# Electrical Drives

Lecture 14 (19-02-2024)


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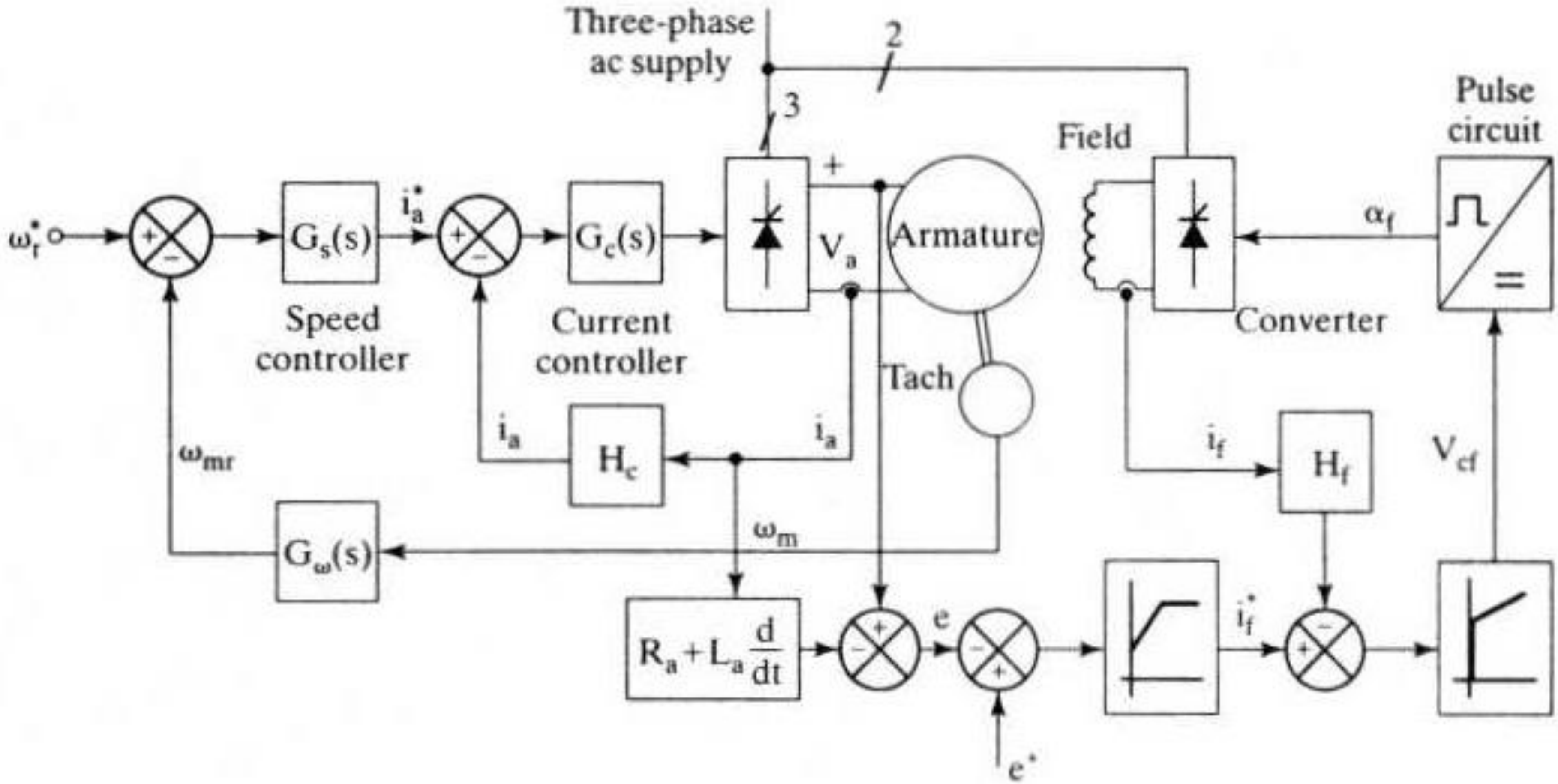
# Two-quadrant DC Motor drive with field weakening

- Field weakening is exercised in the DC machine by varying the voltage applied across the field winding.
- Variable voltage can be obtained from 1-ϕ or 3-ϕ controlled rectifiers.
- Because of the large inductance of the filed winding the field current is smooth without any ripple.
- The converter time lag is negligible compared to the field time constant and the speed of response is primarily determined by the field time constant.
- A schematic of the two-quadrant DC motor drive with flux weakening is shown in the next figure.

# Two-quadrant DC Motor drive with field weakening



# Two-quadrant DC Motor drive with field weakening

- The command or reference field current is determined by the induced emf ( back emf) error function.
- The induced emf error is the difference between the reference induced emf and the estimated induced emf.
- The induced emf is estimated by subtracting resistive and inductive drops in armature from the applied voltage to the armature.
- This induced emf estimation is machine parameter dependent.
- The induced emf error is passed through a PI controller and then limited to obtain the filed current reference.

# Two-quadrant DC Motor drive with field weakening

field-current reference is enforced by a current-control loop feedback very similar to the armature current-control loop. The outer induced-emf feedback loop enforces a constant induced emf for speeds higher than the base speed. This amounts to

$$e_n = \phi_{fn}\omega_{mn}$$

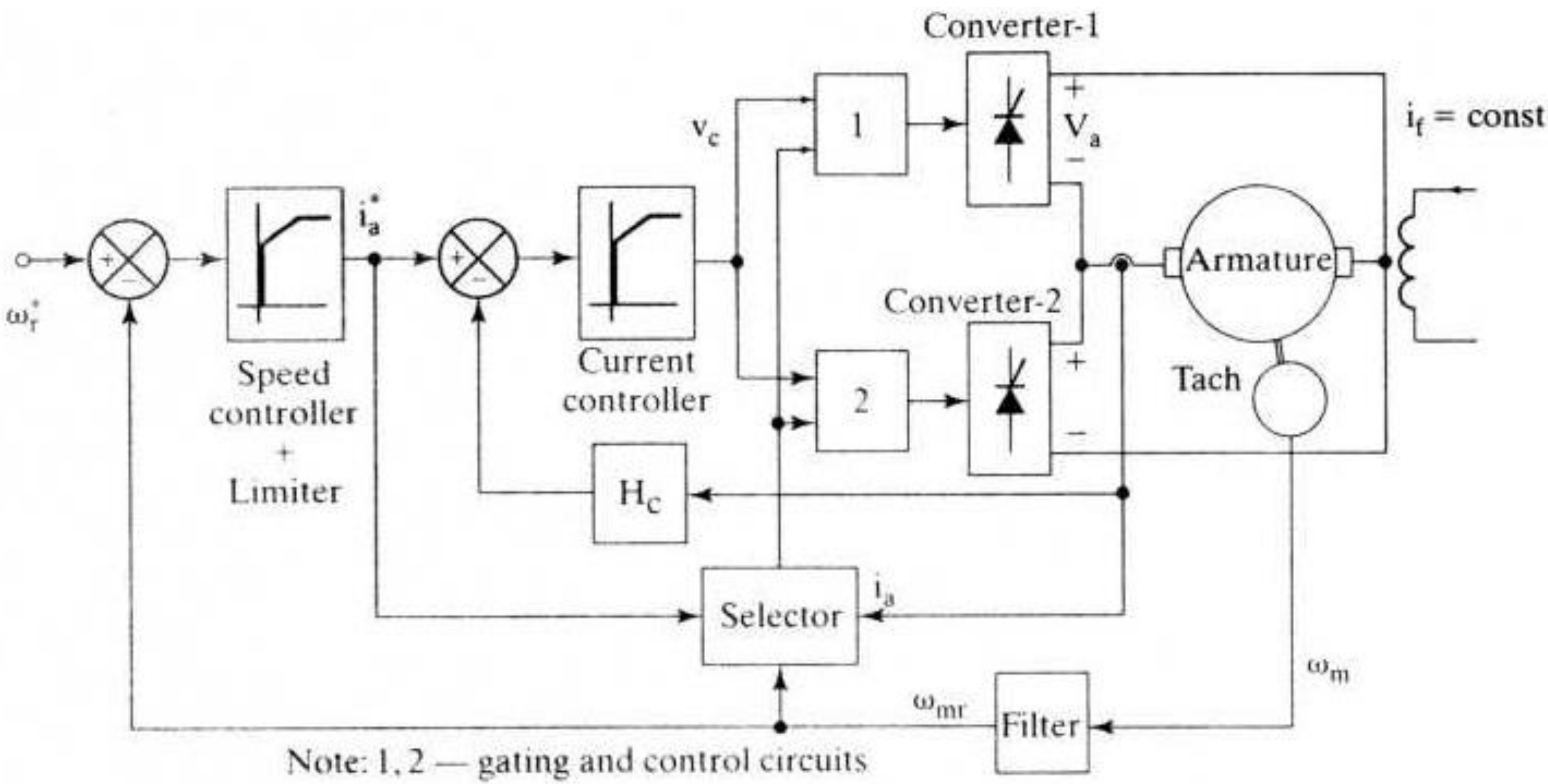
If the induced emf $e_n$ is kept at rated value, say 1 p.u., then the field flux is inversely proportional to the rotor speed. This condition also enables constant-air gap-power operation.

