Lecture 7
Forced commutation circuits

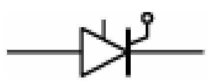
Objectives

- To consider circuits containing thyristor which operate with a DC source voltage (instead of an AC supply) which cannot rely on natural commutation
- Examples of such circuits are DC choppers and inverters
- To consider the development, for these cases, of forced commutation circuits
- To consider in detail forced commutation circuits including those using external voltage sources, those using capacitor discharge and those based on bridge circuits

Introduction

- Large class of power electronic circuits which operate from DC source
- For these circuits natural commutation is not possible
- The principal examples of such circuits are DC choppers and inverters
- Where self-commutating devices such as power transistors, power MOSFETs, IGBTs and GTO thyristors are used, turn-off can be achieved by control of device base or gate conditions
- In applications where thyristors are required for reasons of rating, then achievement of controlled turn-off required use of external circuits, this is referred to as forced commutation

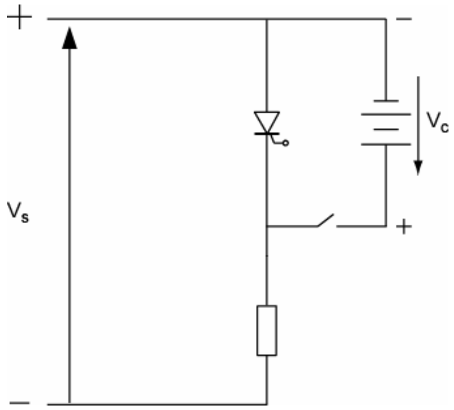
- The following symbol is used for a thyristor with external commutating circuits



- Function of a forced commutation circuit:
  - First to reduce current through conducting thyristor to zero (or below the holding current).
  - Then to maintain reverse voltage across this thyristor for a duration equal to or greater than the thyristor turn-off time, to re-establishes the blocking state.

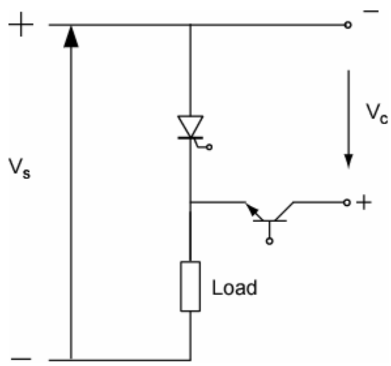
Commutation by an external voltage source

- External voltage source reduces forward current through thyristor to zero:

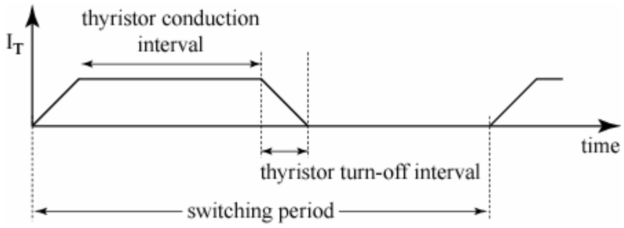


- When switch closes, external voltage source is more preferred route for load current than thyristor; hence thyristor current falls to zero
- Voltage on cathode of thyristor $V_s + V_c$ becomes higher than that on cathode V_s and thereby provides and maintains necessary reverse voltage across thyristor to complete turn-off
- Once thyristor turn-off is complete, switch can be opened to let load current fall to zero

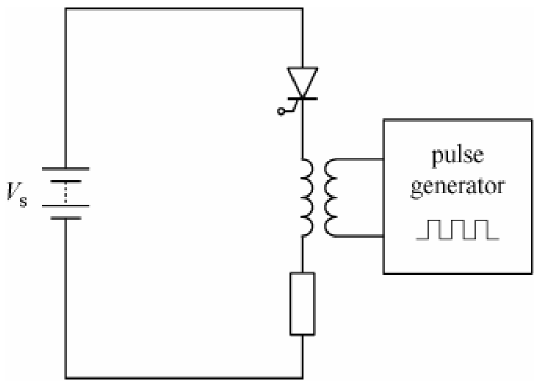
- Switch realised using bipolar transistor:



  - Acceptable from power dissipation point of view to use bipolar transistor to switch off high power thyristor because bipolar transistor is dissipating power only for very short interval when thyristor is being switched off

