DC Drives

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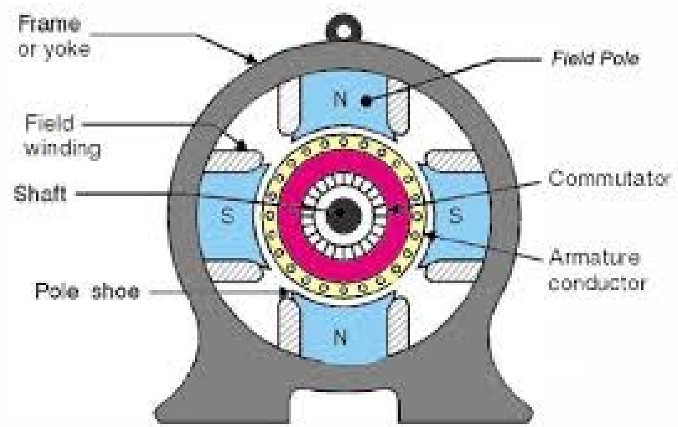
Learning Objectives and Outcomes

- Learning Objectives:
  - Understand the basic principle of operation of DC drive system.
  - Classification of DC Drive system.
  - Speed control of DC Drive system and comparison of phase-controlled and chopper control schemes.
  - Closed-loop speed/current control schemes.
  - Single-, two- and four-quadrant dc drive system.
  - Electrical braking in dc drive system.

- Learning outcome
  - You should be able to specify the right type of dc drive system along with control mechanism for any given application.

Introduction to DC Machines

- Any rotating electrical machines has two parts: (a) stator and (b) rotor.
- Stator is stationary part and rotor is rotating part of the machine.
- In DC machines:



  - the main field winding or the permanent magnet (which produces the main flux) is on the stator, and
  - the armature winding (which induces the force or produce emf on its conductors) is on the rotor.

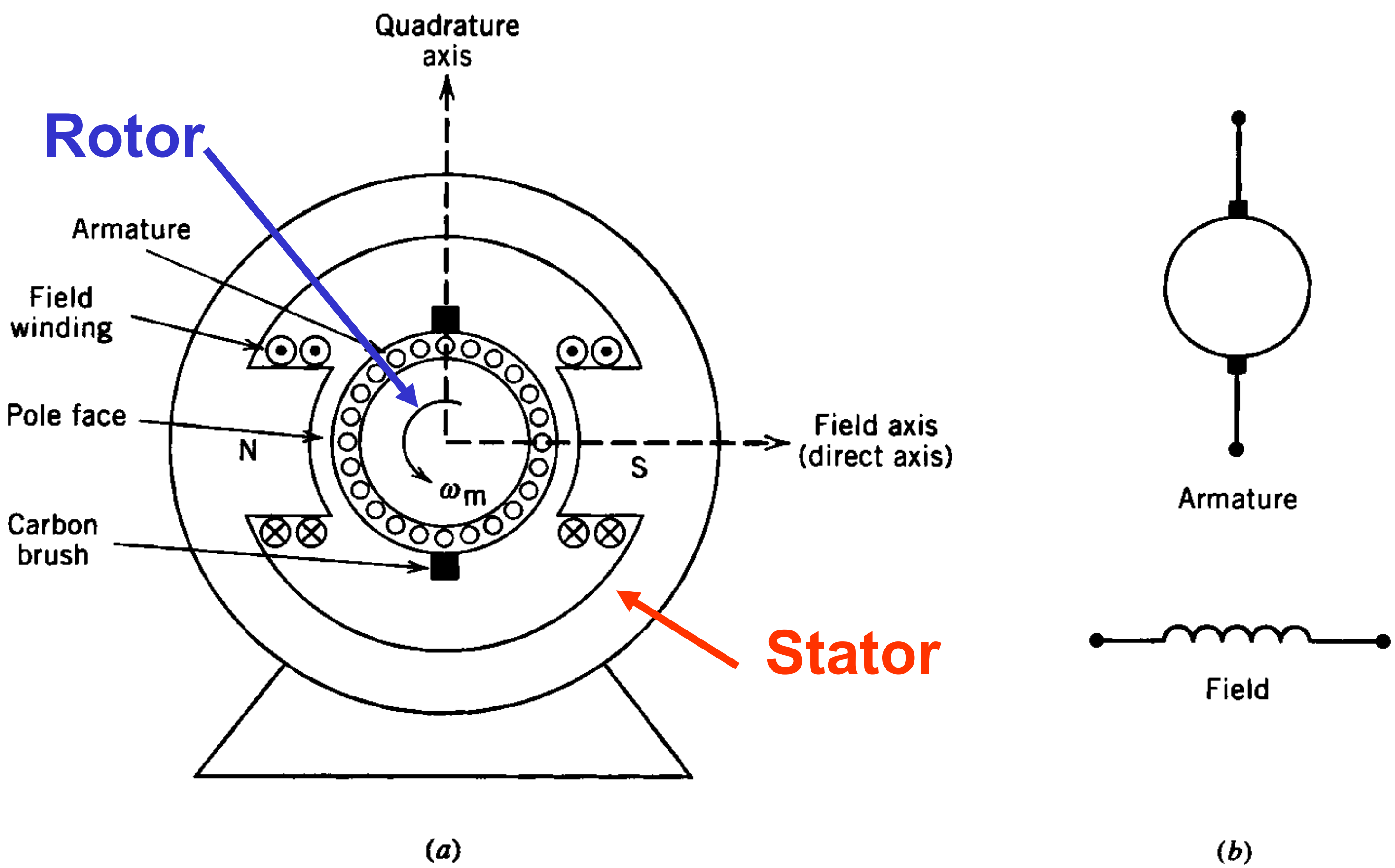


Figure 3.1: A two-pole DC Machine (a) schematic representation and (b) circuit representation. (Courtesy: Electromechanical Energy Devices and Power Systems by Yamayee and Bala)

DC Machine Classifications

There are five different types of dc machines:

1. **Separately excited**
2. Shunt
3. Permanent-magnet
4. Series
5. Compound

DC Machine Equivalent Circuit

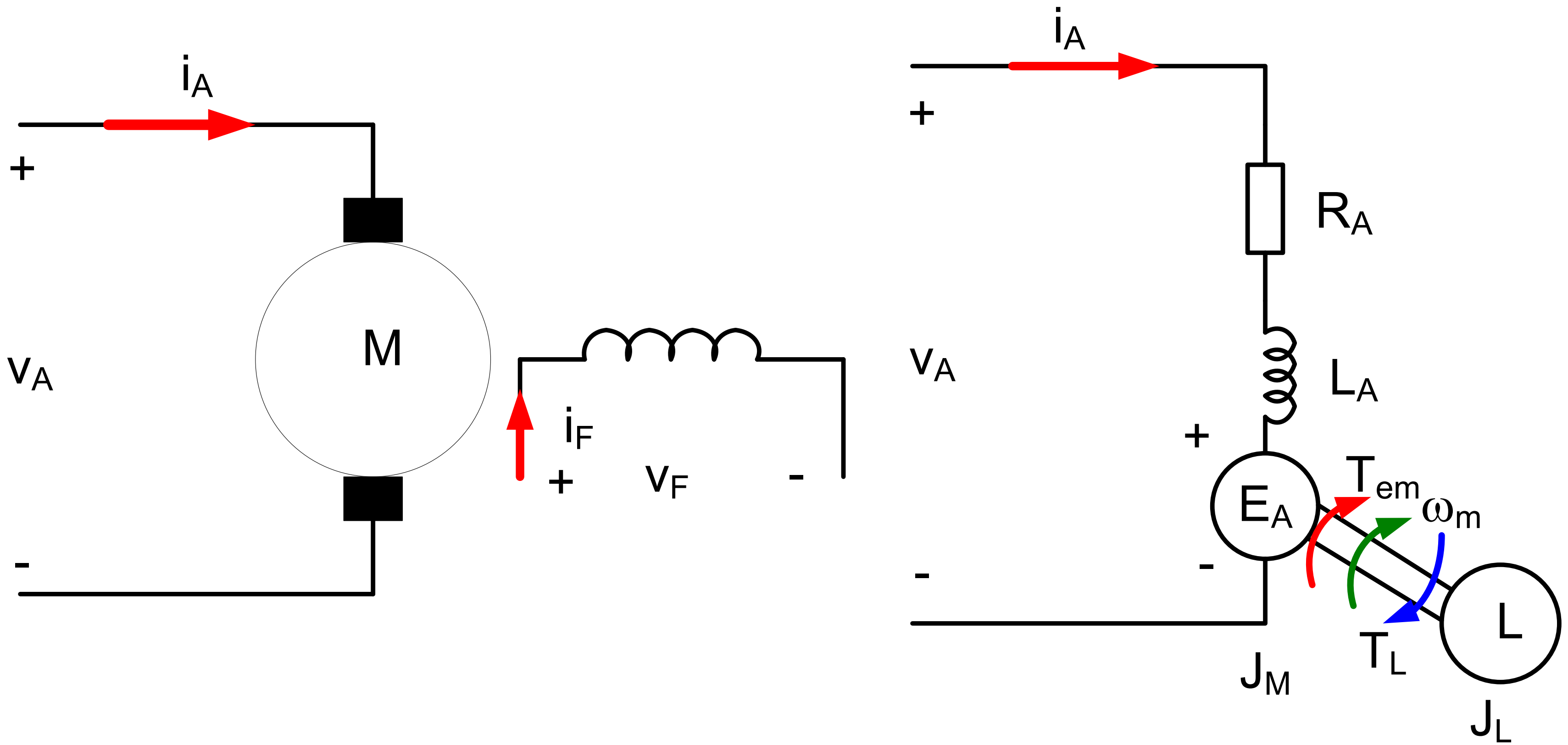
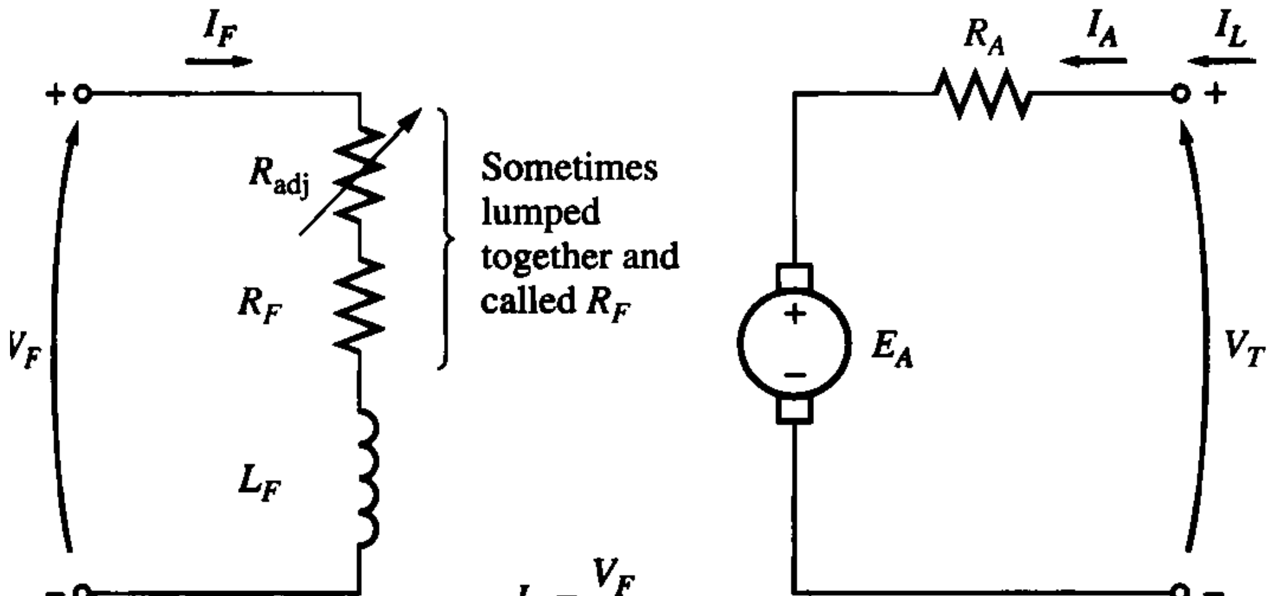


Figure 3.2: Equivalent circuit of the armature of a dc motor drive.

Separately Excited DC Machines



$$I_F = \frac{V_F}{R_F}$$

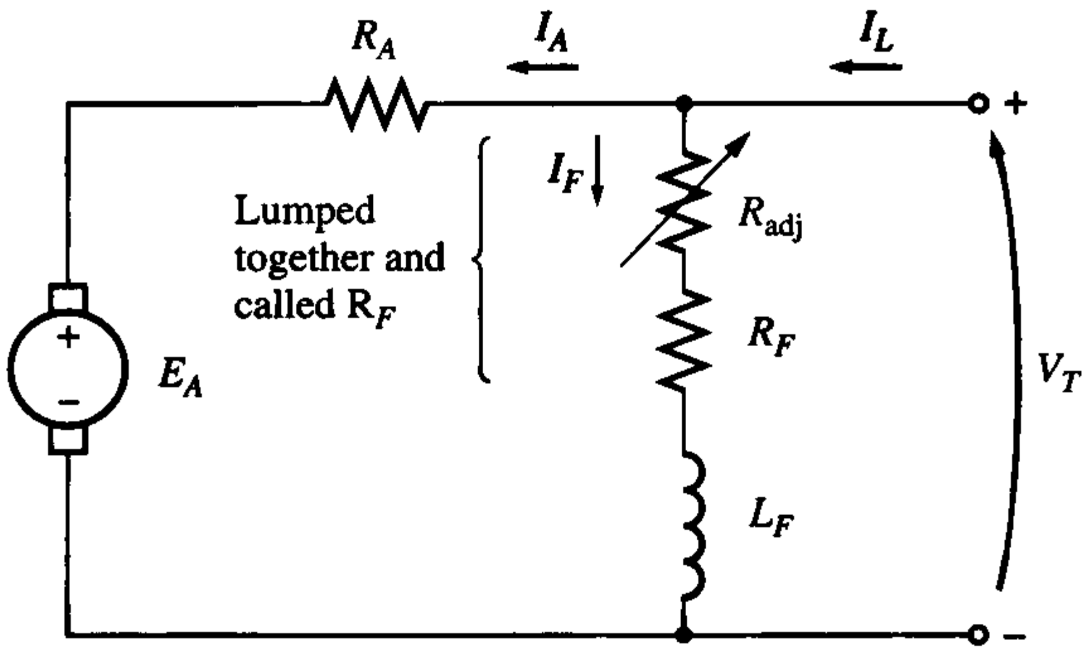
$$V_T = E_A + I_A R_A$$

$$I_L = I_A$$

(*a*)

Figure 3.3: (a) Equivalent circuit of a separately-excited dc motor. (Courtesy: Electric Machinery Fundamentals by S J Chapman)

Shunt DC Machine



$$I_F = \frac{V_T}{R_F}$$

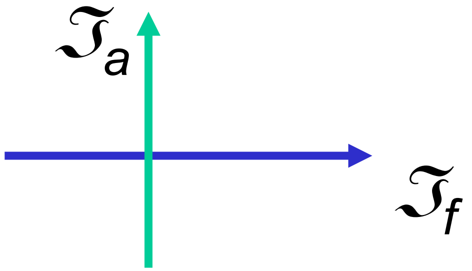
$$V_T = E_A + I_A R_A$$

$$I_L = I_A + I_F$$

Figure 3.3: (b) Equivalent circuit of a dc shunt motor.

(Courtesy: Electric Machinery Fundamentals by S J Chapman)

- DC drives have dominated the field of adjustable speed drives for long – due to simple control requirements i.e. the field and armature magneto-motive-forces (*MMFs = N x I =* $\mathfrak{I}$) are decoupled and therefore can be controlled independently.



- However, DC drives suffer from the disadvantage such as regular maintenance needs.
- AC Drives are gradually replacing DC drives in new as well as retrofit applications:
  - robust construction;
  - maintenance free operation and
  - provide similar dynamic performance as separately excited DC motor drives.

Classification of DC Drives

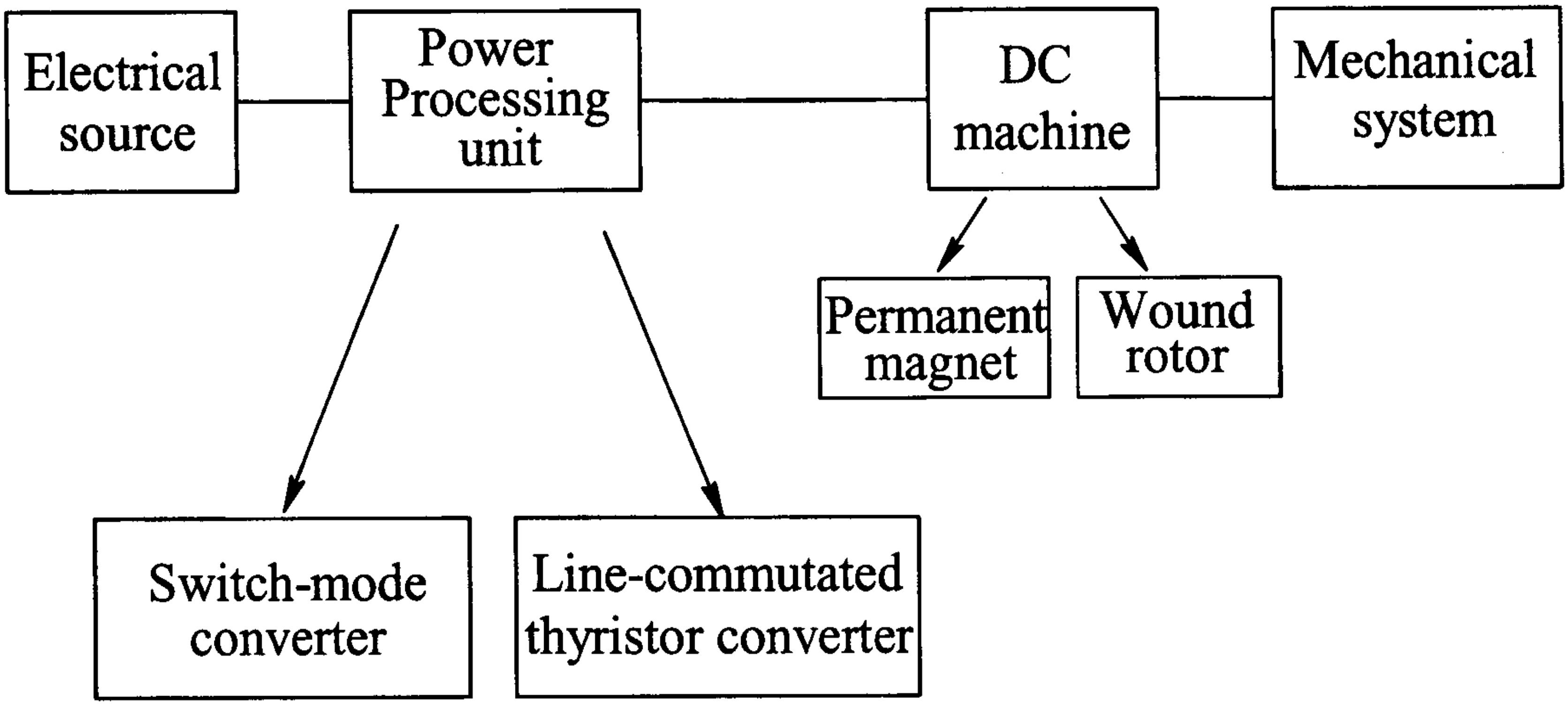


Figure 3.4: Classification of DC drives

(Courtesy: Electric Drives by N Mohan)

- Basic steady-state equations applicable to all dc motors are:

$$E_a = k_e\phi\omega_m = k_E\omega_m \qquad (3.1),$$

$$V_a = E_a + I_a R_a \qquad (3.2),$$

$$T_{em} = k_e\phi I_a = k_T I_a \;\; (k_E = k_T) \;\; (3.3)$$

- Basic dynamic equations are:

$$e_a = k_e\phi\omega_m = k_E\omega_m \qquad (3.4)$$

$$v_a = e_a + i_a R_a + L_a \frac{di_a}{dt} \qquad (3.5)$$

$$T_{em} = k_e\phi i_a = k_T i_a \qquad (3.6)$$

$$\frac{d\omega_m}{dt} = \frac{1}{J_{eq}}\left(T_{em} - T_{mech} - B\omega_m\right) \qquad (3.7)$$

