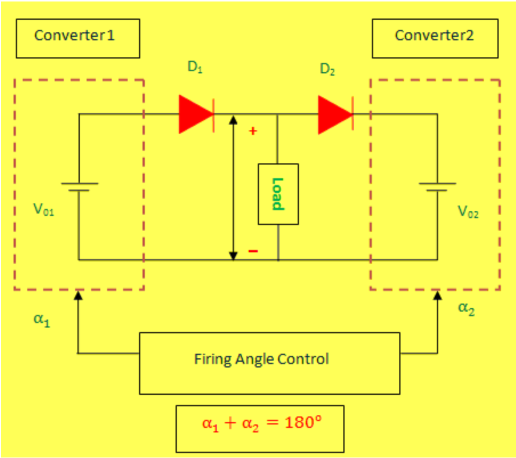
ÇİFT DÖNÜŞTÜRÜCÜLER

Çoğunlukla değişken hızlı sürücülerde bulunan elektrikli bir cihazdır. İleri dönüştürücü ve ters dönüştürcü tarafından AC düzeltmesinden polarite DC'yi almak için bir güç elektroniği kontrol sistemidir. Çift dönüştürücüde, iki dönüştürücü arka arkaya birbirine bağlanır.

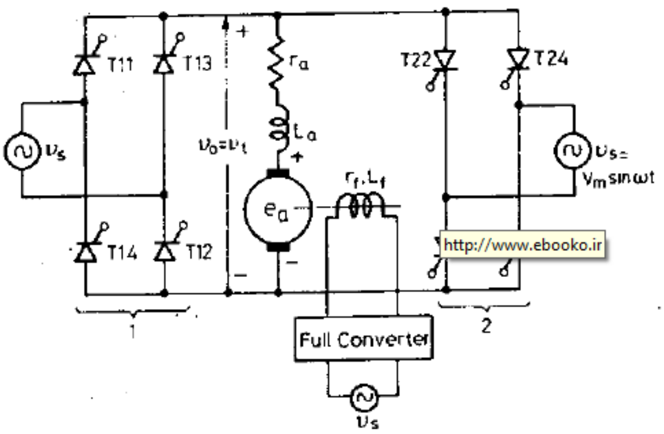
Köprülerden biri doğrultucu olarak çalışır (AC'yi DC'ye dönüştürür), diğer yarım köprü inverter olarak çalışır (DC'yi AC'ye dönüştürür) ve yaygın olarak bir DC yüküne bağlanır. Burada iki dönüştürme işlemi aynı anda gerçekleşir, bu nedenle çift dönüştürücü olarak adlandırılır. Çift dönüştürücü dört bölgeli çalışma sağlayabilir.

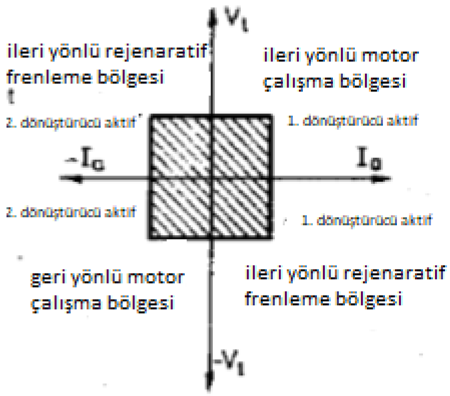


Çift dönüştürücüler idealdir, yani herhangi bir dalgalanma içermeyen saf DC çıkış terminalleri üretirler.Her iki dönüştürücünün, bir diyot ile seri olarak bağlanan kontrol edilebilir bir doğrudan voltaj kaynağı olduğu varsayılır.Burada Diyot D1 ve D2, dönüştürücülerin tek yönlü akım akış özelliklerini temsil eder. Bununla birlikte, akımın yönü herhangi bir şekilde olabilir. Dönüştürücü 1'in ortalama çıkış voltajının V01 ve dönüştürücü 2'nin V02 olduğunu varsayalım. İki dönüştürücünün çıkış voltajını aynı polarite ve büyüklükte yapmak için tristörlerin tetikleme açıları kontrol edilmelidir.

TEK FAZLI ÇİFT YÖNLÜ DÖNÜŞTÜRÜCÜ

Bu tip dönüştürücünün kaynağı tek fazlı besleme olacaktır. Bu dönüştürücüde iki tane birbirine ters paralel baglı iki dönüştürcüden oluşur. Bu uygulama 15 KW kadar olan dc motor sürme uygulamalarında kullanılır. Dönüştürücünün dolaşım dışı çalışma modunda olduğunu düşünün. Birinci dönüştrücü doğrultucu olarak çalışır. Alternatif akım doğru akıma dönüştürülür daha sonra filtre uygulanarak yüke verilir.





1 nolu dönüştürücü için $Vt = \frac{2\,Vm}{\pi}\, cos\alpha_1 \qquad 0 \le \alpha_1 \le \pi$

2 nolu dönüştürücü için $Vt = \frac{2\,Vm}{\pi}\, cos\alpha_2 \qquad 0 \le \alpha_2 \le \pi$

$\alpha_1 + \alpha_2 = \pi$

- 1 nolu dönüştürücüde 1. bölgede ileri yönlü motor çalışma sağlanır $\alpha_1 < 90°$ olmalıdır
- 1 nolu dönüştürücüde 4. Bölgede ileri yönlü rejeneratif frenleme modunda çalışma sağlanır $\alpha_1 > 90°$ olmalıdır.
- 2 nolu dönüştürücüde 3. Bölgede geri yönlü motor çalışma sağlanır $\alpha_2 < 90°$ olmalıdır
- 2 nolu dönüştürücüde 2. Bölgede geri yönlü rejeneratif frenleme modunda çalışma sağlanır $\alpha_2 > 90°$ olmalıdır

3 FAZLI ÇİFT YÖNLÜ DÖNÜŞTÜRÜCÜLER

Yüksek güçlü uygulamalarda tek fazlı çift dönüştürücüler yerine üç fazlı çift dönüştürücülr kullanılır. Düşük THD, dengeli üç faz giriş akımıgibi avantajları vardır. Birbirine ters paralel bağlı iki adet üç fazlı tam kontrollü köprü dönüştürücüden oluşur. Dönüştürücülerin biri 3 fazlı AC kaynağı DC dönüştürür üç fazlı doğrultucu kullanılır. Dönüştürücünün yapısı tek fazlı çift dönüştürücü ile aynıdır. Üç fazlı doğrultucunun çıkışı filtreye beslenir ve filtrelendikten sonra saf DC yüke beslenir. Sonunda, yükten gelen besleme ters çevrilen son köprüye verilir.Diger dönüştürücü ise inverter olarak çalışır ve DC skımı 3 fazlı AC'ye dönüştürür.

1 nolu dönüştürücüde 1. Ve 4.bölgede çalışma sağlanır. 2 nolu dönüştürücüde 3. ve 2.bölgede çalışma sağlanır. Bu uygulamayı 2MW a kadar olan motor sürme uygulamalarında kullanbiliriz.

1 ve 2 nolu dönüştürücüler için ortalama çıkış voltajı;

$Vt = \frac{3\,Vml}{\pi}\, cos\alpha_1 \qquad 0 \le \alpha_1 \le \pi$

$$Vf = \frac{3\,Vml}{\pi}\, cos\alpha_1 \qquad 0 \le \alpha_f \le \pi$$

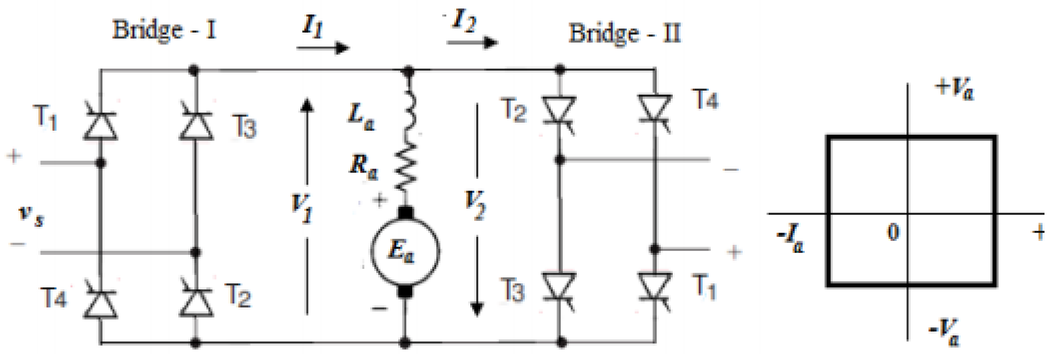
$\alpha_1 + \alpha_2 = \pi$

İki yönlü dönüştürcülerin kullanıldığı yerler;

- DC motorların yönü ve hız kontrolü.
- Tersinir DC'nin gerekli olduğu her yerde uygulanabilir.
- Endüstriyel değişken hızlı DC sürücüler.

13.2.4 Single-Phase Dual Converter Drives

In some industrial applications, d.c. motor may require to be operated in four quadrants without a switching changeover. In this case, duplication of power electronics converters is used. Fig.13.11 shows a simple dual converter drive circuit diagram which consists of two single-phase full bridge converters connected in inverse-parallel supplying a d.c motor. One bridge for one direction of motor current and the other bridge for the opposite direction of current. The controls are interlock to prevent their simultaneous operation to avoid short circuits on one another. Bridge-I provides operation in the first and fourth quadrants while bridge-II provides operation in second and third quadrants. Therefore, the dual converter is a four quadrant drive which allows four quadrant of machine operation without a switching changeover.



(a) (b)

Fig.13.11 Dual converter drive: (a) Circuit diagram, and (b) Quadrants of operation.