# Four-quadrant DC Motor drive

A four-quadrant dc motor drive has a set of dual three-phase converters for the power stage. Its control is very similar to that of the two-quadrant dc motor drive. Converters have to be energized depending on the quadrant of operation.

- Converters 1 and 2 are for forward and reverse directions of rotation of the motor, respectively.
- The changeover from one converter to another is safely handled by monitoring speed, current-command, and zero-crossing current signals.
- These signals form the inputs to the selector block, which assigns the pulse-control signals to the appropriate converter.
- The converters share the same current and speed loops.
- A control schematic of the four-quadrant DC motor drive is shown in figure.

# Four-quadrant DC Motor drive



# Four-quadrant DC Motor drive

- The selector block will switch the converters over only when the current in the outgoing converter has come to zero.
- Apart from this, some more conditions have to satisfied to transfer the control of converters.
- Let us assume that a positive speed command is required for forward running and negative speed command is required for reverse running.
- The machine is running at rated speed and the speed command is changed to reverse the rated speed.
- The current command becomes negative, indicating that the machine has to become regenerative in order to decelerate the motor in the forward direction.

# Four-quadrant DC Motor drive

- Forward regeneration is possible only in fourth quadrant, and the converter to provide this quadrant of operation is converter 2.
- Before the current is reversed, it has to go through zero.
- This is achieved by increasing the triggering angle of converter 1.
- When the current is zero, a certain dead time is given to enable the thyristors in converter 1 to recover reverse blocking capability.
- After this interval, converter 2 is enabled.
- At this time, the armature current has been forced to zero, but the speed is still positive.
- The triggering angle of the converter 2 is set such that its output voltage equals and opposes the induced emf.
- Then, slowly decreasing the triggering angle increases the armature current in the opposite direction.

# Four-quadrant DC Motor drive

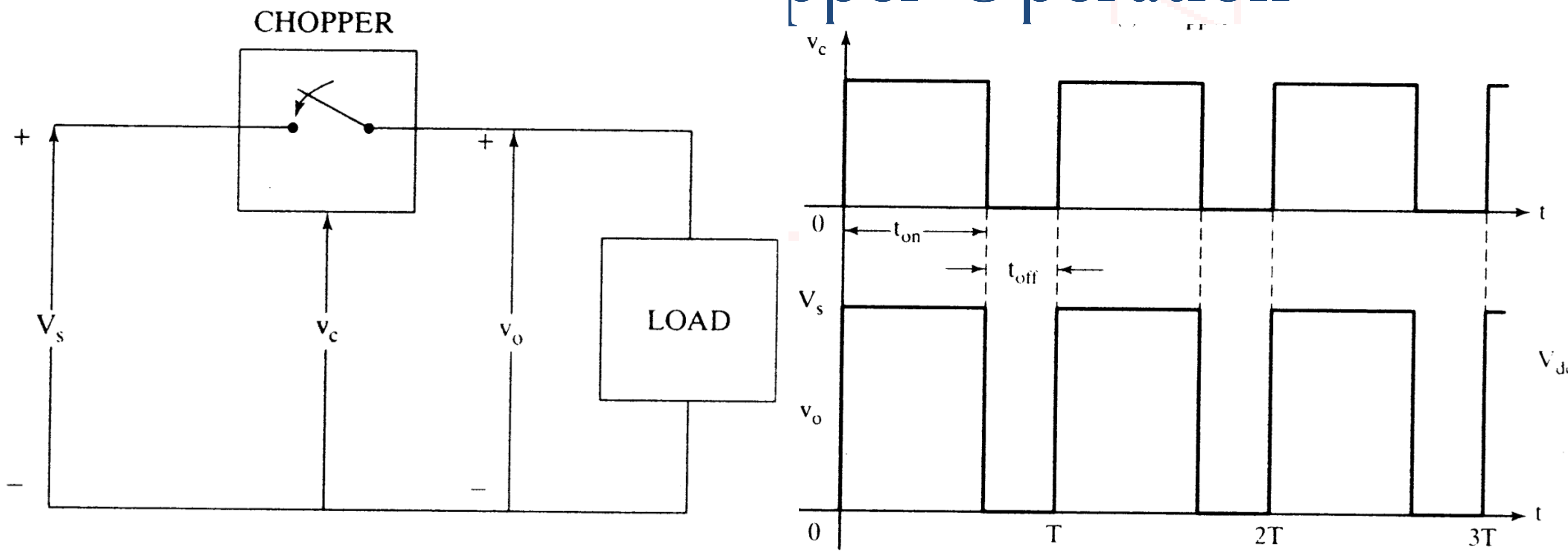
- By varying the triggering angle, the armature current is fully reversed and then is maintained at the reference level.
- When the motor reaches zero speed, the operation of converter 2 is continued by bringing it into rectification mode.
- That will accelerate the motor in reverse direction until it matched the speed reference.
- The function of the selector block is to determine which converter has to be operating.
- As soon as the current command goes negative, the selector block will transfer the control from converter 1 to converter 2 with proper initial triggering angle.
- If the triggering angle of converter 1 is $\alpha_1$, then the initial triggering angle, $\alpha_2$ , of converter 2 is 180 - $\alpha_1$ , to match the output voltage of the converter.

