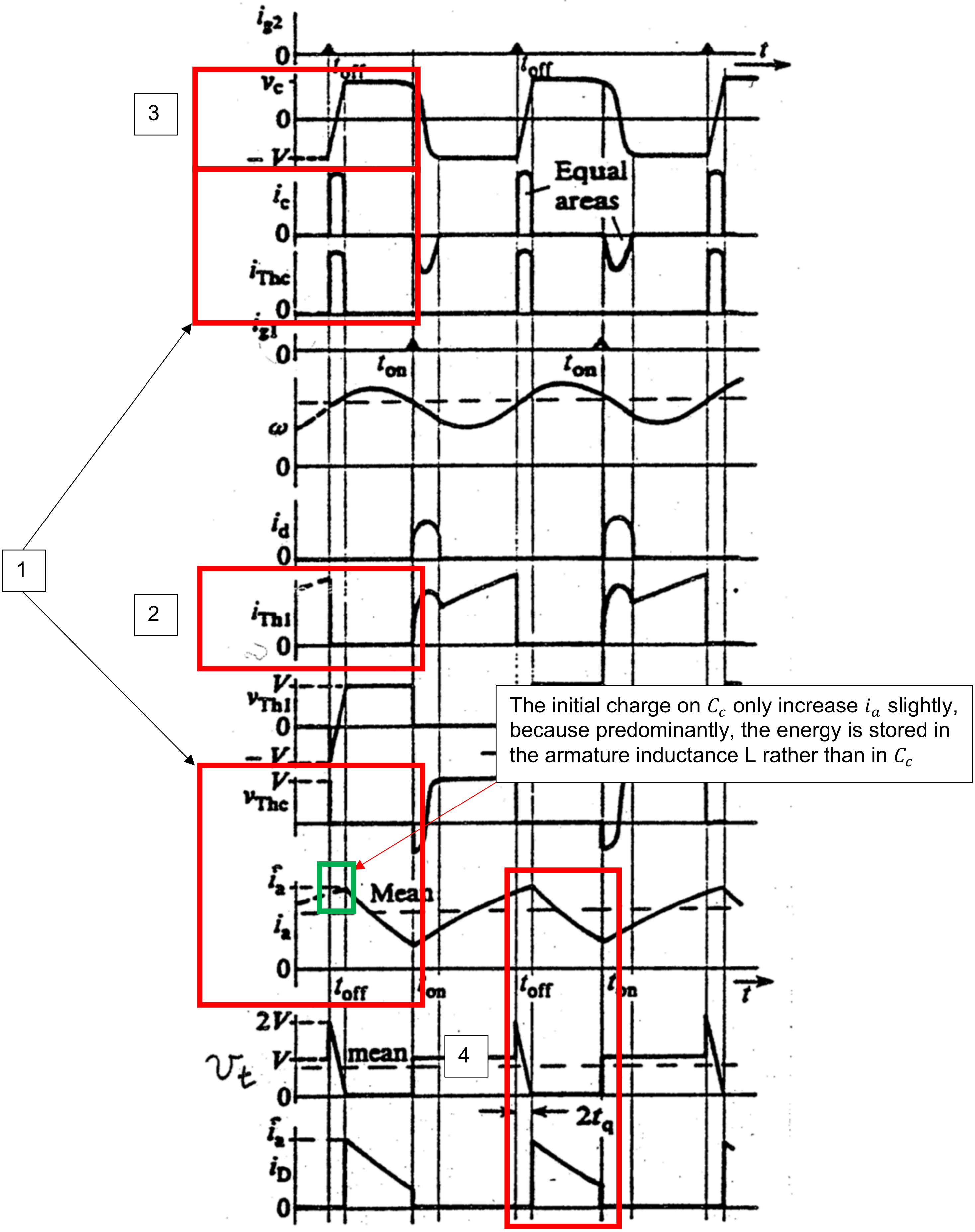
At time $t = t_{OFF}$:



1. Th_C received an impulse i_{g2}, C_c will therefore discharge, such that $i_C = i_{THC} = i_a$
2. Since, for now, $i_C = i_a = i$, Th_1 has no current, so turned off
3. The capacitor C_c then have its voltage v_c increase at a fairly constant rate from -V to V
4. When $v_c = V$, the current i_a given by C_c will cease. The exponentially decreasing current i_a will then flow through the diode D_1 such that $i_D = i_a$. At this point $v_t = V - v_c \leq 0$, and v_c maintain constant.
5. The constant $v_c = V$ and the exponentially decreasing current $i_D = i_a$ are maintained until the time $t = t_{ON}$

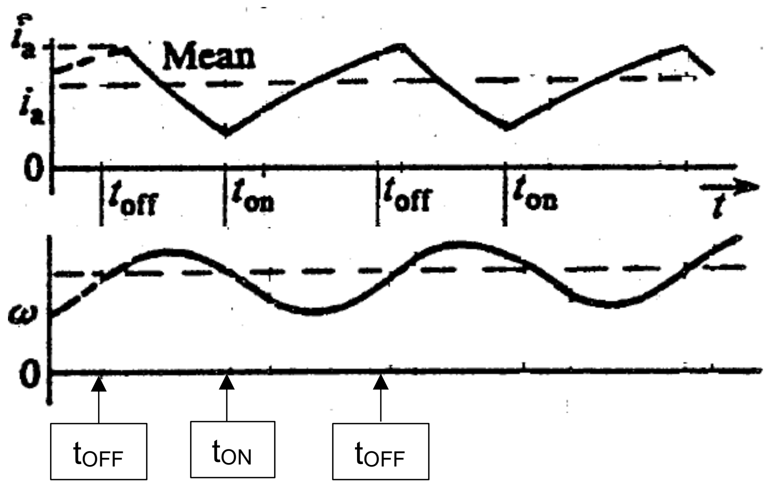
All in all:

- Th_1 is the main switching thyristor.
- Th_C is the commutating thyristor to connect the capacitor C_c across the anode and cathode of Th_1 to turn it off and maintaining negative anode cathode voltage for sufficient time to ensure recovery to the blocking condition.
- The armature inductance L is crucial to effective operation of the circuit because it provides a reservoir of energy and enable the armature current to be continuous, whereas the D.C. supply current $i_{TH1} + i_C$ is pulsed.
- D_1 is the free wheel diode, which permits the armature current to be sustained by the stored energy of series inductance L to circulate and continue the development of torque.
- D_C and L_C form a series resonant circuit with C_c, oscillate for a period of $\frac{T}{2}$ only after Th_1 has been triggered, thus reversing the polarity of C_c.

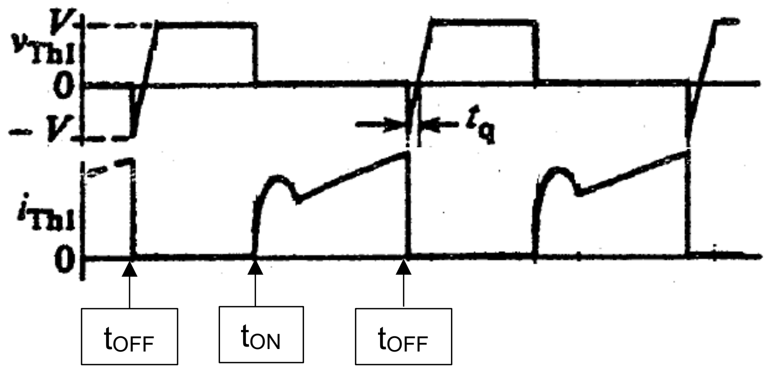

i_{g2}
t_{off}
t_{off}
t
v_c
$-V$
i_c
Equal areas
i_{Thc}
i_{g1}
t_{on}
t_{on}
ω
i_d
i_{Th1}
V
v_{Th1}
$-V$
V
v_{Thc}
$\hat{i}_a$
Mean
i_a
t_{off}
t_{on}
t_{off}
t_{on}
t
$2V$
v_t
V
mean
$2t_q$
$\hat{i}_a$
i_D
0
1
2
3
4
The initial charge on C_c only increase i_a slightly, because predominantly, the energy is stored in the armature inductance L rather than in C_c