To illustrate how a speed reversal takes place, bridge-I has its firing signals removed; i_l falls to zero and after few milliseconds delay, bridge-II is fired. This drive is employed for motors of rating up to 15 kW. On the circuit of Fig.13.13, positive voltages are shown by the arrowheads, though in the equations, these voltages may have negative values. These equations are:

Bridge – I operating:

$$V_1 = V_{a(av)\,1} = \frac{2V_m}{\pi}\cos\alpha_1 = V_{do}\ \cos\alpha_1 = E_a + I_1\ R_a \qquad (13.29)$$

Bridge – II operating:

$$V_2 = V_{a(av)\,2} = -\left(\frac{2V_m}{\pi}\cos\alpha_2\right) = V_{do}\ \cos\alpha_2 = E_a - I_1\ R_a \qquad (13.30)$$

where

$$V_{do} = \frac{2V_m}{\pi}$$

Which is the output voltage of the converter when $\alpha = 0^\circ$.

Equations (13.29) and (13. 30) are shown as straight lines on Fig.13.12, the intersection of the machine and bridge characteristics giving the operating points.

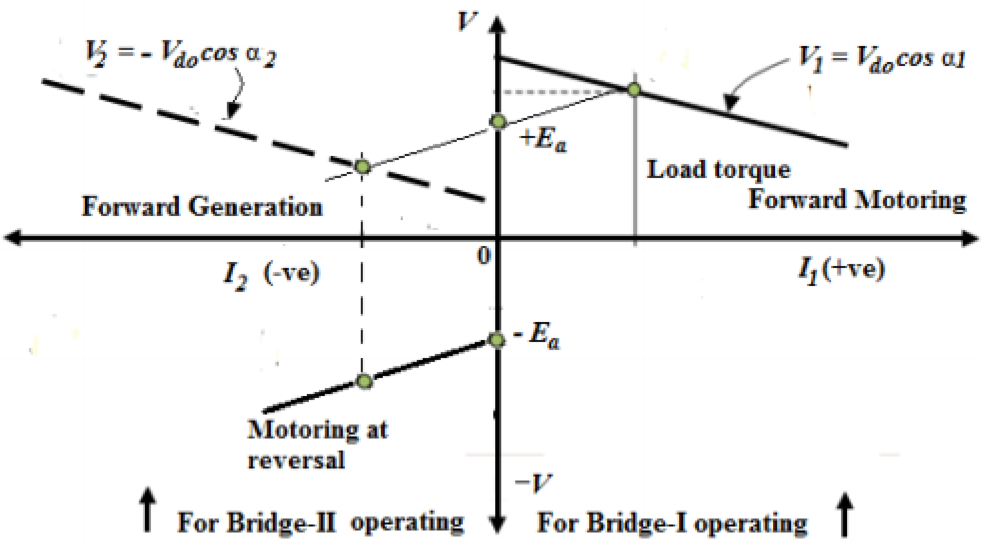


Fig.13.12 Dual converter.

Example 13.9

A d.c. separately-excited motor rated at 10 kW, 200 V is to be controlled by dual converter. The armature circuit resistance is 0.2 Ω and the machine constant $K_e\emptyset$ is 0.35 V/ rpm. For the following conditions, determine the firing angles of the converter, the back *emf* and the machine speed given that for the converter system V_{do} = 250 V. Neglect any losses in the converter circuit.

(a) Machine operates in a forward motoring mode at rated current and with terminal voltage of 200 V.

(b) Machine operates at forward generation mode at rated current and with terminal voltage of 200 V.

Solution

(a) For the motoring case,

$$V = V_{do}\ \cos\alpha \quad \rightarrow \quad 200 = 250\cos\alpha \quad \rightarrow \quad \cos\alpha = \frac{200}{250} = 0.8$$

$$\therefore\ \alpha = cos^{-1}(0.8) = 36.8°$$

The rated current of the machine $I_a = 10000 / 200 = 50$ A.

$$V = E_a + I_a\ R_a \quad \rightarrow \quad 200 = E_a + 50 \times 0.2$$

$$\therefore \quad E_a = 200 - 10 = 190\ \text{V}$$

The speed of the motor can be calculated as,

$$E_a = K_e \emptyset\, n \quad \rightarrow \quad n = \frac{E_a}{K_e \emptyset} = \frac{190}{0.35} = 542.85\ \text{rpm}$$

(b) For generating mode,

$$-V = V_{do}\ \cos\alpha \quad \rightarrow \quad -200 = 250\cos\alpha$$

$$\therefore\ \alpha = cos^{-1}(-0.8) = 143.13°$$

$$E_a = V + I_a\ R_a \quad \rightarrow \quad E_a = 200 + 50 \times 0.2 = 210\ \text{V}$$

$$E_a = K_e \emptyset\, n \quad \rightarrow \quad n = \frac{E_a}{K_e \emptyset} = \frac{210}{0.35} = 600\ \text{rpm}$$

13.3.4 Three-Phase Dual Converter Drive

Four-quadrant operation of a medium and large size d.c. motor drive (200-2000 hp) can be obtained by the three-phase dual converter shown in Fig.13.20. The average motor voltage is required to be equal for both converters, which required that the firing angles of the two sets of the thyristors should sum to 180°.

The armature voltage supplied by converter-1 (for continuous current operation) is

Bridge – I operating:

$$V_1 = V_{a(av)1} = \frac{3\sqrt{3}V_m}{\pi}\cos\alpha_1$$

$$= V_{do}\ \cos\alpha_1\ = E_a + I_1\ R_a \qquad (13.43)$$

Bridge – II operating:

$$V_2 = V_{a(av)2} = -\left(\frac{3\sqrt{3}V_m}{\pi}\cos\alpha_2\right)$$

$$= V_{do}\ \cos\alpha_2 = E_a - I_1\ R_a \qquad (13.44)$$

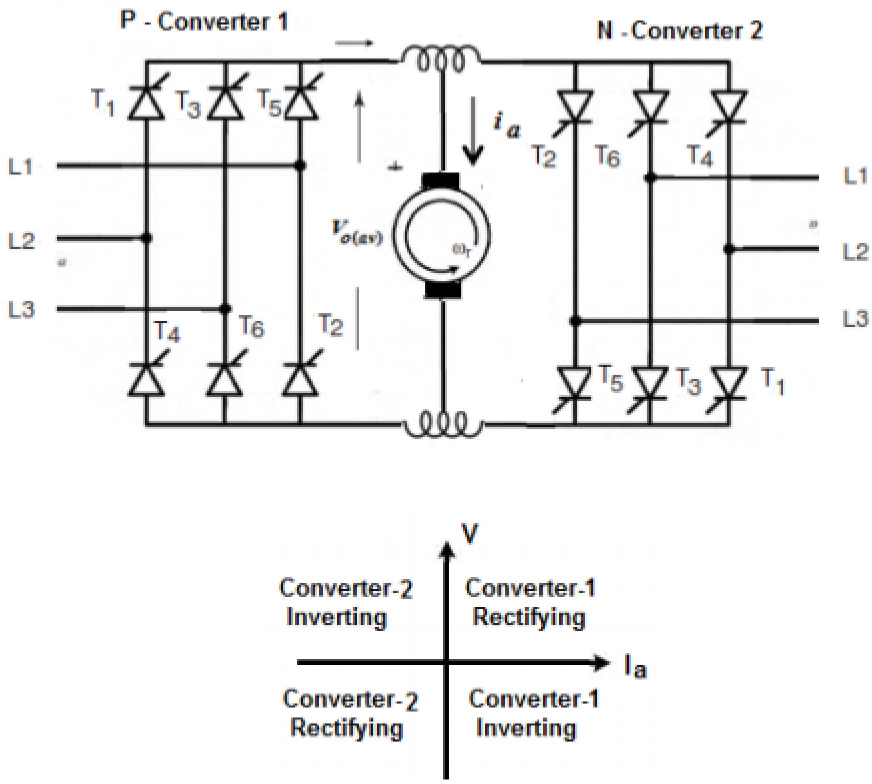


Fig.13.20 Four-quadrant three-phase d.c. drive.

where $$V_{do} = \frac{3\sqrt{3}V_m}{\pi}$$

and $\alpha_2 = \pi - \alpha_1$.

Two modes of operation can be achieved with this circuit:

(a) Circulating current operating mode:

Here, instantaneous values of circulating current are limited by use of reactors and mean level is controlled by current loop. Circulating current may be constant giving linear characteristic or it may be reduced to zero giving higher gain portion of overall characteristic.

Advantage: Continuous bridge current maintain armature current at all times, no discontinuity occurs.

Disadvantage: Presence of circulating current reduces efficiency.

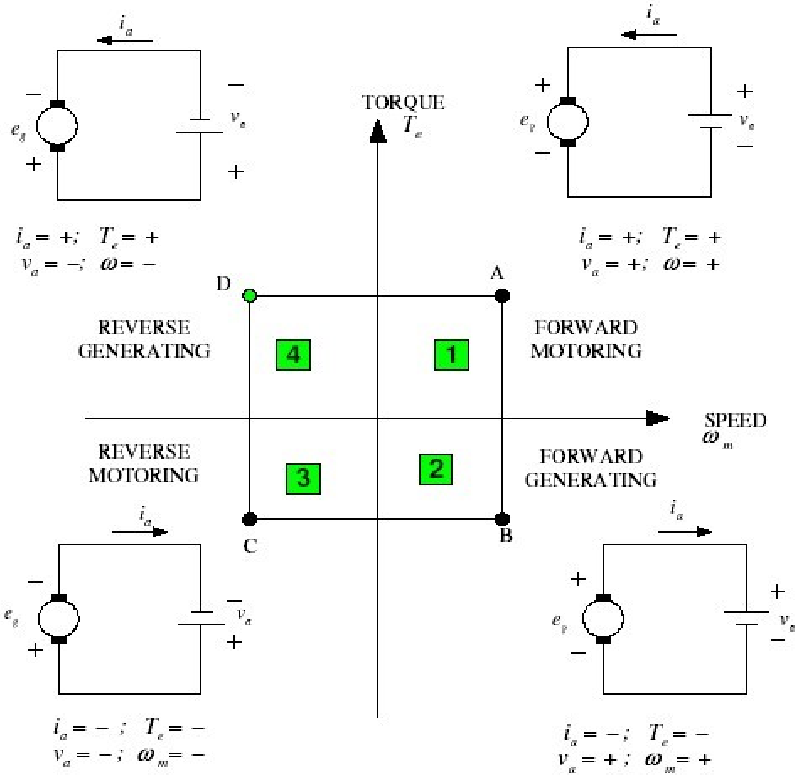
(b) Circulating current-free operation mode:

In this mode only one converter operates at a time. Logic used to prevent the two bridges being turn on at the same time. Reactors or inductors used to maintain continuous current down to acceptable low levels. Discontinuity occurs at zero and also a time delay (*ms*) introduced at the zero current level.