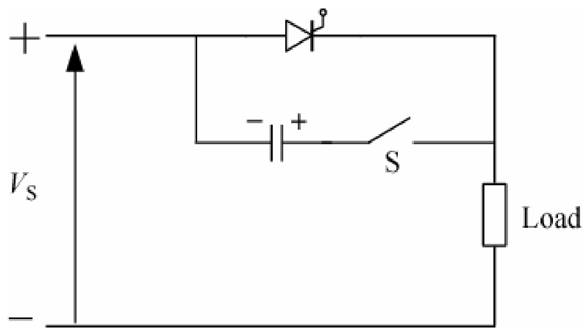


- Alternatively, pulse transformer can be used to place appropriate voltage across thyristor



Simple commutation circuit using a capacitor

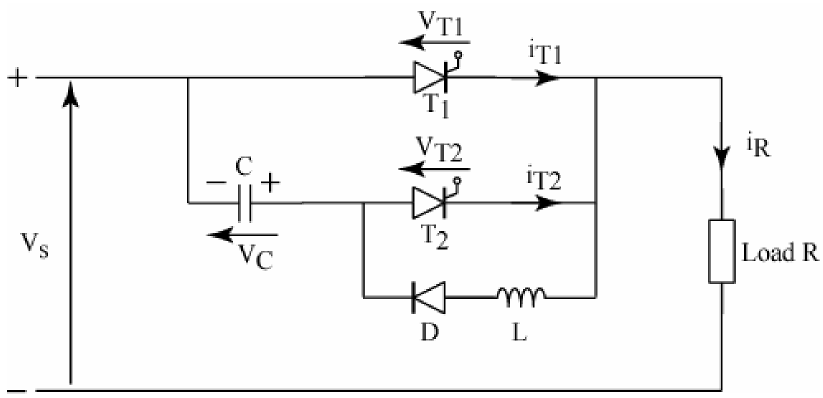
- Reverse voltage can be applied using capacitor:

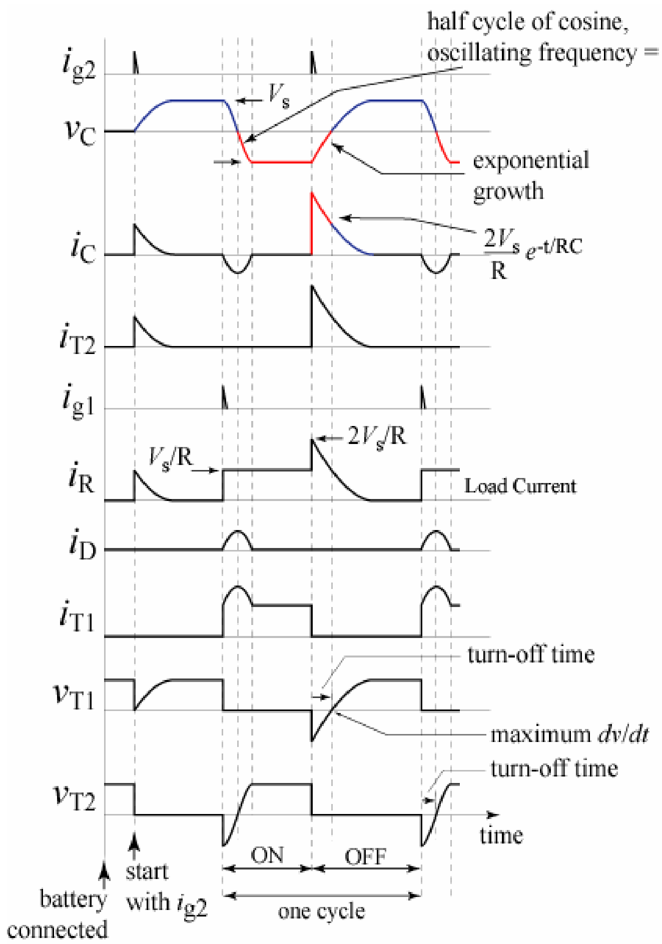


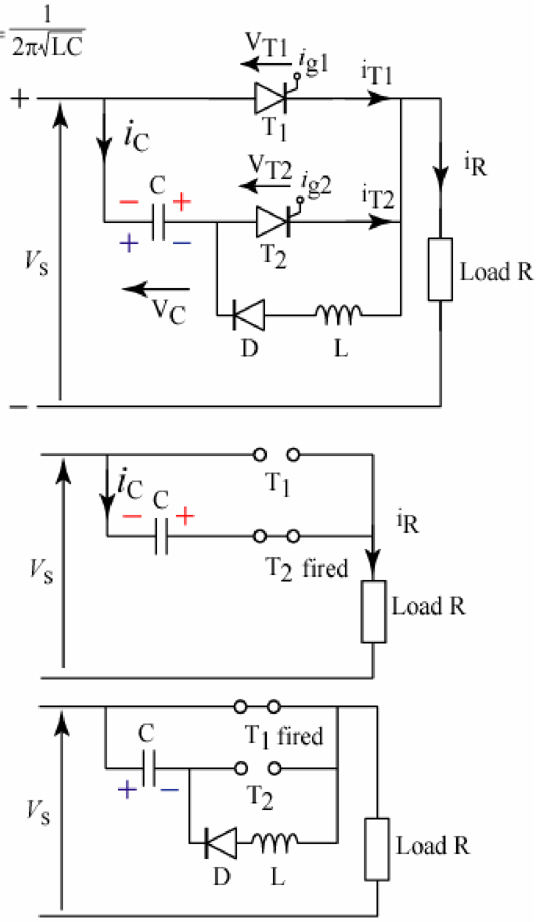
  - Assume that capacitor is <u>initially charged</u> in direction shown (+ −)
  - When switch (S) is closed, capacitor provides load current in preference to thyristor because of its higher voltage

- This forces thyristor forward <u>current below level of holding current</u>
- Reduction of forward current to zero takes place almost instantaneously
- Capacitor discharges through load, maintaining necessary <u>reverse voltage across thyristor</u> to complete turn-off before its voltage falls to zero and it then recharges in reverse direction
- In practice, additional circuitry provides required initial condition voltage on capacitor and initiates discharge

- Second thyristor T_2 acts as auxiliary switch:







- Circuit operation:

Time	Action
t_0	With the both thyristors T_1, T_2 are not conducting, the capacitor is charged to $V_c = 0$.
t_1	When the commutating thyristor T_2 fired, the capacitor starts to be charged by current flowing through T_2.
t_2	The capacitor continue to charge in the reverse direction to $V_c = +V_s$.
t_3	Forward current through the commutating thyristor T_2 fails below the holding current.
t_4	The main thyristor T_1 is fired; the capacitor will begin to discharge via thyristor T_1, diode D and the inductance L in an oscillatory fashion

Time	Action
t_5	The voltage across the commutating thyristor T_2 which completed its turn-off falls to zero
t_6	After one half-cycle of the oscillation, the current through the diode attempts to reverse and the diode ceases to conduct, stopping the oscillation; the capacitor is now charged in the original direction $V_c = -V_s$ ready for the next commutation cycle
t_7	With the main thyristor T_1 conducting, the capacitor is charged to $V_c = -V_s$ in the direction shown
t_8	When the commutating thyristor T_2 fired, the capacitor is connected across the main thyristor, forcing a reverse current through this thyristor and reducing the forward current to zero. Thyristor T_2 will then continue to conduct as the capacitor continues to discharge through the load, maintaining a reverse voltage across the main thyristor
t_9	The turn-off of thyristor T_1 is complete. The capacitor will then continue to charge in the reverse direction to $V_c = +V_s$

- Frequency of oscillation, and hence period, determined by values of capacitor and inductor

$$\omega = \frac{1}{\sqrt{LC}}$$

- Critical aspects of switching cycle:

Required Action	Refer to graph	Condition
Turn off T_1	V_{T1}	exponential decay time > thyristor turn-off time
Turn off T_2	I_{T2}	I_{T2} < holding current
	V_{T2}	¼ period > thyristor turn-off time

Worked Example On Commutation Circuit

- Simple commutation circuit using capacitor is used to supply 12Ω load from 36 V DC source
- Switching frequency is 250 Hz and main and commutating thyristors each have holding current of 50 mA and turn-off time of 80 μs
- 1) Estimate values of L and C

- *Solution*
  - Turn-off of main thyristor T_1 is complete when capacitor voltage reaches zero following firing commutating thyristor
  - From the curve of V_{T1}:

$$V_{T1} = -V_s\left(1 - 2e^{-t/RC}\right)$$

  - When V_{T1} reaches zero:

$$e^{-t/RC} = \frac{1}{2}$$

  - Hence,

$$\frac{-t}{RC} = \ln\frac{1}{2}$$

$$RC = \frac{-t}{\ln 1/2}$$

- For $t = t_{off}$ = 80 μs:

$$C = \frac{-t_{off}}{R\ln\frac{1}{2}} = 9.62\times10^{-6}\ \mathrm{F} = 9.62\ \mu F$$

