Chapter 3

DC–DC Converters (or) Choppers

LEARNING OBJECTIVES

After reading this chapter, you will be able to understand:

- Principle of operation and control
- Time ratio control
- Current limit control
- Step up chopper
- Step down chopper
- Types of chopper circuits
- Second quadrant (type-B) chopper
- Voltage commutated chopper
- Current commutated chopper
- Peak commutating current
- Load commutated chopper
- Multiphase chopper

Principle of Operation and Control

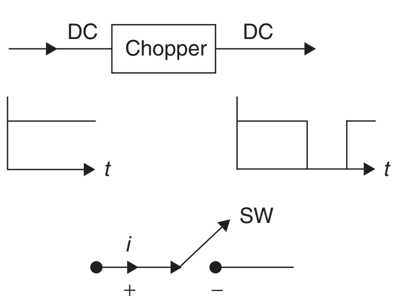
In industries, several applications need DC supply, it will be better if it is a variable DC voltage source.

- This conversion of fixed DC voltage to an adjustable DC output voltage by using semiconductor devices are called chopping examples of such DC systems are trolley buses, battery operated vehicles, subway cars, battery charging, etc.

Principle of Chopper

Chopper is a static device that converts fixed DC input voltage to a variable DC output voltage directly.

- It is a high-speed on/off semiconductor switch (connects source to the load and disconnects the load from the source of a fast speed).
- The device used for a chopper circuit can be force commutated thyristor, power BJT, Power MOSFET, GTO or IGBT.



- It is a DC equivalent of an AC transformer.
- It can be used to step up and step down the fixed DC input voltage.
- Step–down DC chopper is most commonly used.

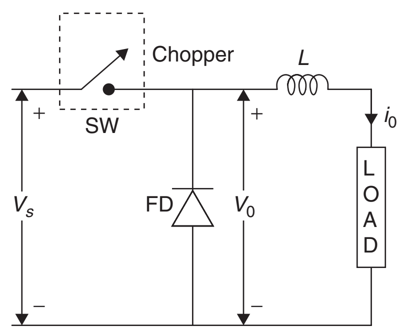
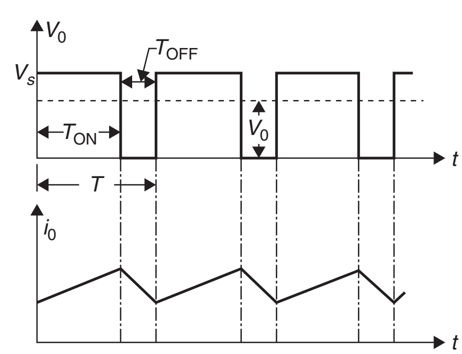


Figure 1 Basic chopper circuit



Output voltage and current waveforms

When chopper is ON, T_{ON} load voltage is equal to source voltage vs. during off period T_{OFF} load current flows through the free-wheeling diode FD. Load terminals are short-circuited by FD and V_0 is zero.

The load power can be controlled by varying the ON and OFF times.

The ratio of T_{ON} to $(T_{ON} + T_{OFF})$ is known as duty cycle.

There are three ways of obtaining the variable ON-time to OFF time for voltage control.

1. T_{ON} constant and T varying (Frequency modulation)
2. T constant and T_{ON} varying (Pulse width modulation)
3. T_{ON} and T are both varying and for all three

Average load voltage

$$V_0 = \frac{T_{ON}}{T_{ON} + T_{OFF}} \times V_s$$

$$= \left(\frac{T_{ON}}{T}\right) V_s$$

where T_{ON} = ON – time

T_{OFF} = OFF – time

$T = T_{ON} + T_{OFF}$ = chopping period

and $\alpha = \frac{T_{ON}}{T}$ = duty cycle

then $V_0 = \alpha V s$

$V_0 = T_{ON} f \cdot V_s$

$f = 1/T$ = chopping frequency

- Therefore, load voltage can be controlled by varying duty cycle α.

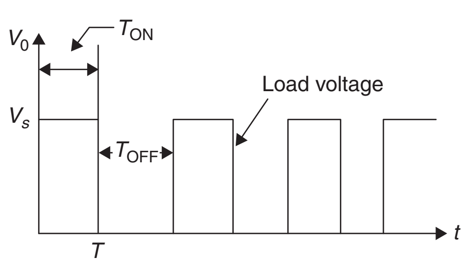
Control Strategies

Average output voltage V_0 can be varied through α by opening and closing the semiconductor switch periodically. The various control strategies for varying duty cyclo α are as follows:

1. Time ratio control
2. Current limit control

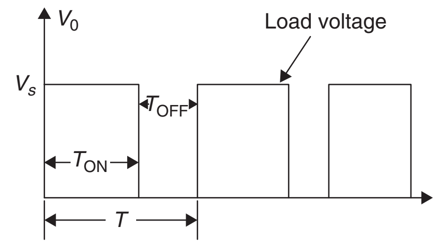
Time Ratio Control

1. **Constant frequency system:**



In this method, T_{ON} is varied but chopping frequency $f(T)$ is kept constant Also called as pulse-width modulation scheme.

2. **Variable frequency system**



In this method, chopping frequency f is varied and either

- ON-time T_{ON} is kept constant
- OFF-time T_{OFF} is kept constant

This method is also called as frequency modulation scheme.

- Frequency modulation scheme has some disadvantages compared to pulse-width modulation scheme.
  Chopping frequency has to be varied over a wide range for the control of output voltage and so the design of filter is quite difficult.
- For the control of α, frequency variation is wide. Due to which interference with signalling and telephone lines in frequency modulation.
- The large time T_{OFF} in frequency modulation make the load current discontinuous which is undesirable. Therefore pulse width modulation scheme is better than variable frequency scheme.
- The only limitation in PWM is T_{ON} cannot be reduced to near zero for most of the commutation circuits used in choppers. So, low range of a control is not possible in PWM.

Current Limit Control

In this control strategy, the ON and OFF of chopper circuit is guided by the previous set value of load current. These two set values are maximum load current I_{max} and minimum Road current I_{min}. When load current reaches the upper limit I_{max}, chopper is switched OFF. Now load current free wheels and begins to decay exponentially. When it falls to lower limit I_{min} chopper is switched on and load current begins to rise. So the load current fluctuates between I_{max} and I_{min}. Therefore it cannot be discontinuous. current limit control involves feedback loop, the trigger circuitry for the chopper is therefore more complex.

Chopper system offers smooth control, high efficiency, fast response and regeneration.

There are two types of choppers

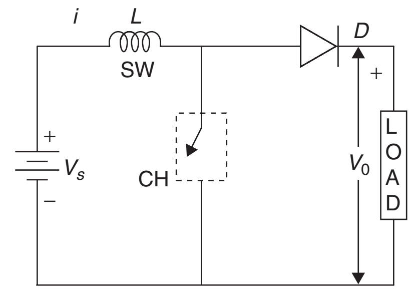
1. Step-down chopper
2. Step-up chopper

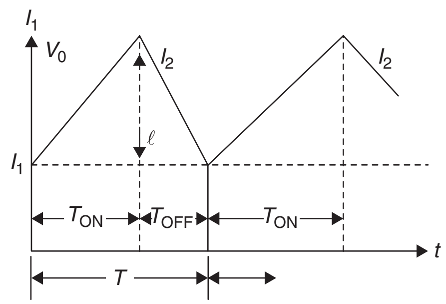
Step-up Chopper

Average output voltage V_0 is greater than input voltage.

$V_0 > V_s$ is called step-up chopper and $V_0 < V_s$ is called step-down chopper.

Working Principle





When the switch is ON, the current circulates in the loop and inductor stores energy.

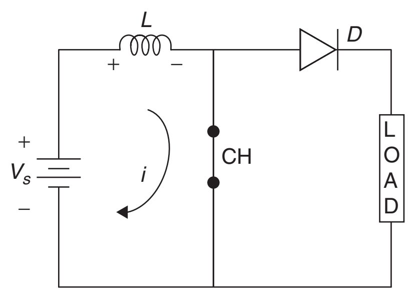
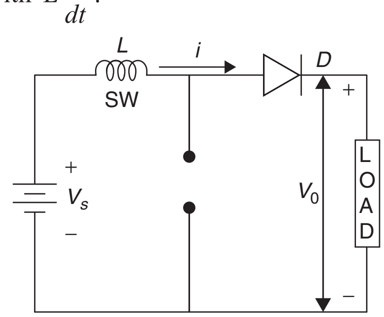


Figure 2 L' stores energy

When the switch is opened the total input voltage is now added up with $L\dfrac{di}{dt}$.



$L\,di/dt$ is added to V_s

$$\therefore \qquad V_{IN} = V_s + L\frac{di}{dt}$$

Therefore, average output voltage V_0 is greater than the input voltage V_s, assuming the output current is linear energy input to conductor from the source, during period T_{ON}, W_{IN} = Avg. volt across Lx Avg. current the inductor x time

$$W_{IN} = V_s\left[\frac{I_1+I_2}{2}\right]T_{ON}$$

Energy released by the inductor to the load during period T_{OFF}.

W_{OFF} = Average voltage across × Average Current × Time.

$$= (V_0 - V_s)\left(\frac{I_1+I_2}{2}\right)\times T_{OFF}$$

For a lossless system

$$V_s\left[\frac{I_1+I_2}{2}\right]T_{ON} = (V_0 - V_S)\left[\frac{I_1+I_2}{2}\right]T_{OFF}$$

$$V_0 = V_S\left[\frac{T}{T-T_{ON}}\right]$$

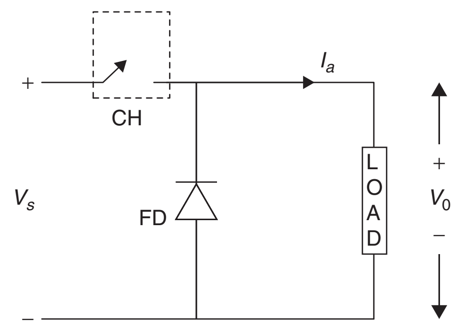
$$T = T_{ON} + T_{OFF}$$

$$V_0 = \frac{V_s}{1-\infty}$$

where $\qquad \alpha = T_{ON}/T$

From the above equation the average voltage across the load can be stepped up by varying the duty cycle.

Step-down Chopper



If $V_0 < V_s$, it is called step-down chopper

$$V_0 = V_s \times \left(\frac{T_{ON}}{T'}\right) = V_S \times f \times T_{ON}$$

$$V_0 = \alpha V_s$$

α-duty cycle of chopper. The average output voltage is less than the input voltage.

RMS output voltage, $V_{RMS} = \left[\dfrac{1}{T}\displaystyle\int_0^{T_{ON}} V_s^2\,dt\right]^{1/2}$

$$V_{RMS} = \sqrt{\alpha}\,V_s$$

Effective Source Resistance (R_{eff})

$$R_{eff} = \frac{(V_s)_{avg}}{(I_s)_{avg}} = \frac{V_s}{\alpha\cdot\dfrac{V_s}{R}} = \frac{R}{(\alpha)}$$

It can be used in static rotor resistance control of an induction motor.