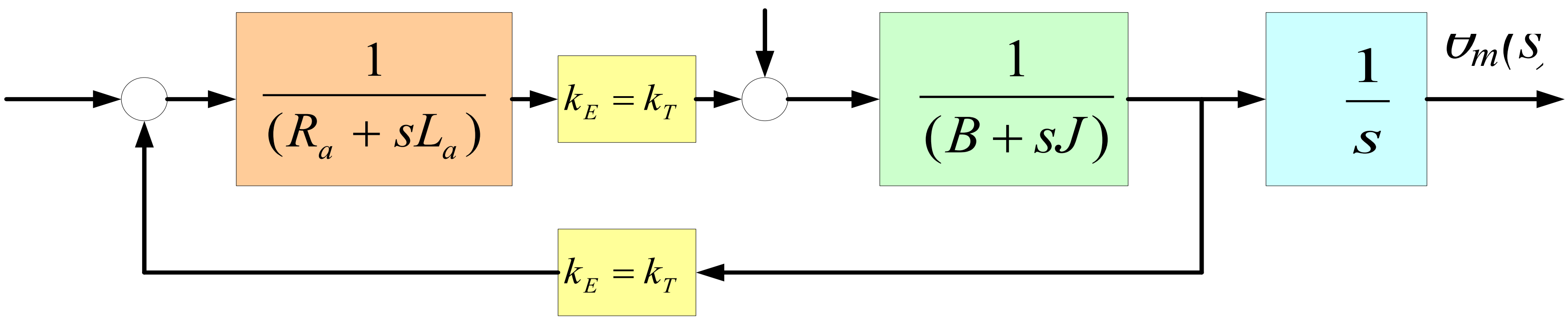


Figure 3.5: Block diagram of the DC motor

- From eqns. 3.1, 3.2, 3.3 it is possible to derive the relationship between operating motor speed ω_m and motor torque, T_{em} as:

$$\omega_m = \frac{V_a}{k_e\phi} - \frac{R_a}{(k_e\phi)^2} T_{em} \quad (3.8)$$

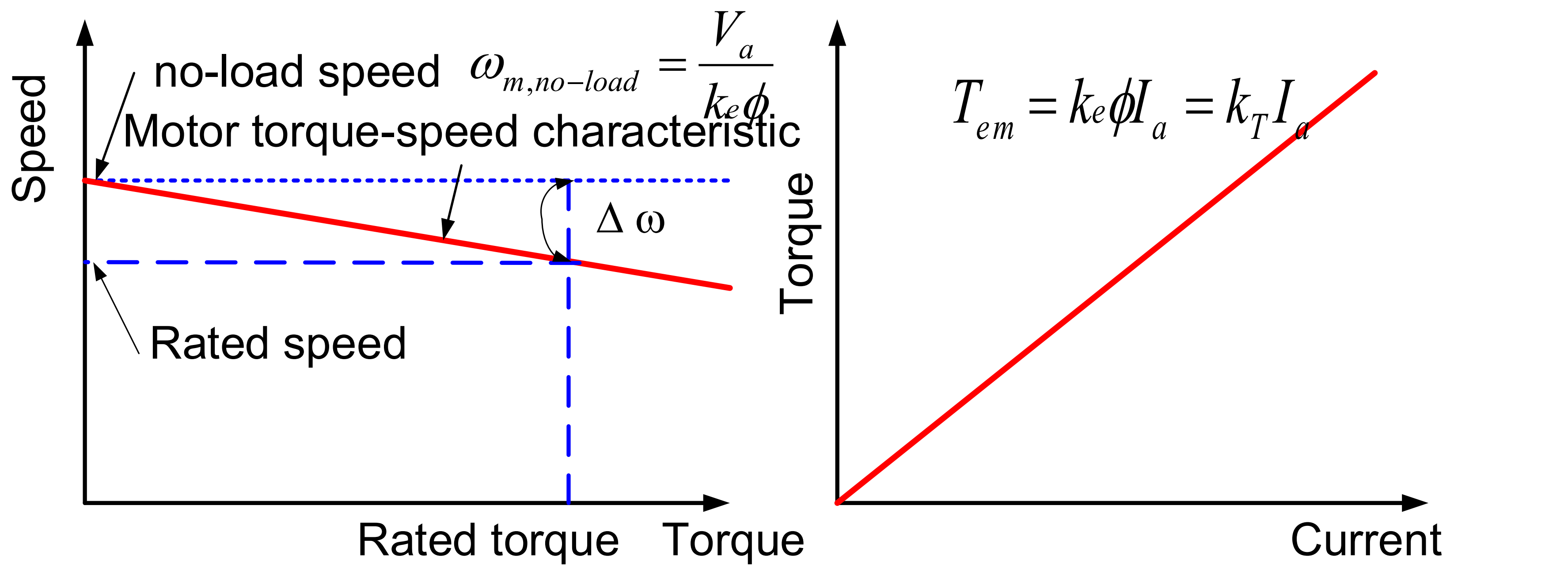


Fig. 3.6: (a) Torque-Speed and (b) Torque-Current characteristics.

- From eqn. 3.8 it can be seen that speed control of dc motors can be carried out by three different ways:
  a) armature voltage control, V_a
  b) field flux control, ϕ and
  c) armature resistance control, R_a.
- **Armature voltage control** method is preferred for speed control below base (rated) speed. (why?)
- **Field flux control** method is preferred for speed control above the base speed. (why?)
- Armature resistance control method is inefficient so hardly used anymore.

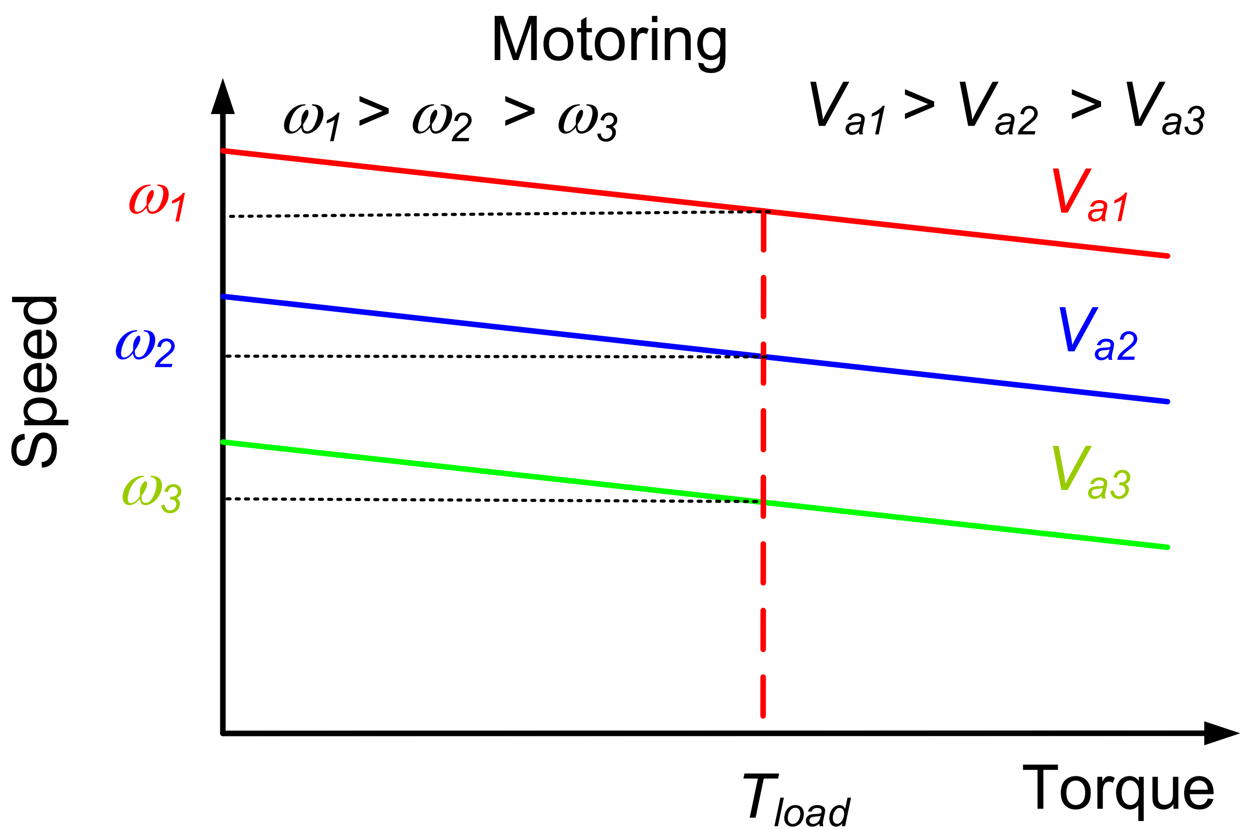


Figure 3.6(c): Motoring torque-speed characteristics of a separately excited dc motor with variable armature voltage.

Torque and Power Limits

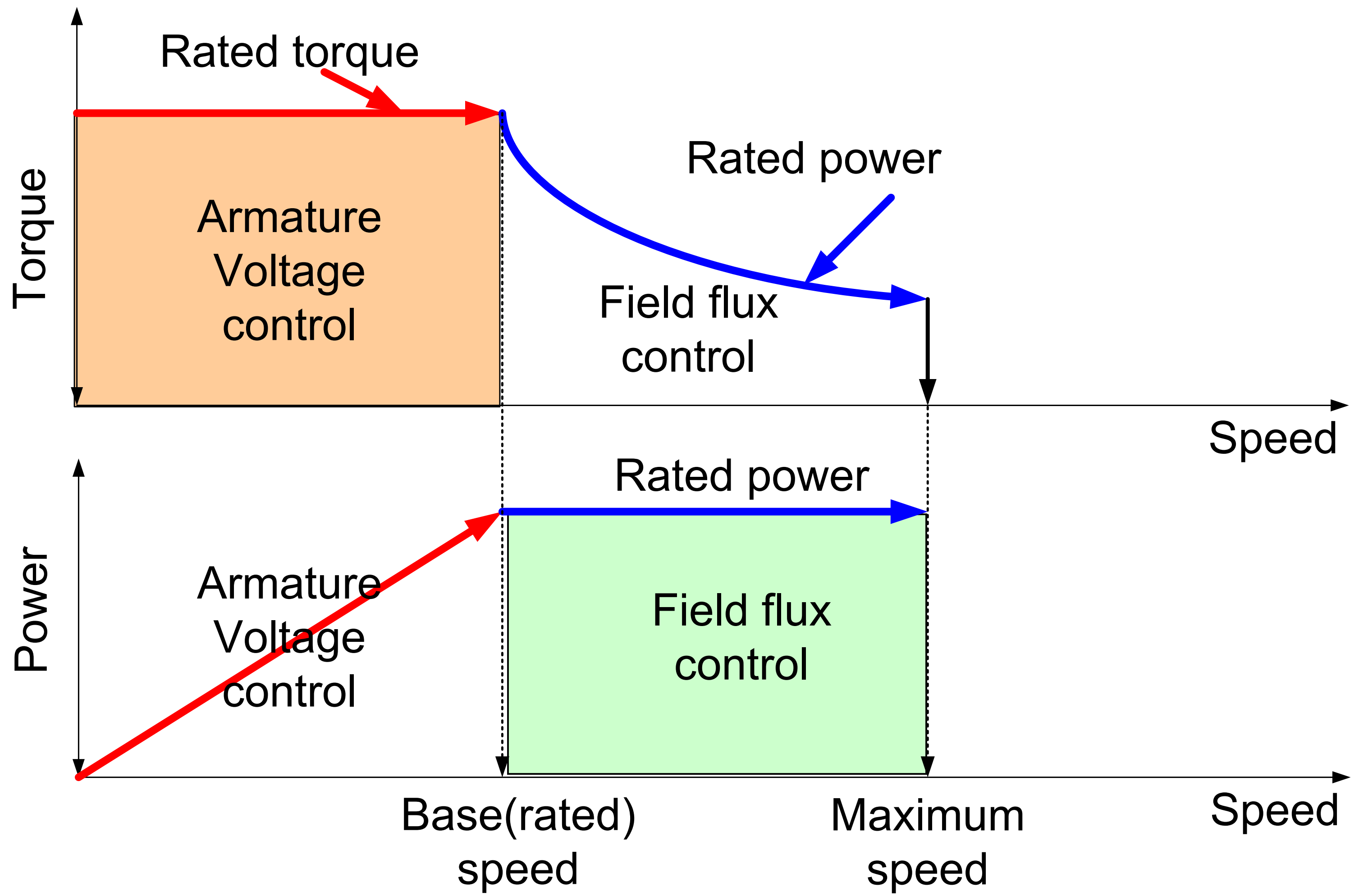


Figure 3.7: Torque and power limits in combined armature voltage and field control

Electrical Braking

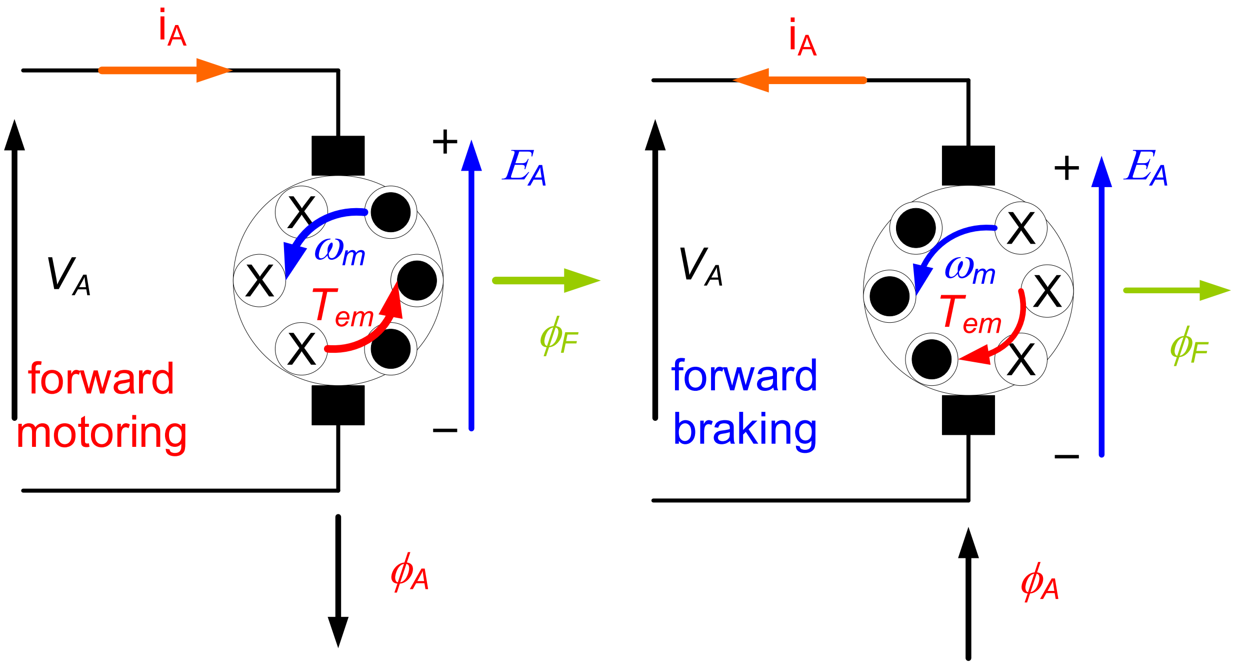


Fig. 3.8: Regenerative braking

- Regenerative braking: energy recovered is fed back to electrical source while braking.
  - Current and torque directions are reversed
  - Polarity of induced emf and direction of speed remain the same

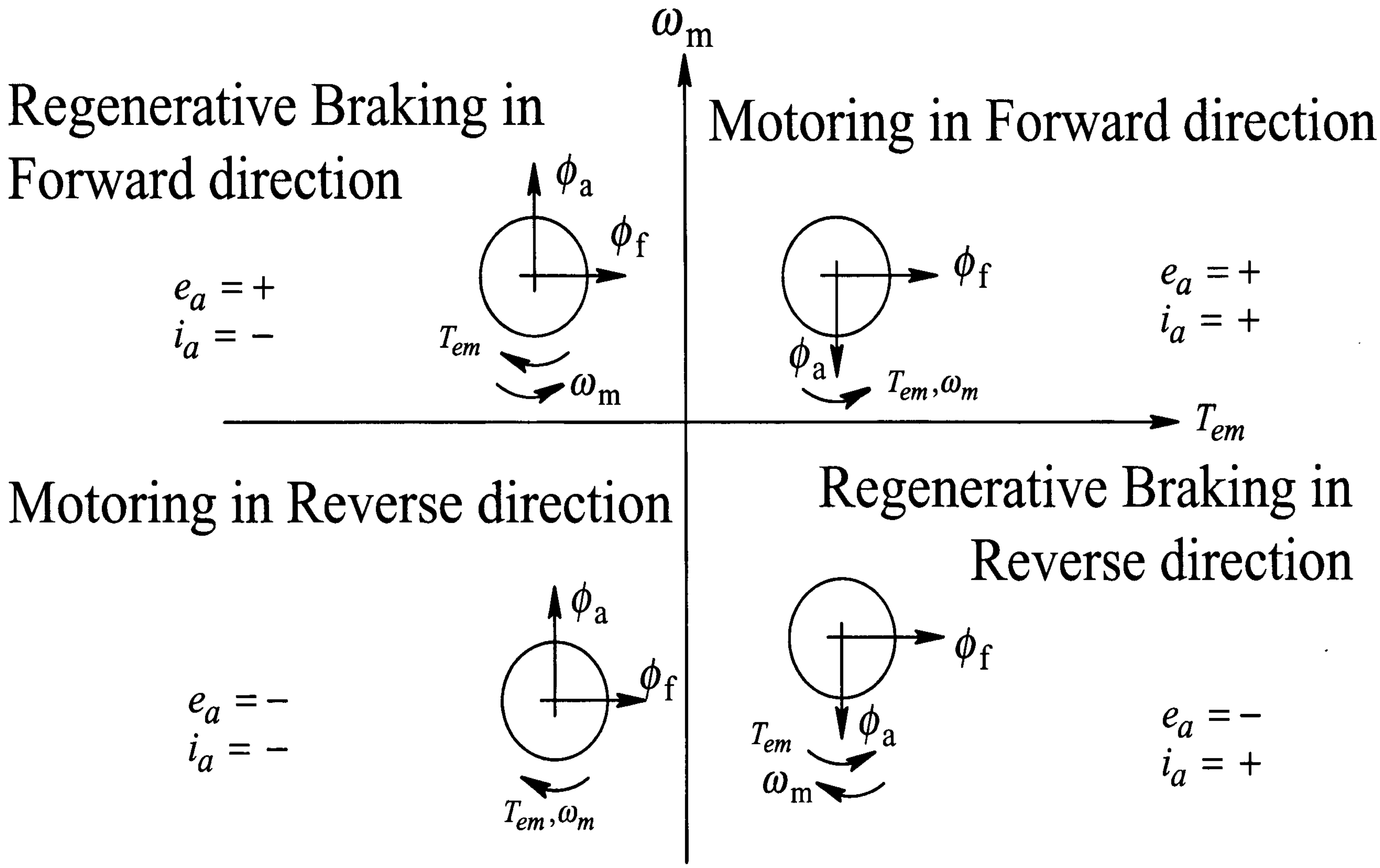


Fig.3.9: Four-quadrant operation of DC drive
(Courtesy: Electric Drives by N Mohan)

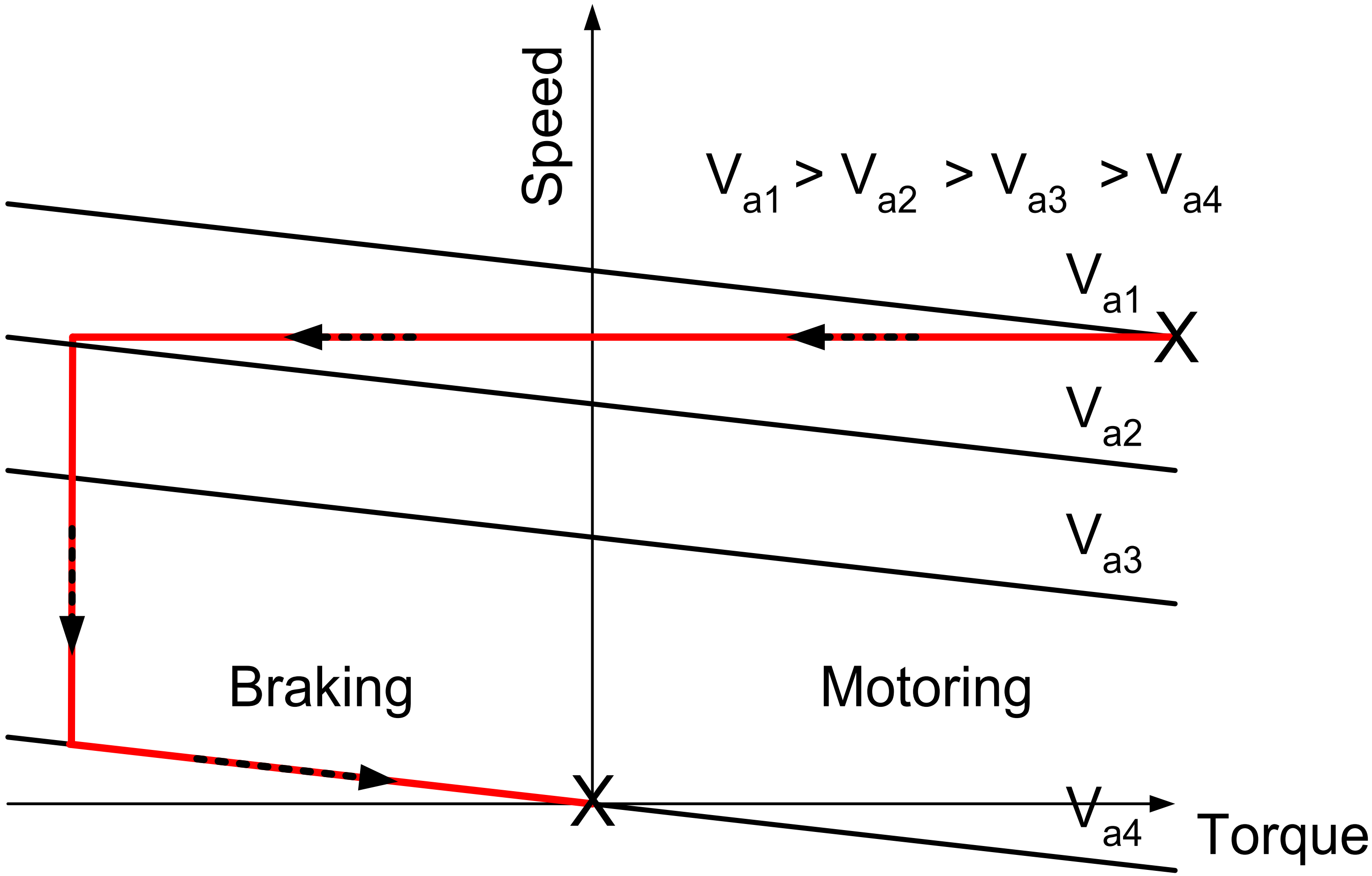


Figure 3.10: Regenerative braking torque-speed characteristics of a separately excited dc motor

- **Dynamic Braking** – The re-generated braking energy is dissipated as heat in the braking resistor, R_B.