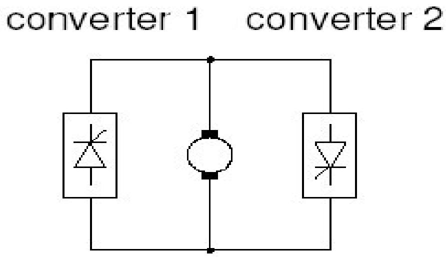
Advantage: Higher efficiency than circulating current schemes, hence used more widely.

Disadvantage: Dead time, discontinuity in zero current regions.

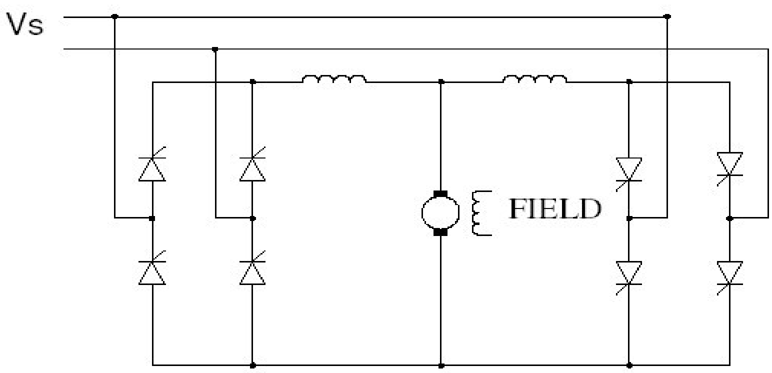
Four quadrant operation



Reversing using double converters



Principle of reversal



Practical circuit

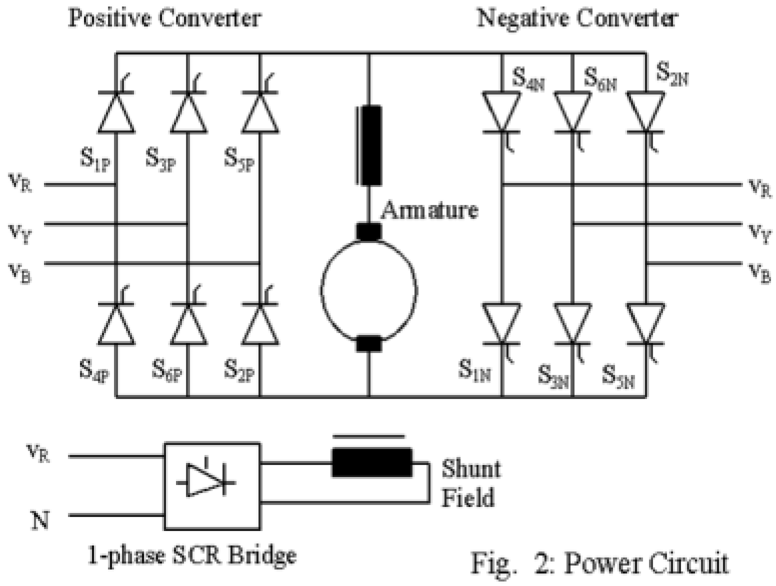
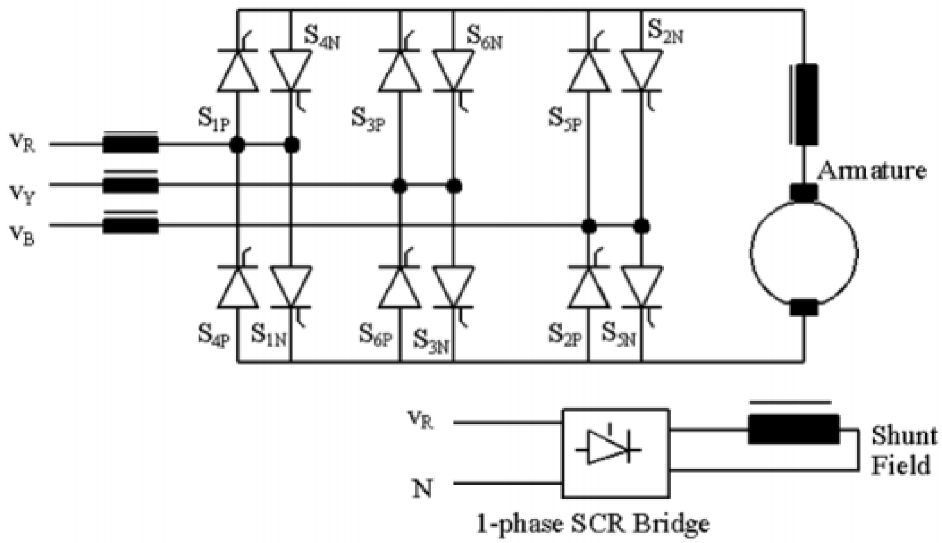


Fig. 2: Power Circuit

Dual converter fed DC motor

closed loop operation of DC motor with four quadrant operations



Dual converter fed DC separately excited motor

The operation of the circuit in the circulating-current free mode is not very much different from that described in the previous pages. In order to drive the motor in the forward direction, the positive converter is controlled.

To control the motor in the reverse direction, the negative converter is controlled. When the motor is to be changed fast from a high value to a low value in the forward direction, the conduction has to switch from the positive converter to the negative converter.

$$\frac{3\,U}{\pi} \times \mathrm{Cos}\ (\alpha_P) = -\ \frac{3\,U}{\pi} \times \mathrm{Cos}\ (\alpha_N) \quad (1)$$

$$\mathrm{Cos}\ (\alpha_P) = \mathrm{Cos}\ (\pi - \alpha_N) \quad (2)$$

$$\alpha_P + \alpha_N = \pi \quad (3)$$

In a dual-converter, the firing angles for the converter are changed according to equation (3). But it needs to be emphasized that only one converter operates at any instant.

When the speed of the motor is to be increased above its base speed, the voltage applied to the armature is kept at its nominal value and the phase-angle of the single phase bridge is varied such that the field current is set to a value below its nominal value.

If the nominal speed of the motor is 1500 rpm, then the maximum speed at which it can run cannot exceed a certain value, say 2000 rpm. Above this speed, the rotational stresses can affect the commutator and the motor can get damaged.

Four quadrant operation of DC Motors using Dual Converter:

As studied earlier, a fully controlled converter can provide a reversible output voltage and current in one direction. In terms of conventional Voltage-Current diagram shown in the figure below it can work in quadrants 1 and 4

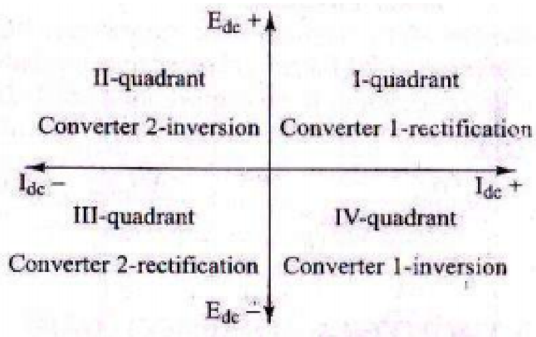
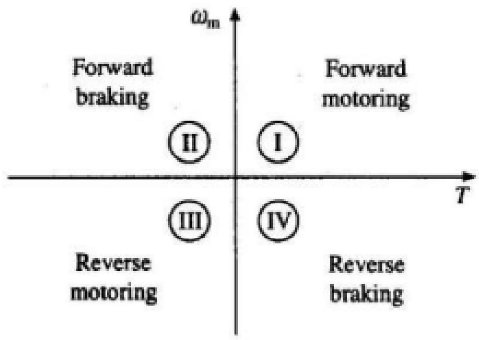


Fig: Voltage-Current Diagram

A converter can be used say in the first quadrant for motoring operation alone in one direction (and in the third quadrant for motoring operation in other direction) during steady state conditions. But during transient requirements such as starting and braking it would be required to operate in second (fourth) quadrant also to extract energy from the load for quick braking. (For faster system response)

If four quadrant operation of a motor is required i.e. reversible rotation and reversible torque in the Torque Speed Plane as shown in the figure below, a single converter along



with changeover contactors to reverse the armature or field connections along with firing angle changeover control [($0° \leq \alpha \leq 90°$)or($90° \leq \alpha \leq 180°$)] can be used so as to change the relationship between the converter voltage and the direction of rotation of the motor.(As explained in the introduction to Regenerative braking). Though they are practicable, a better performance can be achieved by going in for a Dual Converter.

A dual converter as shown in the figure below consists of two fully controlled converters connected in anti-parallel configuration across the same motor armature terminals. Since both voltage and current of either polarity can be obtained with a dual converter, it can support four quadrant operation of DC motors.

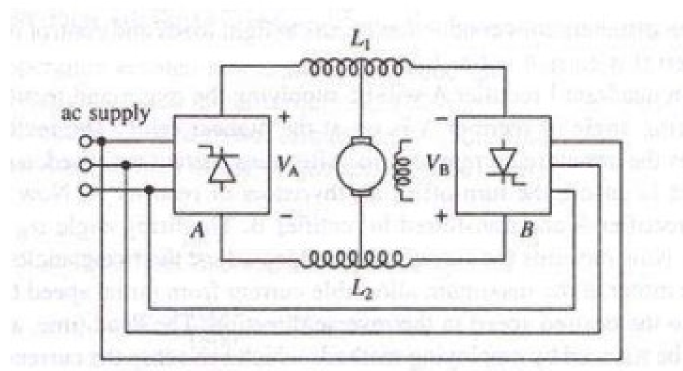


Fig: Dual Converter Control of a DC separately excited motor.
(Inductors L1 and L2 are used in only simultaneous or Circulating current mode)

For lower power ratings i.e. up to 10 Kw, single phase Full converters are used and for higher ratings three phase Full converters are used. Typical configuration of both Single phase and Three phase Dual converters are shown in the figures below.