Solved Examples

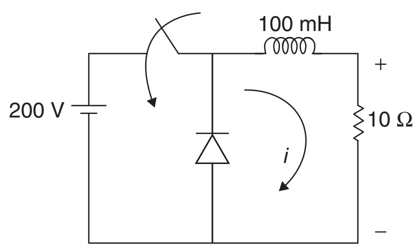
Example 1: If V_{OUT} and V_{IN} are the magnitudes of output voltage and DC input voltages, respectively, for a step-down chopper. If the chopper is operated in a steady state with a constant duty ratio α and continuous conduction mode, then the ratio $\frac{V_{OUT}}{V_{IN}}$ is given by

(A) $\left(\frac{\alpha}{1-\alpha}\right)$ (B) $\left(\frac{1}{1-\alpha}\right)$ (C) α (D) $\left(\frac{\alpha-1}{\alpha}\right)$

Solution: (C)
For a step-down chopper

$$V_{OUT} = \alpha V_{IN} \quad \frac{V_{OUT}}{V_{IN}} = \alpha$$

Example 2: The peak-to-peak ripple in load current in a step-down chopper (as shown below) switched at 2 kHz with a duty ratio of 0.75 is close to
(A) 0.125 A (B) 0.25 A (C) 0.5 A (D) 1 A



Solution: (B)
Maximum ripple current

$$\Delta I_{max} = \frac{V_s}{4fL} = \frac{200}{4\times 2000\times 0.1}$$
$$= 0.25 \text{ A}$$

Example 3: If the desired output voltage of a step DC–DC chopper with an input DC voltage of 230 V is 280 V. The conducting time for the thyristor chopper operating at a T_{OFF} of 50 μs would be
(A) 33.33 μs (B) 66.66 μs
(C) 50 μs (D) 100 μs

Solution: (A)

$$V_0 = \frac{V_s}{1-\alpha}$$

$$380 = 230\left(\frac{1}{1-\alpha}\right)$$

$$(1-\alpha) = 0.6$$

$$\alpha = 0.4 = \frac{T_{ON}}{T_{ON}+T_{OFF}}$$

$$1+\frac{T_{OFF}}{T_{ON}} = \frac{1}{0.4} = 2.5$$

$$T_{ON} = \frac{50}{(2.5-1)} = 33.33\ \mu\text{s}$$

Example 4: The duty cycle of a boost regulator which has an input voltage of 4 V and an average output voltage of 8 V is

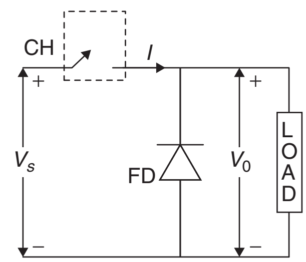
(A) 1/2 (B) 3/2 (C) 2/3 (D) 5/2

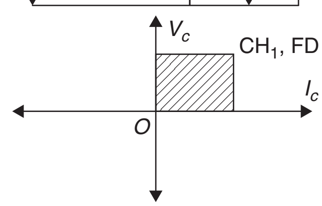
Solution: (A)
For a boost regulator

$$V_0 = \frac{V_s}{1-\alpha} \Rightarrow 1-\alpha = \frac{4}{8} = \frac{1}{2}$$
$$\alpha = (1 - 1/2) = (1/2)$$

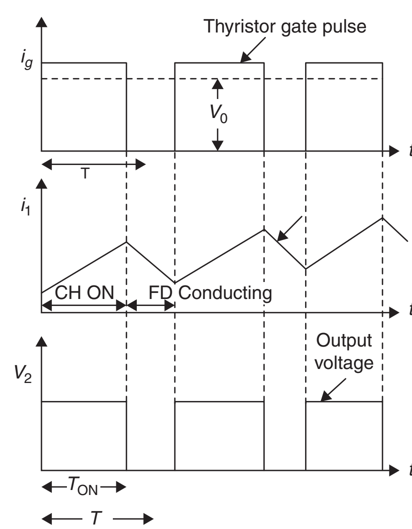
Types of Chopper Circuits

First-quadrant (Type-A) Chopper



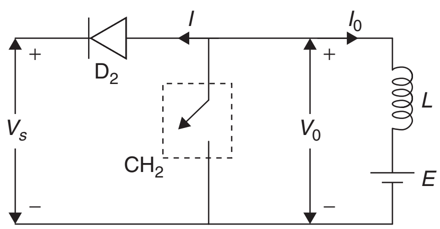


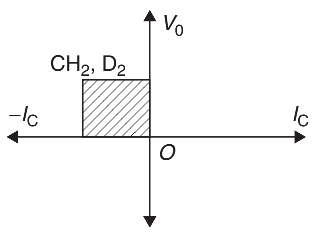
- When chopper CH_1 is ON, $V_0 = V_s$ and current i_0 flows in the direction as shown.
- When CH_1 is OFF $V_0 = 0$ but i_0 in the load continues flowing in the same direction through FD (free-wheeling diode).
- Hence average values of both load voltages and currents, i.e. V_0 and I_0 are always positive as shown by the shaded area in the I quadrant.
- The average output voltage V_0 is always less than input DC voltage V_s and hence it is also known as step-down chopper.
- The power flow in Type-A chopper is always from source to load.



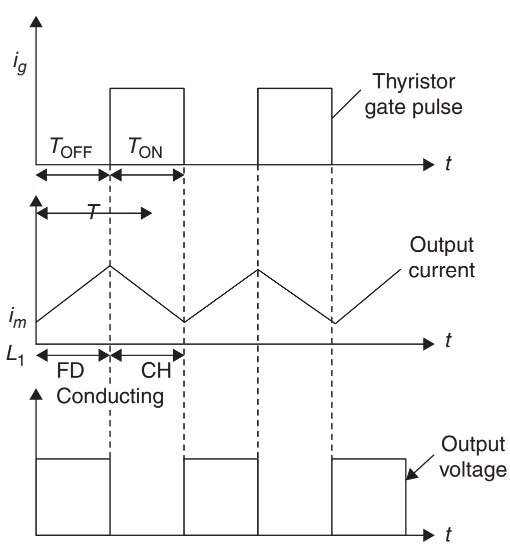
It is a step-down chopper in which the average value of output voltage and current is always positive, A free-wheeling diode is connected across the load to prevent the output current being negative. Its region of operation is in the first quadrant only, so it is also called first–quadrant chopper.

Second-quadrant (Type-B) Chopper



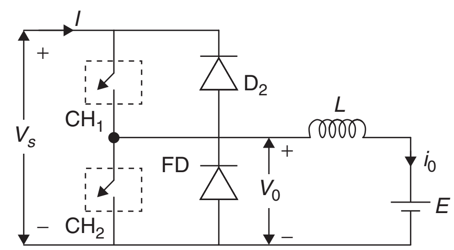


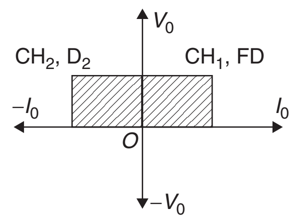
- When CH_2 is ON, $V_0 = 0$ but load voltage E drives current through L and CH_2. Inductance stores energy during T_{ON} of CH_2.
- When CH_2 is OFF $V_0 = \left(E + L\dfrac{di}{dt}\right)$ exceeds source voltage V_s: then D_2 becomes forward biased and begins conduction thus allowing power to flow to the source.
- CH_2 may be ON or OFF, current I_0 flows out of the load, current i_0 is therefore treated as negative. Since V_0 is always positive and I_0 is negative, power flow is always from load to source.
- As load voltage $V_0 = \left(E + L\dfrac{di}{dt}\right)$ is more than source voltage V_s, type-B chopper is also called step-up chopper.



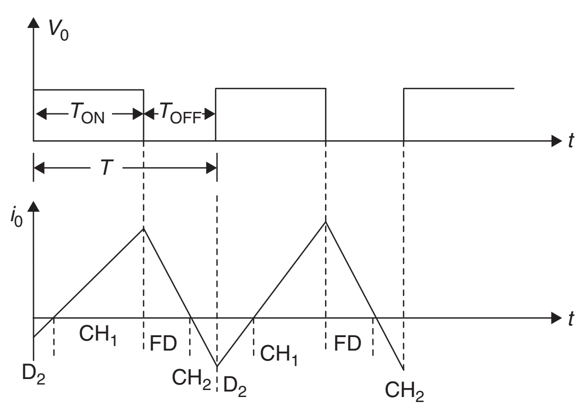
In this type the average output voltage is positive but the average output current is negative. Therefore the class B chopper operates in the second quadrant. Power flows from the load to the source. It is a step-up chopper. It is widely used for regenerative breaking of DC Motor.

Two-quadrant Type-A (Type-C) Chopper





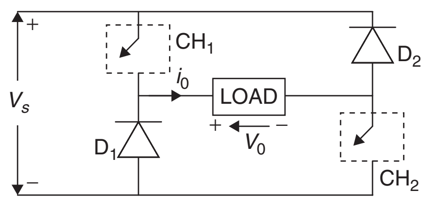
- This chopper is obtained by connecting type-A and type-B choppers in parallel.
- V_0 is always positive due to the presence of FD across the load.
- When CH_2 is ON (or) FD conducts $V_0 = 0$, and in case CH_1 is ON or diode D_2 conducts and $V_0 = V_s$.
- Load current i_0 can however reverse its direction. i_0 is positive when CH_1 is ON and FD conducts. I_0 is negative when CH_2 is ON or D_2 conducts.
- CH_1 and FD operate together as type-A chopper in the I quadrant CH_2 and D_2 operate together as type-B in the second quadrant.
- Average load voltage is always positive but average load current may be positive or negative. Hence the power flow may be from source to load (I quadrant operation) or from load to source (II quadrant operation).
- Choppers CH_1 and CH_2 should not be ON at the same time as this would lead to a direct short circuit of supply lines.
- Such choppers are used for motoring and regenerative braking of DC motors.

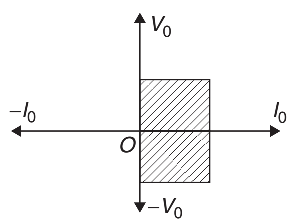


Class C chopper is a combination of class A and class B choppers. For first-quadrant operation, CH_1 is ON or D_1 conducts. For second quadrant, CH_2 is ON or D_1 conducts. When CH_1 is ON, the load current is positive. The output voltage is equal to 'V' and the load receives power from the source.