- Once current in commutating thyristor has fallen below level of holding current, reverse voltage must be maintained for t_{off} = 80 μs
- From curve of V_{T2}, this corresponds to quarter of oscillation period
- Oscillation period:

$$T_0 = \frac{1}{f} = \frac{2\pi}{\omega} = 2\pi\sqrt{LC}$$

- Hence,

$$\frac{T_0}{4} = \frac{2\pi\sqrt{LC}}{4} = t_{off}$$

$$\sqrt{LC} = \frac{2t_{off}}{\pi}$$

$$L = \frac{4t_{off}^2}{C\pi^2} = 0.270 \times 10^{-3}\ H = 0.270\ mH$$

- 2) Find peak and RMS currents in main and commutating thyristors when mean load voltage is at minimum and maximum values.
- *Solution*
  - Steady state load current is: I_L = 36/12 = 3 A
  - Peak capacitor current may be obtained from energy considerations

$$\frac{1}{2}CV^2 = \frac{1}{2}LI^2$$

  - For lossless system maximum capacitor voltage is supply voltage V_s;

$$I_{C,\max} = V_s\sqrt{\frac{C}{L}} = 6.8\,\text{A}$$

  - This must be supplied by main thyristor

- Peak current in main thyristor:

$$I_{C,\max} + I_L = 6.8 + 3 = 9.8A$$

- Peak current in commutating thyristor is capacitor current immediately after firing:

$$I_{T2,\max} = \frac{2V_s}{R} = 6A$$

- Commutating thyristor stops conducting when forward current falls below thyristor holding current I_h; $\therefore$

$$I_h = 6e^{-t/RC}$$

$$t = -RC\ln\frac{I_h}{6}$$

- Since I_h = 50 mA, we have,

$$t = 0.553ms$$

- This is the minimum turn-off time for commutating thyristor
- If main thyristor is fired before this then commutating thyristor will be forced to turn off but capacitor will not be fully charged
- Usually, off period is made long enough to ensure that voltage on capacitor has reached at least 80% of maximum value
- Minimum on-time for main thyristor is therefore normally equivalent to half cycle of oscillatory waveform i.e. 160 μs
- Repetition period = $1/250 = 4\ ms$

- Minimum mean load voltage corresponds to minimum on-time of main thyristor; in this case:

$$I_{T1,RMS} = \left(\frac{1}{4\times10^{-3}} \int_0^{160\times10^{-6}} (3 + 6.8\sin\omega t)^2 \, dt \right)^{1/2}$$
$$= 1.13A$$

and

$$I_{T2,RMS} = \left(\frac{1}{4\times10^{-3}} \int_0^{160\times10^{-6}} \left(6e^{-t/RC}\right)^2 dt \right)^{1/2}$$
$$= 0.52A$$

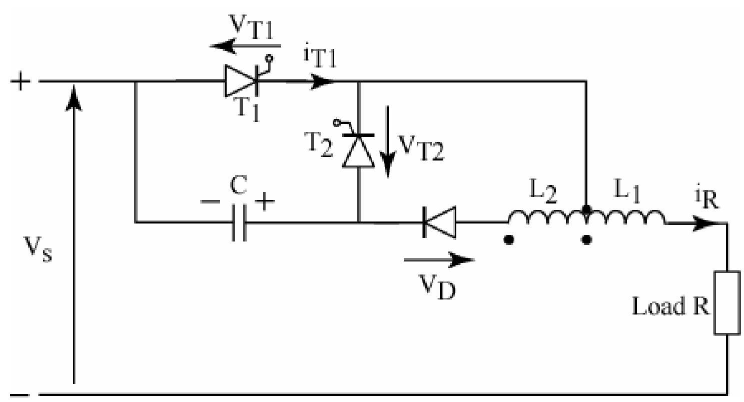
- Maximum mean load voltage corresponds to maximum on period of main thyristor:

$$I_{T1,RMS} = \left[\frac{1}{4\times10^{-3}} \left(\int_0^{160\times10^{-6}} (3 + 6.8\sin\omega t)^2 \, dt + \int_{160\times10^{-6}}^{3.447\times10^{-3}} 3^2 \, dt \right) \right]^{1/2}$$
$$= 2.95A$$

- $I_{2,RMS}$ remains same as before

The Jones circuit

- Simple commutation circuit using a capacitor has disadvantage that, in order to initiate commutation sequence following initial turn-on with capacitor uncharged, capacitor voltage has to be primed
- Jones circuit is similar in that it also uses auxiliary thyristor for commutation purposes but has advantage of reliably initiating commutation sequence following initial turn-on