# Four-quadrant DC Motor drive

- If circulating current is not allowed between the converters, zero crossing of the armature current is required to transfer the control from one converter to another.
- The actual rotor speed is required to determine the quadrant of operation.
- Based on the rotor speed, the armature current and its command, the selector block identifies the converter for control and operation.
- The method discussed here does not allow circulating current between converters 1 and 2.
- This type of control has a drawback: slower current transfer from one converter to the other, due to the dead time.
- But it has the advantage that no additional passive component in the form of an interphase reactor is needed to limit the circulating current.

# Chopper-controlled DC Motor Drive

# Principle of Chopper Operation

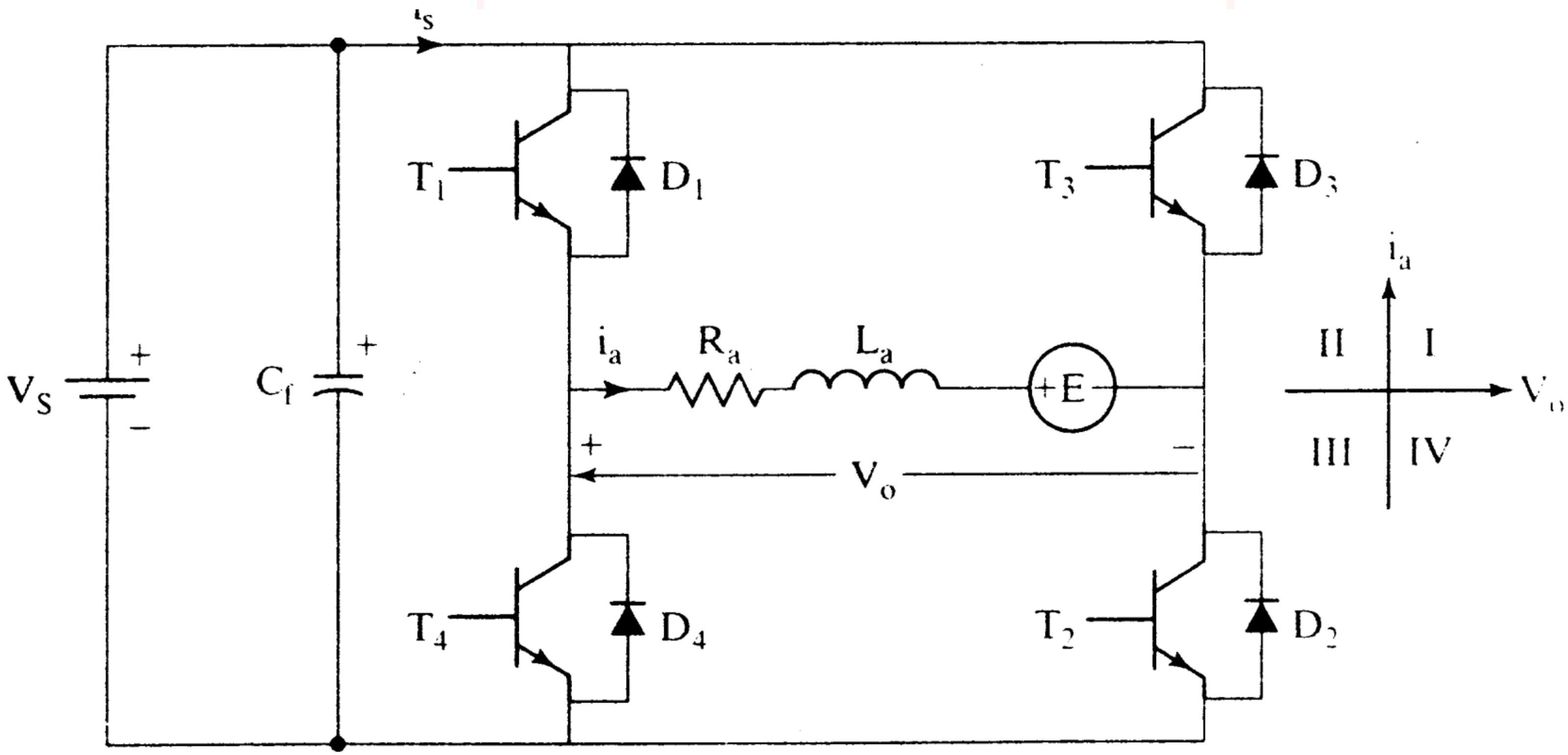



- A schematic diagram of the chopper is shown in Fig. above. The control to its gate is $v_c$. The chopper is on for a time $t_{on}$, and its off time is $t_{off}$.
- Its frequency of operation is $$f_c = \frac{1}{(t_{on} + t_{off})} = \frac{1}{T}$$
- and its duty cycle is defined as $$d = \frac{t_{on}}{T}$$
- Average output voltage is given by $$V_{dc} = \frac{t_{on}}{T} V_s = dV_s$$

# Principle of Chopper Operation

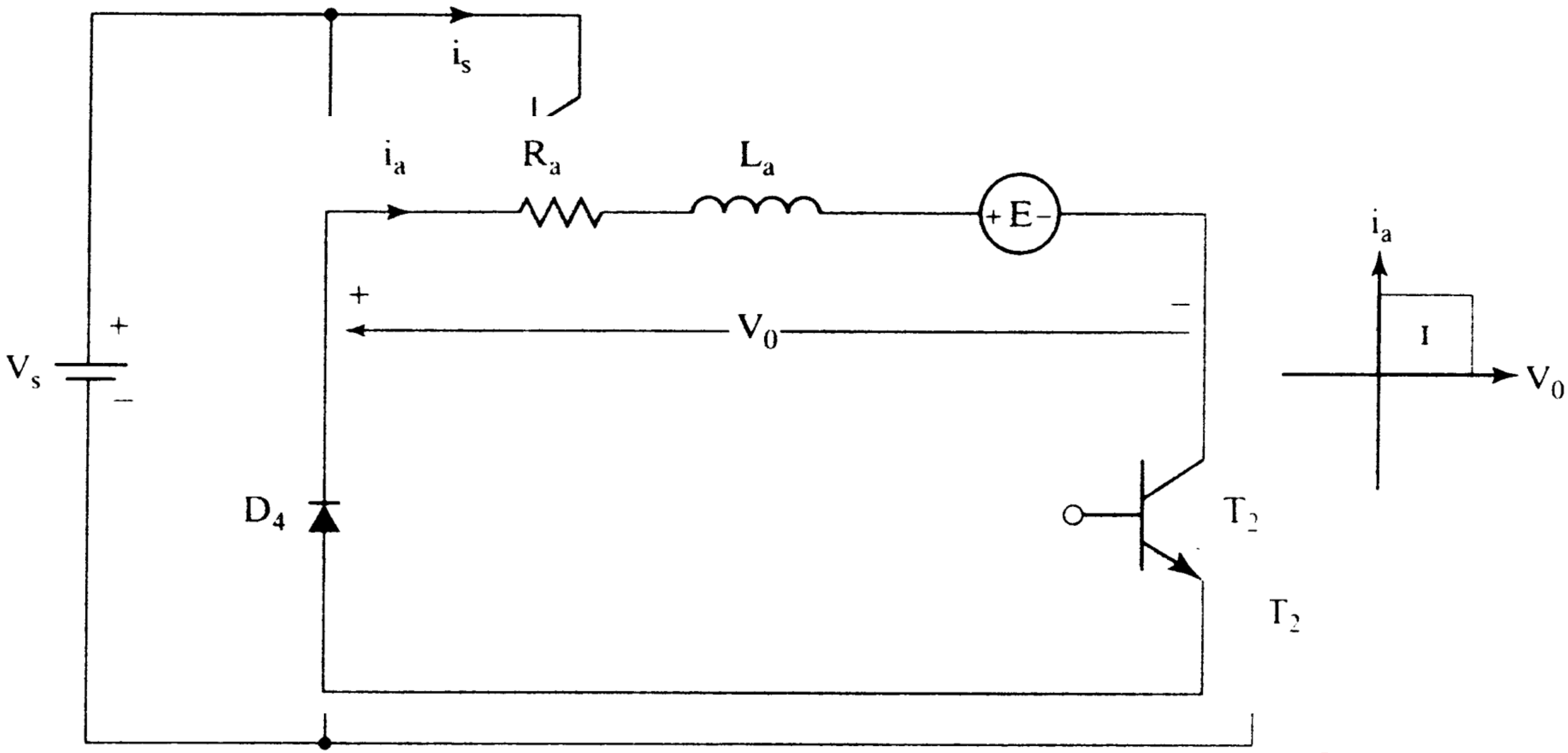
- Output voltage can be controlled by varying d
- duty cycle d can be controlled in two ways.
  - By keeping the switching frequency constant and varying the on time of the switch.
  - By keeping the on-time constant varying the switching frequency.
- The advantages of keeping switching frequency constant are
  - Predetermined switching losses – optimal heat sink design for power circuit.
  - Predetermined harmonic content – leads to optimal filter.
- Both these advantages are lost in variable switching frequency