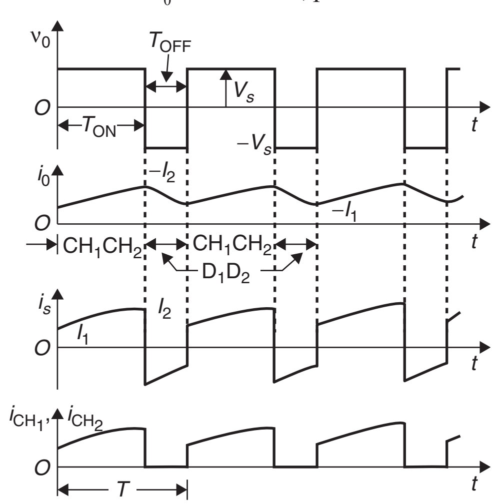
When CH_1 is turned OFF, energy stored in inductance, L forces current to flow through the diode D_2 and the output voltage in zero. Current continuous to flow in positive direction. $\Rightarrow$ When CH_2 is triggered, the voltage E forces current to flow in opposite direction through L and CH_2. The output voltage is zero turning OFF CH_2, the energy stored in the inductance drives current through diode D_1 and the supply output voltage is V_1 the input current becomes negative and power flows from load to source.

Two-quadrant Type-B (Type-D) Chopper

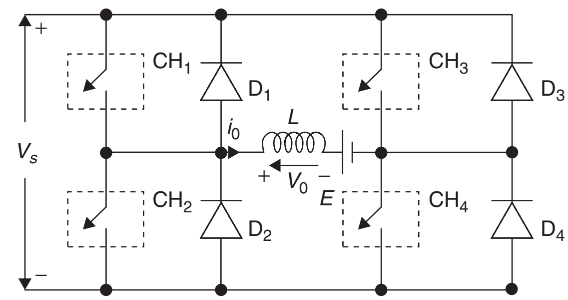


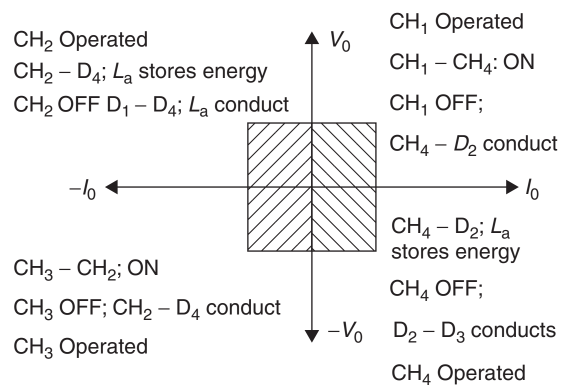


- Type-D chopper is obtained by connecting Type-A and Type-B chopper in differential mode, i.e., load is connected in between them.
- When both CH_1 and CH_2 are ON $V_0 = V_s$.
- When both choppers are off D_1 and D_2 conducts $V_0 = -V_s$.
- Average output voltage V_0 is positive when their $T_{ON} < T_{OFF}$ and V_0 is negative when their $T_{ON} > T_{OFF}$.
- The direction of load current is always positive because choppers and diodes can conduct current only in the direction of arrows. As V_0 is reversible, power flow is reversible.



Four-quadrant Type-E Chopper





First Quadrant

- CH_4 is kept ON, CH_3 is kept OFF and CH_1 is operated. With CH_1, CH_4 ON $V_0 = V_s$ and i_0 begins to flow. Here both V_0 and i_0 are positive resulting first quadrant operation. When CH_1 is turned OFF positive current freewheels through CH_4 and D_2.

Second Quadrant

- CH_2 is operated and CH_1, CH_3, CH_4 are kept OFF. With CH_2 ON, reverse (negative) current flows through L, CH_2, D and E. Inductance L stores energy during the time CH_2 is ON. When CH_2 is turned OFF, current is fed back to source through diodes D_1, D_4. Here, $E + L\dfrac{di}{dt}$ is more than the source voltage V_s.
- As V_0 is positive and I_0 is negative, it is second-quadrant operation of chopper.
- Power is fed back from load to source.

Third Quadrant

CH_1 is kept off, CH_2 is kept ON and CH_3 is operated. Polarity of load emf E must be reversed for this quadrant working when CH_3 ON, load gets connected to V_s so that both V_0 and I_o are negative leading to third-quadrant operation.

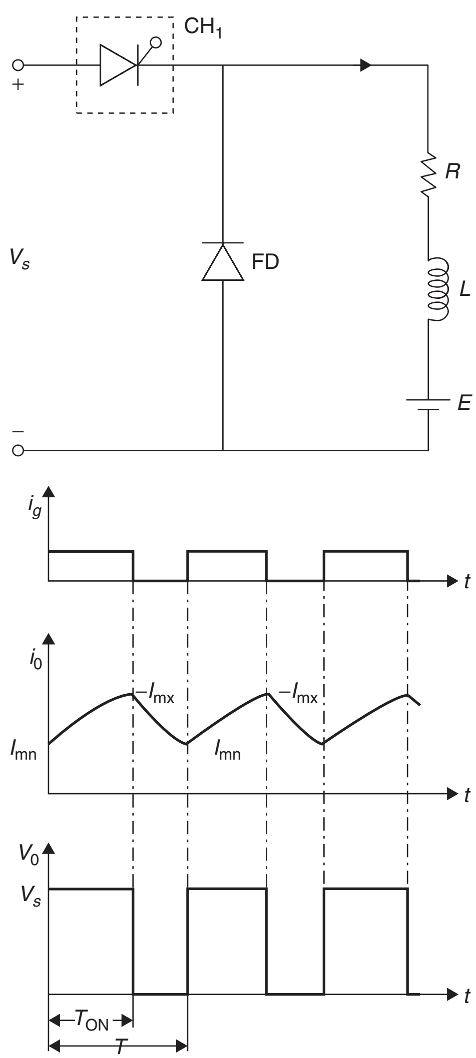
- When CH_3 is turned off, negative current freewheels through CH_2, D_4. In this manner, V_0 and i_0 can be controlled in the third quadrant.
- Here, the chopper operates as step-down chopper.

Fourth Quadrant

CH_4 is operated and other devices are kept OFF. Load emf E must have its polarity reversed, for operation in IV Quadrant. With CH_4 ON positive current flows through CH_4, D_2, L and E.

- L stores energy during the time CH_4 is ON. When CH_4 is turned OFF current is fed back to the source through diodes D_2, D_3. Here, load voltage is negative, but load current is positive leading to the chopper operation in IV quadrant.
- Power is fed back from load to source. Chopper here operates as step-up chopper.

Steady-state Analysis of Type-A Chopper



For type A-chopper with RLE load, for $0 < t\ T_{ON}$

$$V_s = Ri + \frac{Ldi}{dt} + E$$

$$V_0 = V_s$$

$$RI(s) + L\left[SI(s) - I_{mn}\right] = \frac{V_s - F}{s}$$

$$I(s) + \frac{V_s - E}{R}\left[\frac{1}{S} - \frac{1}{(S + R/L)}\right] + \frac{I_{mn}}{S + (R/L)}$$

$$I(t) - \frac{V_s - E}{\frac{R}{I_{mn}\ e^{-R/L\times t}}}\left[1 - e^{-(R/L)L}\right] +$$

$$I(t) - \left[\frac{V_s - E}{R}\right]\left[1 - e^{-(R/L)t}\right] + I_{mn}\ e^{-R/Lt}$$

When $\quad t = T_{ON}$, then $i(t) = I_{mx}$

$\quad t = T;\ i(t) = I_{mn}$

Let $\dfrac{L}{R} = T_a$ (Time constant)

$$I_{max} = \frac{V_s}{R}\left[\frac{1 - e^{-T_{ON}/T_a}}{(1 - e^{-T/T_a}}\right] - \frac{E}{R}$$

$$I_{min} = V_s / R \frac{\left[e^{T_{ON}/T_a} - 1\right]}{\left[e^{T/T_a} - 1\right]} - \frac{E}{R}$$

Steady-state ripple current

$$\Delta I = I_{max} - I_{min}$$

$$\Delta I = \frac{V_s}{R}\left[\frac{\left(1 - e^{T_{ON}/T_a}\right)\left(1 - e^{-(T - T_{ON})/T_a}\right)}{1 - e^{-T/T_a}}\right]$$

$\Rightarrow$ The ripple current given by the equation is independent of load converter emf E with $T_{ON} = \alpha T$ and $(T - T_{ON}) = (1 - \alpha)T$ and duty cyclo $\delta = \dfrac{T_{ON}}{T}$.

$$\Delta I = \frac{V_s}{R}\left[\frac{\left(1 - e^{\delta x}\right)\left(1 - e^{-(1-\delta)x}\right)}{1 - e^{-x}}\right]$$

For maximum value of ripple current,

$$\delta = 0.5 = 1/2$$

From which we can get

$$\Delta I_{max} = \frac{V_s}{4fL} \text{ at } \alpha = 0.5$$

Fourier Analysis of Output Voltage

$$V_0 = V_0 + \sum_{n=1}^{\infty} V_n$$

where $\quad V_n$ = value of n^{th} harmonic voltage

$$= \frac{2V_s}{n\pi}\sin(n\pi\alpha)\sin(n\omega t + \theta n)$$

$$V_0 = \alpha V_s;\ \alpha = T_{ON}/T$$

$$\theta_n = \tan^{-1}\left[\frac{\sin(2\pi n\alpha)}{1 - \cos(2\pi n\alpha)}\right]$$

$$\text{Ripple Factor} = \frac{\text{AC ripple voltage}}{\text{DC voltage}}$$

$$\text{R.F.} = \sqrt{\frac{\alpha V_s^2 - \alpha^2 V_s^2}{\alpha V_s}}$$

$$= \frac{V_s \times \sqrt{\alpha - \alpha^2}}{\alpha V_s}$$

$$\text{R.F.} = \sqrt{(1/\alpha) - 1}$$

RMS value of output voltage

$$= \sqrt{1/T \int_0^{T_{ON}} V_s^2 dt}$$

$$= \sqrt{1/T V_s^2 \cdot T_{ON}}$$

$$(V_0)_{RMS} = \sqrt{\alpha} V_s$$

Example 5: The duty ratio of a chopper, operating at a fixed frequency and feeding an RL load is increases from 0.3 to 0.7. The ripple in the load current

(A) Increases with duty ratio
(B) Does not change
(C) Would decrease, reach minimum at 50% duty ratio and then increase
(D) Would increase, reach maximum at 50% ratio and then decrease

Solution: (D)

Example 6: A transistor chopper operates at 0.5 duty cycle and at a frequency of 2 kHz. The chopper is supplied from a fixed voltage DC source and feeds a fixed RL load and a freewheeling diode. If it is desired to reduce the ripple content of load current, without changing the value of average DC current through the load. The chopper should be operated

(A) With constant duty cycle and increased frequency
(B) By decreasing only duty cycle
(C) By increasing the value of frequency and duty cycle α in equal proportion
(D) By decreasing only chopper frequency

Solution: (A)

Average DC current through the load $I_0 = \frac{V_0}{R}$ and $V_0 = \alpha V_s$

If α changes, average value of I_0 changes which has to be kept constant.

Hence, α has to be constant.

$$\text{Ripple } \Delta I = \frac{V_s}{4 fL}$$

Ripple can be reduced by increasing the chopper frequency that is constant average DC load current and reduced ripple content can be obtained by constant α and increasing chopper frequency.

Example 7: A DC motor armature with a back emf E. is fed from a step-down chopper which is connected to supply of V. When the average output DC current of the chopper was observed in a CRO the following were noted in every chopping cycle.