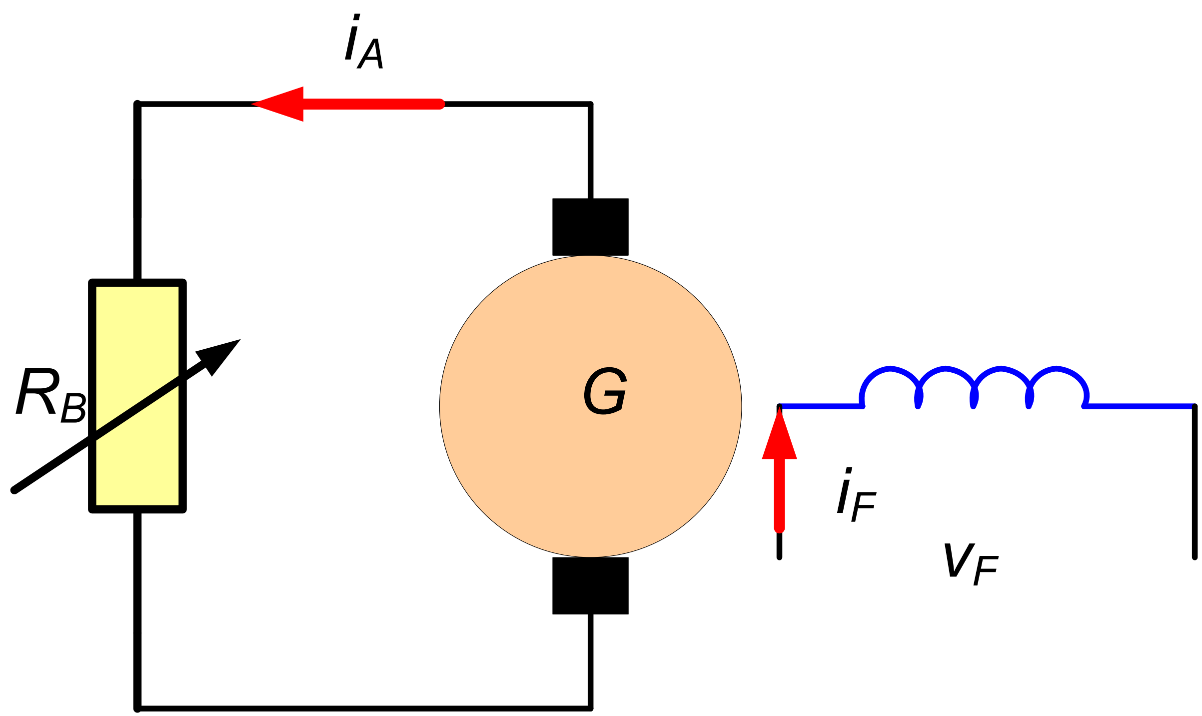


Figure 3.11: Dynamic braking of a separately-excited dc motor drive

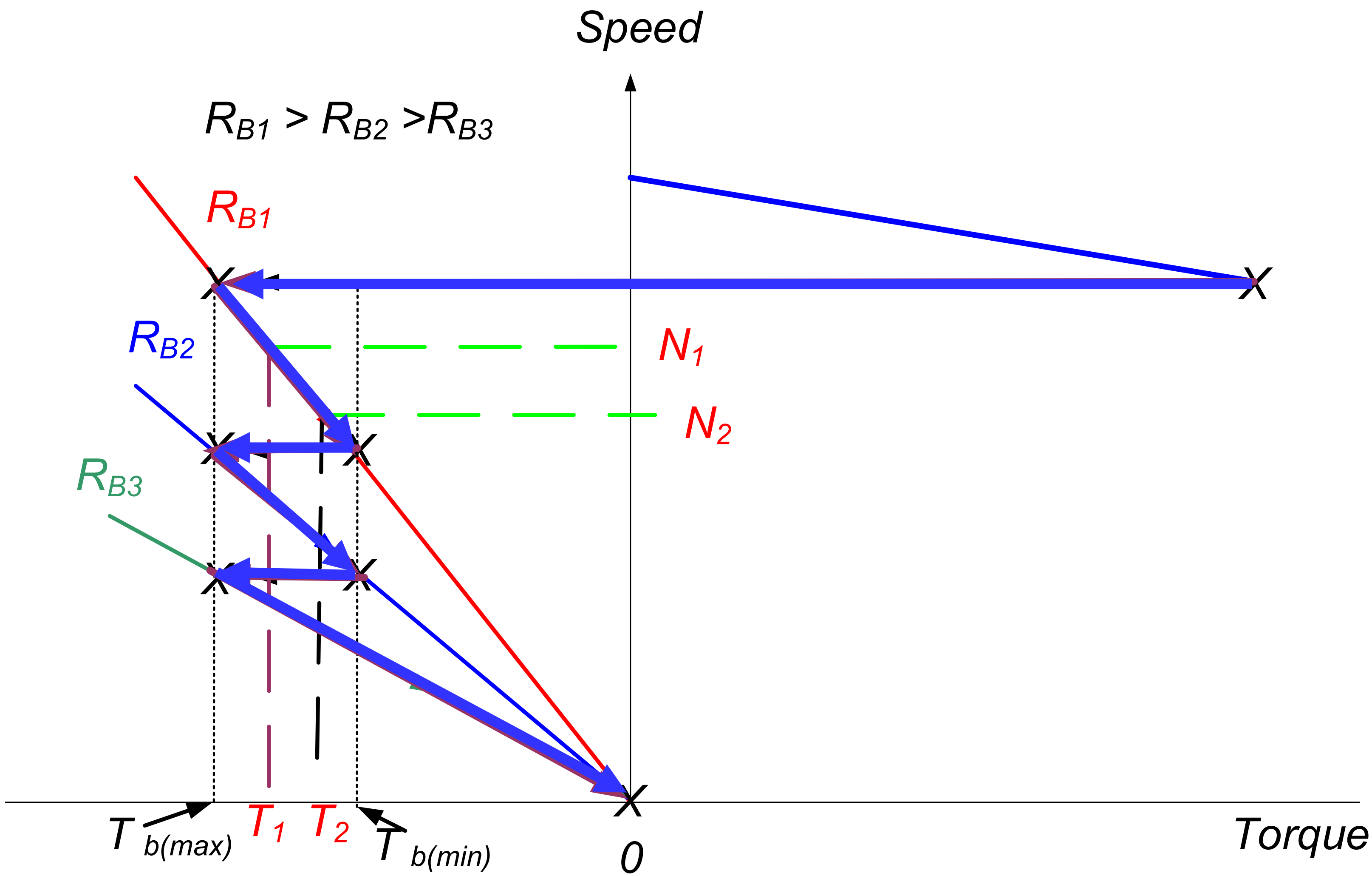


Figure 3.12 Dynamic braking dc motor torque-speed characteristics

Speed Control

- Speed control of dc motors can be carried out by two different methods:
  - Armature Voltage Control
  - Field Flux Control

Armature Voltage Control

- This method of speed control is highly efficient and provides good transient performance. It is applicable for speed control below the base speed (WHY ?).

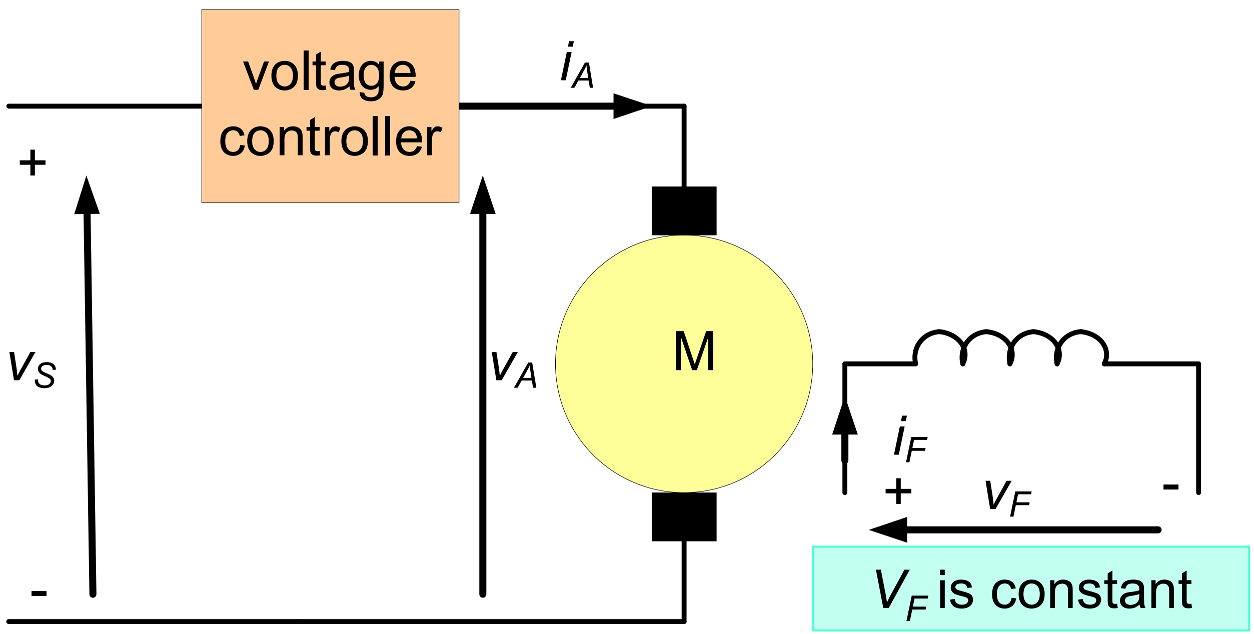


Fig. 3.13: Armature voltage control of DC Motor

$$\omega_m = \frac{V_a}{k_e\phi} - \frac{R_a}{(k_e\phi)^2} T_{em} \quad (3.8)$$

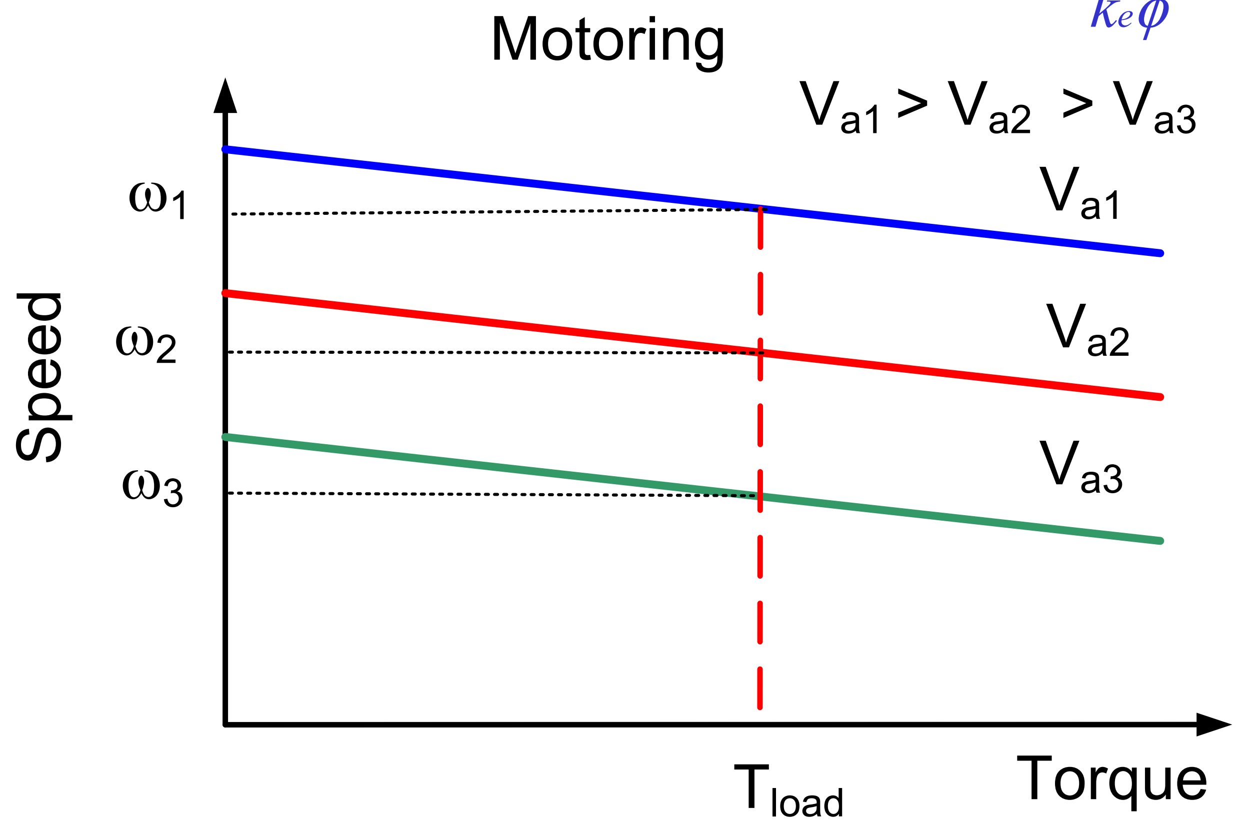


Figure 3.14: Torque-speed characteristics of dc motor by armature voltage control

Field Flux Control

- Note that flux control or field weakening is carried out for speed control above the base speed (WHY?).

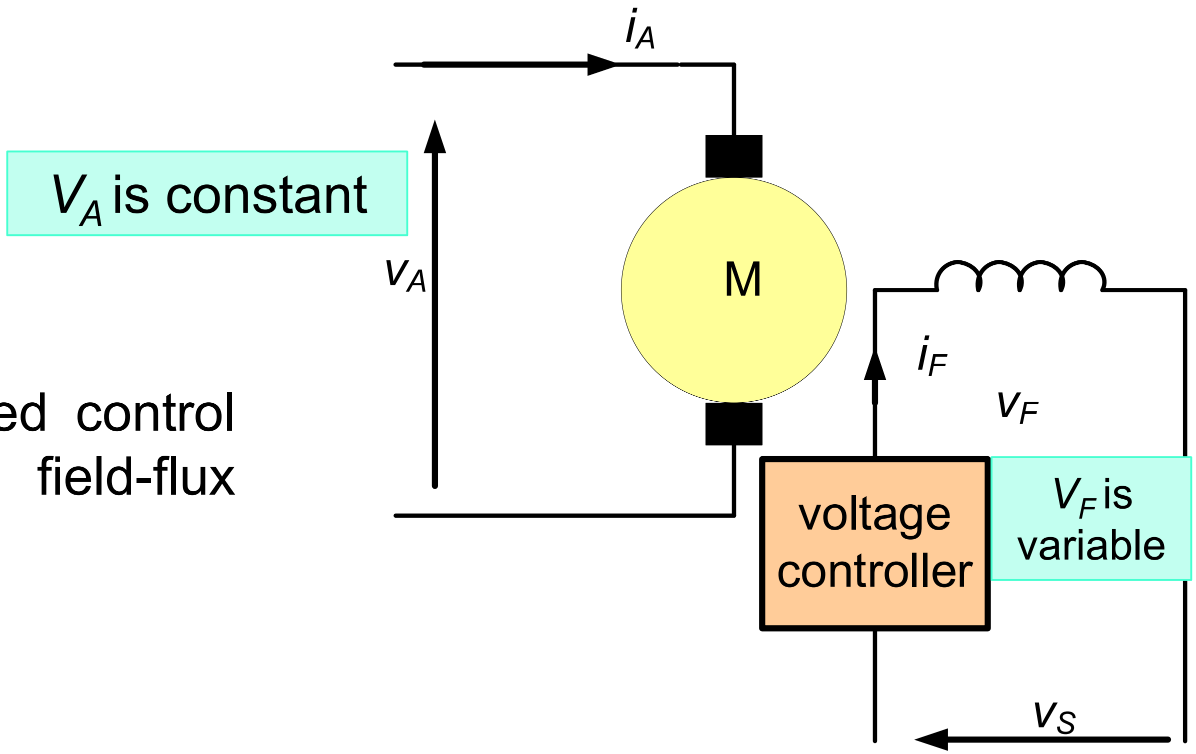


Figure 3.15: Speed control of dc motor by field-flux control

$$\omega_m = \frac{V_a}{k_e\phi} - \frac{R_a}{(k_e\phi)^2} T_{em} \quad (3.8)$$

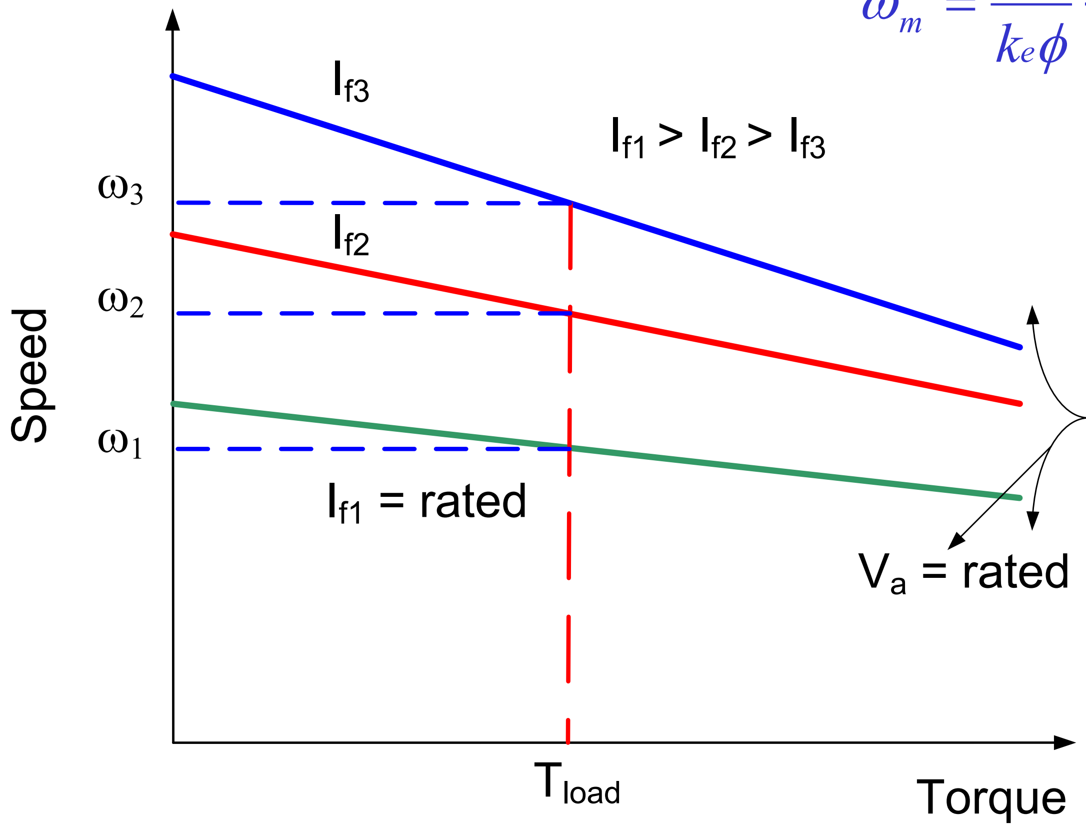


Figure 3.16: Torque-speed characteristics of dc motor by field flux control

Armature Voltage Control

- It is known that armature voltage has to be controlled from zero voltage to rated voltage under this scheme.

- We can achieve this by:
  - when the supply is AC, we can make use of the **phase-controlled rectifiers** to obtain variable dc voltage. **This method is hardly used anymore.**
  - when the supply is DC, we can make use of **choppers** to obtain variable dc voltage.

Phase-Controlled Rectifiers

- Phase-controlled rectifiers can be either single-phase or three-phase and classified as:
  - **fully-controlled** - output dc voltage can take either polarity ($-V_{a(max)} < V_a < V_{a(max.)}$)
  - **half-controlled** - output voltage can only have positive polarity ($0 < V_a < V_{a(max.)}$)
- Currents through thyristors can flow only in one direction i.e. ($I_A \geq 0$).
- Output voltage V_A of the rectifier or converter can be made positive ($V_A \geq 0$) or negative ($V_A \leq 0$) depending on the firing delay angle, α.
- DC drive with fully-controlled rectifiers ($-V_{max} \leq V_A \leq +V_{max}$) can operate either in quadrant I or in quadrant IV.
- In half-controlled rectifiers ($V_A \geq 0$) and therefore, the drive can only operate in quadrant-I.