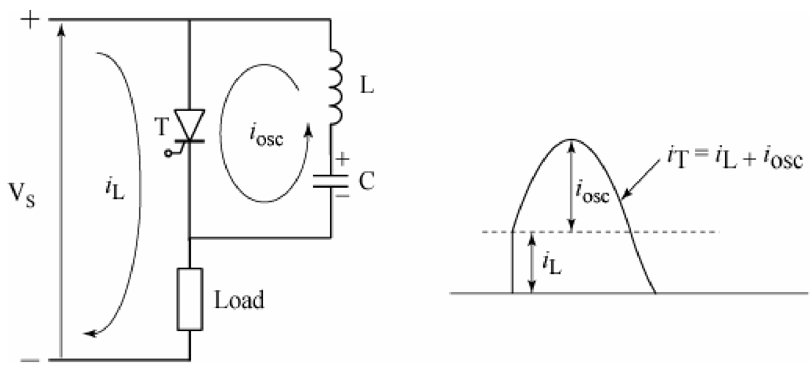


- Operation is as follows:
  1) Capacitor C is initially uncharged
  2) Main thyristor T_1 is fired
  3) Coupling between inductors L_1 and L_2 causes a voltage to be induced into inductance L_2 which charges capacitor C via diode D in direction shown
  4) Capacitor C is now charged in correct direction to turn off main thyristor T_1 when commutating thyristor T_2 is fired

5) Subsequent operation of circuit follows pattern of simple commutation circuit, e.g.:
- i_{T1} is forced to zero
- V_{T1} remains < 0 V for at least thyristor turn-off time
- C is charged in reverse direction
- Current in T_2 falls to zero turning T_2 off

Commutation circuits using resonant turn-off

- Resonance set up in auxiliary LC circuit can be used to turn thyristor off, eliminating need for auxiliary thyristors or diodes, though at expense of loss of control over instant of turn-off
- Parallel resonant turn-off
  - Typical parallel resonance circuit for thyristor turn-off:

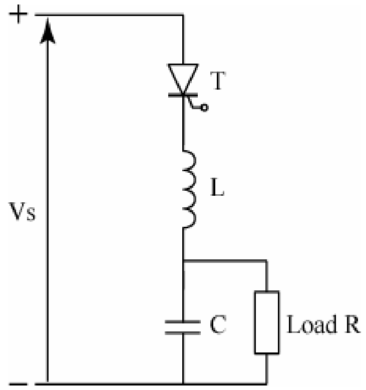


- Before thyristor is fired, i.e. during thyristor off period, capacitor is charge to supply voltage V_s
- When thyristor fired, current flows which can be considered as sum of two currents:
  - A steady load current $I_L = V_s/R$ flows through T to the load
  - An oscillatory current I_{OSC} flows around the loop L, C, T due to the initial voltage V_s on C
- Current through T is the sum of i_L and i_{OSC}

- Provided $i_{OSC} > i_L$, then when i_{OSC} becomes negative in 2nd half of its oscillatory cycle, current in thyristor falls to zero and thyristor will be turned off
- Thyristor on-period is function of frequency of oscillation of LC circuit and therefore cannot be controlled
- Off-period must be sufficient to allow capacitor to be adequately
- Capacitor is usually charged to at least 80% of V_s

Series resonant turn-off

- Series resonance circuits can also be used for thyristor turn-off:

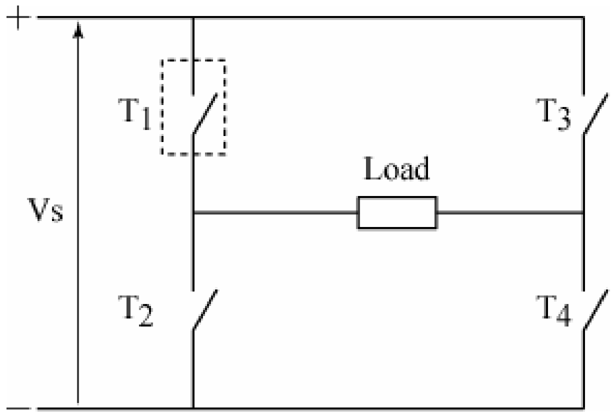


- Before thyristor is fired, i.e. during thyristor off period, capacitor is discharged to 0 V
- Firing thyristor will set up oscillating current which will turn thyristor off at first current zero, provided circuit is under-damped, i.e. $Q >> 0$, where $Q = R/(\omega L) = \omega CR$ and $\omega = 1/\sqrt{(LC)}$
- Capacitor will then discharge through load
- On time of thyristor is determined by frequency of oscillation circuit