Voltage and Current break down
[t_{ON} is triggered at Th_1, t_{OFF} is triggered at Th_c]**

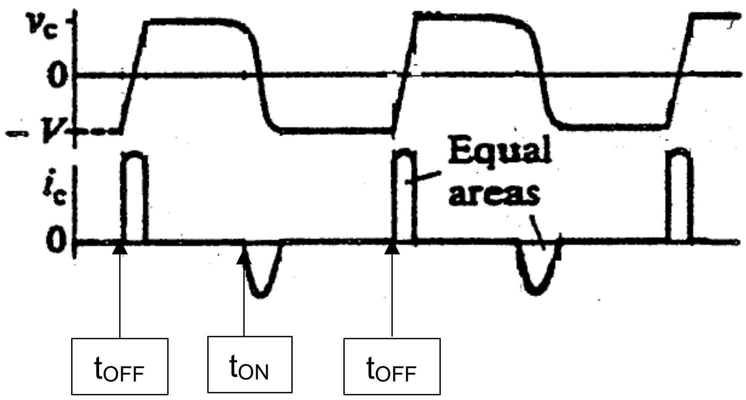
Armature:



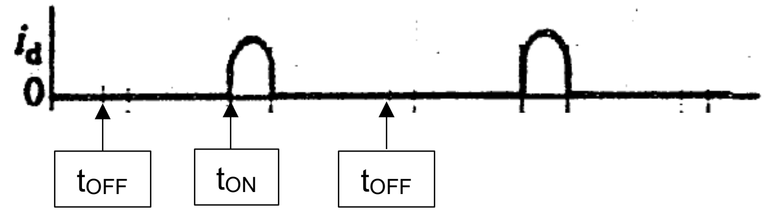
Th_1:



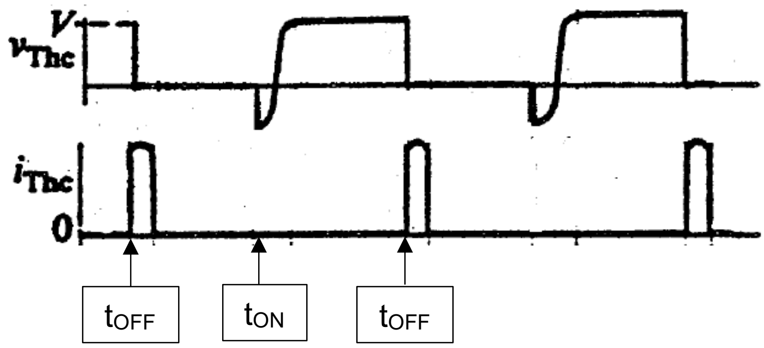
Capacitor:



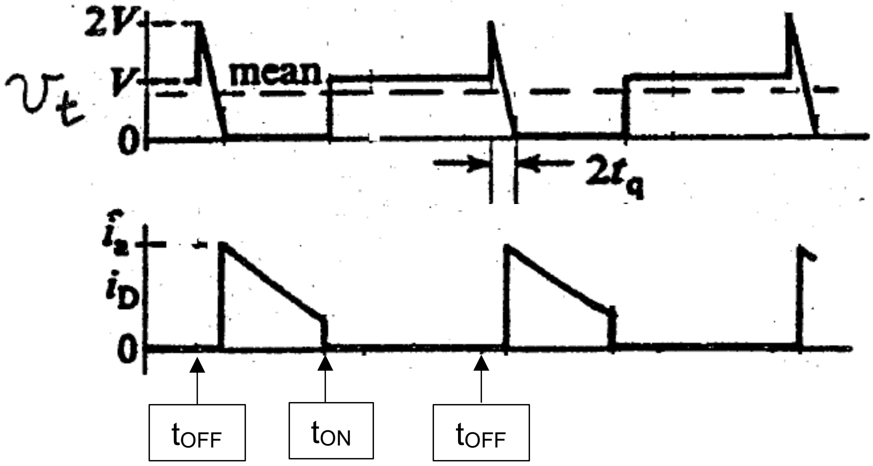
D_c:


i_d
0
t_{OFF}
t_{ON}
t_{OFF}

Th_c:


V
v_{Thc}
i_{Thc}
0
t_{OFF}
t_{ON}
t_{OFF}

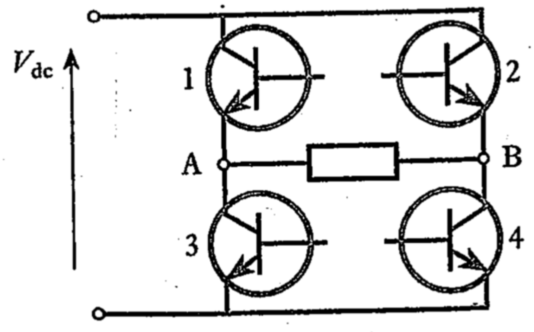
D_1:


$2V$
V
mean
v_t
0
$2t_q$
$\hat{i}_a$
i_D
0
t_{OFF}
t_{ON}
t_{OFF}

DC / AC inverter

Such circuit is to change a waveform from D.C. → A.C. The significance of this inversion process is that we can choose the frequency of the alternating signal, which is important when controlling the speed of an induction motor.

Circuit diagram of a one phase inverter circuit:

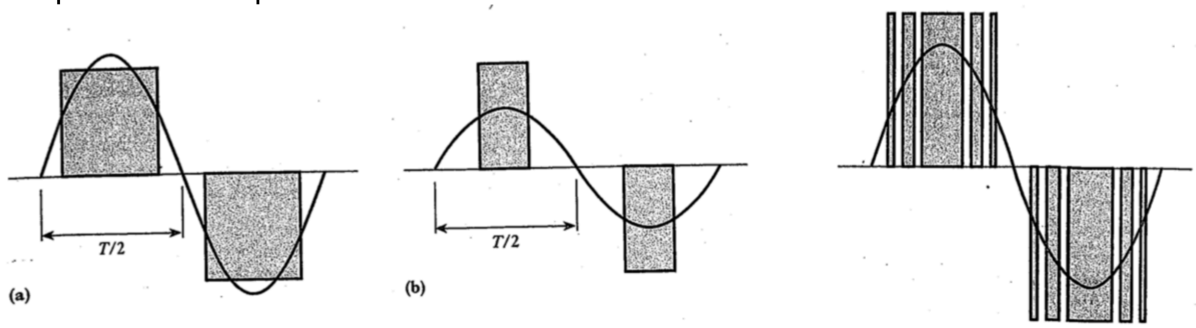


The D.C. supply can come from battery or rectified A.C. supply.

There are 2 ways to control the output voltage:

1. Vary the input D.C. voltage, which require a controlled A.C. to D.C. converter. The converter needs extra cost and therefore usually used for high power applications.
2. D.C. input is derived from simple rectifier system. Pulse Width Modulation (PWM) is used to control the output voltage. This is cheaper and is used for lower power applications.

Below is a comparison of simplistic control and PWM control:



"Simplistic" control

PWM control

Switching devices in inverters

There are 4 types of switching devices:

- Bipolar Junction Transistors (BJT)
  - Can be switched off by simply switch off the base emitter current
  - Do not require a commutation circuit
  - Used in applications up to ~5kW with voltages up to 415 / 240V
  - Dissipate ~1% of the output power

- MOSFET
  - Can be easily turn on and off
  - Control circuit is less complex compared to BJT's, therefore cheaper
  - Power dissipation is higher than that of BJT's

- Insulated gate bipolar transistor (IGBT)
  - Gate can switch on and off easily
  - Power dissipation in the collector-emitter circuit is low
  - Power rating ~1MW with voltage rating ~1kV
  - Brings together the advantages of BJT and MOSFET

- Gate turn off thyristor (GTO)
  - Can be switched off by a negative gate-cathode current, unlike conventional thyristor
  - Usually deal with high power ratings, around a few MW
  - Require higher gate pulses
  - Double forward voltage drops compare with the conventional ones