Single-phase Fully-Controlled Rectifiers

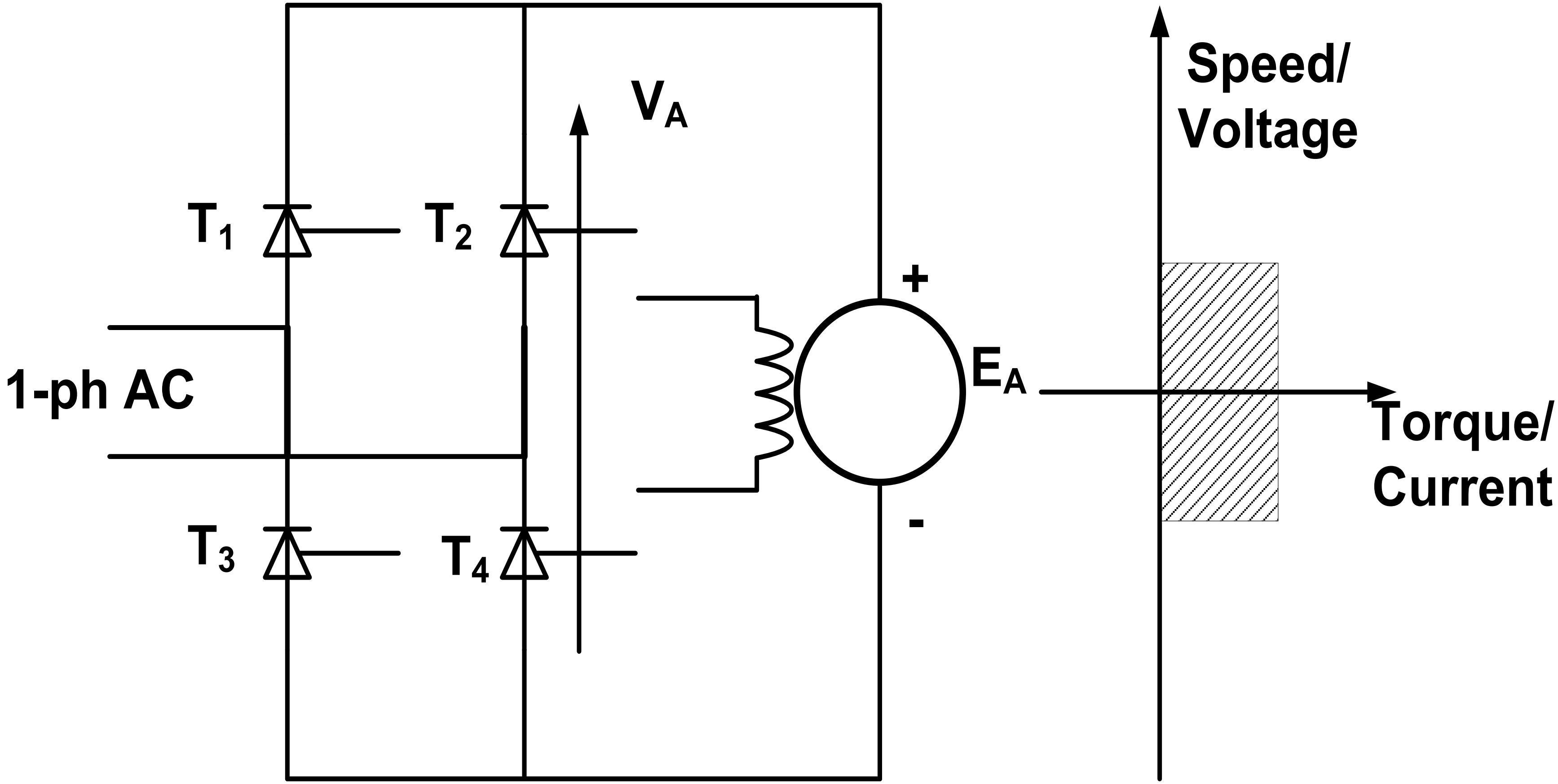


Figure 3.17: Single-phase fully-controlled bridge rectifier

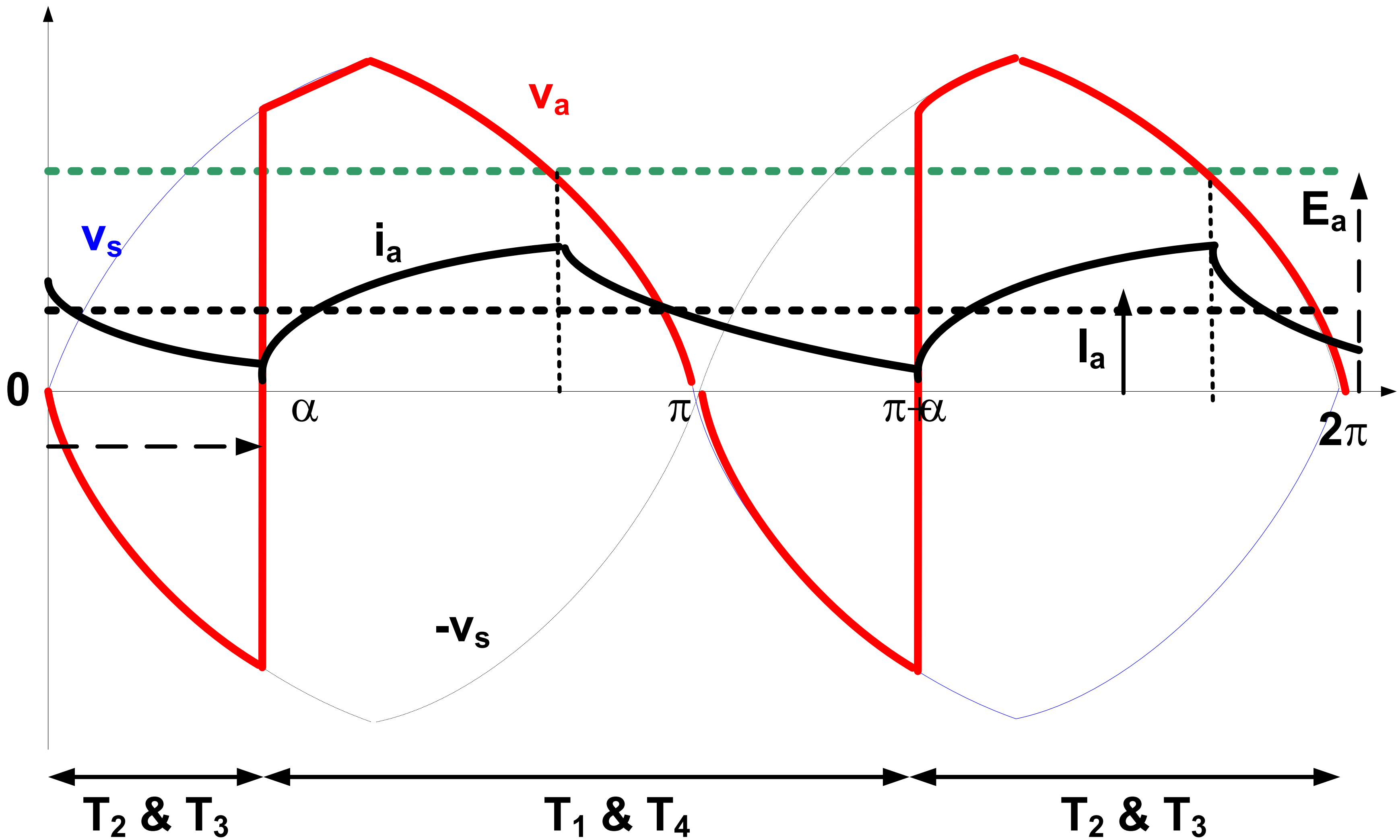


Figure3.17(a): Waveforms of Single-phase fully controlled rectifier-fed separately excited dc motor (continuous mode of operation).

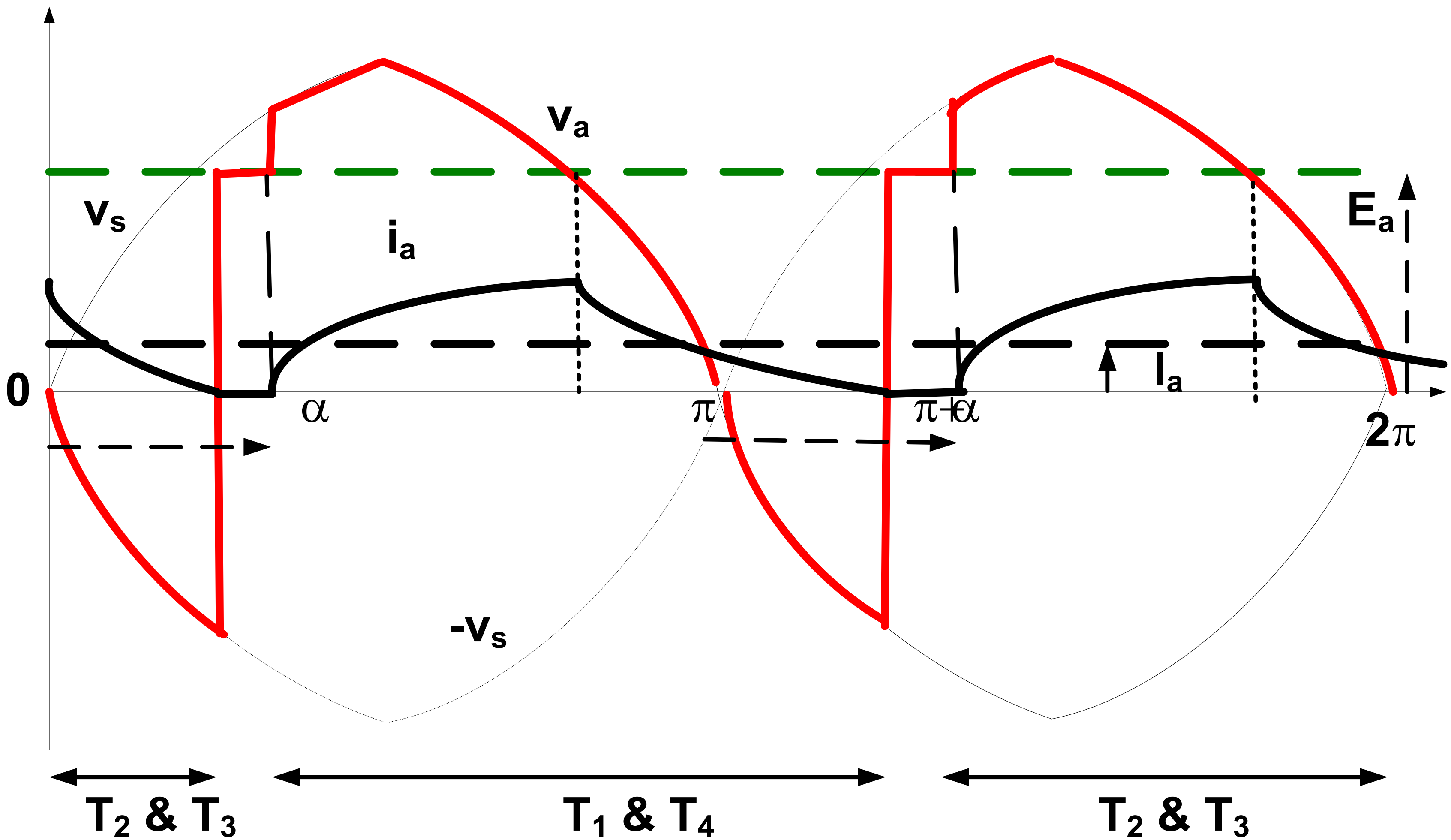


Figure3.17(b): Waveforms of Single-phase fully controlled rectifier-fed separately excited dc motor (discontinuous-mode of operation).

- Assuming continuous conduction the average converter output voltage is given by

$$V_o = \frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} V_m \sin \omega t \; d(\omega t) = \frac{2V_m}{\pi}\cos\alpha \quad (3.9)$$

- Substituting in torque-speed eqn., we have

$$\omega_m = \frac{\frac{2V_m}{\pi}\cos\alpha}{k_e\phi} - \frac{R_a}{(k_e\phi)^2}T_{em} \qquad (3.10)$$

- The drive operates in quadrants I or IV as shown in Fig. 3.17(c).

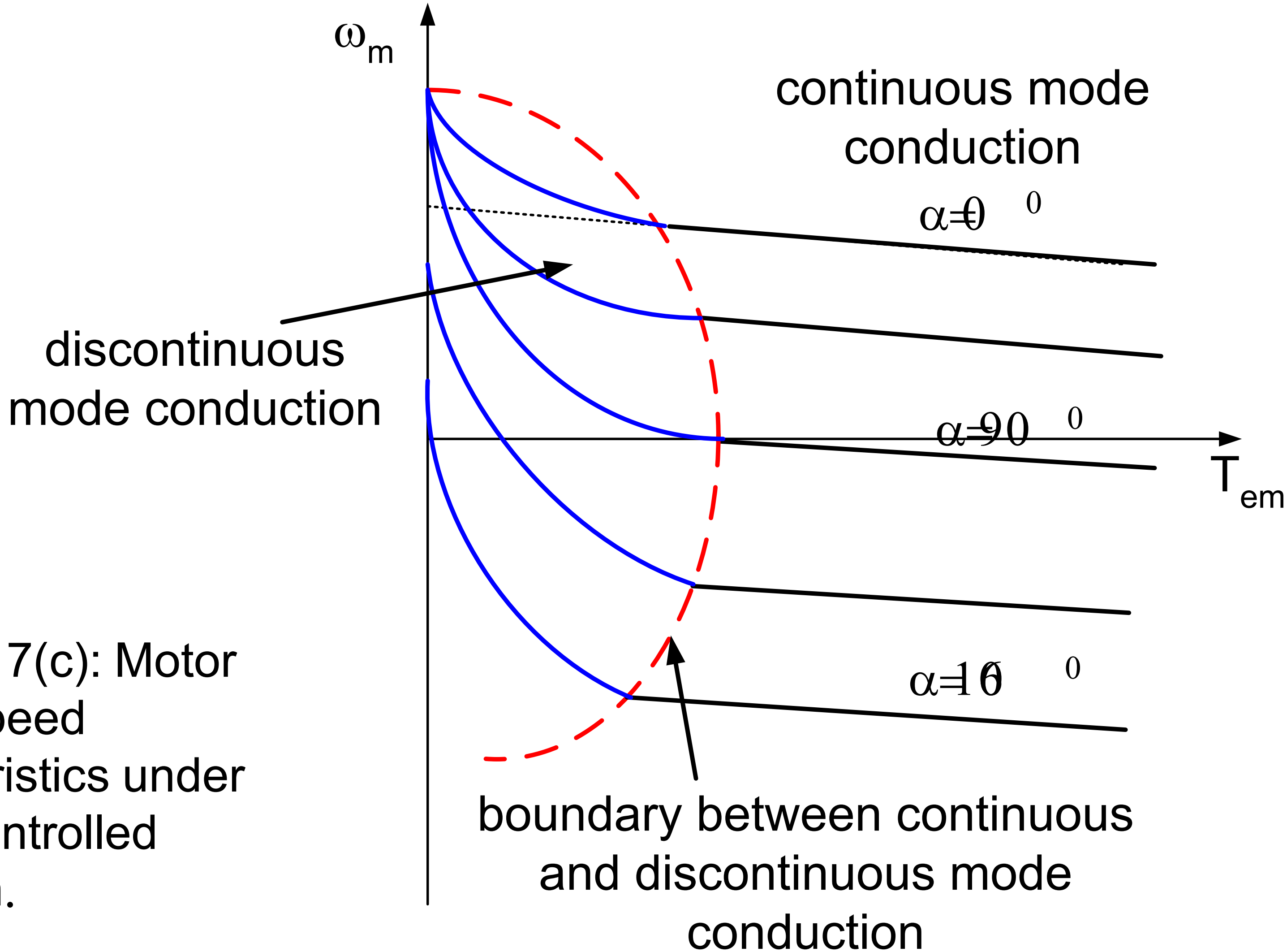
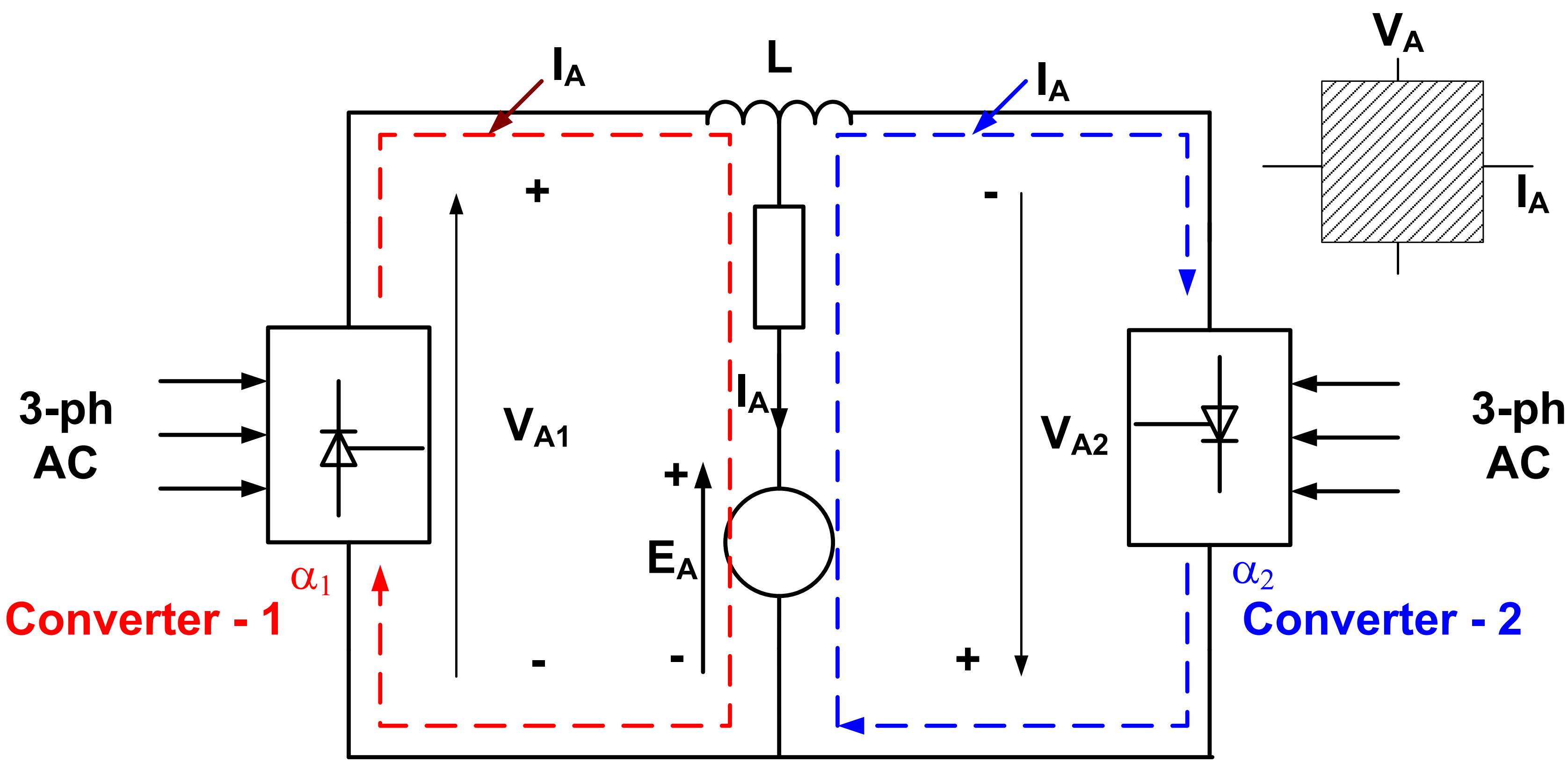


Figure3.17(c): Motor torque-speed characteristics under phase-controlled operation.

Dual Converter



$$\alpha_1 + \alpha_2 = 180^0$$

Fig. 3.18: Dual converter for DC Motor Drive

- Dual converter allows four-quadrant operation.
- Coverter-1 provides operation in quadrant-I ($\alpha_1 < 90^0$) and quadrant-IV by making ($\alpha_1 > 90^0$), $I_A > 0$ and $-V_{a,max} < V_a < V_{a,max}$.
- Coverter-2 provides operation in quadrant-II ($\alpha_2 < 90^0$) and quadrant-III by making ($\alpha_2 > 90^0$) $I_A < 0$ and $-V_{a,max} < V_a < V_{a,max}$.
- In order to make $|V_{A1}| = |V_{A2}|$, the necessary condition is $\alpha_1 + \alpha_2 = 180^0$.
- The inductor, L is provided to limit the circulating current.

- Phase controlled converter fed DC Motor Drive has certain limitations:
  - Operation at line (supply) frequency of 50 Hz leads to significant armature current ripples (ripple frequency 100 Hz);
  - At light-load conditions armature current may be discontinuous leading to poor dynamic performance;
  - A two quadrant phase-controlled converter can't provide forward-motoring and forward-braking or reverse–motoring and reverse-braking mode of operations simultaneously.
- Some or all of the above mentioned problems can be overcome if chopper controlled DC Drive is utilized.

Chopper Control of DC Motors

- For control of dc motors, choppers provide a number of advantages over the phase controlled rectifiers:
  - choppers operate at much higher frequency(> 10 kHz) reducing ripples in the armature current - region of discontinuous conduction is smaller;
  - a reduction in armature current ripples reduces machine's rms current and therefore losses and hence de-rating of the machine; and
  - a reduction or elimination of armature current ripples improves the transient response of the drive system.