$$t_{on} = \frac{T_0}{2} = \frac{1}{2f_0} = \pi\sqrt{LC}$$

Commutation circuit using bridge structure

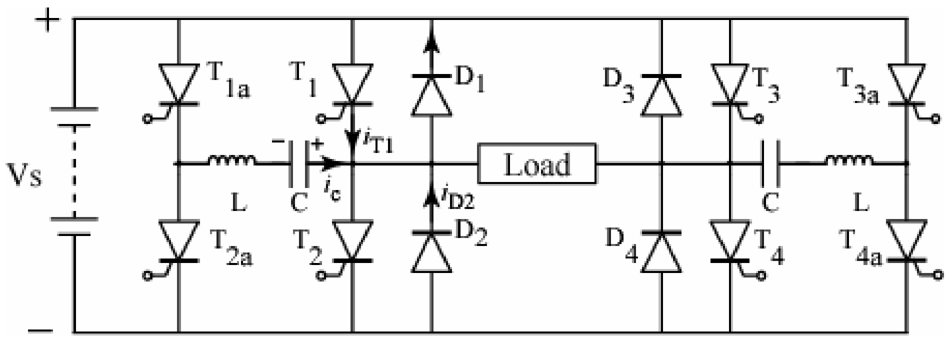
- Bridge circuit often used in systems with DC supplies
- General structure:



  - V_s is DC supply voltage; $T_1 - T_4$ are switching devices

- By controlling on and off times of four switching devices in different ways circuit can provide
  - Controllable DC load voltage that can be reversed (class C DC chopper) AC load voltage controllable in amplitude and frequency
- In medium-to-high power application where thyristor are necessary, forced commutation circuits are necessary to switch off thyristors
- In case of bridge circuit, advantage can be taken of existing bridge structure to develop efficient forced commutation circuits

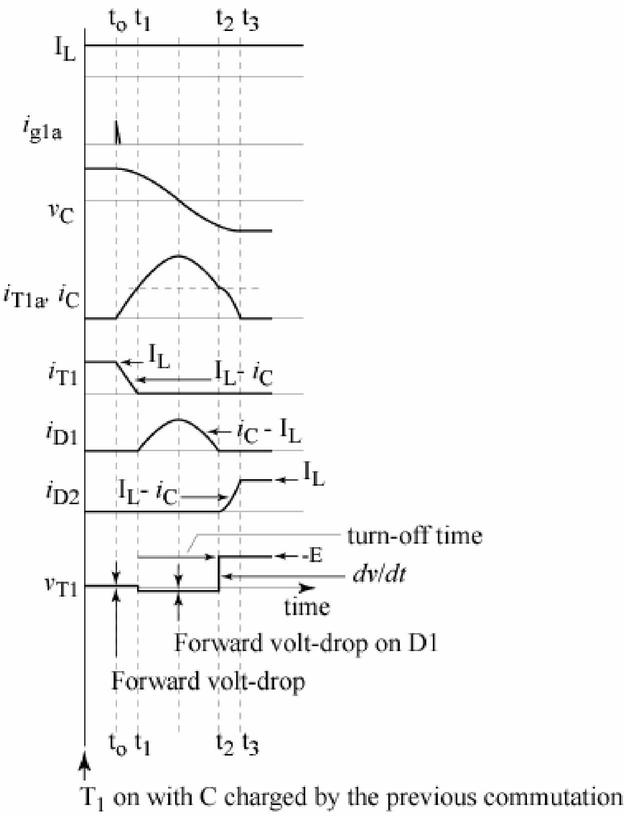
The McMurray circuit



- Structure of circuit is symmetrical
- Assume bridge circuit is used to supply inductive load with load current I_L substantially constant over the commutation (or switching) interval.

- Thyristor T_1 and T_2 are main thyristors making up half bridge
- T_{1a} and T_{2a} are their associated auxiliary thyristors
- Consider operation at point in cycle when T_1 is conducting and capacitor is charged in direction shown $(+ -)$

- The relevant current waveforms in the circuit are as follows:



- Operation of the circuit:

Time	Action
t_0	The auxiliary thyristor T_{1a} is fired This allows the capacitor to discharge via T_1 and inductor L, producing an oscillatory circulating current whose magnitude is arranged to be much greater than the load current
t_1	The forward current through T_1 is reduced to zero At this instant, the oscillatory current is diverted to diode D_1 The forward voltage across D_1 now appears as a reverse voltage across thyristor T_1 to complete the turn-off and re-establish the blocking mode Hence t_2 - t_1 must be greater than the thyristor turn-off time As the capacitor discharges, its voltage reverse