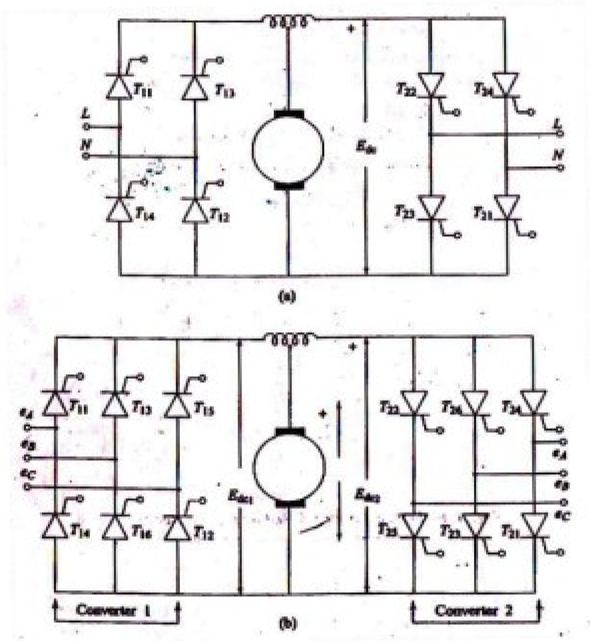


Fig: Single Phase and Three Phase Converters connected as Dual converters.

In a dual converter the converters are configured such that converter-A works in quadrants 1 and 4 and converter-B works in quadrants 2 and 3.

The operation of Dual converter is explained with the help of an Ideal dual converter (same figure as shown above but without reactors) with the following assumptions:

- They produce pure DC output voltage without any ac ripple.
- Each two quadrant converter is a controllable DC voltage source with unidirectional current flow. But the current through the load can flow in either direction.

The firing angle of the converters is controlled by a control voltage E_{DC} such that their DC output voltages are equal in magnitude but opposite in polarity. So, they can drive current through the load in opposite directions as per requirement.

Thus when one converter is operating as a Rectifier and is giving a particular DC output voltage, the other converter operates as an inverter and gives the same voltage at the motor terminals.

The average DC output voltages are given by:

$$E_{DCA} = E_{max} \cos \alpha_A \text{ and}$$
$$E_{DCB} = E_{max} \cos \alpha_B$$

Where $E_{max} = 2E_m/\pi$ for Single Phase Full converter and

$= 3\sqrt{3}E_{mph}/\pi$ for Three Phase Full converter

In an Ideal converter

$$E_{DC} = E_{DCA} = -E_{DCB}$$

and substituting the above values of E_{DCA} and E_{DCB} in this equation we get

$$E_{max} \cos \alpha_A = -E_{max} \cos \alpha_B$$
$$\text{or } \cos \alpha_A = -\cos \alpha_B$$
$$= \cos(180° - \alpha_B)$$
$$\text{or } \quad \alpha_A = 180° - \alpha_B$$
$$\text{or } (\alpha_A + \alpha_B) = 180°$$

The terminal voltage as a function of the firing angle for the two converters is shown in the figure below. A firing angle control circuit has to see that as the control voltage E_c changes the firing angles α_A and α_B are to satisfy the above relation $(\alpha_A + \alpha_B) = 180°$

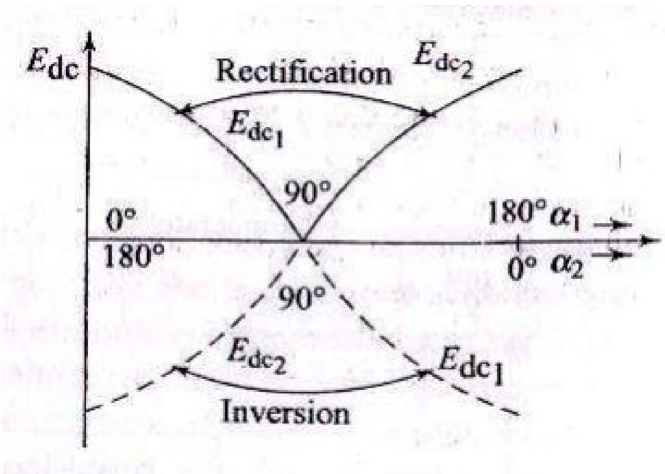


Fig: Firing angle versus Terminal voltage in Dual converter

Practical Dual Converters:

In the above explanation of the Dual Converter it is assumed that when the firing angle is controlled as per the above equation the output voltage is a pure DC voltage with out any AC ripple. But in practical dual converters there will be AC ripple and hence the instantaneous voltages from the two converters will be different resulting in circulating current which will not flow through the load. If these are not limited they will damage the converters.Hence in order to avoid/limit such circulating currents two methods are adopted.

Method 1: Dual Converter without circulating current: In this mode the flow of circulating current is totally inhibited by controlling the firing Pulses such that only one converter which is required to conduct the load current is active at a time. The other converter is kept inactive by blocking its firing pulses. Since only one converter is operating and the other one is in blocking state , no reactor is required.

Suppose converter-A is operating and supplying the load current in a given direction and the converter-B is blocked. If now direction is required to be changed, the pulses to converter-A are withdrawn and load current gets reduced to zero. Now converter-B is made operational by applying the firing pulses and it would build up the current through the load in the other direction. The pulses to Converter-B are applied only after confirming that the current through the load due to converter-A has completely come to zero and in addition after a further gap of a few milli seconds to ensure reliable commutation of converter-A.

Speed reversal is carried out as follows: When operating in quadrant-1 Converter–A will be supplying the motor current and converter–B is not operational. The firing angle of Converter-A is set at the maximum value. Converter-A then starts working as an Inverter and forces the armature current to zero. After zero current is sensed, firing pulses for converter-A are withdrawn, a further dead time of a few milli seconds is allowed and then firing pulses are given to the converter-B. The firing angle α_B *is initially set at the highest value. Now onwards the current loop adjusts the firing angle continuously so as to brake the motor at the highest possible current (torque) from initial speed to zero speed and then accelerates it to the desired speed in the opposite direction. The dead time and hence the reversal time can be reduced by going for accurate zero current sensing methods. When this is done nonsimultaneous control provides faster response than simultaneous control. Because of these advantages nonsimultaneous control is more widely used.*

In this method at certain load conditions the load current may not be continuous which is not a desirable operating condition . To avoid this second method is used.

Method 2: Dual converter with circulating current: In this mode Current limiting reactors are introduced between the DC terminals of the two converters as shown in the figure to allow the flow of circulating current due to the AC ripple/unequal volatages. Just like in an Ideal Dual converter the firing angles are adjusted such that

$$(\alpha_A + \alpha_B) = 180^\circ. \quad \text{--------} \quad (1)$$

For e.g. Firing angle of converter A is say 60°, then the firing angle of converter B will be 120°. With these firing angles, Converter A will be working as a converter and converter B will be working as an inverter. So, in circulating current mode both converters will be operating. The operation of the converters is interchanged if the load current direction is to be reversed. i.e. converter1 which was working as a converter would now work as an Inverter and converter 2 which was working as an Inverter would work as a converter. Two separate firing circuits have to be used for the two converters.

Speed reversal is carried out as follows. When operating in quadrant 1 Converter-A will be working as a rectifier ($0^\circ \leq \alpha \leq 90^\circ$) and converter-B will be working as an Inverter ($90^\circ \leq \alpha \leq 180^\circ$) For speed reversal α_A is increased and α_B is decreased while simultaneously satisfying the above condition (1)

Converter output voltages will reduce faster than the speed and hence the motor back emf exceeds the magnitude of both V_A and V_B. The armature current reduces to zero, reverses direction , shifts to Converter B and the motor will now operate initially in quadrant 2 during braking and then in quadrant 3 during acceleration and finally at the required steady state speed. The current loop adjusts the firing angle α_B continuously so as to brake the motor at the maximum allowable current from initial speed to zero speed and then accelerates to the desired speed in the opposite direction. As α_B is changed α_A is also changed continuously so as to maintain the above relation-1. During this entire operation, the closed loop control system will ensure the smooth transfer from quadrant 1 to quadrant 2 to quadrant 3.

Advantages and Disadvantages of the Circulating current mode of Dual Converters:

Advantages:

(i) Over the whole control range, the circulating current keeps both converters in virtually continuous conduction, independent of whether the external load current is continuous or discontinuous.

(ii) The reversal of load-current is inherently a natural and smooth procedure due to the natural freedom provided in the power circuit for the load current to flow in either direction at anytime.

(iii) Since the converters are in continuous conduction, the time response of the scheme is very fast.

(iv) The current sensing is not required and the normal delay period of 10 to 20 ms as in the case of a circulating current free operation is eliminated.

(v) Linear transfer characteristics are obtained.

Disadvantages:

The circulating current scheme has the following main disadvantages:

(i) Since the current limiting reactor is required in this scheme, the size and cost of this reactor may be quite significant at high power levels.

(ii) Since the converters have to handle load as well as circulating currents, the thyristors with high current ratings are required for these converters.

(iii) The efficiency and power factor are low because of circulating current which increases losses.

In spite of these drawbacks a dual converter with circulating current mode is preferred if load current is to be reversed quite frequently and a fast response is desired in the four-quadrant operation of the dual converter.

Comparison between Circulating current mode and non circulating current mode Dual converters:

	Non Circulating current Mode	Circulating current Mode
1.	In this mode of operation, only one converter operates at a time and the second converter remains in a blocking state.	In this mode of operation, one converter operates as a rectifier and the other converter operates as an inverter.
2.	Converters may operate in discontinuous current mode.	Converters operates in continuous current mode.
3.	Reactors may be needed to make load-current continuous.	Reactors are needed to limit circulating current. These reactors are costly.
4.	Since no circulating current flows through the converters, efficiency is higher.	Circulating current flows through the converters and hence increases the losses.
5.	Due to discontinuous current, non-linear transfer characteristics are obtained.	Due to continuous current, linear transfer characteristics are obtained.