Chopper Classifications

- Choppers can be classified as:
  - step-down and
  - step-up.
- Alternatively, they can also be classified as:
  - Class A (single-quadrant, quadrant-I),
  - Class B (single-quadrant, quadrant-II),
  - Class C (two-quadrant, quadrants-I and II),
  - Class D (two-quadrant, quadrants-III and IV) and
  - Class E (four-quadrant) choppers.

Step-down Chopper (Forward Motoring)

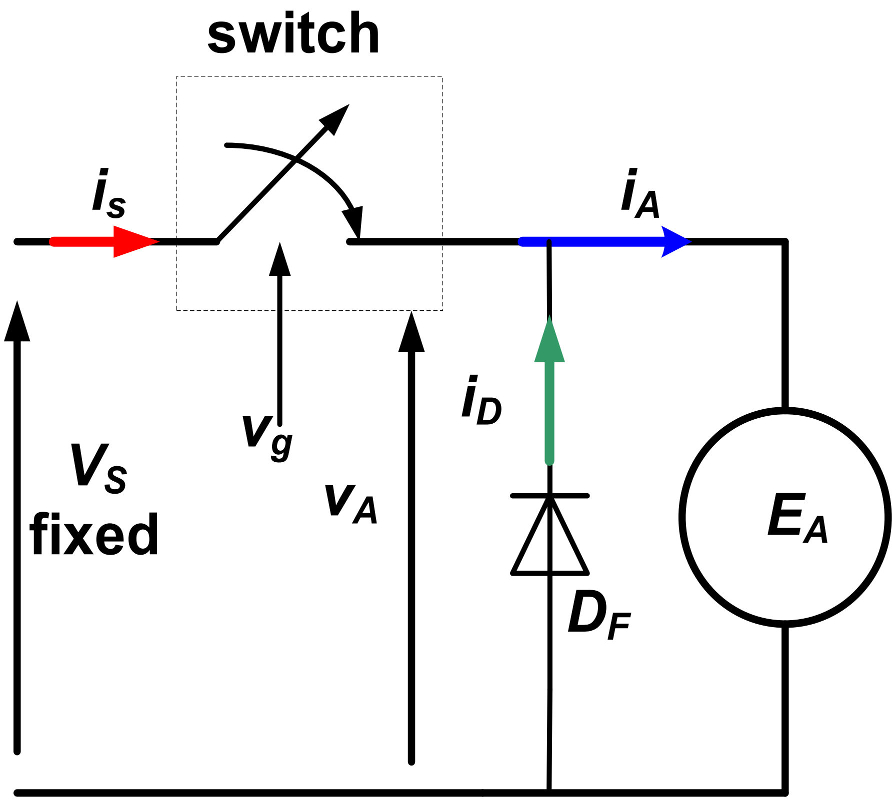


Figure 3.19: Principle of operation of a step-down or Class A chopper: (a) basic chopper circuit

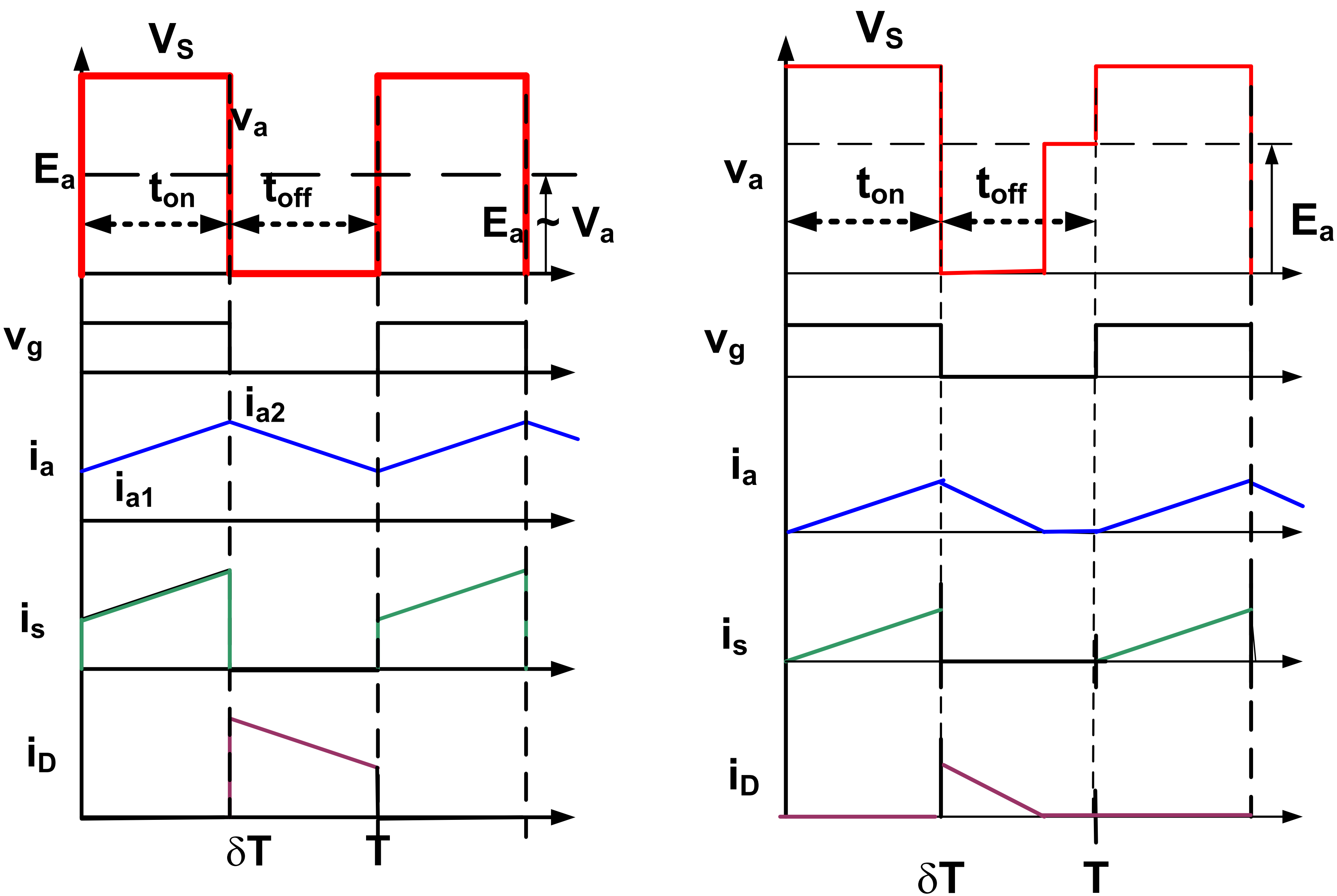


Fig.3.19 voltage and current waveforms: (b) continuous (c) discontinuous mode of conduction.

- Such a chopper operates in quadrant-I of the torque-speed plane.

- Output voltage as well as current can only take positive polarity.

- Assuming continuous mode of conduction, the average output voltage is given by

$$V_A = \frac{1}{T}\int_0^T v_a \, dt = \frac{1}{T}\int_0^{\delta T} V_s \, dt = \delta V_s \qquad (3.11)$$

- By controlling the duty-cycle, *d* $(0 < \delta < 1)$, we can obtain $0 < V_A < V_s$.

- During the duty-interval *($0 \le t \le \delta T$)*

$$R_a i_a + L_a \frac{di_a}{dt} + E_a = V_s \qquad (3.12)$$

- with $i_a(0) = i_{a1}$, we have

$$i_a(t) = \left(\frac{V_s - E_a}{R_a}\right)\left(1 - \exp(-t/\tau_a)\right) + i_{a1}\left(\exp(-t/\tau_a)\right) \quad (3.13)$$

where $\tau_a = L_a/R_a$. For $t = \delta T$, we have

$$i_{a2} = \left(\frac{V_s - E_a}{R_a}\right)\left(1 - \exp(-\delta T/\tau_a)\right) + i_{a1}\left(\exp(-\delta T/\tau_a)\right) \quad (3.14)$$

- During the freewheeling-interval ($\delta T \le t' \le T$)

$$R_a i_a + L_a \frac{di_a}{dt'} + E_a = 0 \quad (3.15)$$

- where $t' = t - \delta T$, with $i_a(t' = 0) = i_{a2}$, we have

$$i_a(t) = \left(-\frac{E_a}{R_a}\right)\left(1 - \exp(-t'/\tau_a)\right) + i_{a2}\left(\exp(-t'/\tau_a)\right) \; (3.16)$$

For $t' = T - \delta T$, we have

$$i_{a1} = \left(-\frac{E_a}{R_a}\right)\left(1 - \exp(-(1-\delta)T/\tau_a)\right) + i_{a2}\left(\exp(-(1-\delta)T/\tau_a)\right) \; (3.17)$$

- Solving eqns. 3.14 and 3.17, we have

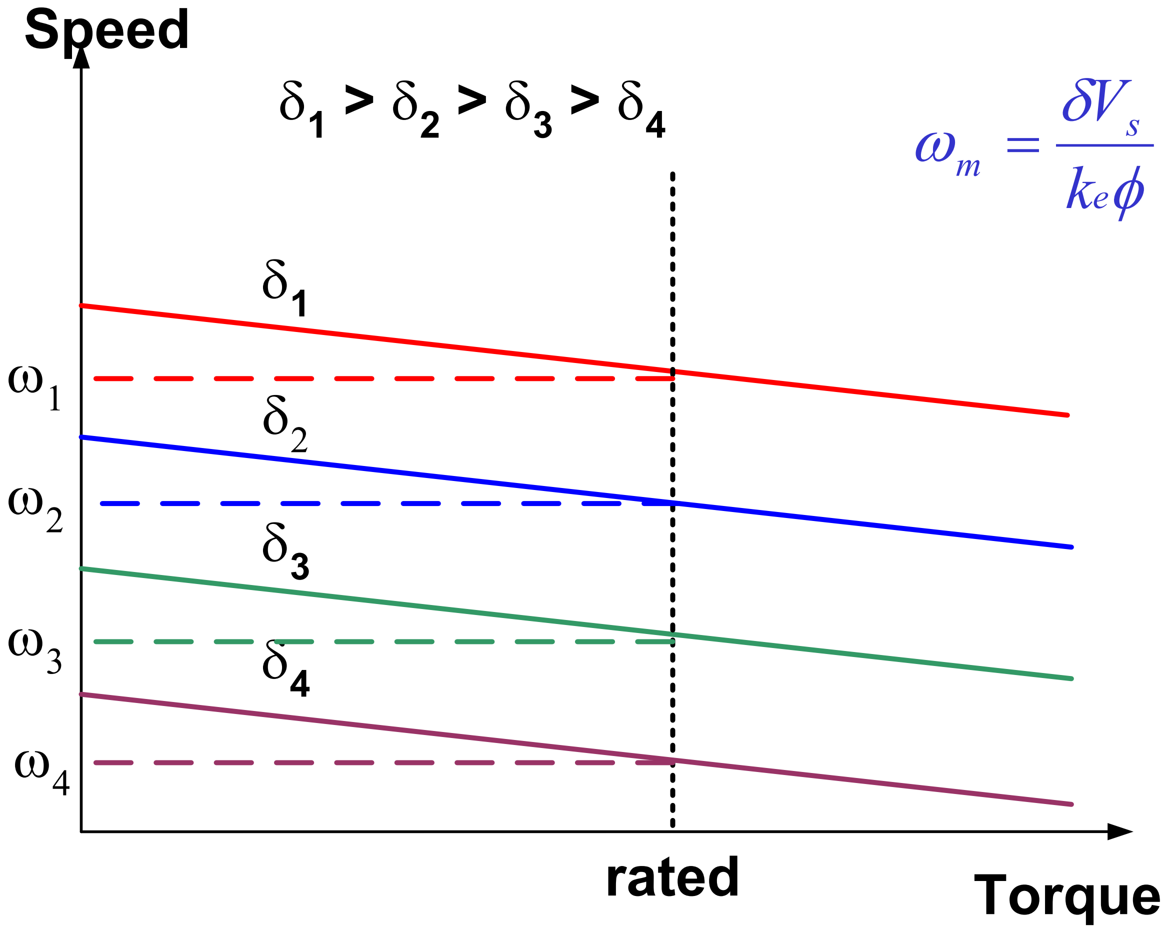
$$i_{a1} = \frac{V_s}{R_a}\left(\frac{\exp(\delta T/\tau_a)-1}{\exp(T/\tau_a)-1}\right) - \frac{E_a}{R_a} \quad (3.18)$$

$$i_{a2} = \frac{V_s}{R_a}\left(\frac{1-\exp(-\delta T/\tau_a)}{1-\exp(-T/\tau_a)}\right) - \frac{E_a}{R_a} \quad (3.19)$$

- At steady-state, we have

$$V_a = \delta V_s = E_a + I_a R_a \Rightarrow I_a = \frac{\delta V_s - E_a}{R_a} \Rightarrow T_m = k_e \phi I_a$$

$$\omega_m = \frac{\delta V_s}{k_e\phi} - \frac{R_a}{(k_e\phi)^2} T_{em} \qquad (3.20)$$



$$\omega_m = \frac{\delta V_s}{k_e \phi} - \frac{R_a}{(k_e \phi)^2} T_{em} \quad (3.8)$$

Figure 3.20: Torque-speed characteristics of dc motor by armature voltage control

- Thus, a step-down chopper allows a variable dc voltage to be obtained from a fixed voltage dc source.
- Duty cycle, δ can be varied by varying the ON period of the switch while keeping the total time period, T constant. This is referred to as pulse-width-modulation (PWM) control.
- Modern power semiconductor devices can be operated at frequencies more than 20 kHz for examples with MOSFETS and IGBTs.
- At such high frequency operations, discontinuous mode of conduction can be almost eliminated.

Example 1: A permanent-magnet DC motor has the following parameters:

$R_a = 0.5\ \Omega$; $L_a = 20$ mH; $V_{a,rated} = V_{dc} = 500$ V ; $N_{rated} = 1170$ rpm; $I_{a,rated} = 20.0$ A

The DC machine is being driven by a single-quadrant step-down chopper. The chopper frequency is set at 1.0 kHz.

Determine the chopper duty-cycle for a machine speed of 800 rpm at rated load.

Solution: The parameters given are:

R_a = 0.5 Ω; L_a = 20 mH; V_{dc} = 500 V ;N_{rated} = 1170 rpm; $I_{a,rated}$ = 20.0 A

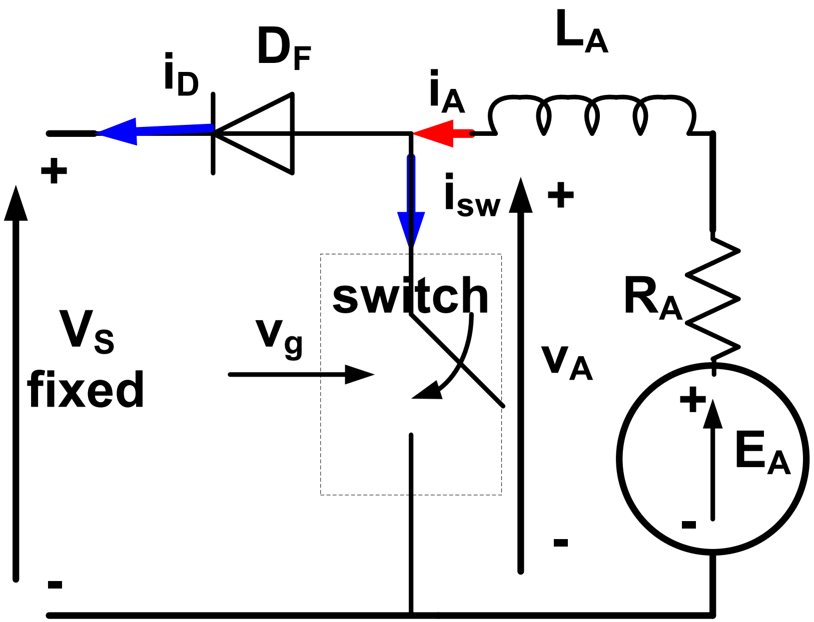
At rated condition we have $k_E = 4 \left({}^{V}\!/_{rad/s} \right)$

- At 800 rpm, we have

$$\delta = 0.7$$

Step-up Chopper (Regenerative Braking)

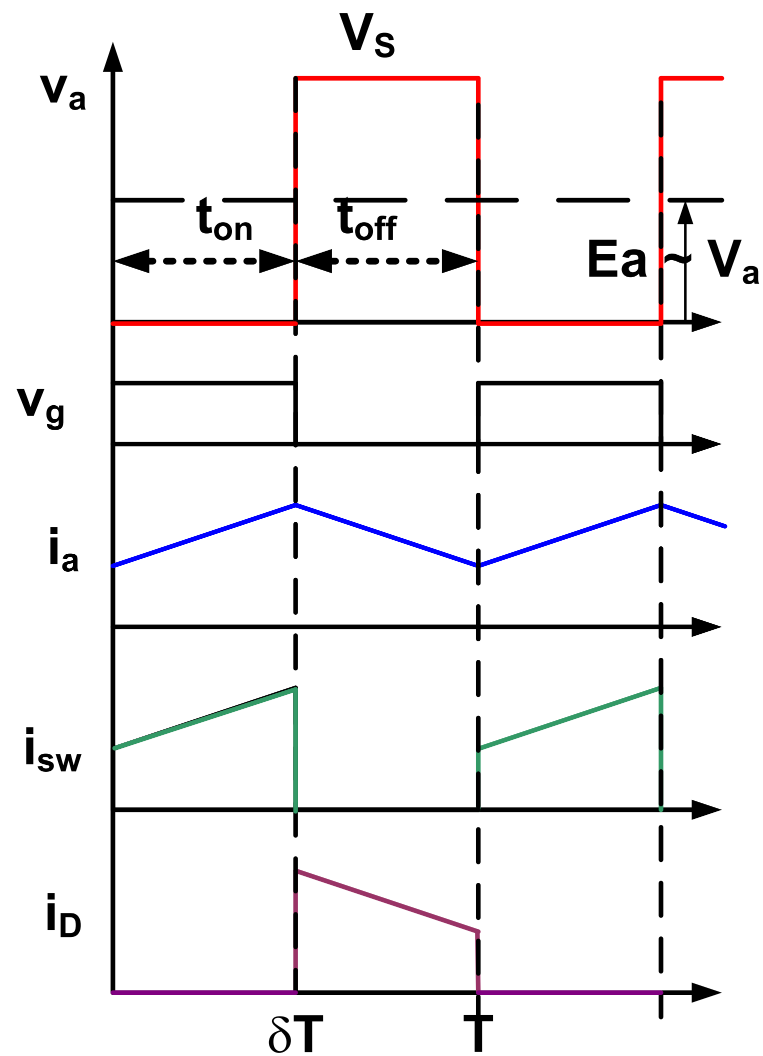
- When fed from a fixed voltage dc source at rated armature voltage level, regenerative braking of dc motors can be carried out only at speeds above the base speed.
- However, with chopper control regenerative braking can be carried out even at speeds below the base speed down near to zero speed.



step-up chopper circuit

Figure 3.21: Regenerative braking of separately excited dc motor

Normally, $|V_s| > |E_a|$



continuous mode of conduction

- The interval $0 \le t \le \delta T$ is called the energy storage interval and the interval $\delta T \le t \le T$ is called as the duty interval.
- If we define the duty cycle, δ' as

$$\delta' = \frac{\text{duty}-\text{interval}}{T} = \frac{T-\delta T}{T} = 1-\delta \qquad (3.21)$$

- Note that δ - duty cycle of the switch, whereas δ' – duty cycle of the chopper.

$$V_A = \frac{1}{T}\int_0^T v_a dt = \frac{1}{T}\int_{\delta T}^T V_s dt = \delta' V_s \qquad (3.22)$$

$$V_s = \frac{V_A}{\delta'} = \frac{V_A}{1-\delta} \Rightarrow (V_A \le V_s \le \infty) \; for \; 0 \le \delta \le 1.$$

- The armature current, I_A is given by

$$I_A = \frac{\delta' V_s - E_A}{R_A} < 0 \qquad (3.23)$$

- Since the armature current, I_A is negative it gives rise to braking torque.