# Four Quadrant Chopper Circuit

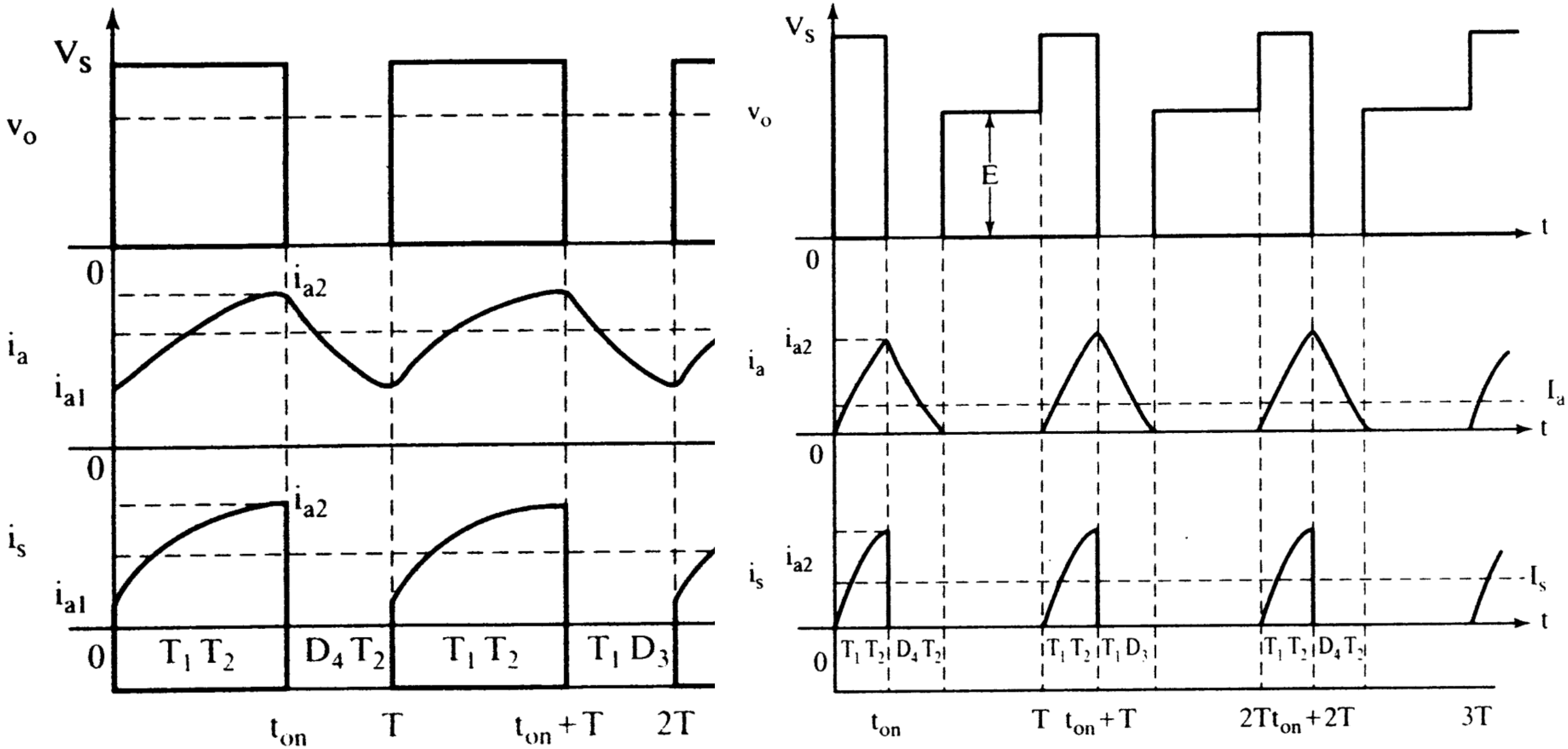


# Four Quadrant Chopper Circuit

## First-Quadrant Operation



# Four Quadrant Chopper Circuit




(i) Continuous Conduction

(ii) Discontinuous Conduction

# Four Quadrant Chopper Circuit

The output voltage can also be varied by another switching strategy. Armature current is assumed continuous. Instead of providing zero voltage during turn-off time to the load, consider that T1 and T2 are simultaneously turned off, to enable conduction by diodes D3 and D4. The voltage applied across the load then is equal to the negative source voltage, resulting in a reduction of the average output voltage. The disadvantages of this switching strategy are as follows:

**(i)** Switching losses double, because two power devices are turned off instead of one only.

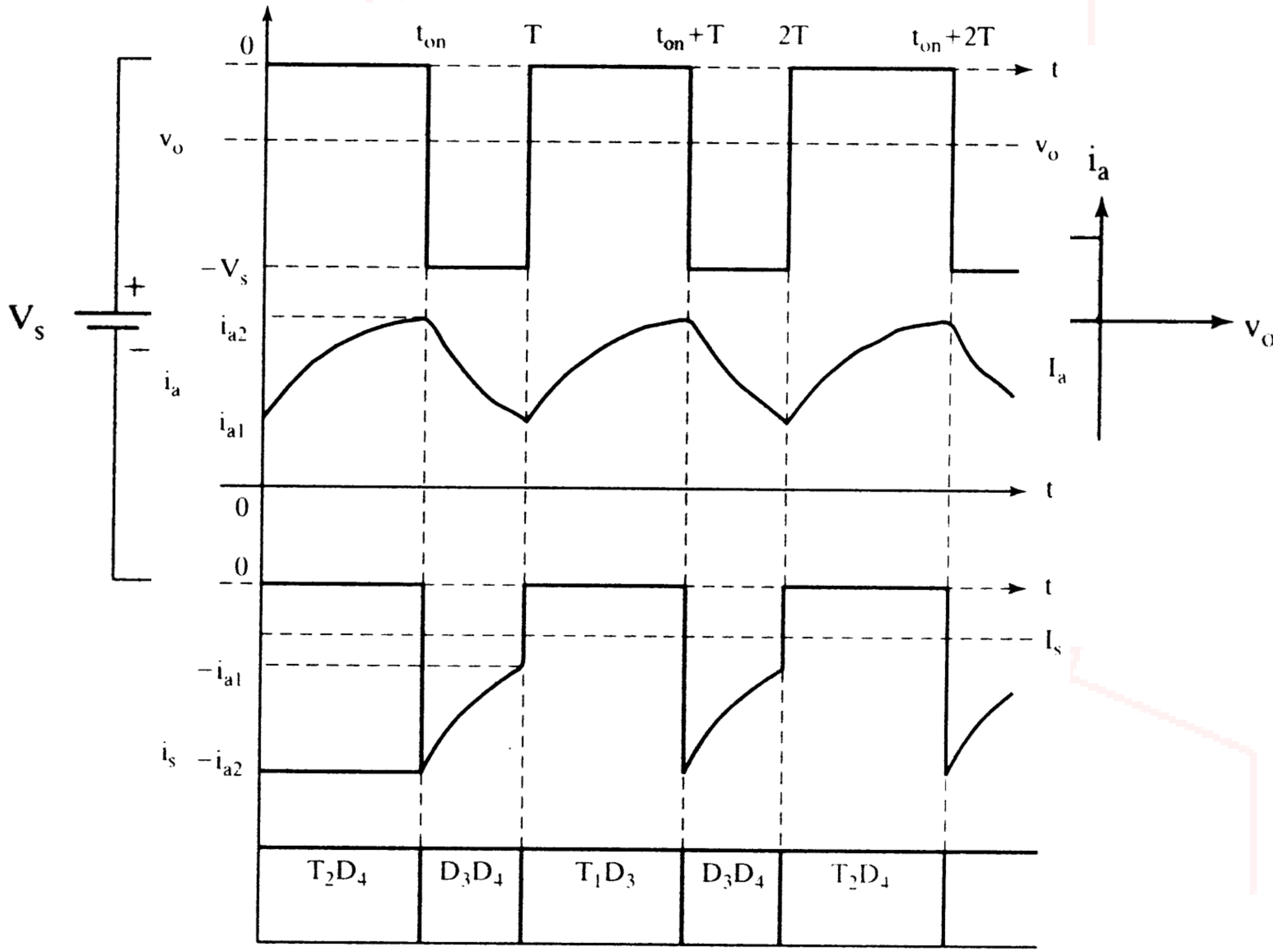
**(ii)** The rate of change of voltage across the load is twice that of the other strategy. If the load is a dc machine, then it has the deleterious effect of causing higher dielectric losses in the insulation and therefore reduced life. Note that the dielectric is a capacitor with a resistor in series.

**(iii)** The rate of change of load current is high, contributing to vibration of the armature in the case of the dc machine.

**(iv)** Since a part of the energy is being circulated between the load and source in every switching cycle, the switching harmonic current is high, resulting in additional losses in the load and in the cables connecting the source and converter.