Time	Action
t_2	The discharge current falls below the load current At this instant diode D_1 stops conducting Load current continues to flow via the auxiliary thyristor T_{1a}, charging the capacitor to the source voltage in the reverse direction at which point diode D_2 starts to conduct D_2 then continues to take an increasing proportion of the load current as the energy in the magnetic field of the inductor L is transferred to the capacitor This reduces the current in the auxiliary thyristor T_{1a} to zero turning it off The capacitor is now charged to approximately $2V_s$ in the reverse direction ready for the commutation of thyristor T_2 by the auxiliary thyristor T_{2a}

Time	Action
t_3	The load current now decays to zero, turning diode D_2 off and allowing thyristor T_2 to be fired, reversing the current in the load T_2 would normally be supplied with a continuous gate signal during this period to ensure turn-on at the earliest appropriate instant

- Opposite half-bridge assumed to have been commutated simultaneously, i.e. T_4 is turned off at same time as T_1 is turned off

Worked example on the McMurray circuit

- Full bridge circuit used to supply inductive load such that load current is continuous during commutation
- Load resistance is 12 Ω and bridge supplied from constant 400 V DC
- Thyristor used have turn-off time of 50 μs
- Estimate values of circuit components

- *Solution*
  - Referring to above waveform diagram, interval t_2 - t_1, for which there is a negative voltage cross T_1, must be ≥ thyristor turn-off time
  - This interval = period for which capacitor current I_c > load current I_L
  - I_c has form:

$$I_c = I_{cm} \sin \omega_0 t \quad \text{where} \quad \omega_0 = \frac{1}{\sqrt{LC}}$$

  - t_1 is the instant when I_c first equals I_L (I_c increasing) and t_2 is the instant when I_c next equals I_L (I_c decreasing); hence:

$$I_L = I_{cm} \sin \omega_0 t_1 = I_{cm} \sin \omega_0 t_2$$

$$t_1 = \frac{1}{\omega_0} \sin^{-1} \left. \frac{I_L}{I_{cm}} \right|_{\omega_0 t_1 < \pi/2} \qquad t_2 = \frac{1}{\omega_0} \sin^{-1} \left. \frac{I_L}{I_{cm}} \right|_{\omega_0 t_2 > \pi/2}$$

- Maximum capacitor current I_{cm} must be > I_L; let I_{cm} = 1.5 I_L; then

$$t_1 = \frac{1}{\omega_0}\sin^{-1}\left(\frac{2}{3}\right)\Bigg|_{\omega_0 t_1 < \pi/2} = \frac{0.7297}{\omega_0}$$

$$t_2 = \frac{1}{\omega_0}\sin^{-1}\left(\frac{2}{3}\right)\Bigg|_{\omega_0 t_2 > \pi/2} = \frac{2.4119}{\omega_0}$$

- Let $t_2 - t_1$ = thyristor turn-off time = 50 μs

$$t_2 - t_1 = \frac{2.4119 - 0.7297}{\omega_0} = \frac{1.6822}{\omega_0} = 50\times 10^{-6}\, s$$

- Hence:

$$\omega_0 = \frac{1.6822}{50\times 10^{-6}\, s} = 3.364\times 10^4 \ \ \text{rad/s}$$

$$\omega_0 = \frac{1}{\sqrt{LC}}$$

$$LC = \frac{1}{\omega_0^2} = \frac{1}{\left(3.364\times 10^4\right)^2} = 0.884\times 10^{-9}$$

- Considering resonance effect, maximum energy in inductor must equal maximum energy in capacitor

$$\frac{1}{2}CV_{cm}^2 = \frac{1}{2}LI_{Lm}^2 = \frac{1}{2}LI_{cm}^2 \quad \therefore \quad \frac{C}{L} = \frac{I_{cm}^2}{V_{cm}^2}$$

- Assuming maximum capacitor voltage is V_{cm} = $2V_s$ = 800 V
- Load current I_L = V_s/R = 400/12 = 33.33 A
  $\therefore$ I_{cm} = $1.5I_L$ = 50 A