Non Circulating current Mode **Circulating current Mode**

6.	Due to discontinuous current, response is sluggish.	Due to continuous-current in the converters, response is fast.
7.	Due to spurious firing, faults between converters results in dead short-circuit conditions.	Due to spurious firing, fault currents between converters are restricted by the reactor.
8.	In this mode of operation, the cross-over technique is complex.	In this mode of operation, the crossover technique is simple.
9.	Loss of control for 10 to 20 ms is observed in this mode of operation.	Since converters do not have to pass through blocking unlocking and safety intervals of 10 to 20 ms, hence control is never lost in this mode of operation.
10.	The control scheme needs command module to sense the change in polarity.	As both the converters are operating at the same time, the control scheme does not require command module.
11.	The complete scheme is cheaper compared to circulating current mode.	The complete scheme is expensive.
12.	In this mode of operation, tha converter loading is the same as the output load.	In this mode of operation the converter loading is higher than the output load.

Example 7.1 Compute the peak value of the circulating current for the 3-ϕ circulatory current type dual converter consisting of two three-phase fully controlled bridges for the given data.

Per phase supply RMS voltage = 230 V, ω = 315 rad/s, L = 12 mH

$$\alpha_1 = 60°, \alpha_2 = 120°.$$

Solution: The peak value of the circulating current from Eq. (7.18) is given by

$$i_{cp} = \frac{3\sqrt{2}E_{rms}}{\omega L}(1 - \cos \pi/6), = \frac{3\sqrt{2} \times 230}{315 \times 12 \times 10^{-3}}(1 - \cos \pi/6) = 34.58 \text{ A}.$$

Example 7.2 Design a dual converter to achieve a four-quadrant operation of the separately excited d.c. motor. Motor and converter specifications are given by

(i) Motor specifications

E_a = 220 V, I_a = 30 A, N = 1500 rpm.

(ii) Converter specifications

Supplied from 3-ϕ, 400 V, 50 Hz supply

Assume drop in the circuit is 15%.

Solution: Consider that dual converter consist of six-pulse converters to achieve a four-quadrant operation.

(i) Step 1 *Rectifier operation:*

Total drop in the system = $220 \times 0.15 = 33$ V.
$\therefore$ Total d.c. voltage, $E_{dc\alpha} = E_{dc}$ + drop, = 220 + 33 = 253 V.
For six-pulse bridge converter, we have the relation

$$E_{dc\ \alpha} = 1.35\ E_{ac} \cos \alpha_1.$$

where E_{ac} = RMS value of a.c. voltage.

$\therefore$ $253 = 1.35 \times 400 \times \cos \alpha_1 \quad \therefore \cos \alpha_1 = 0.469 \quad \therefore \alpha_1 = 62°.$

A.C. line current $I_{ac} = 0.817. I_{dc} = 0.817 \times 30 = 24.51$ A.

A.C. terminal power, $P_{ac} = \sqrt{3} \times E_{ac} \times I_{ac} = \sqrt{3} \times 400 \times 24.51 = 16.98$ kW.

$$P_{ac} = 1.05\ P_{dc}, \quad \therefore P_{dc} = \frac{p_{ac}}{1.05} = \frac{16.98 \times 10^3}{1.05} = 16.17 \text{ kW}.$$

(ii) Step 2

Current limiting inductance L_C is given by, $L_C = \frac{2 \times 1.35 \times E_{ac}}{6\omega I_{ripple}}\left[\frac{1}{7} + \frac{1}{5}\right]$

where $I_{ripple} = \frac{I_d}{5}$ for six-pulse converter $= \frac{30}{5} = 6$ A.

$$\therefore \quad L_c = \frac{2 \times 1.35 \times 400}{6 \times 2\pi \times 50 \times 6} = 33 \text{ mH}$$

(iii) Step 3

Firing angle $\alpha_2° = 180° - \alpha_1 = 180° - 62 = 118°$

(iv) Selection of SCR

(a) Voltage rating, PIV = $2\sqrt{2}\ E_{ac} = 2\sqrt{2} \times 400 = 1131.37$ PIV = 1200 V.
(b) Current rating

$$I_T = 2\sqrt{2} \times I_{ac} = 2\sqrt{2} \times 24.51 = 69.32 \text{ A} \cong 70 \text{ A}.$$

Example 5.22

Design a four-quadrant dc motor drive system for a dc motor with separate excitation using three-phase bridge fully controlled rectifier topologies. The system requirements are the following:

Stator voltage nominal value: $\overline{V}_a = 220$ V;
Stator current nominal value: $\overline{I}_a = 30$ A;
Motor nominal speed: $N_o = 220$ RPM;
ac utility line-to-line voltage: 400 V 50 Hz;
Total voltage drop in converter: 15% of power supply line voltage.

Solution

The power circuit of the motor drive system and its quadrants of operation are presented in Fig. 5.35. As can be seen, it consists of two antiparallel connected three-phase thyristor rectifiers.

During rectification operation the converters operate as rectifiers and power is delivered from the input power voltage sources to the machine and, consequently, the machine operates as a motor. During inversion operation the converters operate as inverters (i.e., convert dc to ac) and power is delivered from the machine, which operates as a generator, to the input power voltage sources.

Voltage drop value = (0.15)(400) = 33 V.

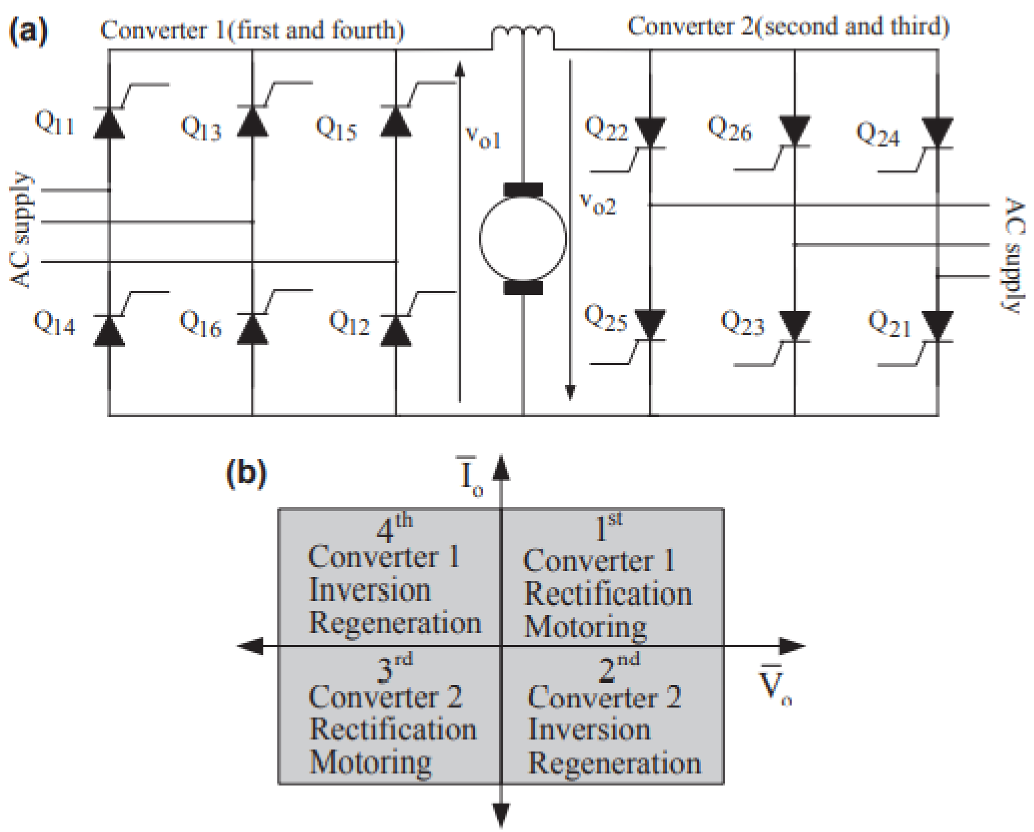


Figure 5.35 Four-quadrant dc motor drive system. (a) Power circuit; (b) quadrants of operation.

The required rectifier dc output voltage is

$$\overline{V}_{o(total)} = \overline{V}_o + 33 = 220 + 33 = 253\ \text{V}.$$

$$\overline{V}_o = \frac{3\sqrt{6}}{\pi}\tilde{V}_i \cos\alpha = \frac{3\sqrt{6}(400/\sqrt{3})}{\pi}\cos\alpha = 540.5\cos\alpha = 253\ \text{V}$$

$$\text{or}\quad \alpha = \cos^{-1}\left(\frac{253}{540.5}\right) = 62^\circ$$

The input line current waveform of the three-phase rectifier is shown in Fig. 5.36. According to the above waveform, the rms input current of a three-phase rectifier is:

$$\tilde{I}_a = \overline{I}_a\sqrt{\frac{2}{3}} = 30\sqrt{\frac{2}{3}} = 24.49\ \text{A}$$

Finally, the output and input active power are respectively given by:

$$\overline{P}_o = \overline{I}_a\overline{V}_a = (220)(30) = 6.6\ \text{kW} \quad P_i = 1.15\overline{P}_o = (1.15)(6600) = 7.59\ \text{kW}$$

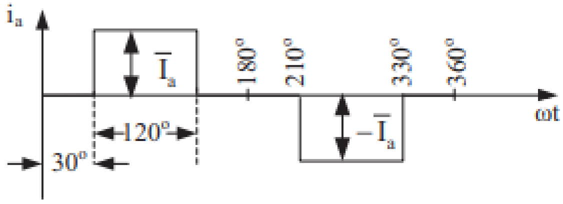


Figure 5.36 Input line current waveform of the dc motor drive system.

5.9. THE DUAL CONVERTER - FOUR-QUADRANT OPERATION

A high power d.c. motor drive sometimes has to undergo four-quadrant operation. Two full converters are connected back to back for this purpose (Figure 5.10).