(A) The current increases for the time t_1.
(B) The current falls to zero over t_2.
(C) The current remains zero for time t_3.
(D) The average DC voltage across the freewheeling diode is

(A) $\frac{V_s t_r}{(t_r + t_f + t_0)}$ (B) $\frac{V_s t_r + E_b t_f}{(t_r + t_f + t_0)}$

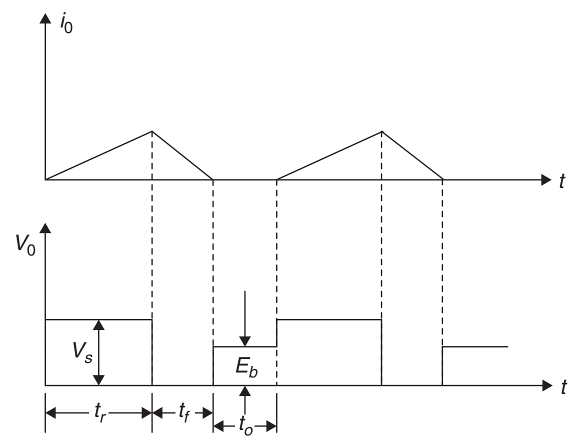
(C) $\frac{V_s t_r + E_b t_0}{(t_r + t_f + t_0)}$ (D) $\frac{V_s t_r + E_b (t_f + t_0)}{(t_r + t_f + t_0)}$

Solution: (C)

For step-down chopper for R_L load

$$V_t = V_0 = \alpha V_s = \frac{T_{ON}}{T} V_s$$

For RLE load, the output waveform is



$$T = t_r + t_f + t_0$$

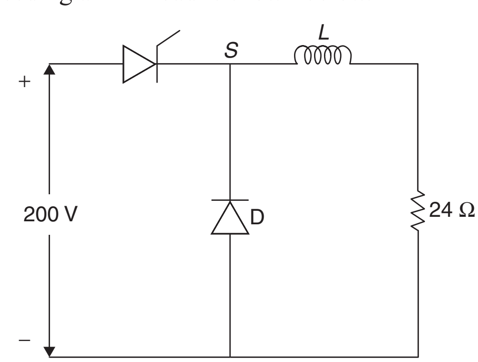
The terminal voltage

Exist only for the periods t_r and t_0 remaining time zero

∴ The average voltage

$$= \frac{V_s t_r + E_b t_0}{t}$$

Example 8: A chopper connected to a supply of 200 V DC input feeding an RL load is shown below.



The duty cycle of the main switch is 0.6 and the load inductance is sufficient enough to maintain a constant, ripple-free load current. The average steady-state diode current would be

(A) 1.6 A (B) 2 A (C) 2.6 A (D) 8 A

Solution: (B)

During chopper operation switch (s) conducts during T_{ON} and diode D conducts during T_{OFF}. Average diode current

$$I_D = I_D \times \frac{T_{OFF}}{T} = I_0 \times \frac{(1-\alpha)T}{T}$$

$$I_D = I_D(1 - \alpha)$$

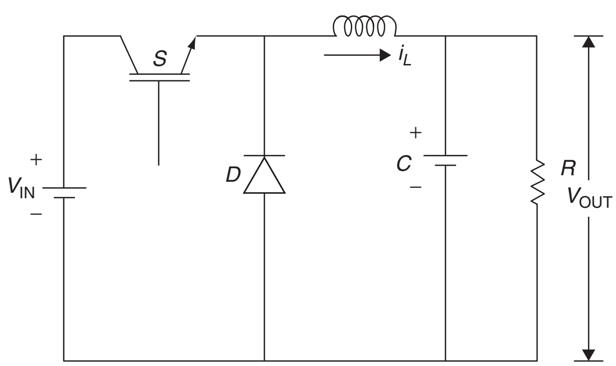
$$I_0 = \frac{V_0}{R}$$

$$V_0 = \alpha V_S = 0.6 \times 200 = 120 \text{ V}$$

$$I_0 = \frac{120}{24} = 5 \text{ A}$$

$$I_D = 5 \times (1 - 0.6) = 2 \text{ A}$$

Example 9: The chopper shown below is operated with a constant input source voltage V_{IN} and ripple free output voltage V_{OUT}. The value of duty ratio D at the boundary of continuous and discontinuous conduction of the inductor current I_L would be (assume that the switch S is operated with a switching time period T)



(A) D = $2L/RT$

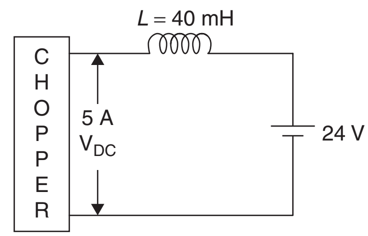
(B) D = RT/L

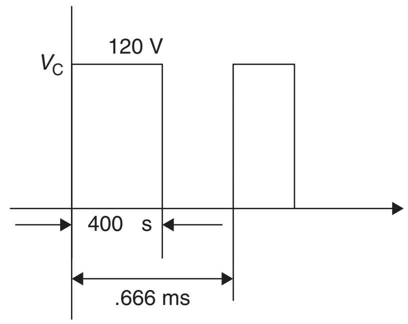
(C) D = $1 - \dfrac{V_s}{V_o}$

(D) D = $1 - 2\,L/RT$

Solution: (D)

Example 10: A battery charger employs a DC–DC which is operating at a duty ratio of 0.6 and supplying a charging current of 7.5 A is shown in Fig I. The chopper output voltage is as seen in Fig II. The peak-to-peak ripple current in the charging current is





(A) 0.48 A (B) 1.2 A (C) 1 A (D) 2.4 A

Solution: (C)

$$T_{ON} = 400\ \mu\text{s} \qquad T = 0.666 \text{ ms}$$

Charging current peak to peak

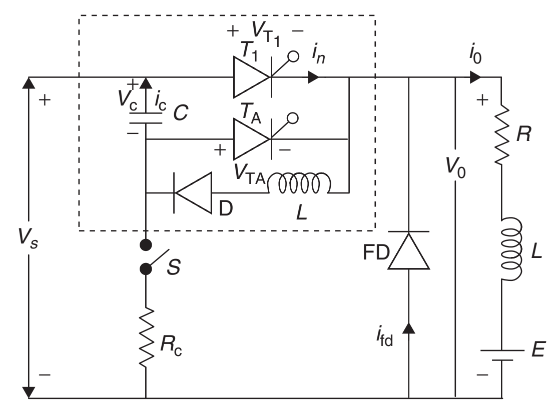
$$I_P = \left[\frac{V-E}{L}\right]T_{ON} = \left[\frac{120-24}{40\times10^{-3}}\right]\times 400\times10^{-6}$$

$$= 0.96 \text{ A} \cong 1 \text{ A}$$

Thyristor Chopper Circuits

The process of turning off a conducting thyristor is called commutation. In a DC chopper, it is essential to provide a separate commutation circuitry to commutate the main power SCR.

Voltage Commutated Chopper



Operating Modes

Chopper operation is divided into 4 modes.

Mode 1: For $0 < t < t_1$

T_1 and D_1 are ON T_2 and FD are kept OFF. The output voltage $V_0 = V_s$ and simultaneously the capacitor gets charged to a voltage $V_c = V_s$.

The direction of output current remains the same.

Mode 2: For $t_1 \le t \le t_2$

Only T_1 is kept ON and all other devices are turned OFF.

- The source voltage V_s appears across the output and i_0 flows through T_1 and then to the load.

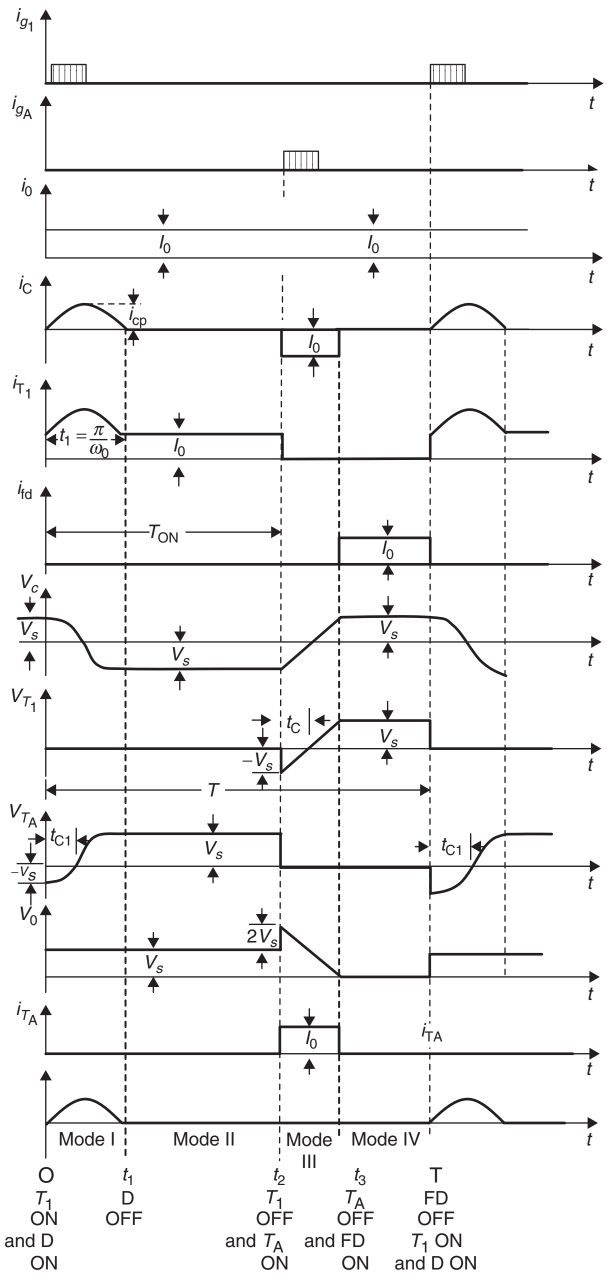
Mode 3: For $t_2 \le t \le t_3$

- Now T_A is operated and all other devices are turned off.
- Now V_s is in series with V_c; hence the total input voltage is $(V_s + V_c)$, which appears across load. $V_0 = V_s + V_c$.
- Load current i_0 flows through T_2 and then flows through load.

Mode 4: For $t_3 \le t \le T$

The capacitor is now fully discharged and all other devices except FD are switched OFF.

- Though there is no current flow from source to load since $V_0 = i_0$ in the load continues flowing in the same direction through free-wheeling diode.



For a constant load current I_0 commutating capacitor $C = \dfrac{t_c I_0}{V_s}$.

T_c = Commutation circuit turn off time t_c must be greater than t_q.