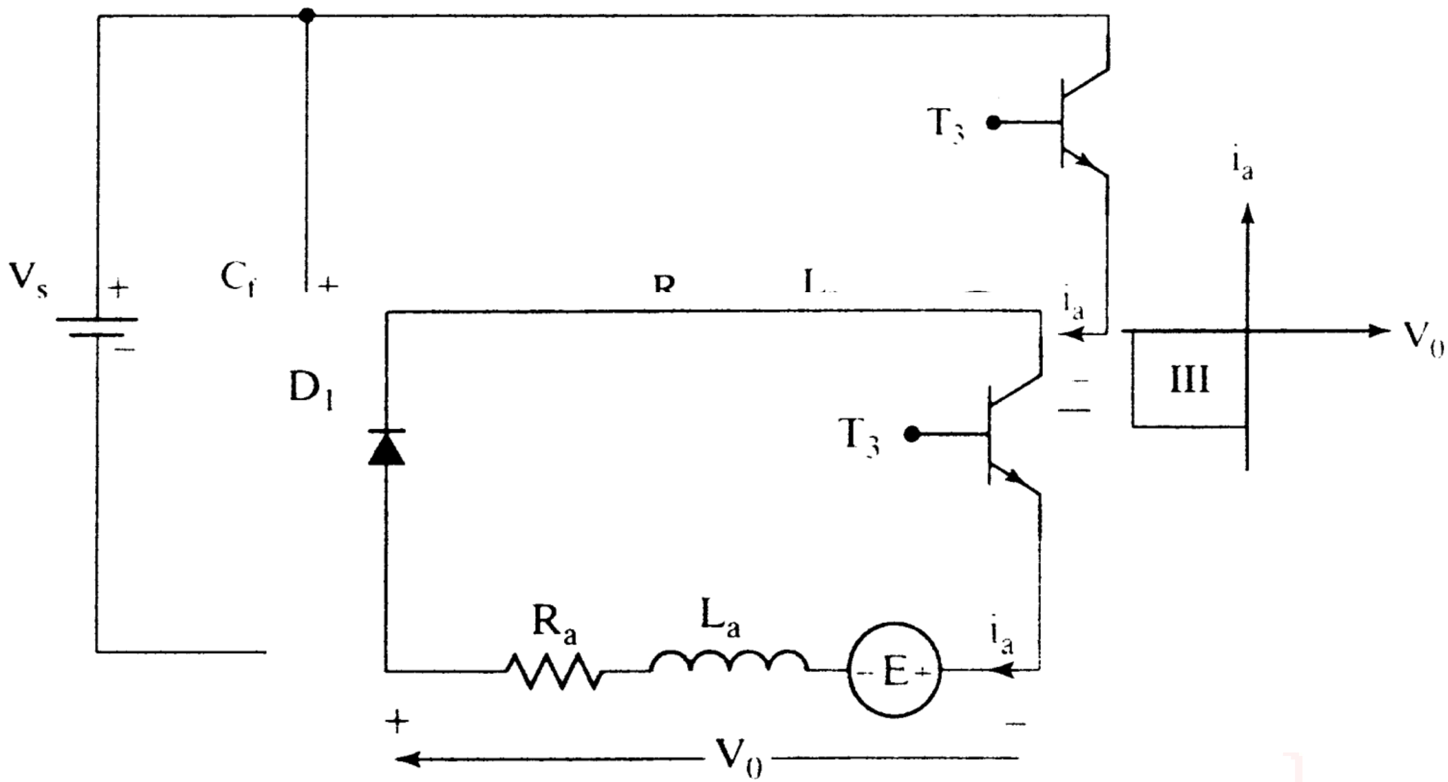
# Four Quadrant Chopper Circuit

## Second-Quadrant Operation



# Four Quadrant Chopper Circuit

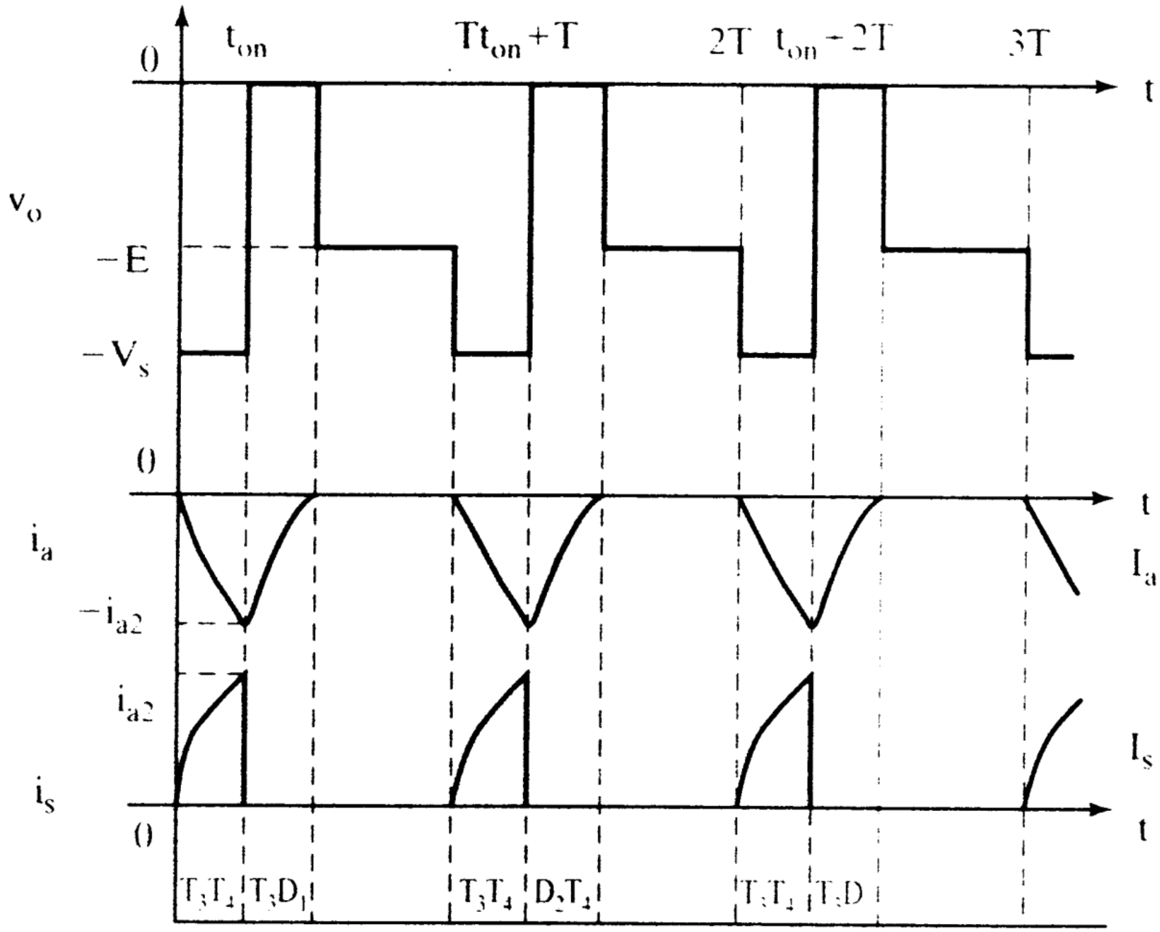
## Third-Quadrant Operation




(ii) Decreasing load current

# Four Quadrant Chopper Circuit

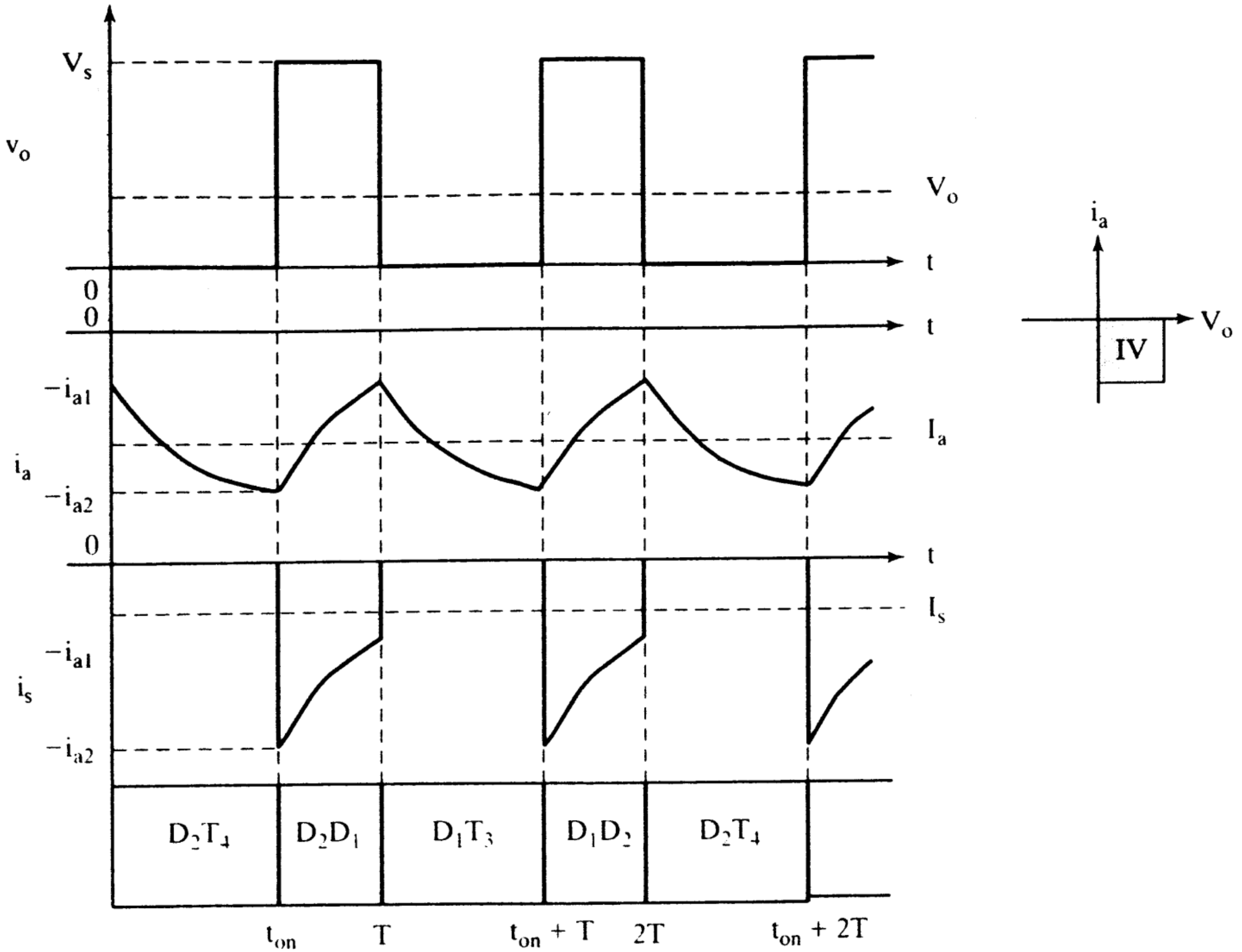
## Third-Quadrant Operation




(ii) Discontinuous Conduction

# Four Quadrant Chopper Circuit

## Fourth-Quadrant Operation



# MODEL OF THE CHOPPER

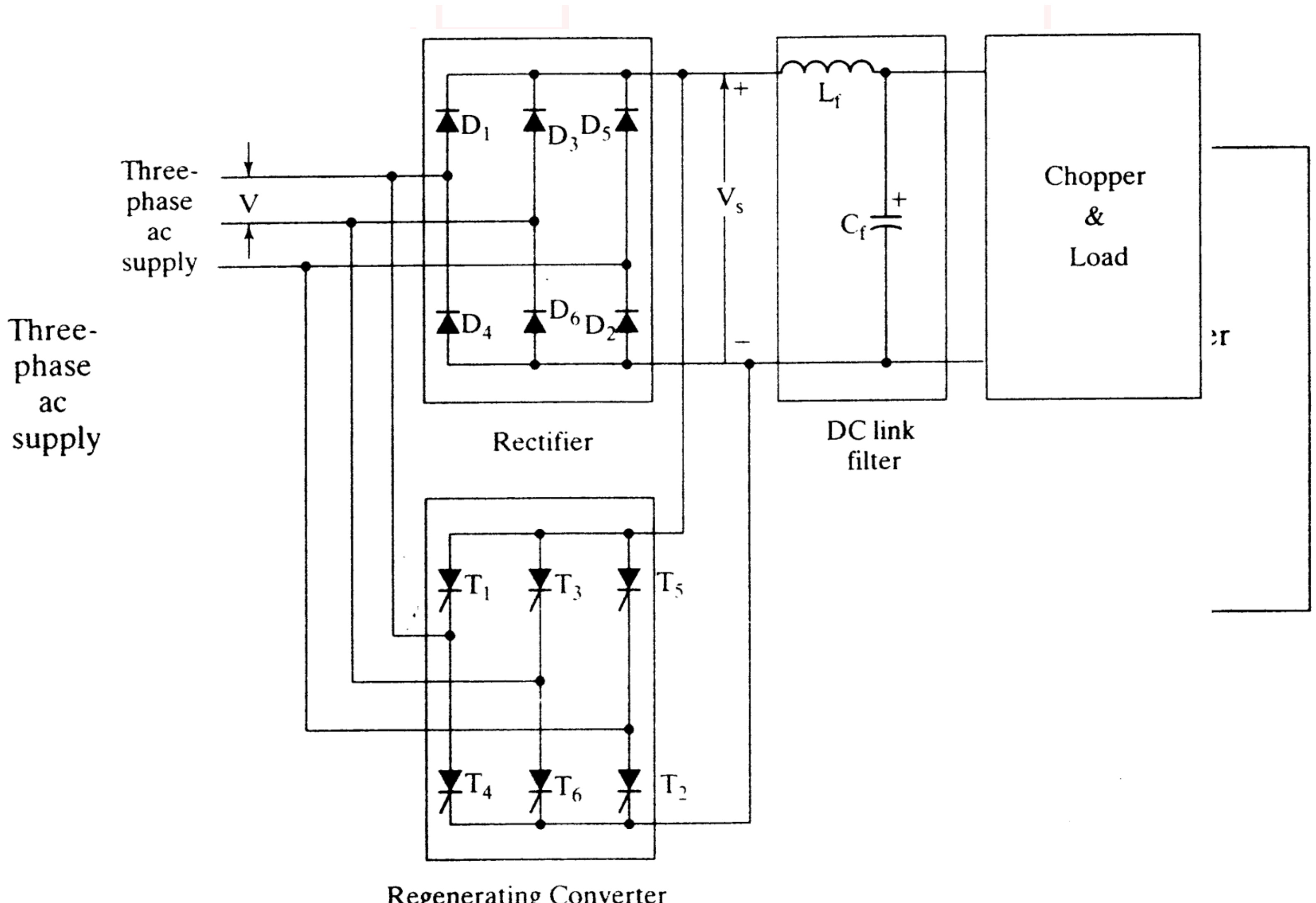
The chopper is modeled as a first-order lag with a gain of $K_{ch}$. The time delay corresponds to the statistical average conduction time, which can vary from zero to T. The transfer function is then

$$G_r(s) = \frac{K_r}{1 + \frac{sT}{2}}$$

where $K_r = V_s/V_{cm}$, $V_s$ is the source voltage, and $V_{cm}$ is the maximum control voltage.

Increasing the chopping frequency decreases the delay time, and hence the transfer function becomes a simple gain.

# INPUT TO THE CHOPPER



# Steady state analysis of Chopper controlled DC Motor drive

- Analysis by averaging
- Instantaneous steady state computation

# Analysis by averaging

The steady-state performance of the chopper-controlled dc motor drive is obtained either with average values, by neglecting harmonics, or including harmonics. The justification for using average values is that the average torque is the useful torque that is transmitted to the load. The torque components due to the current harmonics produce an average torque of zero over one cycle of switching. They do not contribute to useful power production. Further, they result in increased armature losses, because the harmonic currents increase the effective motor current. From an output point of view, neglecting harmonics and using only average values gives easier steady-state computation. The analysis by this method is known as *analysis by averaging*.

# Instantaneous steady state computation

When losses, maximum steady-state current, and precise electromagnetic torque are required to fully analyze and design the drive system for an application, the true current waveforms in steady state need to be computed. Therefore, the harmonics cannot be excluded in the steady-state computation. A computationally efficient, analytical closed-form expression is obtained by the novel technique of boundary-matching conditions. This method is referred to as *instantaneous steady-state computation.*