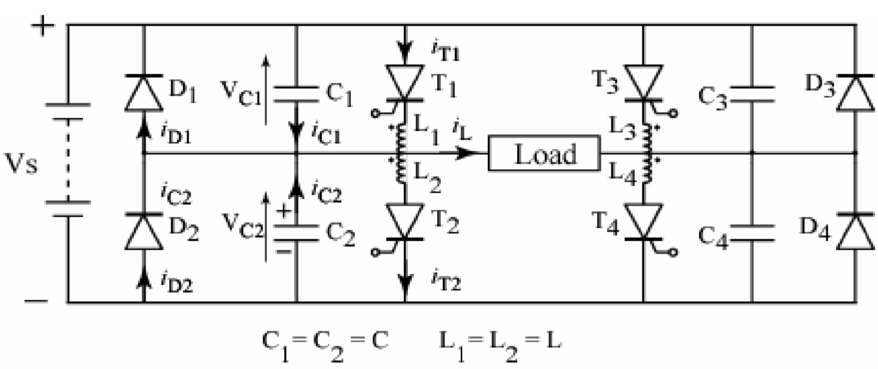
$$\frac{C}{L} = \frac{50^2}{800^2} = 3.906 \times 10^{-3}$$

- From the values of LC and C/L, we have:

$$L = 0.476\, mH \; and \; C = 1.86 \mu F$$

The McMurray – Bedford circuit

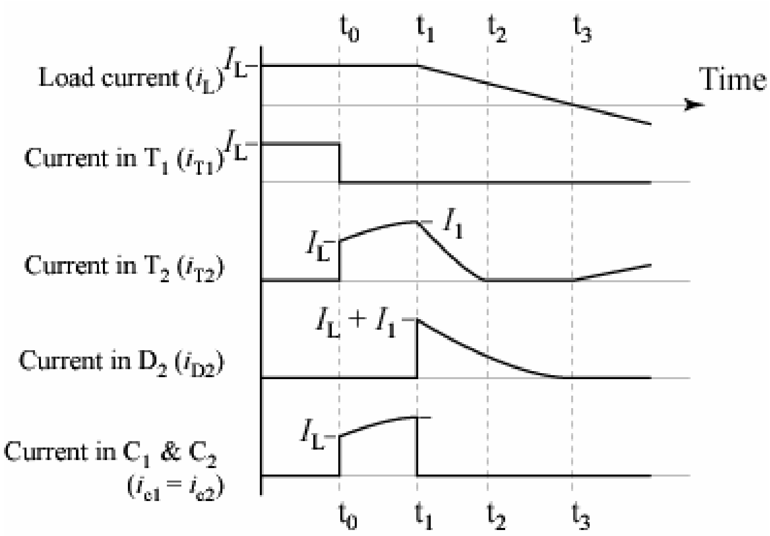
- Variation on McMurray circuit:



- Normally, following constraints on component values apply:

$$L_1 = L_2 = L \qquad C_1 = C_2 = C$$

- Waveforms of currents in circuit are as follows:



Time	Action
$< t_0$	With T_1 conducting, C_1 is uncharged and C_2 charged as shown (+ -)
t_0	T_2 is fired and one end of L_2 is connected to the negative supply rail Capacitor voltage cannot change instantaneously, so supply voltage now appears across L_2 As L_1 and L_2 are close coupled, an equivalent voltage is induced in L_1, raising the cathode potential of T_1 to $2V_s$ to turn it off The load current now transfers to T_2 and L_2, preserving the Ampere-turns balance in the $L_1 L_2$ coil and maintaining the reverse bias on T_1 The current in the inductive load is maintained during this period by the charging currents of C_1 and C_2

Time	Action
	As C_2 discharges, the voltage across L_2 is decreased, reducing the induced voltage in L_1
	At the same time, C_1 is charging, eliminating the reverse bias on T_1 when the forward voltage on C_1 exceeds the reverse voltage on L_1
t_1	The load current transfers to D_2, at which point C_1 is charged to V_s
	The energy stored in L_2 is then dissipated in the loop L_2 - T_2 - D_2
t_2	Current in T_2 falls to zero
	T_2 turns off when the energy stored in L_2 has been dissipated
	D_2 continues to supply a decreasing current

Time	Action
t_3	D_2 turns off when the load current reaches zero
	A reverse load current can now be supplied via T_2
	In practice, T_2 would be supplied with a continuous gate signal to ensure turn-on at the appropriate instant

- McMurray-Bedford circuit more robust at start-up than McMurray circuit
- Does not rely on specific initial conditions

Summary

- Showed that circuits containing thyristors which operate with DC source voltage (instead of an AC supply), such as DC choppers and inverters, cannot rely on natural commutation
- Considered introduction, for these cases, of forced commutation circuits
- Considered in detail forced commutation circuits using external voltage sources, those using capacitor discharge and those based on bridge circuits
- Next, first application of circuits with DC supplies, namely DC chopper circuits