T_q = S.C.R. turn off time

$$T_c = t_q + \Delta t$$

$$C = \frac{(t_q + \Delta t)I_0}{V_s}$$

Commutating inductor $L \ge \left(\dfrac{V_s}{I_0}\right)^2 C$

Turn-off time $t_{c_1} = \dfrac{t_1}{2\omega_0} = \dfrac{\pi\sqrt{LC}}{2}$

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

$$L = \left(\frac{2t_{c_1}}{\pi}\right)^2 \cdot \frac{1}{C}$$

Peak current through T_1 is

$$I_{T1P} = I_0 + V_s\sqrt{\frac{C}{L}}$$

Peak diode current $I_{DP} = V_s\sqrt{\dfrac{C}{L}}$ = Peak capacitor current.

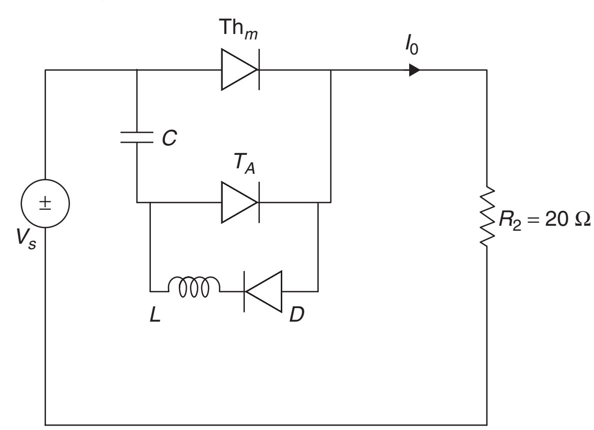
Effective on period $T'_{ON} = T_{ON} + \dfrac{2V_s}{I_0}C$

Commutating capacitor

$$I_0 = C\,\frac{\left(V_s - (-V_s)\right)}{2t_c}$$

$$C = \frac{I_0 t_c}{V_s}$$

Example 11: For the current shown below if the circuit turn off time and peak value of capacitor current are 55 αs and 15 A, respectively. Then the values of 'L' and 'C', respectively, are



$V_s = 200$ V

(A) 1.2 mH, 24 µF (B) 2.4 mH, 44 µF
(C) 1.1 mH, 24 µF (D) 1.1 mH, 2.75 µF

Solution: (D)

$$i_0 = \frac{V_s}{R} = \frac{200}{20} = 10 \text{ A}$$

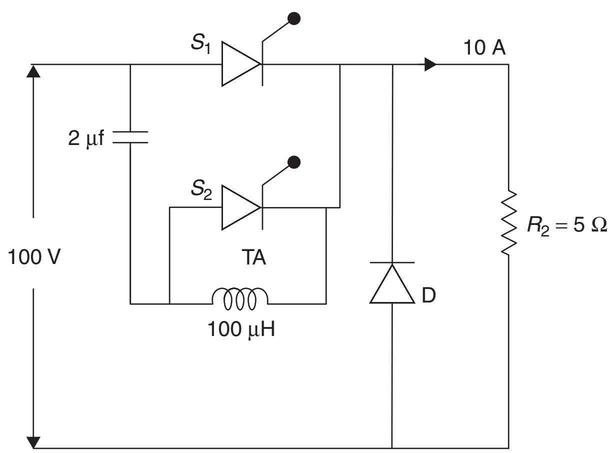
$$(t_c)_{\text{OFF}} = \frac{CV_s}{I_0} \quad C = \frac{(t_c)_{\text{OFF}} \times I_0}{V_s}$$

$$C = \frac{55 \times 10^{-6} \times 10}{200} = 2.75\ \mu\text{F}$$

$$L = \left[\frac{V_s}{I_0}\right]^2 \times C = \left[\frac{200}{10}\right]^2 \times 2.75 \times 10^{-6}$$

$$L = 1.1 \text{ mH}$$

Example 12: The figure shown below is that of a chopper with S_M being the main switch rated for 200 V, 30 A and S_S being the auxiliary commutation device rated for 200 V, 20 A. The main device operates at a duty ratio of 75% and the load current is 10 A. The peak current through S_M is



(A) 40 A (B) 20 A (C) 30 A (D) 10 A

Solution: (B)
When S_M is triggered L, C and S_M forms a tank circuit. The current through circuit is given by

$$I_C = \frac{V_s}{\omega_0 L} \sin \omega_0 t \left[\text{where } \omega_0 = \frac{11}{\sqrt{LC}}\right]$$

Peak capacitor current

$$(I_C)_P = \frac{V_s}{\omega_0 L} = V_s \times \sqrt{\frac{C}{L}}$$

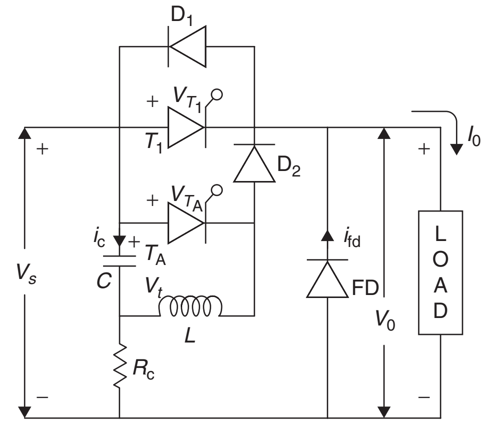
Peak current though S_1 is

$$I = (I_C)_p + I_0$$

$$= V_s \sqrt{\frac{C}{L}} + I_0 = 100 \times \sqrt{\frac{1 \times 10^{-6}}{100 \times 10^{-6}}} + 10$$

$$= 100 \times (0.1) + 10 = 20 \text{ A}$$

Current Commutated Chopper



Operating Modes

The chopper operates in five modes

Mode 1: For $t_1 < t < t_2$

- Initially devices T_1, T_A are switched ON and D_1, D_2, F.D. are turned OFF.
- This charge the capacitor $V_c = V_s$ (through T_A) and simultaneously source voltage appears across the load (through T_1) and current I_0 flows. When capacitor is fully charged T_A is turned off.

Mode 2: For $t_2 < t < t_3$

- When capacitor is fully charged D_2 is forward biased and is conducting. This circulates a current in the loop formed by C-L-D_1-T_1 and the current through T_1 opposes the flow of load current.

$$I_{TI} = i_0 - i_c$$

Mode 3: For $t_3 < t < t_4$
D_1 and D_2 are forward-biased and starts conducting. T_1 is turned OFF and T_A remains OFF as before.

- The source current splits up into diode D_1 and capacitor where

$$I_{D_1} = I_0 - I_c$$

- After this mode capacitor voltage is fully discharged and D_1 is turned off.

Mode 4: For $t_4 < t < t_5$

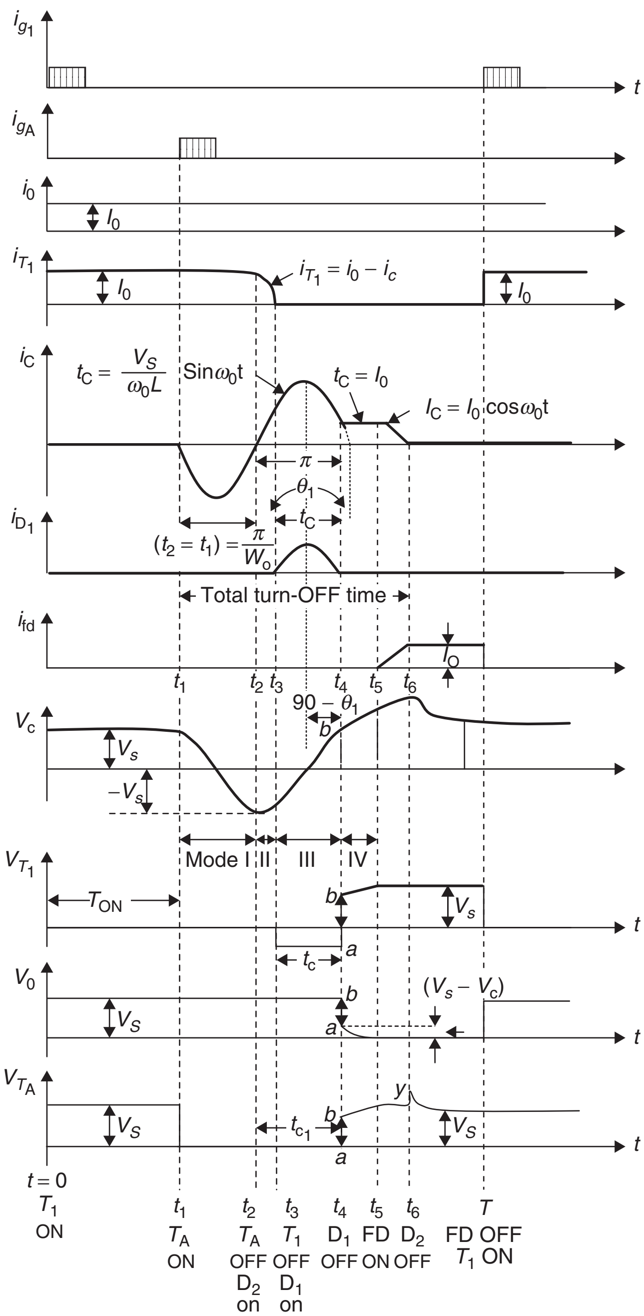
- During this mode, D_1, T_1, T_A and FD are turned OFF.
- The supply current flows through capacitor, charges the capacitor, and then reaches the load through D_2.
- Load current $I_0 = I$.

Mode 5: For $t_4 < t < t_6$
Once the capacitor is fully charged while mode 4 FD starts conducting and the load current keeps circulating in the same direction.

- D_2 and FD are the only conducting devices.
- The output current flowing through the load $I_0 = i_c + i_{fd}$.
- At t_6, D_2 is turned off as well and the load current circulates in the loop FD-LOAD.

Note:

1. In all modes of operations, the output voltage always remains positive.
2. The direction of current will always be from source to load and it is never fed back.



Peak Commutating Current (I_{cp})

$$I_{cp} = V_s\sqrt{\frac{C}{L}} > I_0$$

$$\boxed{I_{cp} = V_s\sqrt{\frac{C}{L}} = XI_0}$$

where $x = \dfrac{I_{cp}}{I_0}$ is greater than 1.

Circuit Turn-off time

$$t_c = \frac{1}{\omega_0}\left[\pi - 2\sin^{-1}\left[\frac{I_0}{I_{cp}}\right]\right]$$

Commutating Inductor

$$L = \frac{V_s t_c}{XI_0\left[\pi - 2\sin^{-1}(1/x)\right]}$$

Commutating Capacitor

$$C = \frac{X\ I_0\ t_c}{V_s\left[\pi - 2\sin^{-1}(1/x)\right]}$$

Turn-off Times

For main SCR, $t_4 - t_3 = t_c = \left[\pi - 2\sin^{-1}\left(\frac{1}{x}\right)\right]\cdot\sqrt{LC}$

For auxiliary SCR

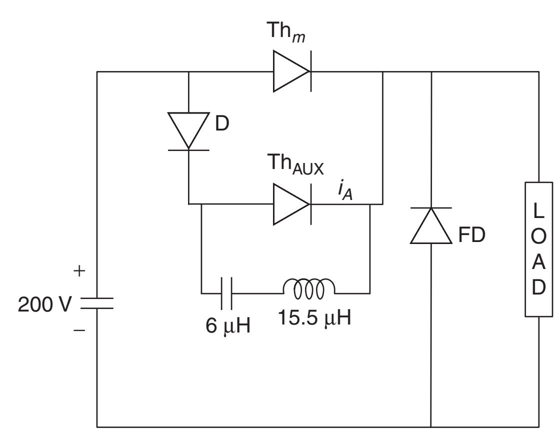
$$t_4 - t_2 = t_{c1} = \left[\pi - 2\sin^{-1}\left(\frac{1}{x}\right)\right]\cdot\sqrt{LC}$$

Example 13: Among the following which would yield best performance in a thyristor DC chopper?