# Analysis by Averaging

The average armature current is

$$I_{av} = \frac{V_{dc} - E}{R_a}$$

where

$$V_{dc} = dV_s$$

The electromagnetic torque is

$$T_{av} = K_b I_{av}$$

# Analysis by Averaging

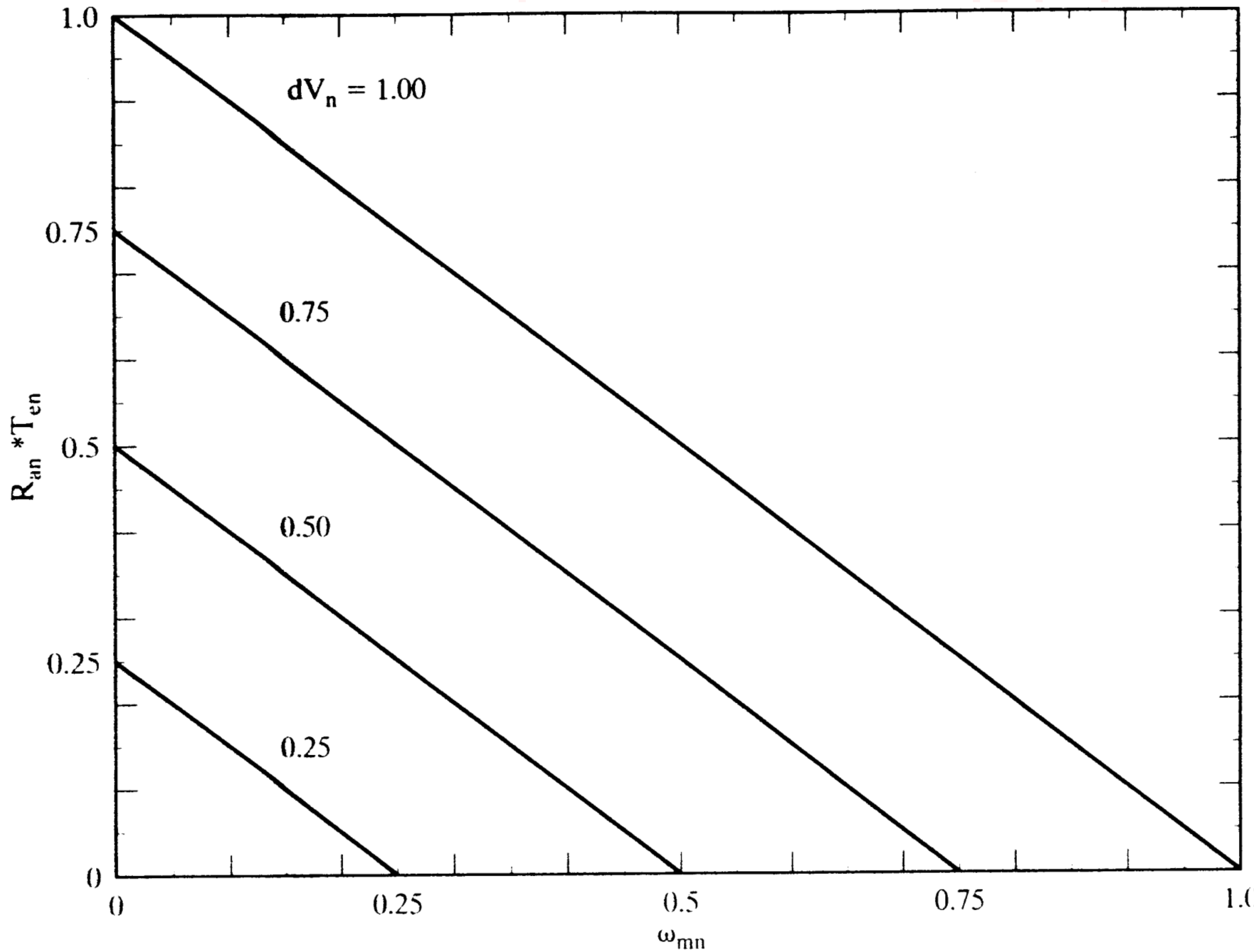
$$T_{av} = \frac{K_b(dV_s - K_b\omega_m)}{R_a}\ (\text{N}\cdot\text{m})$$

The electromagnetic torque is normalized by dividing it by the base torque, $T_b$, and by dividing both its numerator and denominator by the base voltage, $V_b$. The normalized torque is obtained by simplifying the expressions and substituting for $V_b$ in terms of the base speed, ω, and emf constant:

$$T_{en} = \frac{T_{av}/V_b}{T_b/V_b} = \frac{K_b(dV_s - K_b\omega_m)/V_b}{K_b I_b R_a/V_b} = \frac{dV_n - \omega_{mn}}{R_{an}}, \text{ p.u.}$$

where

$$R_{an} = \frac{I_b R_a}{V_b}, \text{ p.u.} \qquad V_n = \frac{V_s}{V_b}, \text{ p.u.} \qquad \omega_{mn} = \frac{\omega_m}{\omega_b}, \text{ p.u.}$$

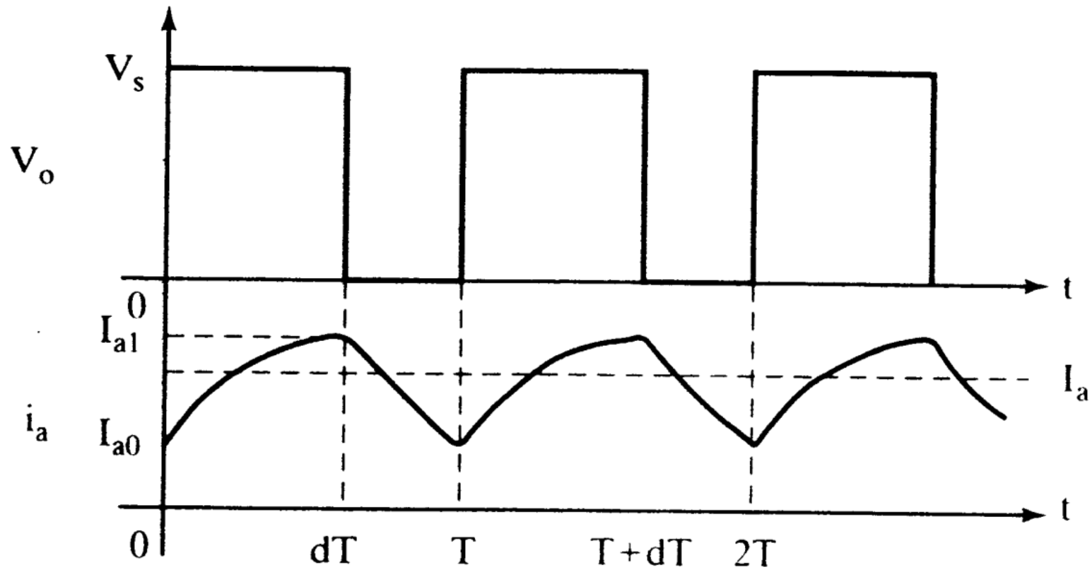

dVn = 1.00
0.75
0.50
0.25
1.0
0.75
0.5
0.25
0
0
0.25
0.5
0.75
1.0
Ran *Ten
ωmn

# Instantaneous Steady-State Computation

## Continuous Current Conduction

$V = E + R\,i + L\,\frac{di_a}{}$ $\quad 0 < t < dT$

$i_a(t) =$




(i) Continuous Conduction

dT

$T_a$

a

a

# Instantaneous Steady-State Computation

## Continuous Current Conduction

$$0 = E + R_a i_a + L_a \frac{di_a}{dt}, \qquad dT \leq t \leq T$$

$$i_a(t) = -\frac{E}{R}\left(1 - e^{-\frac{t}{T_a}}\right) + I_{a1} e^{-\frac{t}{T_a}}, \qquad dT \leq t \leq dT$$

$$I_{a1} = \frac{V_s\left(1 - e^{-dT/T_a}\right)}{R_a\left(1 - e^{-T/T_a}\right)} - \frac{E}{R_a}$$

$$I_{a0} = \frac{V_s\left(e^{dT/T_a} - 1\right)}{R_a\left(e^{T/T_a} - 1\right)} - \frac{E}{R_a}$$

By using this boundary condition, $I_{a0}$ and $I_{a1}$ are evaluated as

# Instantaneous Steady-State Computation

## Discontinuous Current Conduction


The solution for the armature current in three time segments is

$$i_a(t) = \frac{V_s - E}{R_a}\left(1 - e^{-t/T_a}\right), \qquad 0 < t < dT$$

$$i_a(t) = I_{a1} e^{-\frac{(t-dT)}{T_a}} - \frac{E}{R_a}\left(1 - e^{-\frac{(t-dT)}{T_a}}\right), \qquad dT < t < t_x + dT$$

$$i_a(t) = 0, \qquad (t_x + dT) < t < T$$

T −I + d I    2T

(ii) Discontinuous Conduction