- The torque-speed characteristic is represented by the following equation

$$\omega_m = \frac{\delta' V_s}{k_e \phi} - \frac{R_a}{(k_e \phi)^2} T \qquad (3.24)$$

$$\omega_m = \frac{\delta' V_s}{k_e \phi} - \frac{R_a}{(k_e \phi)^2} T_{em} \quad (3.24)$$

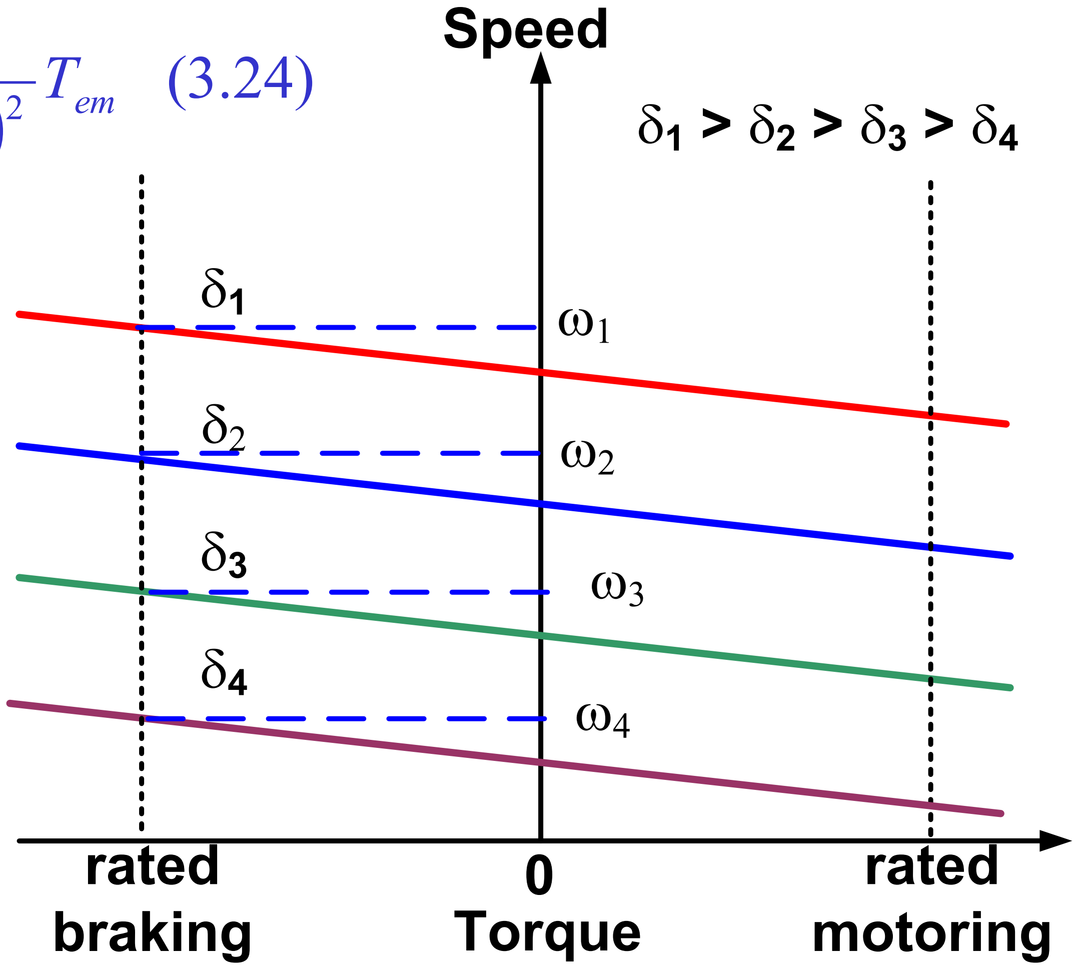


Figure 3.22: Torque-speed characteristics of dc motor by armature voltage control

Dynamic braking using chopper

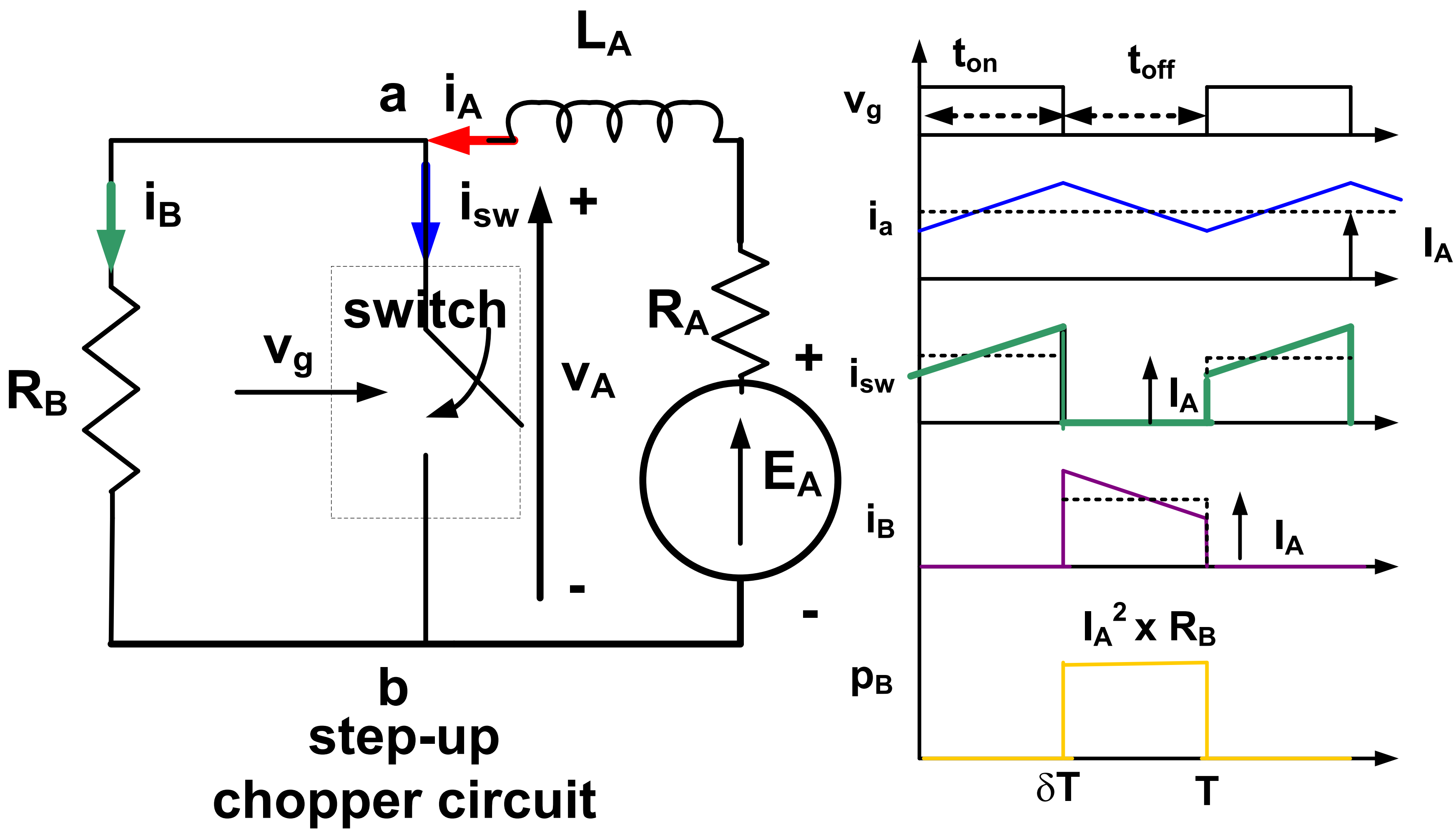


Figure 3.23: Dynamic braking of a separately excited dc motor

- By operating the switch periodically ON/OFF, step-less variation in the effective value of the resistance between the terminals "a" and "b“ is achieved.
- If ripples in the armature current is neglected then the energy consumed by the resistance R_B in one cycle of the chopper is given by

$$E_B = I_A^2 \; R_B (1-\delta) T \qquad (3.25)$$

- Thus, the average power consumed by R_B is

$$P_B = \frac{E_B}{T} = I_A^2 R_B (1-\delta) \qquad (3.26)$$

- Therefore, the effective value of the resistance between the terminals “a” and “b” is

$$R_{effc.} = \frac{P_B}{I_A^2} = R_B(1-\delta) \qquad (3.27)$$

- By varying the duty ratio, δ ($0 \le \delta \le 1$) the effective resistance, $R_{effc.}$ can be varied in a step-less manner in the range 0 to R_B.

- Thus, the braking torque can be maintained at its maximum value irrespective of the drive operating speed.

Example 2: A 250 V, 500 rpm dc separately excited motor has an armature resistance of 0.13 Ω and takes an armature current of 60 A when delivering rated torque at rated flux. The flux is maintained constant at its rated value throughout the operation.

Determine the speed at which braking torque equal in magnitude to the full-load torque is developed while regeneratively braking at normal terminal voltage.

Solution: The parameters given are:

$R_a = 0.13\ \Omega$; $V_{a,rated} = 250$ V ; $N_{rated} = 500$ rpm; $I_{a,rated} = 60.0$ A

At rated condition we have $k_E = 4.62\ \left({}^{V}/_{(rad/s)}\right)$

- At rated braking torque, we have

$$N = 532.2\ rpm$$

Composite Braking for DC motors

- When electrical energy is generated with regenerative braking, it should be fed back to the source or supplied to other loads connected.
- However, a source except for batteries cannot store electrical energy and hence there must be some other loads to consume this generated energy.
- If other loads are not available to consume the regenerated energy then dynamic braking facility must be provided to dissipate the regenerated energy.
- The combination of regenerative and dynamic braking is called composite braking as shown in Fig. 3.24(a) and is widely used for dc traction application.

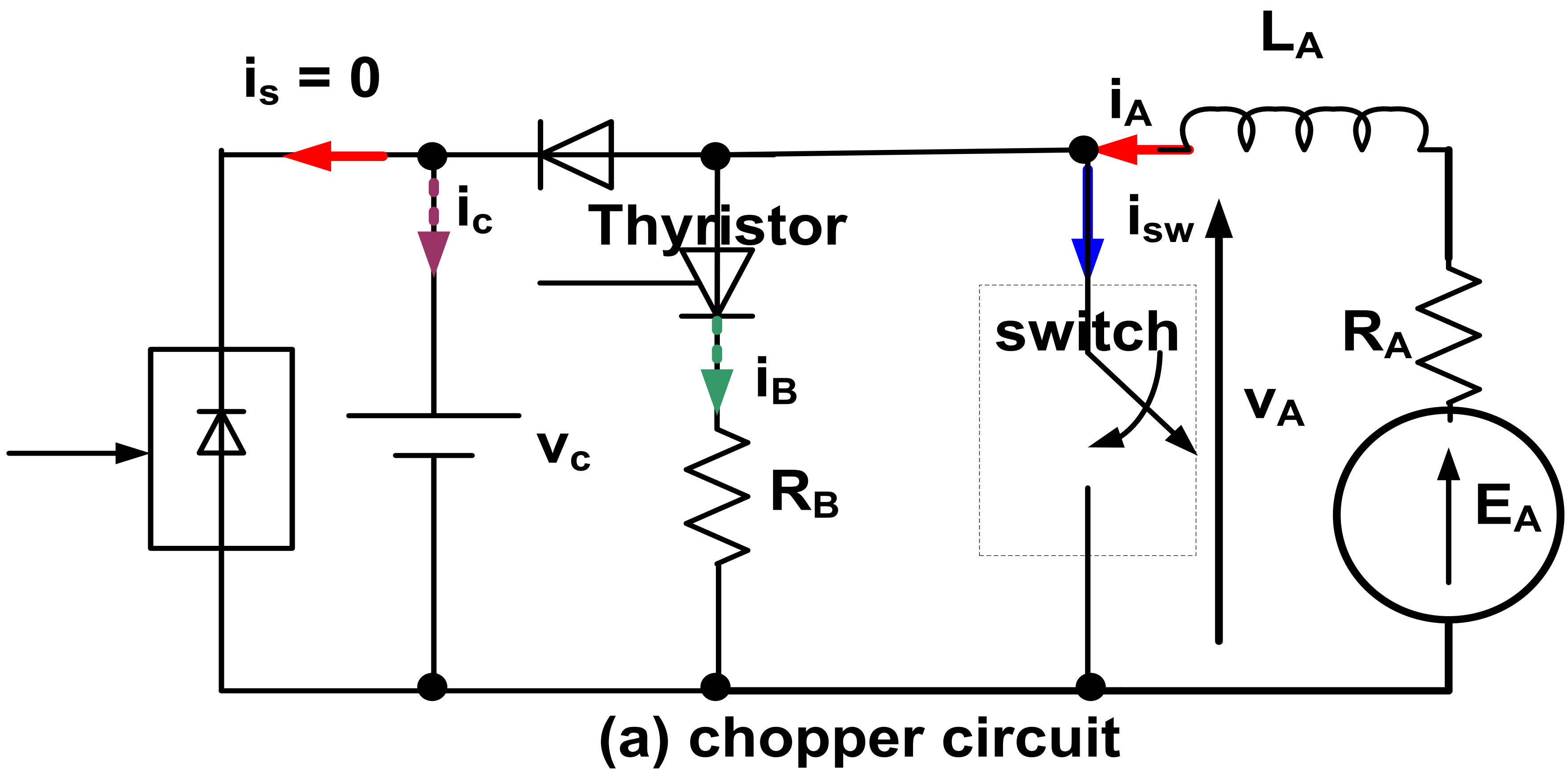
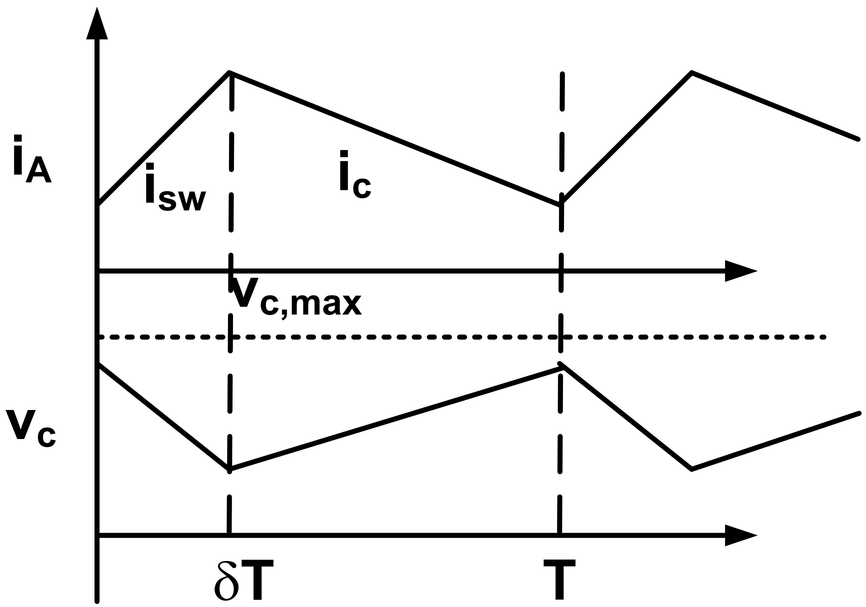
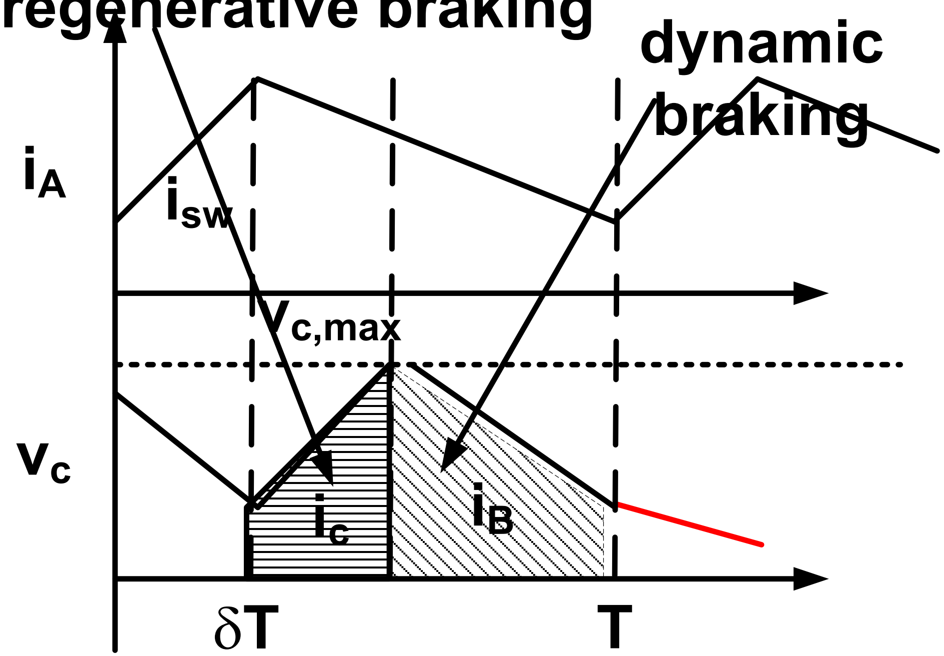


Figure 3.24(a) Composite braking for dc motor



(b) with regenerative braking



(c) with composite braking

Figure 3.24: Composite braking for dc motor

Class-C: Two-quadrant Chopper

- For two-quadrant operation consisting of forward motoring and forward braking it is necessary that the voltage should have a positive polarity and current can flow in either direction.

- The following points can be considered for understanding of Class-C chopper operation:
  - Discontinuous conduction does not occur at all, irrespective of its frequency of operation.

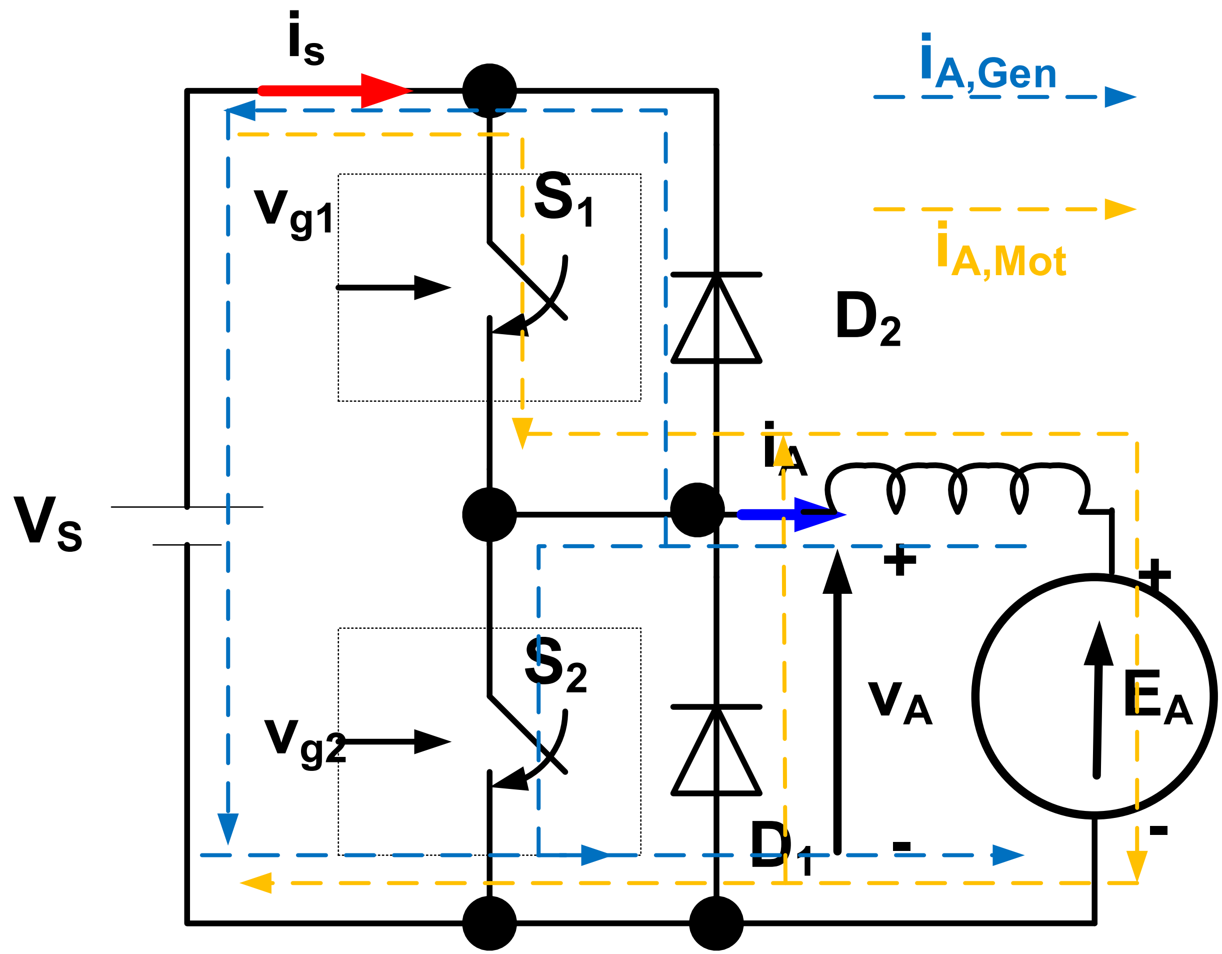


Figure 3.25: Forward motoring and braking control using class C two-quadrant chopper (a) chopper circuit and (b) wave forms

- Since there is no discontinuous conduction, the armature current flows continuously and hence the supply voltage is connected to the armature during the interval $0 \leq t \leq \delta T$ and the armature terminals are shorted during the interval $\delta T \leq t \leq T$.
- During the interval $0 \leq t \leq \delta T$, the positive armature current is carried by S_1 and the negative armature current by D_2. The source current, i_S flows only during this interval and is equal to i_a.