(A) Source commutation
(B) Voltage commutation
(C) Load commutation
(D) Current commutation

Solution: (D)

Example 14: Given below is a current commutated DC–DC chopper where $(Th)_M$ and $(Th)_A$ are main and auxiliary thyristors, respectively.



If the auxiliary S.C.R. is triggered at $t = 0$, when Th_M is conducting and a constant load current of 12 A is flowing through the load. The main thyristor is turned OFF between

(A) $30\ \mu s < t \le 40\ \mu s$ (B) $20\ \mu s < t \le 30\ \mu s$
(C) $10\ \mu s < t \le 20\ \mu s$ (D) $0\ \mu s \le t \le 10\ \mu s$

Solution: (A)

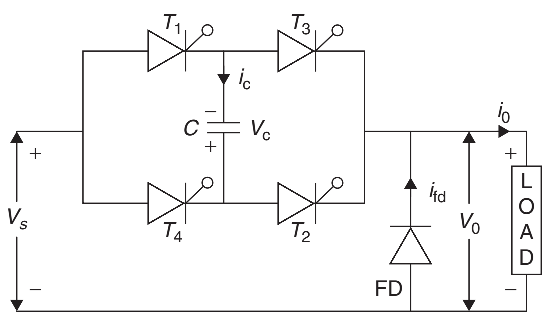
When $(\text{Th})_A$ is triggered, a tank circuit is formed and conducts for $\pi\sqrt{LC}$ seconds

$$\pi\sqrt{LC} = \pi\sqrt{15.5\times10^{-6}\times6\times10^{-6}}$$
$$= 3.03 \times 10^{-5} = 30\ \mu s$$

After 30 µs an opposite current pulse will be injected and Th_M gets off. It is possible when capacitor current equals load current

$(\text{Th})_M$ gets OFF when $30 < t \le 40\ \mu s$

Load-commutated Chopper



Operating Modes

Mode 1: For $0 < t < t_1$

- T_1 and T_2 are turned ON and the current flows through
$$T_1 - C - T_2 - \text{LOAD}$$
- T_3 and T_4 are OFF
- The output voltage across the load $V_o = V_s$ and simultaneously the capacitor gets charged.

Mode 2: For $t_1 < t < t_2$

- All T_1, T_2, T_3, T_4 are turned off.
- The capacitor is fully charged and the polarity of the plates reversed when compared to initial condition.
- Free-wheeling diode D_1 starts conducting and the current through the load circulates in the loop.

Mode 3: For $t_2 < t < t_3$

- T_4 and T_3 conduct output voltage that appears across the load
$$V_o = V_s + V_c$$
- T_1 and T_2 are turned off.
- Since the load voltage is more than source voltage this chopper also is known as step-up chopper.

Multiphase Chopper

A multiphase chopper is one that consists of two or more choppers connected in parallel at the same frequency but with a proper phase shift. This type of operation enables the load and power supply to be subjected to an effective frequency which is a multiple of the chopping frequency.

- As a result, the supply harmonic current is reduced and the ripple amplitude decreases.

A multiphase chopper may be operated in two modes:

1. In phase operation mode
2. Phase-shifted operation mode

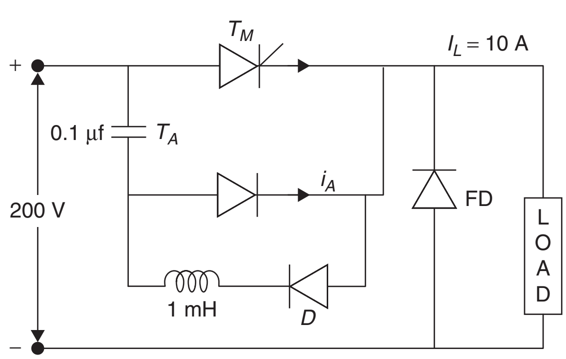
- In the in phase operation mode, all parallel connected choppers are on and off at the same instant.
- In the phase shifted operation mode, different choppers are on and off at different instant of time.
- The inductance L in series with each chopper is sufficiently large so that each chopper operates independent of each other.

Exercises

Practice Problems I

Directions for questions 1 to 15: Select the correct alternative from the given choices.

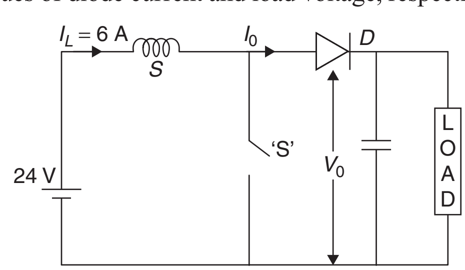
1. A voltage-commuted chopper circuit operated at 50 Hz as shown below.



For a load current of 5 A, the ratio of magnitudes of I_M to I_A (as indicated in the figure) would be

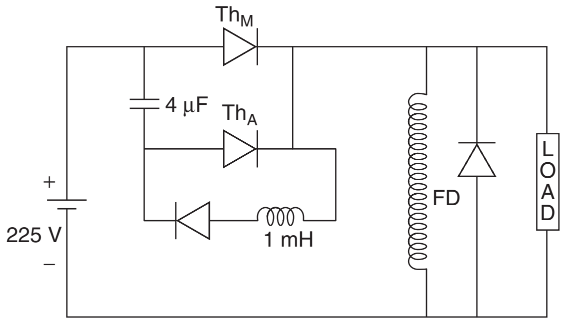
(A) 0.65 (B) 0.833 (C) 1 (D) 1.2

2. A step-up chopper shown below is operated at a duty cycle of 0.6. If a large capacitor is connected across the load and for a constant value of inductor current, then the average values of diode current and load voltage, respectively, are



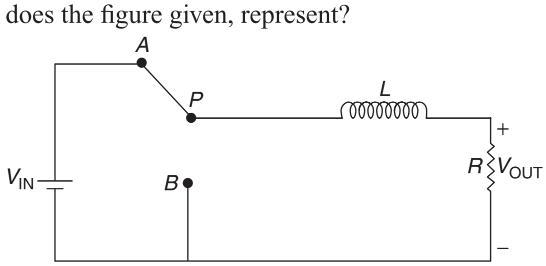
(A) 2.4 A, 60 V (B) 2 A, 40 V
(C) 8 A, 40 V (D) 2 A, 10 V

3. The figure shown below is a voltage commutated chopper operating with a duty ratio of 0.4 and at a frequency of 0.5 kHz. The load current is almost ripple free and remains constant at 15 A. The turn off time available to the thyristor Th_M is (assume the devices to be ideal)



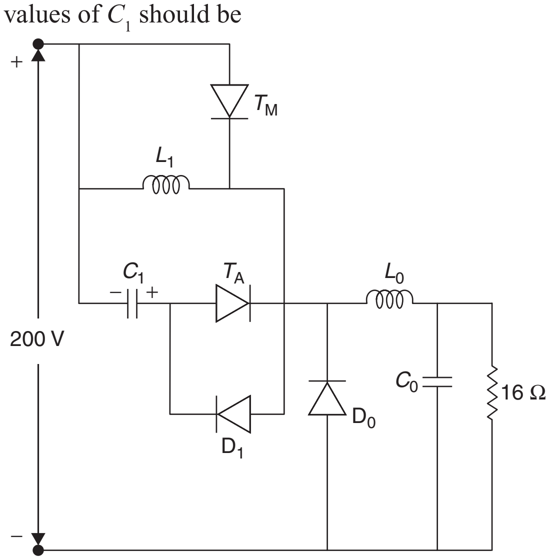
(A) 30 μs (B) 60 μs
(C) 20 μs (D) 40 μs

4. If the pole P of a single pole double throw switch is connected alternately to throws A and B as shown in the figure below. Which among the following converter does the figure given, represent?



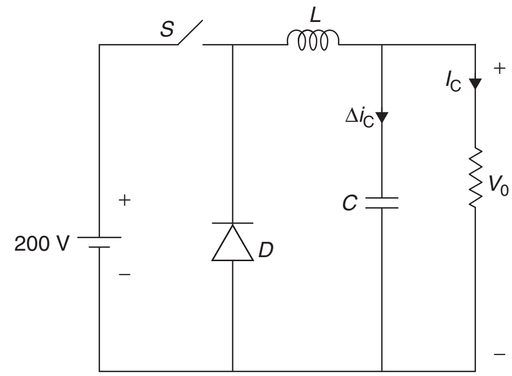
(A) Half-wave rectifier
(B) Step-up chopper [Boost converter]
(C) Step-down converter [Buck converter]
(D) None of the above

5. A chopper circuit shown in the figure below T_M is operated at 50% duty ratio. The maximum allowable reapplied $\frac{dV}{dt}$ on T_M is 10 V/μs. Assuming the ripple current through L_o to be negligible, the theoretical minimum values of C_1 should be



(A) 0.0625 μF
(B) 0.625 F
(C) 0.625 μF
(D) 0.625 mF

6. The ideal S in the circuit shown below is operated at 120 kHz at a duty ratio of 0.8. If I_0 is 10 A and $(\Delta i_c)_{p-p}$ is 1.6 A, the peak current in the switch S is



(A) 11.6 A
(B) 12.4 A
(C) 10.3 A
(D) 9.3 A

7. A 30 V battery charger feeds an ideal chopper which is operating at 400 Hz. It is supplying power to a resistive load of 1.5 , assuming the load is shunted by a perfect commutating diode and a loss less battery. The mean load current at an ON/OFF ratio of 1/1 would be
(A) 15 A
(B) 10 A
(C) 20 A
(D) 25 A

8. A voltage-commutated chopper has following parameters:

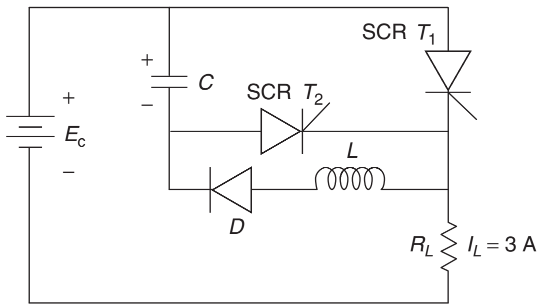
$$V_s = 230 \text{ V}$$

Load circuit parameter 5 Ω, 10 mH, 25 V
Commutation circuit parameters $L = 5$ μH, $C = 10$ μF
For a constant load current at 115 A, the effective ON period and peak current through the main thyristor are, respectively,
(A) 100 μS, 200 A
(B) 22.2 μS, 440 A
(C) 700 μS, 282.2 A
(D) 1000 μS, 440 A

9. In a type-A-chopper, source voltage is 110 V DC, ON period = 200 μS, OFF period = 150 μS and load RLE consists of $R = 4$ Ω, $L = 10$ mH, $E = 20$ V.