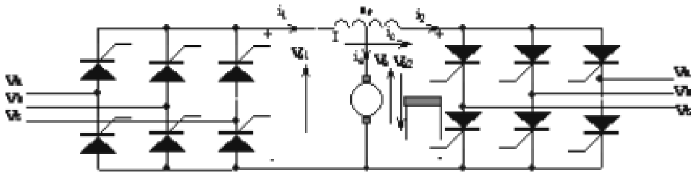


Figure 5.10. Dual converter with circulating current supplying a d.c. brush motor

a. Assuming that the converters are ideal and produce pure d.c. output voltages with one converter as rectifier and the other as inverter, calculate the relationship between the delay angles α_1 and α_2 in the two converters.

b. With $\alpha_1 + \alpha_2$ as above, calculate the circulating current between the two converters and show the voltage and current actual output waveforms. The numerical data are V_L = 220V, ω_1 = 377.8rad/s, L = 10mH, α_1 = 60°.

Solution:

a. In an ideal dual converter the voltages produced by the two full converters should be equal and opposite.

By now we know that

$$V_{a1} = V_{max} \cdot \cos\alpha_1$$
$$V_{a2} = V_{max} \cdot \cos\alpha_2 \qquad (5.69)$$

with $V_a = V_{a1} = -V_{a2}$ it follows that $\cos\alpha_1 + \cos\alpha_2 = 0$.

Hence, $\alpha_1 + \alpha_2$ = 180° (Figure 5.11). In the ideal converter the load voltage is equal to the converter output voltages and thus the current may flow equally through either converter.

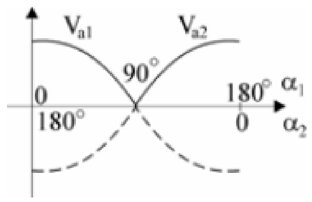


Figure 5.11. Ideal dual converter voltages

b. A real (nonideal) converter produces a voltage with ripples. The ripple voltages of the two converters are out of phase (Figure 5.12). The instantaneous voltage difference produces a circulating current which is limited through a reactor L.

With

$$V_{a,b,c} = \frac{V_L\sqrt{2}}{\sqrt{3}}\sin\left[\omega_1 t - (i-1)\frac{2\pi}{3}\right] \qquad (5.70)$$

during the interval

$$\frac{\pi}{6}+\alpha_1<\omega_1 t<\frac{\pi}{6}+\alpha_1+\frac{\pi}{3} \qquad (5.71)$$

$$\begin{aligned} V_{a1} &= V_a - V_b \\ V_{a2} &= -\left(V_c - V_b\right) \\ e_r &= V_{a1} - V_{a2} = V_a + V_c - 2V_b = -3V_b \end{aligned} \qquad (5.72)$$

The circulating current i_c is

$$i_c=\frac{1}{\omega_1 L}\int_{\alpha_1+\frac{\pi}{6}}^{\omega_1 t} e_r dt=\frac{\sqrt{6}V_L}{\omega_1 L}\left[\cos\left(\omega_1 t-\frac{2\pi}{3}\right)-\cos\left(\alpha_1-\frac{\pi}{2}\right)\right] \qquad (5.73)$$

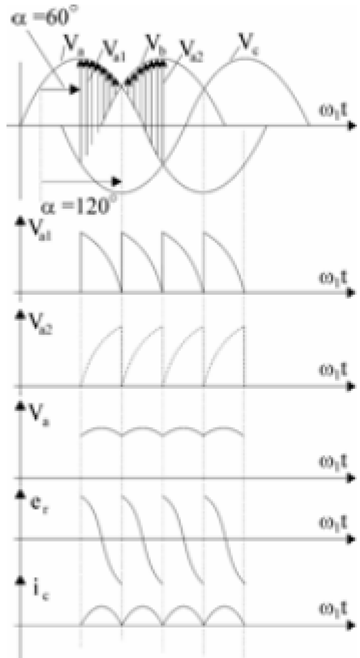


Figure 5.12. The real dual converter

When the motor current is zero, the converter currents are equal to the circulating current $i_1 = i_2 = i_c$ ($i_a = 0$). Consequently, the converters have a continuous current though the load current is zero. However for $\alpha_1 = 60°$ and $\alpha_2 = 120°$ the peak value of circulating current occurs at $\omega_1 t = 2\pi/3$

$$\left(i_c\right)_{peak}=\frac{V_L\sqrt{6}}{\omega_1 L}\left[1-\cos\frac{\pi}{6}\right]=\frac{220\sqrt{6}}{2\cdot\pi\cdot 60\cdot 10^{-3}}\left[1-0.867\right]=19.02 \text{ A} \qquad (5.74)$$

If the load current i_a is constant (no ripples), the first converter ($\alpha_1 = 60°$) carries $i_a + i_c$ while the second converter ($\alpha_1 = 120°$) has the circulating current i_c only. Thus the first converter is "overloaded" with the circulating current. However, for low load current, the discontinuous current mode in the converters is avoided as shown above. This could be an important advantage in terms of control performance.

Example 6.38. (*a*) *Describe the working of a single-phase dual converter with appropriate waveforms.*

Derive expressions for the average output voltage and the circulating current.

(*b*) *A single-phase dual converter is fed from 230 V, 50 Hz source. The load is $R = 30\ \Omega$ and the current-limiting reactor has $L = 0.05$ H. For $\alpha_1 = 30°$, calculate the peak value of circulating current and also the peak currents of both the converters.*

Solution. (*a*) The circuit diagram of single-phase dual converter is shown in Fig. 6.45 (*a*). Single-phase voltage applied across terminals A, B is sketched in Fig. 6.50 (*a*) as v_s. Let the firing angle of converter 1 be α_1, say around 30° or so. Waveform of output voltage v_{01} across output terminals of converter 1 is shown in Fig. 6.50 (*b*). For converter 2, $\alpha_2 = 180 - \alpha_1 = 150°$ and waveforms of its output voltage v_{02} is shown in Fig. 6.50 (*c*). Since v_{02} is mostly below the reference line ωt, its average is negative. As per the polarity markings of output voltages v_{01} and v_{02} in Fig. 6.45 (*a*), the average values of output voltages of both the converters must be positive. Thus, the waveform of output voltage v_{02} of converter 2 must be shown positive above the reference line ωt, this is shown in Fig. 6.50 (*d*)

Now $$v_{01} = V_m \sin \omega t \text{ and } v_{02} = V_m \sin \omega t$$

$\therefore$ Load voltage, $v_o = \dfrac{v_{01} + v_{02}}{2} = V_m \sin \omega t$ as shown in Fig. 6.50 (*e*). Note that from $\omega t = 0$ to $\omega t = \alpha_1$ and from $\omega t = \pi - \alpha_1$ to $\omega t = \pi$, load voltage $v_o = 0$

$\therefore$ Average value of load voltage, $V_o = \dfrac{1}{\pi}\displaystyle\int_{\alpha_1}^{\pi - \alpha_1} V_m \sin \omega t \, . \, d(\omega t) = \dfrac{2V_m}{\pi} \cos \alpha_1$ ...(*i*)

As per Eq. (6.88), voltage v_r across reactor is $v_r = v_{o1} - v_{o1}$. Waveforms of v_{o1} and v_{o2} of Fig. 6.50 (*d*) reveal that

from $\omega t = 0$ to $\omega t = \alpha_1$, $v_r = -2\, V_m \sin \omega t$

from $\omega t = \alpha_1$ to $\omega t = \pi - \alpha_1$, $v_r = 0$

and from $\omega t = \pi - \alpha_1$ to $\omega t = \pi$, $v_r = 2\, V_m \sin \omega t$ and so on. Waveshape of v_r is sketched in Fig. 6.50(*f*). Note that when $\omega t = \alpha_1$, $v_r = -2\, V_m \sin \alpha_1$ and at $\omega t = \pi - \alpha_1$, $v_r = 2\, V_m \sin \alpha_1$.

If i_c is the circulating current due to v_r, then $v_r = L \dfrac{di_c}{dt}$

or $$i_c = \frac{1}{L} \int v_r \, dt$$

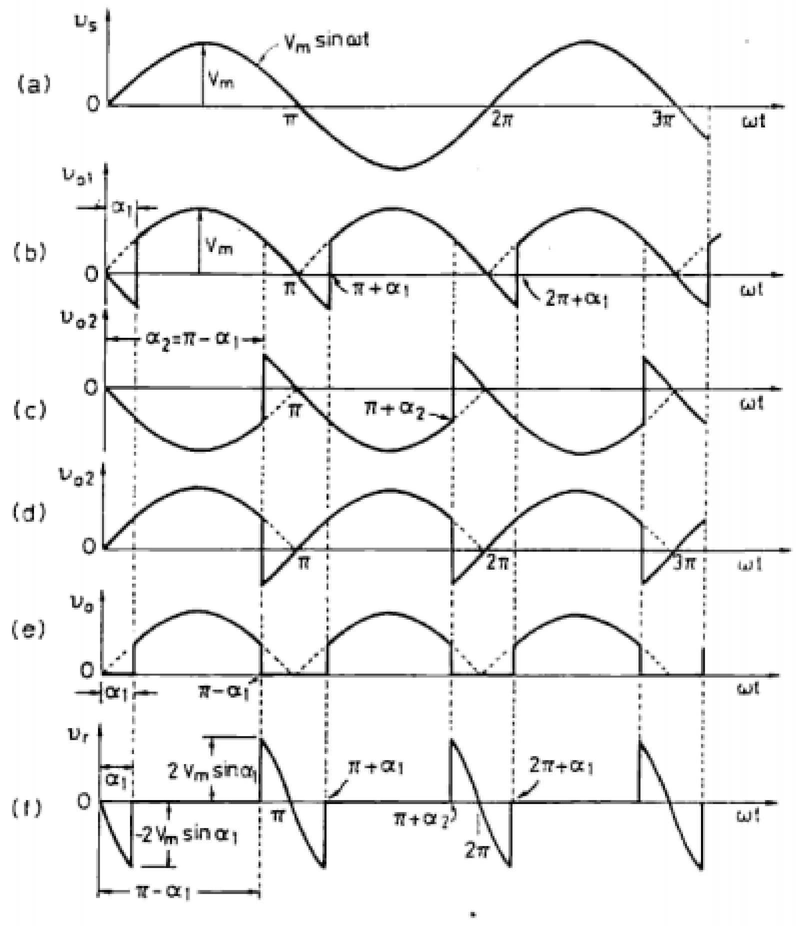


Fig. 6.50. Waveforms for single-phase dual converter, Example 6.38.