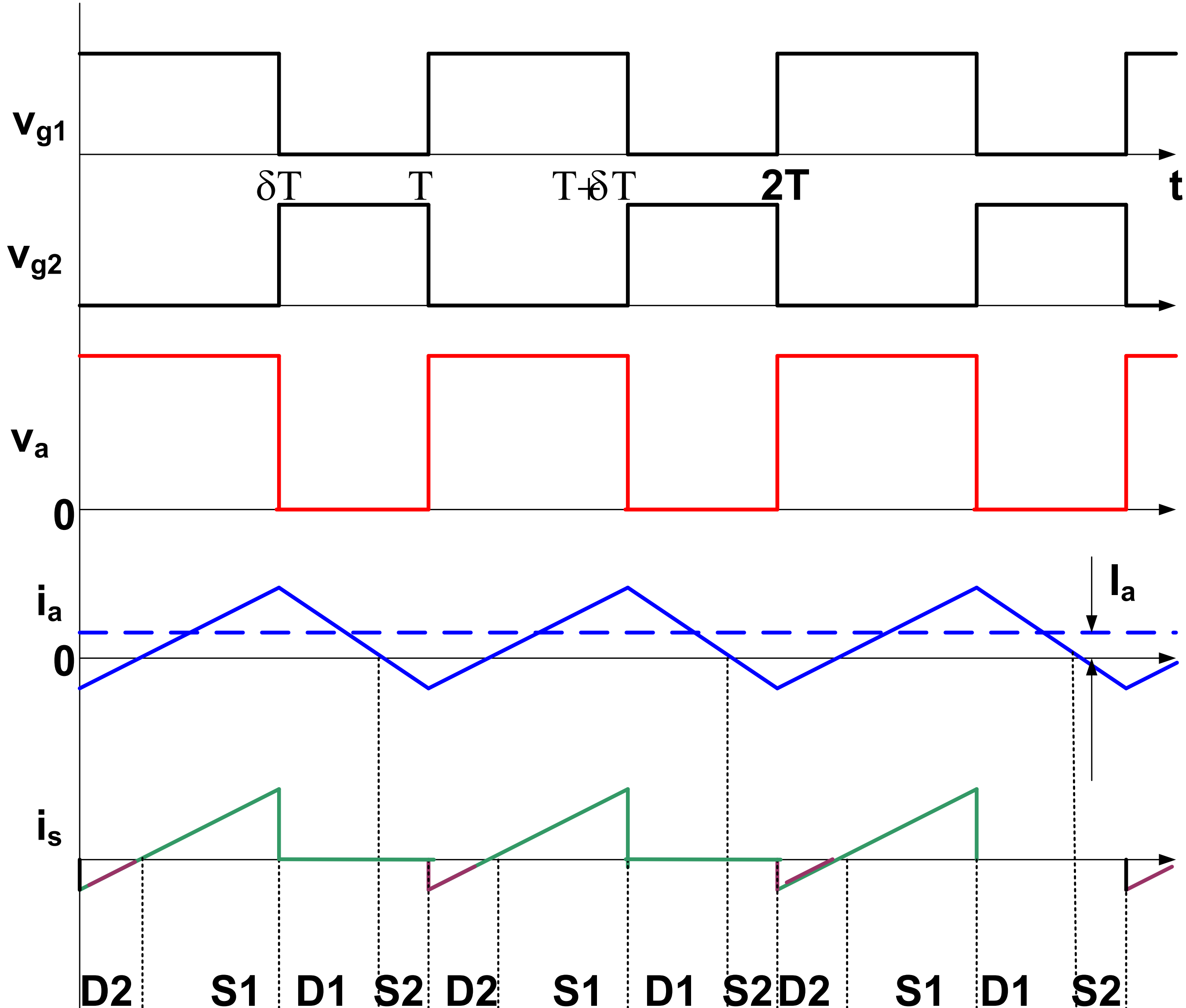


Figure 3.25: (b) wave forms under forward motoring operation

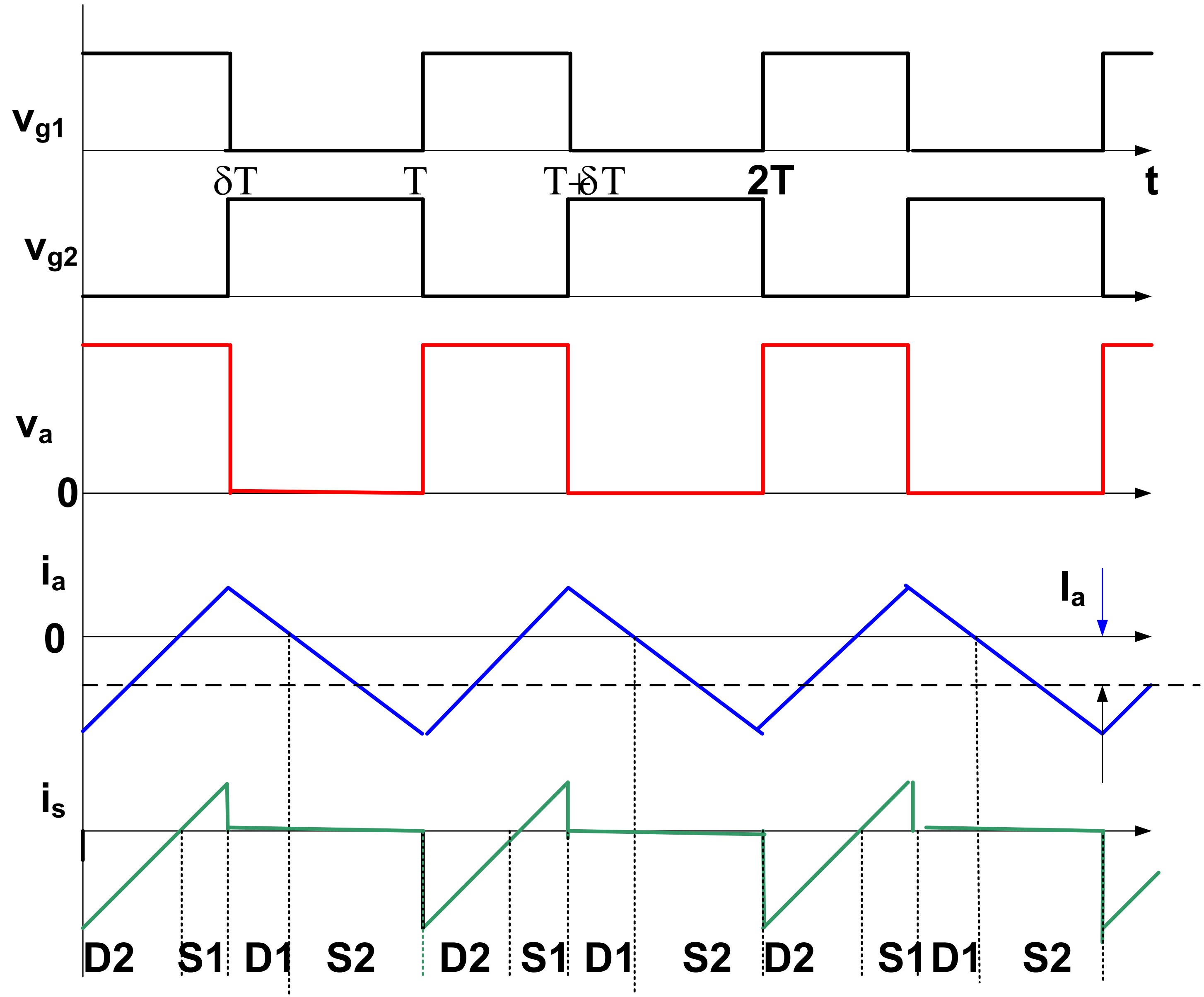


Figure 3.25: (c) wave forms under forward braking operation

- From the motor terminal voltage waveforms

$$V_A = \delta V_S \Rightarrow I_A = \frac{\delta V_s - E_A}{R_a} \qquad (3.28)$$

- This above equation for I_A tells that
  - <u>motoring operations</u> take place when $V_A > E_A$, ($I_A > 0$),
  - <u>braking operations</u> take place when $V_A < E_A$, ($I_A < 0$) and
  - <u>no-load operation</u> is obtained when $V_A = E_A$, ($I_A = 0$).

Example 3: A 230 V, 500 rpm, 90 A separately excited dc motor has the armature resistance and inductance of 0.115 Ω and 11 mH respectively. The motor is controlled by a class-C two quadrant chopper operating with a source voltage of 230 V and a frequency of 400 Hz.

Calculate the motor speed for a motoring operation at D = 0.5, and rated torque.

Solution: The parameters given are:

$V_{a,rated}$ = 230 V ; N_{rated} = 500 rpm; $I_{a,rated}$ = 90.0 A

R_a = 0.115 Ω; L_a = 11.0 mH; f_s = 400 Hz;

At rated condition we have

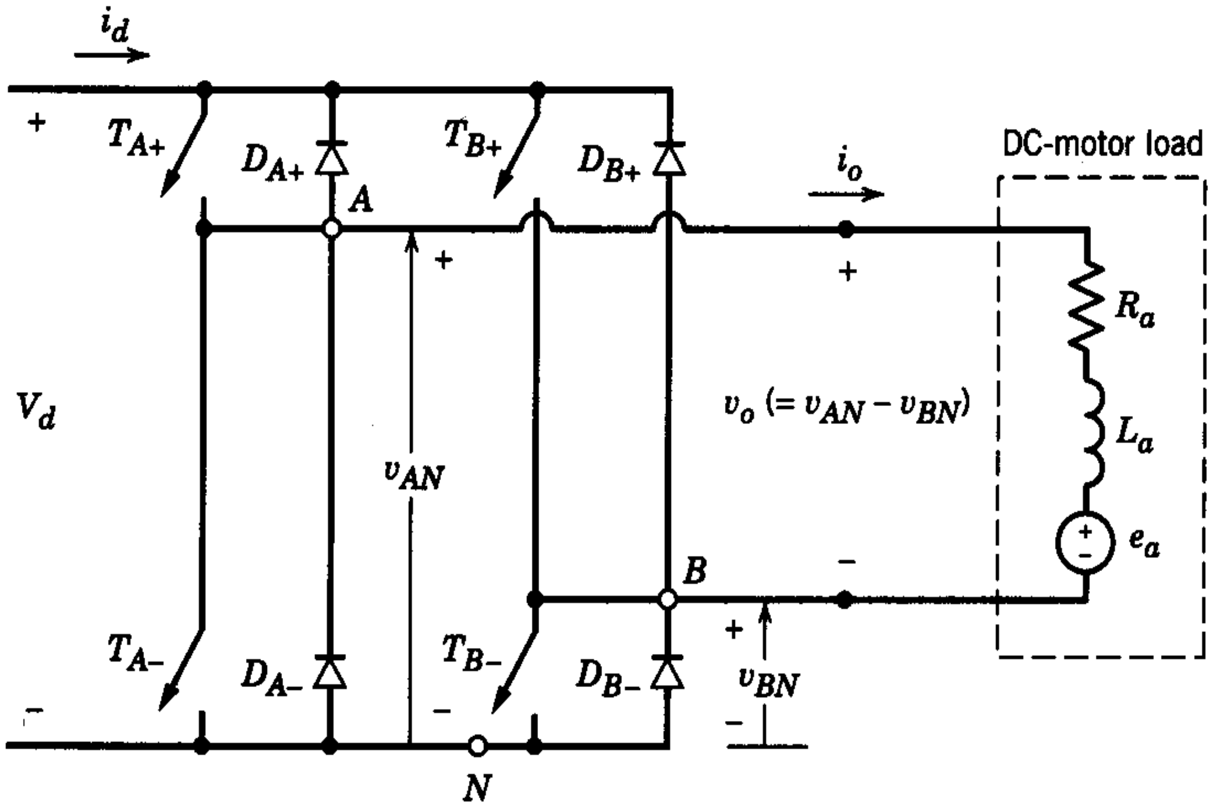
$$k_E = 4.2\ v/(\frac{rad}{s})$$

- At rated motoring torque and D = 0.5, we have

$$N = 238.2\ rpm$$

Full-bridge DC-DC Converter

- Three distinct applications of full-bridge DC-DC switched-mode power converters:
  - dc motor drives;
  - dc-ac (sine-wave) conversion for single-phase UPS;
  - dc-ac (high intermediate frequency) conversion in switched-mode transformer isolated dc power supplies
- The full-bridge converter as shown in Fig.3.36, has a fixed input voltage, V_d, the output voltage, V_o can be varied in magnitude as well as polarity, the magnitude and polarity of the output current, I_o can also be controlled.
- The operating point of the full-bridge dc-dc converter can be anywhere on the four-quadrants of the $v_o - i_o$ plane and therefore the power flow can be bidirectional.



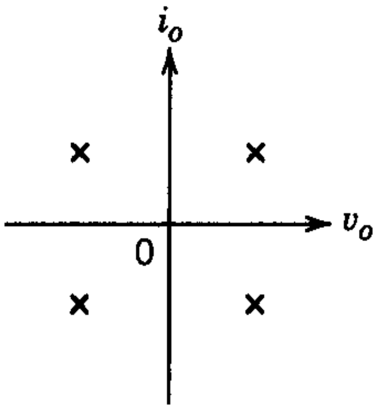


Fig. 3.36 Full-bridge dc–dc converter.

- The presence of the anti-parallel diode across the switch needs to clarify the position of the switch i.e. whether in on-state and conducting-state e.g. if the gating signal is given to switch T_{A+}, it may conduct or it may not conduct and that depends on the output current, i_o. If $i_o > 0$ then the switch T_{A+} will conduct and is said to be in conducting-state otherwise not.
- For leg-A,

$$v_{AN} = V_d \qquad if\, T_{A+} is\ on\ and\ T_{A-}\ is\ off$$

$$v_{AN} = 0 \qquad if\ T_{A-}\ is\ on\ and\ T_{A+}\ is\ off$$

$$V_{AN} = \frac{V_d \times t_{on} + 0 \times t_{off}}{T_s} = V_d \times d_{T_{A+}}$$

$$V_{BN} = V_d \times d_{T_{B+}}$$

$$V_o = V_{AN} - V_{BN}$$

- PWM with bipolar voltage switching –
- A triangular waveform, v_{tri} is used for comparison with $v_{control}$.
- (T_{A+} & T_{B-}) and (T_{A-} & T_{B+}) are considered as pairs and are switched on or off simultaneously.
- When $v_{control} > v_{tri}$ then (T_{A+} & T_{B-}) switch pair is turned-on otherwise the pair (T_{A-} & T_{B+}) is turned on.

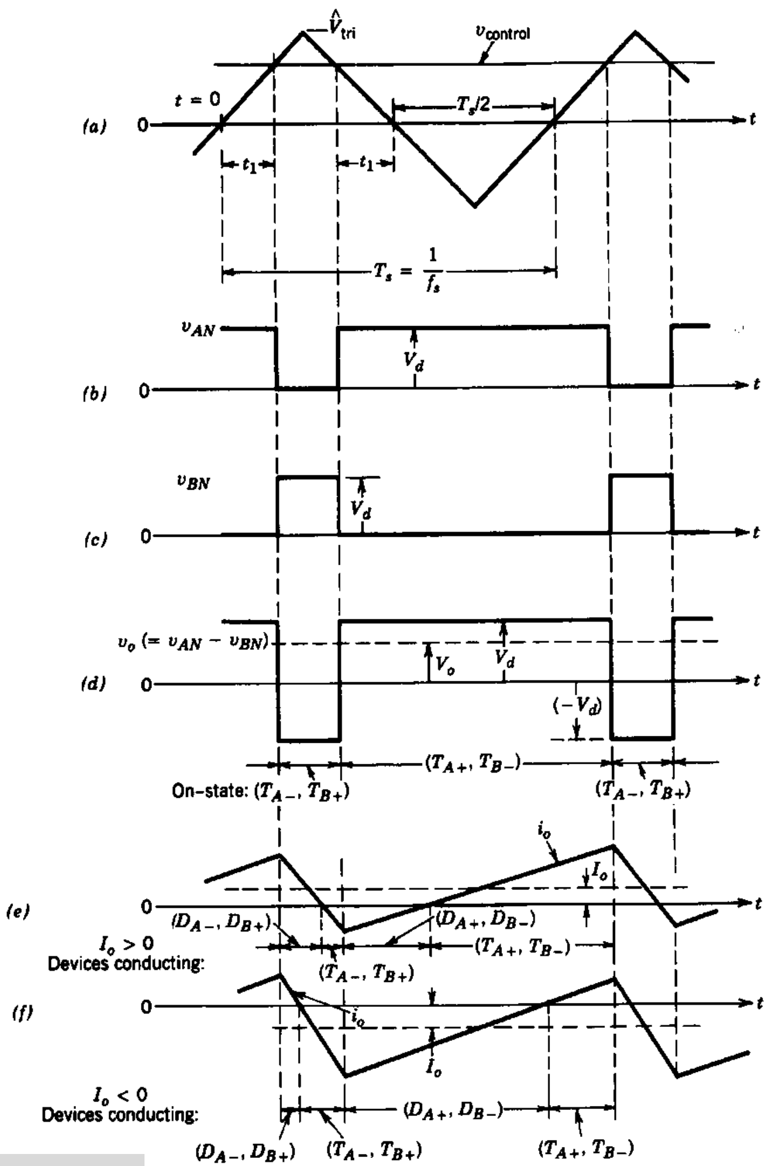


Figure 3.37 PWM with bipolar voltage switching.