For continuous conduction, average output voltage and average output current for this chopper are, respectively,
(A) 40 V, 5 A
(B) 66.6 V, 28.3 A
(C) 62.8 V, 10.7 A
(D) 40 V, 20 A

Common Data for Questions 10 and 11:



For the above class D commutation circuit E_{DC} = 50 V, $I_{cc(max)}$ = 50 A, T_{OFF} of SCR_1 = 30 µS chopping frequency f = 500 Hz load variation required is 10% to 100% t_{DC} = 2 S.

10. The value of capacitor C is
(A) 27 µF (B) 45 µF
(C) 52 µF (D) 57 µF

11. The commutating inductor for allowing large voltage variation at the load is
(A) 90 µH (B) 67.5 µH
(C) 45 µH (D) 72 µH

Common Data for Questions 12 and 13:
A voltage commutated chopper has following parameters: V_s = 200 V, load parameters: 1 Ω, 2 mH, 5 V, commutation circuit parameters L = 25 µH and C = 50 µF

12. For a constant load current of 200 A, the effective ON period is
(A) 350 µS (B) 100 µS
(C) 700 µS (D) 1400 µS

13. The peak current through main thyristor is
(A) 200 A (B) 482.8 A
(C) 382.8 A (D) 282.8 A

Common Data for Questions 14 and 15:
A simple DC chopper is operating at a frequency of 2 kHz from 96 V DC source to supply a load of 8 Ω. The load time constant is 6ms. The average load voltage is 57.6 V.

14. The ON period of the chopper is
(A) 0.3 ms (B) 0.4 ms
(C) 0.6 ms (D) 0.5 ms

15. Average load current is
(A) 7.2 A (B) 14.4 A
(C) 28.8 A (D) 3.6 A

Practice Problems 2

Directions for questions 1 to 15: Select the correct alternative from the given choices.

1. The features of chopper drives are
(A) Smooth control but slow response
(B) Smooth control, fast response but less efficient
(C) Smooth control, and fast response
(D) None of the above

2. Choppers can be used in future electric automobiles
(A) For speed control only
(B) For braking only
(C) For both speed control and braking
(D) None of these

3. Given a step-down chopper of supply voltage 80 V and average output voltage 40 V. Assuming continuous conduction mode and an ON period of 20 µs, the chopping frequency will be
(A) 10 kHz
(B) 20 kHz
(C) 50 kHz
(D) 25 kHz

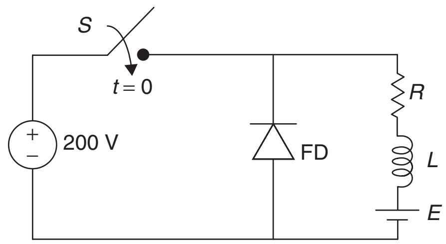
4. The per unit ripple in a step-down chopper would have its maximum value at a duty cycle of
(A) 20% (B) 40%
(C) 50% (D) 75%

5. A type-A chopper is connected to a 200 V DC source and is feeding an RLE load consisting of R = 4 Ω; L = 10 mH; E = 20 V. If the on and off periods are 200 µs and 300 µs, respectively, then the average output voltage and average output current for continuous conduction are, respectively,
(A) 40 V, 15 A (B) 60 V, 25 A
(C) 80 V, 15 A (D) 66.66 V, 28.33 A

6. If a step-down DC chopper is connected to a 230 V supply and a resistive load of R = 20 Ω; if the voltage drop across the converter switch is V_{ch} = 2 V. Then the chopper efficiency at $\alpha = 0.5$ would be
(A) 93% (B) 95%
(C) 97% (D) 99%

7. Which among the following is a correct match for DC chopper?
(A) Input Voltage—Continuous
Output Voltage—Continuous
(B) Input Voltage—Continuous
Output Voltage—Discontinuous
(C) Input voltage—Discontinuous
Output voltage—Continuous
(D) None of the above

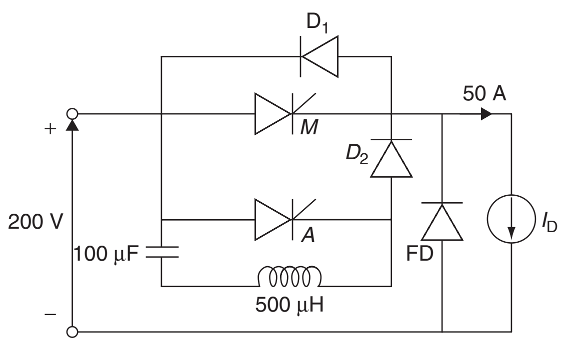
8. For the chopper shown in the figure below if minimum instantaneous load current is I_1 = 32.75 A and peak instantaneous load current is I_2 = 26.05 A. The value of RMS value of load current at $\alpha = 0.5$ would be
(A) 36.17 A (B) 22.13 A
(C) 63.71 A (D) 43.65 A



9. For the above problem, effective value of input resistance would be

(A) 20 Ω (B) 13.6 Ω
(C) 10 Ω (D) 18.36 Ω

10. The figure shows a current commutated chopper feeding a load such that a constant current of 50 A is maintained at the load. The peak commutating current in the circuit is



(A) 40 A (B) 60 A
(C) 20 A (D) 89 A

11. In a current-commutated chopper,

(A) Peak commutating current should be less than maximum load current
(B) Peak commutating current should be equal to maximum load current
(C) Peak commutating current should be greater than maximum load current
(D) There is no relation between peak commutating current and maximum load current

12. A 3-ϕ wound rotor induction motor is controlled by a chopper controlled resistance in its rotor circuit. A resistance of 2 Ω connected in the rotor circuit and a resistance of 4 Ω is additionally connected during OFF periods of the chopper. The OFF period of the chopper is 4 ms. The average resistance in the rotor circuit for the chopper frequency of 200 Hz is

(A) $\frac{26}{5}$ Ω (B) $\frac{24}{5}$ Ω
(C) $\frac{18}{5}$ Ω (D) $\frac{16}{5}$ Ω

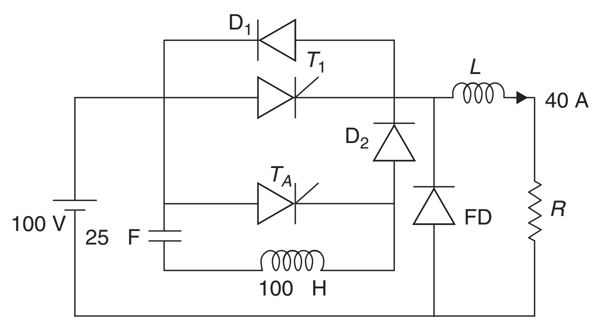
13. A voltage commutated chopper has the following parameters:
V_s = 200 V, load circuit parameter 1 Ω, 2 mH, 5 V.
Commutation circuit parameter: L = 25 µH, C = 50 µF.
For constant load current at 100 A, the effective on period and peak current through the main thyristor are, respectively,

(A) 1000 µs, 200 A
(B) 700 µs, 382.8 A
(C) 500 µs, 282.8 A
(D) 1000 µs, 382.8 A

14. A DC–DC transistor chopper is supplied from a fixed voltage DC source feeds an RLE load and a free-wheeling diode. The chopper operates at 1 kHz and 50% duty cycle. Keeping the average DC value of current and duty cycle unchanged and by increasing chopper frequency; the ripple content of load current would

(A) Increase
(B) Reduce
(C) Remain the same
(D) Cannot be determined

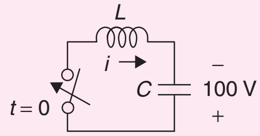
15. The figure shows a DC–DC chopper feeding on RL load such that the load current is 40 A. If the thyristor TA is fired at t = 0



(A) 64 µs (B) 128 µs
(C) 100 µs (D) 200 µs

Previous Years' Questions

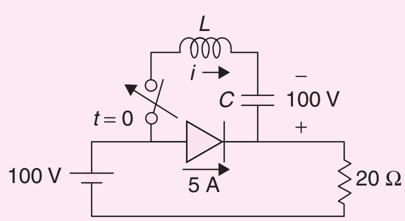
Common Data for Questions 1 and 2:
The L–C circuit shown in the figure has an inductance $L = 1$ mH and a capacitance $C = 10$ μF.



1. The initial current through the inductor is zero, while the initial capacitor voltage is 100 V. The switch is closed at $t = 0$. The current i through the circuit is: **[2010]**

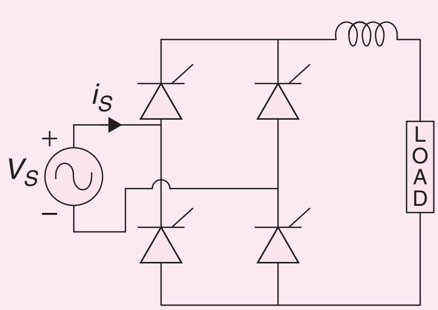
(A) $5\cos(5 \times 10^3 t)$ A (B) $5\sin(10^4 t)$ A
(C) $10\cos(5 \times 10^3 t)$ A (D) $10\sin(10^4 t)$ A

2. The L-C circuit of above question is used to commutate a thyristor, which is initially carrying a current of 5 A as shown in the figure below. The values and initial conditions of L and C are the same as in above question. The switch is closed at $t = 0$. If the forward drop is negligible, the time taken for the device to turn off is **[2010]**

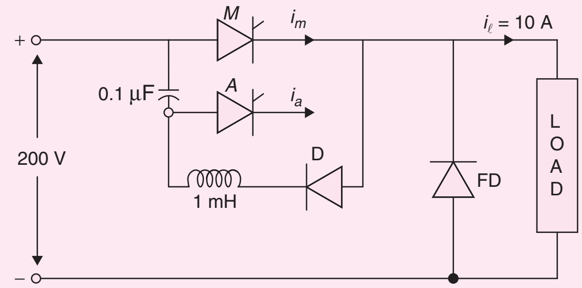


(A) 52 μs (B) 156 μs
(C) 312 μs (D) 26 μs

3. A fully controlled converter bridge feeds a highly inductive load with ripple-free load current. The input supply (v_s) to the bridge is a sinusoidal source. Triggering angle of the bridge converter is $\alpha = 30°$. The input power factor of the bridge is ________ **[2010]**



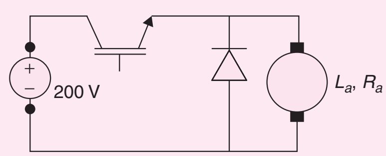
4. A voltage-commutated chopper circuit, operated at 500 Hz, is shown below. **[2011]**



If the maximum value of load current is 10 A, then the maximum current through the main (M) and auxiliary (A) thyristors will be