Now $\qquad v_{01} = V_m \sin \omega t$ and $v_{02} = V_m \sin \omega t$

$\therefore$ Load voltage, $v_o = \dfrac{v_{01} + v_{02}}{2} = V_m \sin \omega t$ as shown in Fig. 6.50 (*e*). Note that from $\omega t = 0$ to $\omega t = \alpha_1$ and from $\omega t = \pi - \alpha_1$ to $\omega t = \pi$, load voltage $v_o = 0$

$\therefore$ Average value of load voltage, $V_o = \dfrac{1}{\pi}\displaystyle\int_{\alpha_1}^{\pi - \alpha_1} V_m \sin \omega t \, . \, d(\omega t) = \dfrac{2V_m}{\pi} \cos \alpha_1$ $\qquad$ ...(*i*)

As per Eq. (6.88), voltage v_r across reactor is $v_r = v_{o1} - v_{o2}$. Waveforms of v_{o1} and v_{o2} of Fig. 6.50 (*d*) reveal that

from $\omega t = 0$ to $\omega t = \alpha_1$, $v_r = -2 V_m \sin \omega t$

from $\omega t = \alpha_1$ to $\omega t = \pi - \alpha_1$, $v_r = 0$

and from $\omega t = \pi - \alpha_1$ to $\omega t = \pi$, $v_r = 2 V_m \sin \omega t$ and so on. Waveshape of v_r is sketched in Fig. 6.50(*f*). Note that when $\omega t = \alpha_1$, $v_r = -2 V_m \sin \alpha_1$ and at $\omega t = \pi - \alpha_1$, $v_r = 2 V_m \sin \alpha_1$.

If i_c is the circulating current due to v_r, then $v_r = L \dfrac{di_c}{dt}$

or $\qquad i_c = \dfrac{1}{L} \int v_r \, dt$

The limits of integration for v_r, from Fig. 6.50 (*f*), are seen to be from zero to α_1.

$$\therefore \qquad i_c = \frac{1}{L}\int_o^{\alpha_1/\omega} 2V_m \sin \omega t \, . \, dt = \frac{2\,V_m}{\omega L} \left| -\cos \omega t \right|_o^{\alpha_1/\omega}$$

$$= \frac{2\,V_m}{\omega L}[1 - \cos \alpha_1] \qquad ...(ii)$$

In case time t is to be included in the i_c expression, then

$$i_c = \frac{1}{L}\int_t^{\alpha_1/\omega} 2\,V_m \sin \omega\, t \, dt = \frac{2\,V_m}{\omega L}[\cos \omega t - \cos \alpha_1]$$

Maximum value of circulating current i_{cp} occurs when $\cos \omega t = 1$.

$$\therefore \qquad i_{cp} = \frac{2\,V_m}{\omega L}[1 - \cos \alpha_1] \qquad ...(ii)$$

(*b*) From Eq. (*ii*), part (*a*) peak value of circulating current

$$i_{cp} = \frac{2\sqrt{2} \times 230}{2\,\pi \times 50 \times 0.05}[1 - \cos 30°] = 5.548 \text{ A}$$

Peak value of load current$= \dfrac{V_m}{R} = \dfrac{\sqrt{2} \times 230}{30} = 10.84$ A

$\therefore$ Peak value of current in converter 1 = 5.548 + 10.84 = 16.388 A

Peak value of current in converter 2 = 5.548 A

ÖRNEK SORULAR VE ÇÖZÜMLERİ

Soru 1: Bir fazlı iki yönlü dönüştürücü 220V 50Hz lik AC kaynakla beslenmektedir. Tristörün tetikleme acısı α_1=30˚ ve α_2=150˚. Yükün direnci 15 ohm. Maksimum sirkülasyon akımı 10,5 A olduğuna göre;

a) Endüktansın değeri nedir?
b) Dönüştürücünün maksimum akımı nedir?

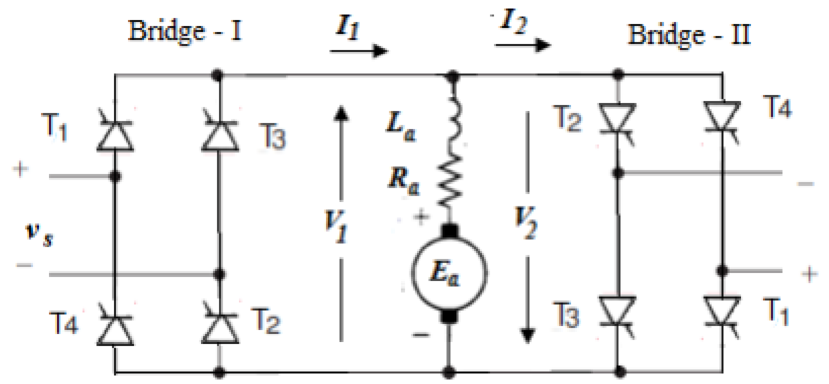
Çözüm:

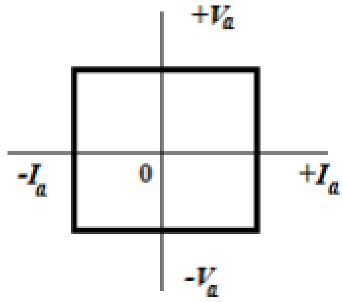
a) $V_m = \sqrt{2}\text{ x }220 = 311.12\text{ V}$
   α_1=30˚, α_2=150˚ ve $\omega = 100\pi$
   Sirkülasyon akımının maksimum olduğu değer ωt = 2 π anında olur
   $$l_r = \frac{2V_m}{\omega\text{Lr}}[\cos\omega t - \cos\alpha_1]$$
   $$Lr = \frac{2\text{ x }311{,}12\text{ x }[\cos 2\pi - \cos 30]}{100\pi\text{ x }l_r} = \frac{2\text{ x }311{,}12\text{ x }[1 - 0{,}886]}{100\pi\text{ x }10{,}5}$$
   $$Lr = 0{,}0252\ H$$
b) Maksimum yük akım 311.12/15= 20.74 A
   1.dönüştürücünün maksimum akımı ile yük akımının maksimum değerinin toplamı maksimum sirkülasyon akımını verir.
   1.dönüştürücünün maksimum akımı: 10,5 + 20,74 = 31,24 A

Soru 2: 3 fazlı çift yönlü dönüştürcü 400 V 50H lik kaynakla beslenmektedir. Endüktansın değer 60 mH. Sirkülasyon akımının $\omega t = 0^{\circ}$, $\omega t = 30^{\circ}$, $\omega t = 90^{\circ}$ için bulunuz. Tristörlerin tetikleme açısını 0˚ olarak kabul ediniz. Ayrıca sirkülasyon akımının maksimum değerini bulunuz.

a) $V_m = \frac{\sqrt{2}}{\sqrt{3}}\text{ x }400 = 326{,}56\text{V}$
   $$\omega\text{Lr} = 2\pi\text{ x}50\ (60x10-3) = 18{,}85\ ohm$$
   $$l_r = \frac{3V_m}{\omega\text{Lr}}[\sin\omega t - 30 - \sin\alpha_1]$$
   $\omega t = 0$, $\alpha_1 = 0$ için,
   $$l_r = \frac{3x326{,}56}{18{,}85}[\sin(-30) - \sin 0] = -25{,}99\ A$$
   $\omega t = 30$, $\alpha_1 = 0$ için,
   $$l_r = \frac{3x326{,}56}{18{,}85}[\sin(0) - \sin 0] = 0\ A$$
   $\omega t = 90$, $\alpha_1 = 0$ için,
   $$l_r = \frac{3x326{,}56}{18{,}85}[\sin(60) - \sin 0] = 45\ A$$
b) Sirkülasyon akımının maksimum değeri $\omega t = 120$ olduğunda gerçekleşir.
   $\omega t = 120$, $\alpha_1 = 0$ için,
   $$l_r = \frac{3x326{,}56}{18{,}85}[\sin(90) - \sin 0] = 51{,}97\ A$$

Soru 3: 3 fazlı 400 V gerilimle beslenen 50 H frekanslı dalgalanama miktarı 15 olan AC kaynakla beslenen iki dönüştürücü kullanılarak dört bölgeli çalışma sağlayan dc motor kontrolü yapılmaktadır. Kontrolü yapılan motor Ea=220V Ia=30A, N=1500 rpm verilerine sahiptir.