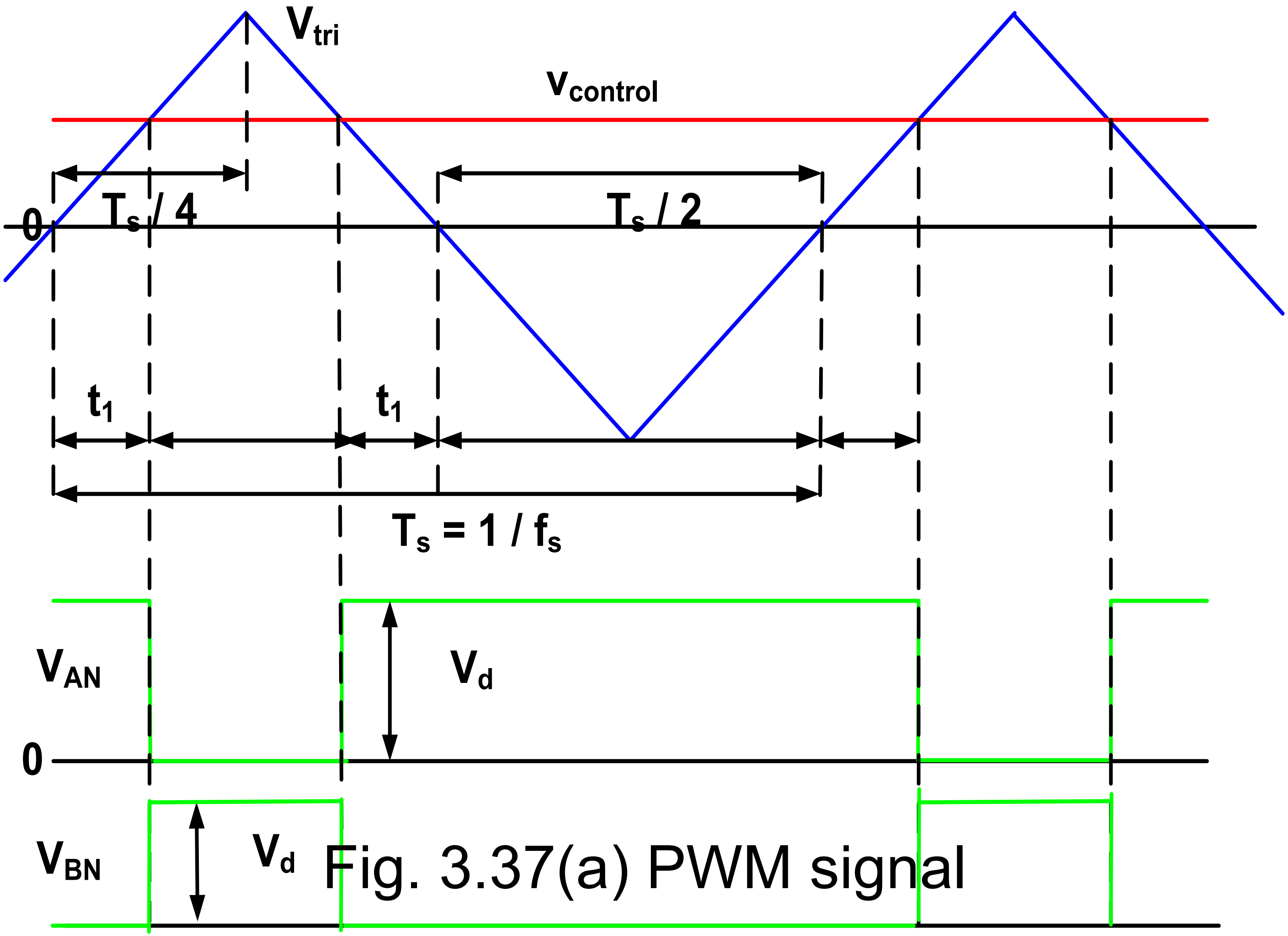


Fig. 3.37(a) PWM signal

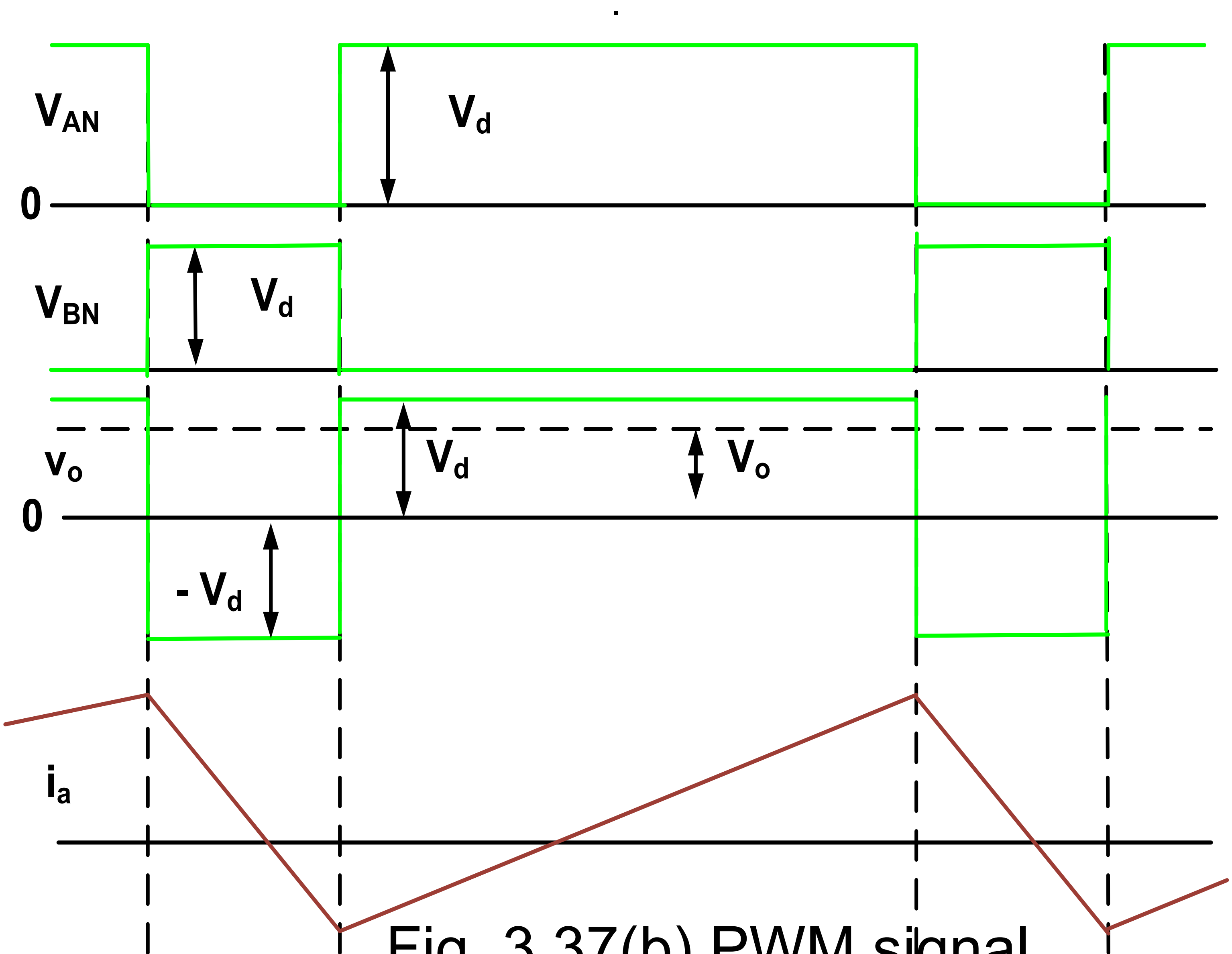


Fig. 3.37(b) PWM signal

- We have

$$v_{tri} = \hat{V}_{tri} \frac{t}{T_s/4} \quad \text{for} \qquad 0 < t < \frac{T_s}{4}$$

$$\text{At } t = t_1, \qquad v_{tri} = v_{control}, \quad v_{control} = \hat{V}_{tri} \frac{t_1}{T_s/4} \Rightarrow t_1 = \frac{v_{control}}{\hat{V}_{tri}} \frac{T_s}{4}$$

$$\text{t}_{\text{on}} \text{ for switch pair 1} (\text{T}_{\text{A}+}, T_{B-}) \text{ is} \qquad \text{t}_{\text{on}} = 2t_1 + \frac{T_s}{2}$$

$$D_1 = \frac{t_{on}}{T_s} = \frac{1}{2}\left(1 + \frac{v_{control}}{\hat{V}_{tri}}\right)$$

$$D_2 = 1 - D_1 \qquad \text{for switch pair2} (\text{T}_{\text{B}+}, T_{A-})$$

$$V_o = V_{AN} - V_{BN} = D_1 V_d - D_2 V_d = (2D_1 - 1)V_d$$

Substituting for D_1 we have

$$\text{V}_\text{o} = (2D_1 - 1)V_d = \frac{V_d}{\hat{V}_{tri}} v_{control} = k v_{control} \quad \text{where k} = \frac{V_d}{\hat{V}_{tri}} = \text{constant}$$

- The average output voltage V_o varies linearly with the control voltage, $v_{control}$ just like in a linear amplifier.
- The output voltage, v_o jumps from $+V_d$ to $-V_d$ and that is why it is called as bipolar voltage-switching PWM scheme.
- Note that as $0 < D_1 < 1$, we have $-V_d < v_0 < +V_d$.
- $i_o > 0$ or $i_o < 0$
- Bidirectional power flow is possible.

Class E - Four-quadrant Chopper

- This chopper can be considered to be a combination of two class-C two-quadrant choppers.
- One class C chopper consisting of S_1, S_4 and S_2 provides operation in quadrants I and II i.e. motor voltage is positive and current can take either polarity.
- Similarly, the combination of switches S_3, S_4 and S_2 provides operation in quadrants III and IV i.e. motor voltage is negative and current can take either polarity.

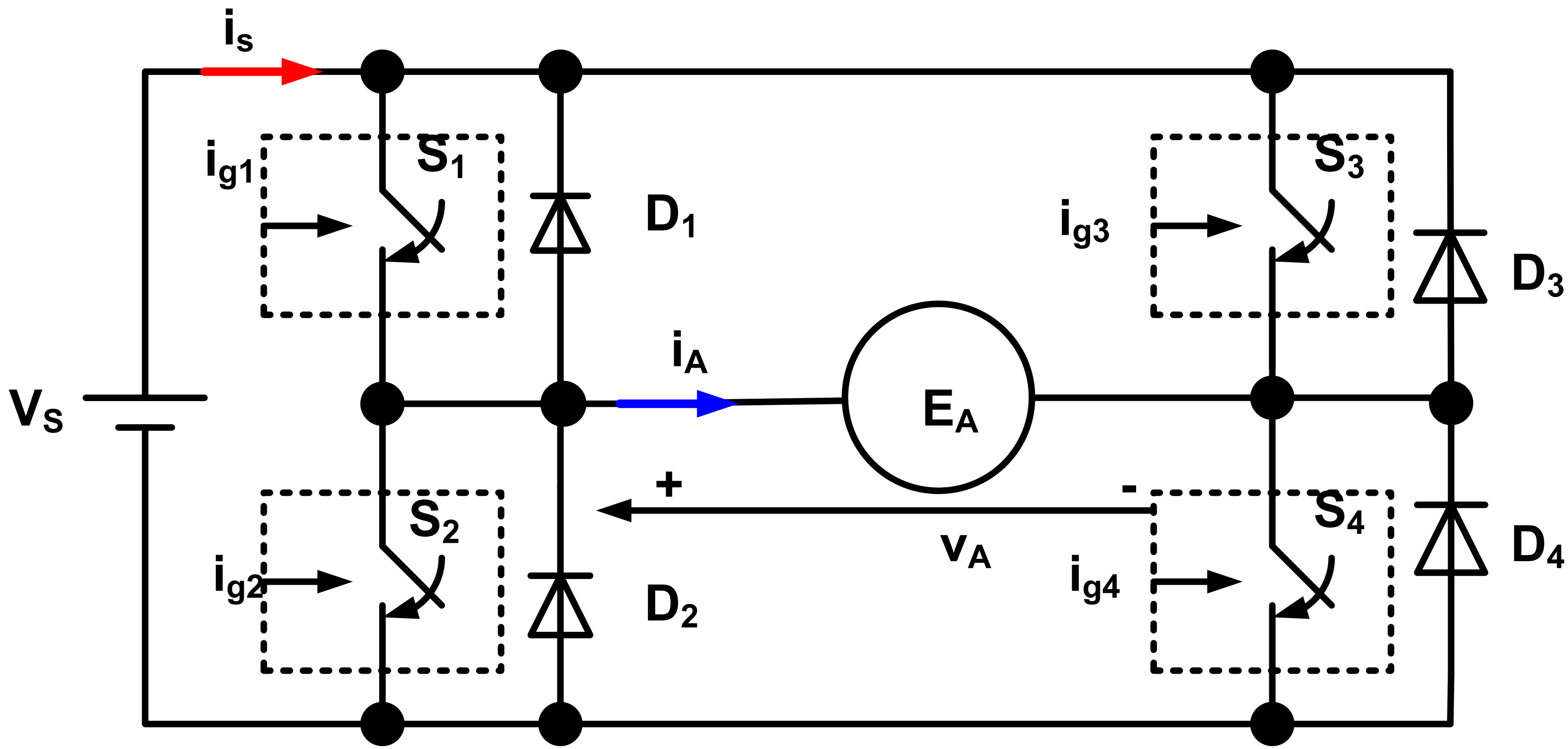


Figure 3.26: Class E four-quadrant chopper

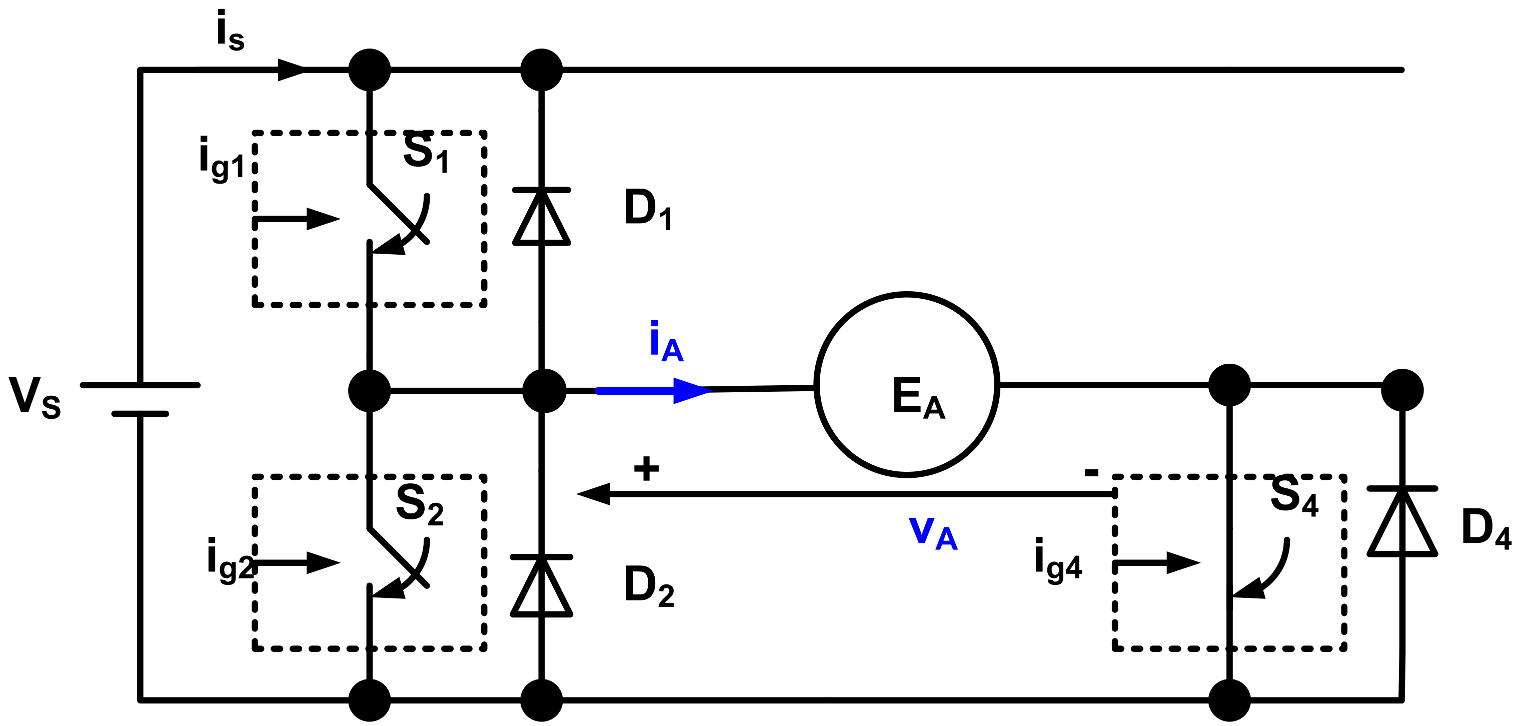


Figure 3.26(a): Four-quadrant chopper operating in quadrants I and II only.

- $v_A \geq 0$ and $i_A > 0$ or $i_A < 0$

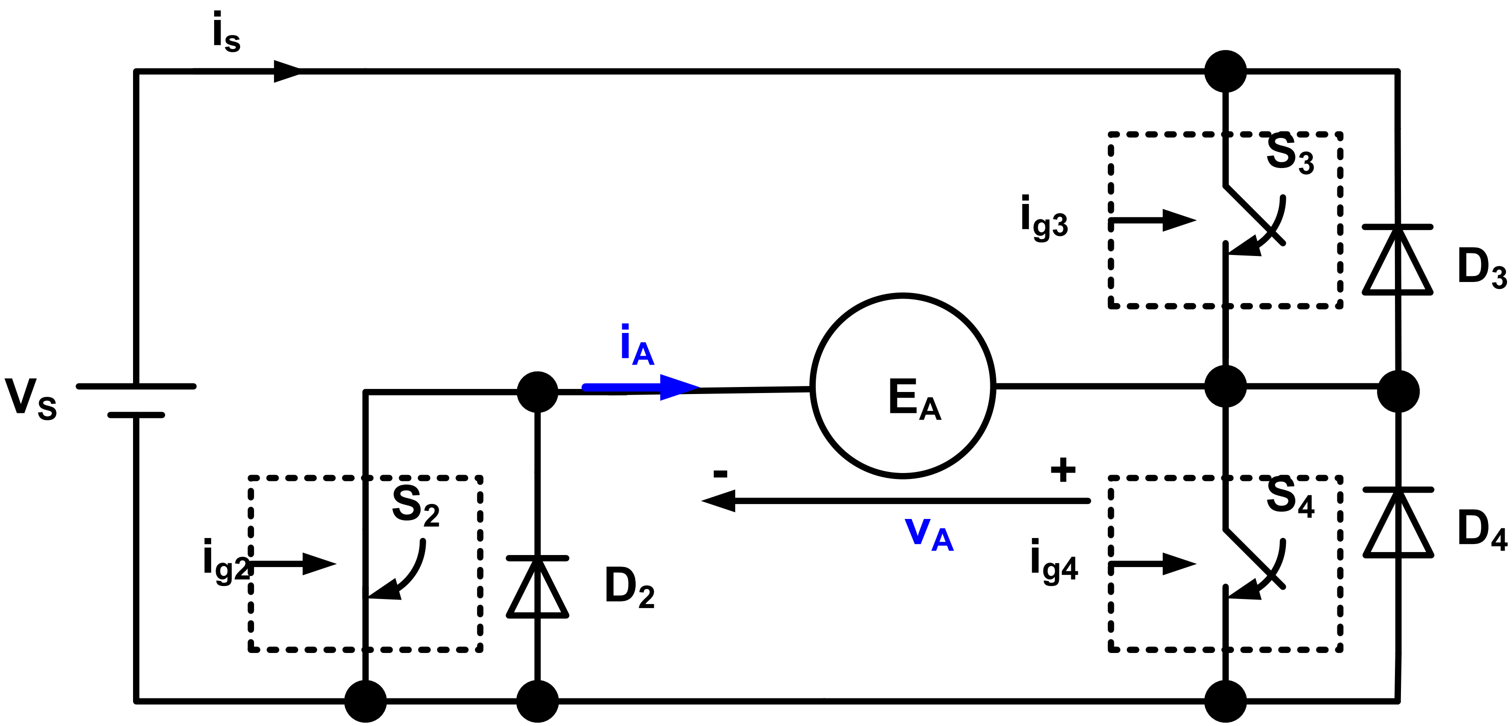


Figure 3.26(b): Four-quadrant chopper operating in quadrants III and IV only.

- $v_A \leq 0$ and $i_A > 0$ or $i_A < 0$

Closed-loop Speed Control of DC Drives

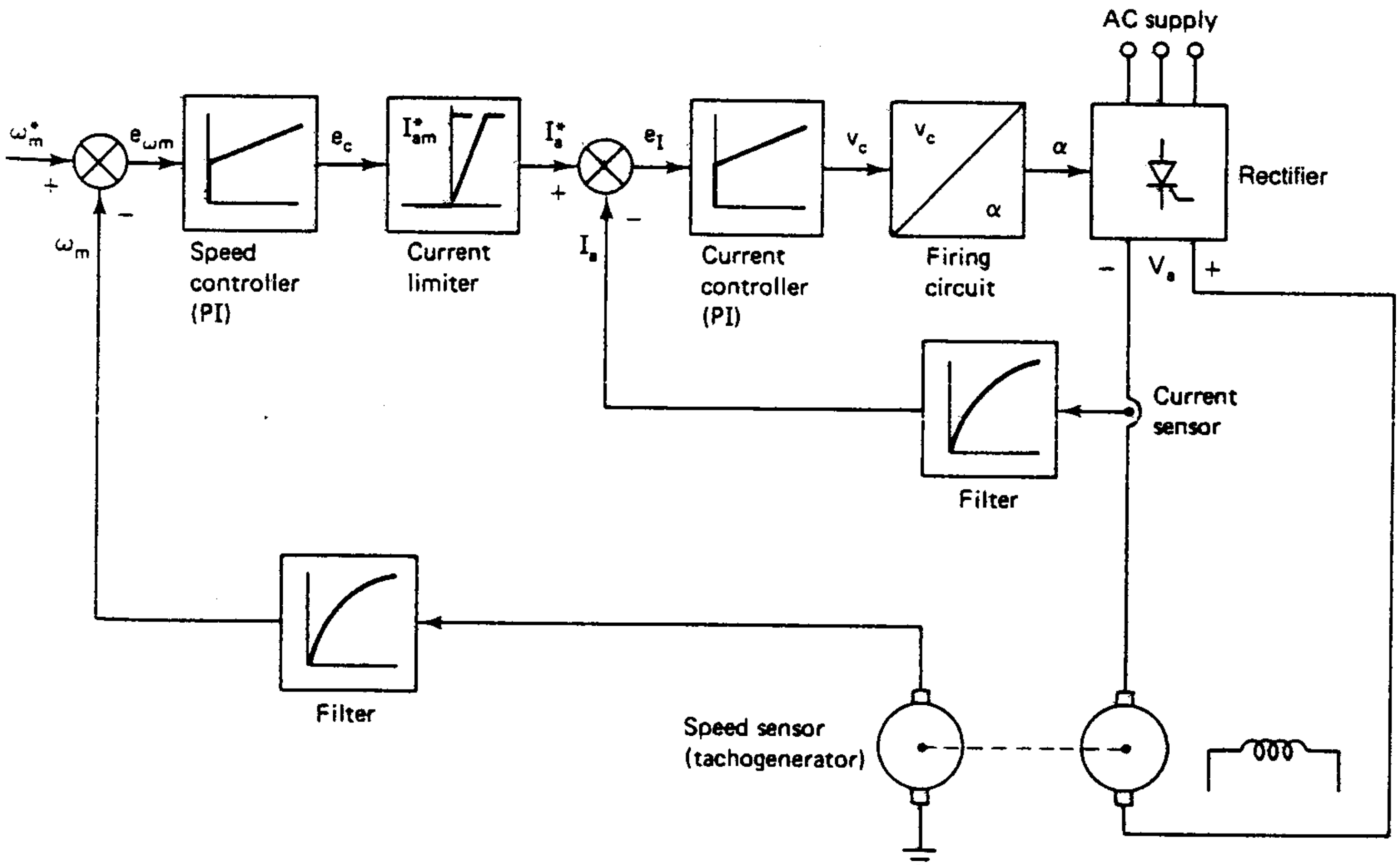


Figure 3.27: One-quadrant closed-loop speed control

Summary

- DC drive is the most simplest form of electric drive to control due to its decoupled nature of armature and field MMFs.
- DC drives are gradually being replaced by AC drives due to maintenance related problems.
- Speed control of DC drive can be carried out by (a) armature voltage control and (b) field-flux control.
- Armature voltage control is preferred for speed control below speed and field flux-control is preferred for speeds above the base speed.

- Armature voltage control can be carried out using (a) Phase-controlled converter or (b) Chopper converter.
- A single, phase controlled converter can provide operation in quadrant-I and quadrant-IV.
- For four-quadrant operation a dual-converter is used.
- Phase-controlled converter has disadvantages such as: poor power-factor at supply side, ripples in armature current etc.

- Chopper-fed DC motor drive has several advantages over phase-controlled converter and is preferred.
- A two-quadrant chopper eliminates the discontinuous mode of operation and provides operation in quadrant-I and quadrant-II, which is normally required for forward operation.
- A four-quadrant chopper provides operation in either of the four-quadrants and are typically used for high-performance servo drive applications such as Computer Numerical Controlled (CNC) machines.

References

1. Electric Drives – An Integrative Approach – Ned Mohan – Chapters 4 and 7.
2. Power Semiconductor Controlled Drives – G K Dubey – Chapters 2, 3, 4 and 5.