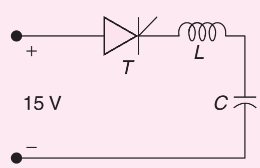
(A) $i_{M_{max}} = 12$ A and $i_{A_{max}} = 10$ A
(B) $i_{M_{max}} = 12$ A and $i_{A_{max}} = 2$ A
(C) $i_{M_{max}} = 10$ A and $i_{A_{max}} = 12$ A
(D) $i_{M_{max}} = 10$ A and $i_{A_{max}} = 8$ A

5. The separately excited DC motor in the figure below has a rated armature current of 20 A and a rated armature voltage of 150 V. An ideal chopper switching at 5 kHz is used to control the armature voltage. If $L_a = 0.1$ mH, $R_a = 1$ Ω, neglecting armature reaction, the duty ratio of the chopper to obtain 50% of the rated torque at the rated speed and the rated field current is **[2013]**



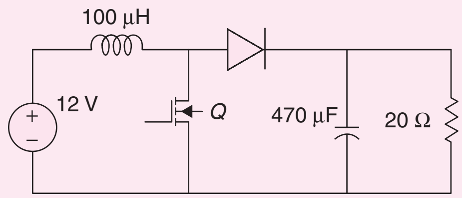
(A) 0.4 (B) 0.5 (C) 0.6 (D) 0.7

6. Thyristor T in the figure below is initially off and is triggered with a single pulse of width 10 μs. It is given that $L = \left(\frac{100}{\pi}\right)$ μH and $C = \left(\frac{100}{\pi}\right)$ μF. Assuming latching and holding current of the thyristor are both zero and the initial charge on C is zero, T conducts for **[2013]**



(A) 10 μs (B) 50 μs
(C) 100 μs (D) 200 μs

Common Data for Questions 7 and 8:
In the figure shown below, the chopper feeds a resistive load from a battery source. MOSFET Q is switched at 250 kHz, with a duty ratio of 0.4. All elements of the circuit are assumed to be ideal.



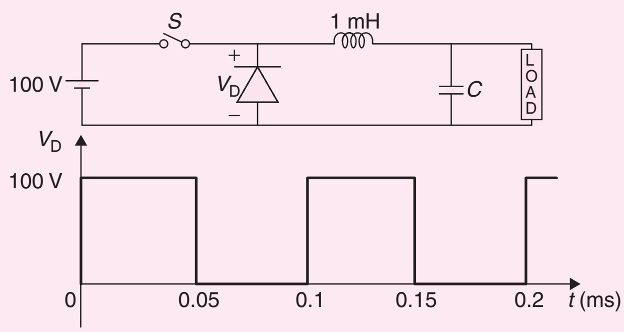
7. The average source current in ampere in steady state is **[2013]**

(A) 3/2 (B) 5/3 (C) 5/2 (D)

8. The PEAK-TO-PEAK source current ripple in ampere is **[2013]**

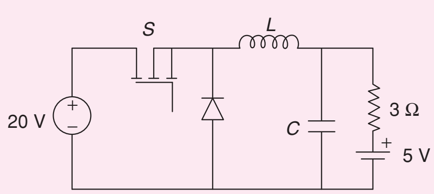
(A) 0.96 (B) 0.144
(C) 0.192 (D) 0.288

9. Figure (i) shows the circuit diagram of a chopper. The switch S in the circuit in figure (i) is switched such that the voltage v_D across the diode has the wave shape as shown in figure (ii). The capacitance C is large so that the voltage across it is constant. If switch S and the diode are ideal, the peak to peak ripple (in A) in the inductor current is ________ **[2014]**

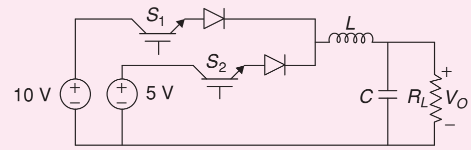


10. A step-up chopper is used to feed a load at 400 V DC from a 250 V DC source. The inductor current is continuous. If the 'off' time of the switch is 20 µs, the switching frequency of the chopper in kHz is ____. **[2014]**

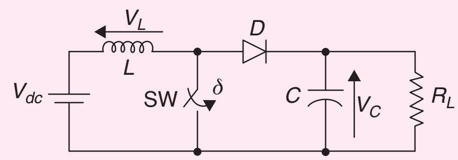
11. In the following chopper, the duty ratio of switch is 0.4. If the inductor and capacitor are sufficiently large to ensure continuous inductor current and ripple free capacitor voltage, the charging current (in Ampere) of the 5 V battery, under steady-state is ______. **[2015]**



12. The circuit shown is meant to supply a resistive load R_L from two separate DC voltage sources. The switches S_1 and S_2 are controlled so that only one of them is ON at any instant. S_1 is turned on for 0.2 ms and S_2 is turned on for 0.3 ms in a 0.5 ms switching cycle time period. Assuming continuous conduction of the inductor current and negligible ripple on the capacitor voltage, the output voltage V_o (in Volt) across R_L is ______. **[2015]**



13. A self commutating switch SW, operated at duty cycle δ is used to control the load voltage as shown in the figure



Under steady state operating conditions, the average voltage across the inductor and the capacitor respectively, are **[2015]**

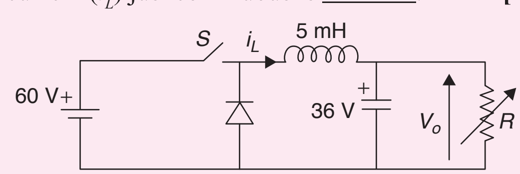
(A) $V_L = 0$ and $V_C = \dfrac{1}{1-\delta} V_{dc}$

(B) $V_L = \dfrac{\delta}{2} V_{dc}$ and $V_C = \dfrac{1}{1-\delta} V_{dc}$

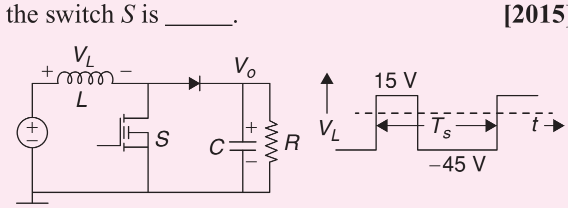
(C) $V_L = 0$ and $V_C = \dfrac{\delta}{1-\delta} V_{dc}$

(D) $V_L = \dfrac{\delta}{2} V_{dc}$ and $V_C = \dfrac{\delta}{1-\delta} V_{dc}$

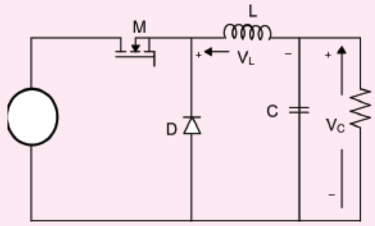
14. A buck converter feeding a variable resistive load is shown in the figure. The switching frequency of the switch S is 100 kHz and the duty ratio is 0.6. The output voltage V_O is 36 V. Assume that all the components are ideal, and that the output voltage is ripple-free. The value of R(in Ohm) that will make the inductor current (i_L) just continuous is _______. **[2015]**

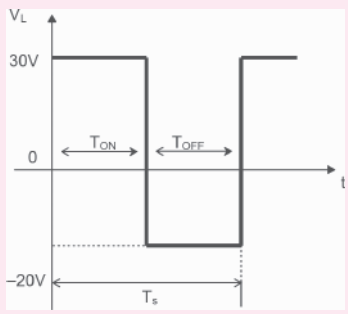


15. For the switching converter shown in the following figure, assume steady-state operation. Also assume that the components are ideal, the inductor current is always positive and continuous and switching period is T_s. If the voltage V_L is as shown, the duty cycle of the switch S is _____. **[2015]**

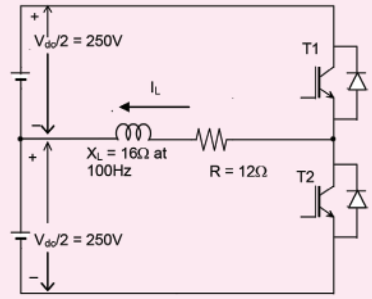


16. A buck converter, as shown in Figure (a) below, is working in steady state. The output voltage and the inductor current can be assumed to be ripple free Figure (b) shows the indicator voltage V_L during a complete switching interval. Assuming all devices are ideal, the duty cycle of the buck converter is ______________. **[2016]**

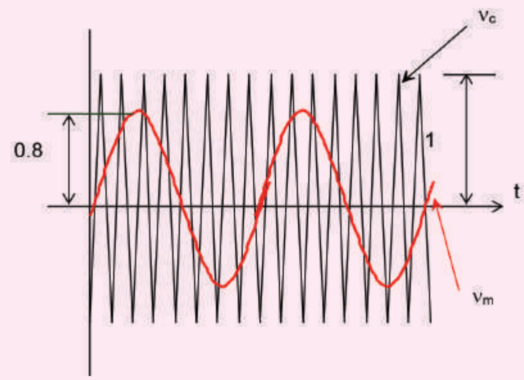




17. The switches T1 and T2 in Figure (a) are switched in a complementary fashion with sinusoidal pulse width modulation technique. The modulating voltage $\nu_m(t)$ = 0.8 sin (200$_t$) V and the triangular carrier voltage (ν_c) are as shown in Figure (b). The carrier frequency is 5 kHz. The peak value of the 100 Hz component of the load current (i_L), in ampere, is **[2016]**

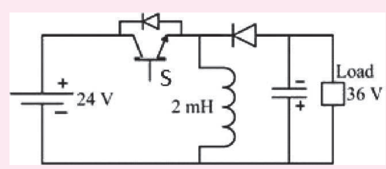


(a)



(b)

18. A buck-boost DC – DC converter, shown in the figure below, is used to convert 24V battery voltage to 36V DC voltage to feed a load of 72W. it is operated at 20KHz with an inductor of 2mH and output capacitor of 1000μF. all devices are considered to be ideal. The peak voltage across the Solid-state switch (S), in volt is ________. **[2016]**



19. A DC - DC boost converter, as shown in the figure below, is used to boost 360V to 400V, at a power of 4kW. All devices are ideal. Considering continuous inductor current, the rms current in the Solid state switch (S), in ampere is ________ **[2016]**

Answer Keys

Exercises

Practice Problems 1

1. D	**2.** A	**3.** B	**4.** C	**5.** C	**6.** A	**7.** B	**8.** B	**9.** C	**10.** B
11. C	**12.** C	**13.** B	**14.** A	**15.** A					

Practice Problems 2

1. C	**2.** C	**3.** D	**4.** C	**5.** C	**6.** D	**7.** B	**8.** A	**9.** B	**10.** D
11. C	**12.** D	**13.** B	**14.** B	**15.** A					

Previous Years' Questions

1. D	**2.** A	**3.** 0.78	**4.** A	**5.** D	**6.** C	**7.** B	**8.** C	**9.** 2.5	**10.** 31.25
11. 1	**12.** 7	**13.** A	**14.** 2480 to 2520		**15.** 0.75	**16.** 0.4	**17.** 10	**18.** 60.03	**19.** 3.51