1.adım Doğrultucu mod da çalışma için;

Toplam Dc voltaj $E_{dc\alpha}$ =220+ 220 x 0,15 =253 V

3 fazlı tam dalga dönüştürücü için;

$E_{dc\alpha}$ = 1,35 x E_{ac} cos α_1 E_{ac}= AC gerilimin rms değeri

253 = 1,35 x 400 x cos α_1

cos α_1 = 0,469

α_1 = 62˚

AC hat akımı;

I_{ac} = 0,817 x I_{dc} = 0,817 x 30 = 24,51 A

$$P_{ac} = \sqrt{3}\ x\ E_{ac}\ x\ I_{ac} = \sqrt{3}\ x\ 400\ x\ 24{,}51 = 16{,}98\ kW$$

$$P_{ac} = 1{,}05\ x\ P_{dc}$$

$$P_{dc} = {P_{ac}}/{1{,}05} = {16{,}98}/{1{,}05} = 16{,}17\ kW$$

2.adım;

Lc endüktansının akım limiti $L_c = \frac{2x1{,}35xE_{ac}}{6\ x\ \omega\ x\ I_{ripple}} x \left[\frac{1}{7} + \frac{1}{5}\right]$

3fazlı tam dalga dönüştürücüler için ;

$$I_{ripple} = \frac{I_d}{0{,}5} = \frac{30}{0{,}5}\ 6\ A$$

$$L_c = \frac{2x1{,}35x400}{6\ x\ 2\pi\ x\ 50\ x\ 6} x \left[\frac{1}{7} + \frac{1}{5}\right] = 33\ mH$$

3.adım

Tetikleme acısı; α_2 = 180˚- α_1 =180˚ - 62˚ = 118˚

Voltaj genişliği $PIV = 2\sqrt{2}\ x\ I_{ac}$ = $2\sqrt{2}\ x\ 24{,}51 = 69{,}32\ A$

1.dönüştürücünün ortalama çıış votajı;

$$V_{dc1} = \frac{2V_m}{\pi} cos\alpha_1$$

2.dönüştürücünün ortalama çııș votajı;

$$V_{dc2} = \frac{2V_m}{\pi} cos\alpha_2$$

$$\frac{2V_m}{\pi} cos\alpha_1 = -\frac{2V_m}{\pi} cos\alpha_2$$

$$cos\alpha_1 = -cos\alpha_2$$

$$\alpha_1 + \alpha_2 = 180$$

$$l_{sir} = \frac{2V_m}{\omega \mathrm{Lr}} [\cos \omega \mathrm{t} - \cos \alpha_1]$$

Soru 4: 3 fazlı tam köprü dönüştürücü 3 fazlı 50Hz kaynak endüktansı 5 mH olan kaynakla beslenmektedir Yük akımı 20 A dir. Yğk sabit olduğunda dc voltaj 400 V lık kaynaktan beslenmektedir iç direnci 1 ohm dur. Tristörlerin tetikleme acısını ve üst üste binem acısın bulunuz.

Dc kaynak şarj durumundaki bir batarya olabilir.

Dönüştürücünün çıkış voltajı Vo=400 +20 x1 =420 V

$$V_o = \frac{3V_{ml}}{\pi} cos\alpha - \frac{3\omega Ls}{\pi} I_o$$

$$420 = \frac{3x400x\sqrt{2}}{\pi} cos\alpha - \frac{3x\ 2\pi x50x5}{1000}$$

$$\alpha = 33{,}58^{\circ}$$

$$420 = \frac{3x400x\sqrt{2}}{\pi} cos(\alpha + \mu) + \frac{3x\ 2\pi x50x5}{1000}\ x\ 20$$

$$(\alpha + \mu) = 42{,}78^{\circ}$$

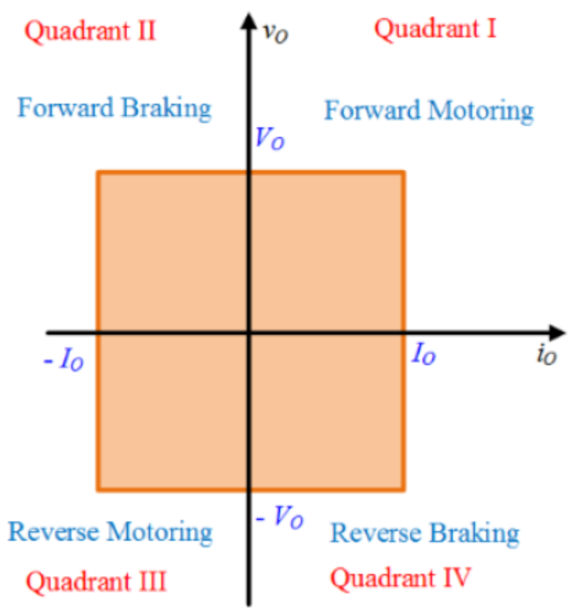
$$\mu = 9{,}2^{\circ}$$

DÖRT BÖLGELİ DC KIYICI İLE MOTOR KONTROLÜ

E tipi kıyıcının (4 bölgeli kıyıcı) aşağıda Resim-1'de verilen $v_o - i_o$ ekseninde 4 çalışma bölgesi gösterilmiştir.

v_o : çıkış geriliminin ortalaması

i_o : çıkış akımının ortalaması



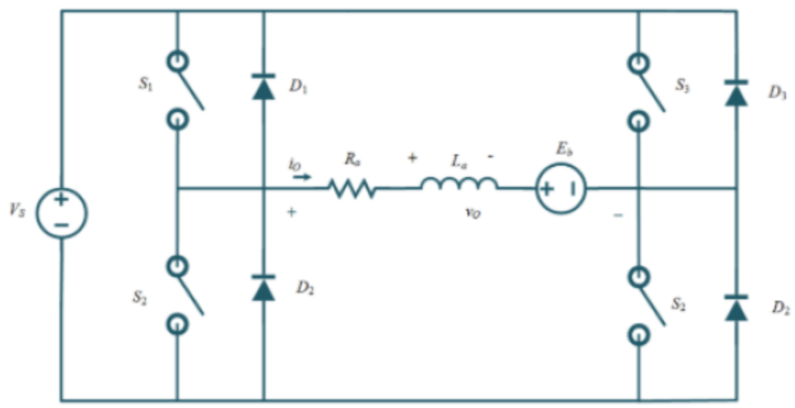
Resim-1: 4 bölgeli çalışma

Resim-2'de 4 bölgeli kıyıcıya ait devre şeması verilmiştir. Burada motor, kıyıcının yükü olarak bağlanmıştır.

R_a: Motor sargı direnci

L_a: Motor sargı endüktansı

E_b: Ters elektro motor kuvveti

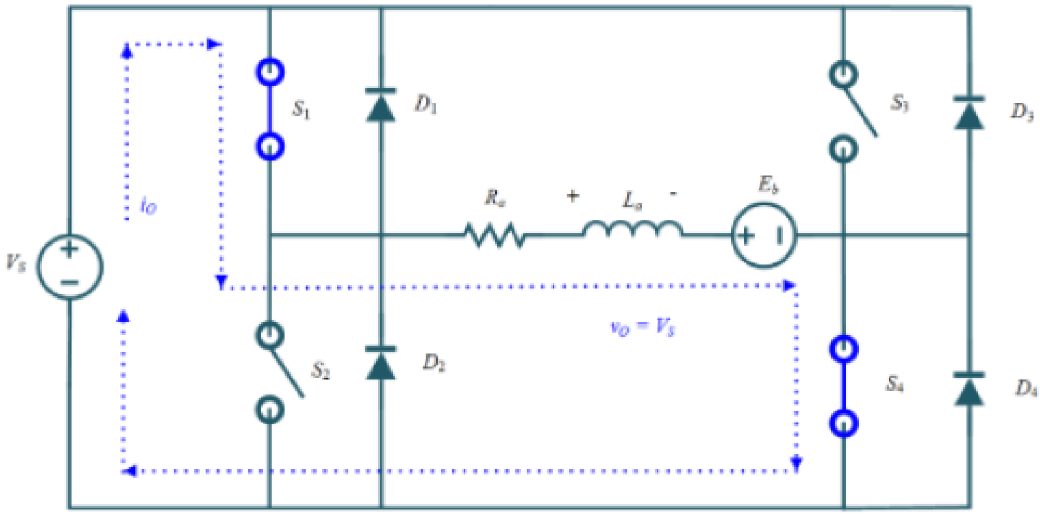


Resim-2: 4 bölgeli DC kıyıcı devre şeması

a) 1. Bölgede Çalışma

- S1 ve S4 İletimde

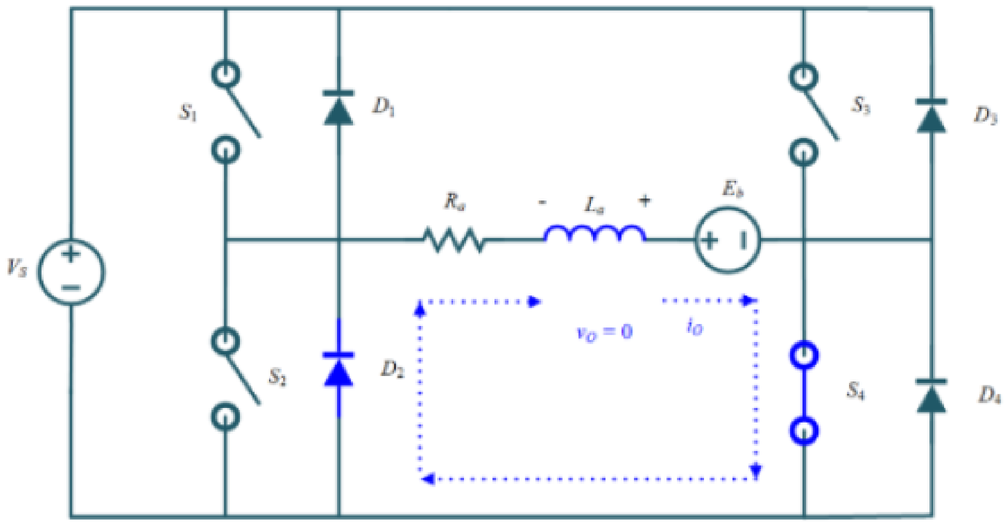
Resim-3'te verilen eşdeğer devre şemasından da görüleceği üzere, S1 ve S4 anahtarı aktif iken çıkış gerilimi v_o pozitif ve çıkış akımı i_o da pozitiftir. Burada güç akışı kaynaktan motora doğrudur ve motor sargı endüktansı enerjiyi depolar, motor referansa göre ileri yönde döner. Buna ileri yönde motor çalışma denir.



Resim-3: ileri yönde motor çalışma

- D2 ve S4 İletimde

Resim-4'te verilen eşdeğer devre şemasından da görüleceği üzere, D2 ve S4 anahtarı aktif iken motor bağlantı uçlarına gerilim uygulanmaz, kaynaktan güç çekilmez motor sargı endüktansında biriken enerji kullanılır. Buna serbest geçiş aralığı denir. Bu çalışma anında motor akımı pozitiftir, motor pozitif yönde döner.



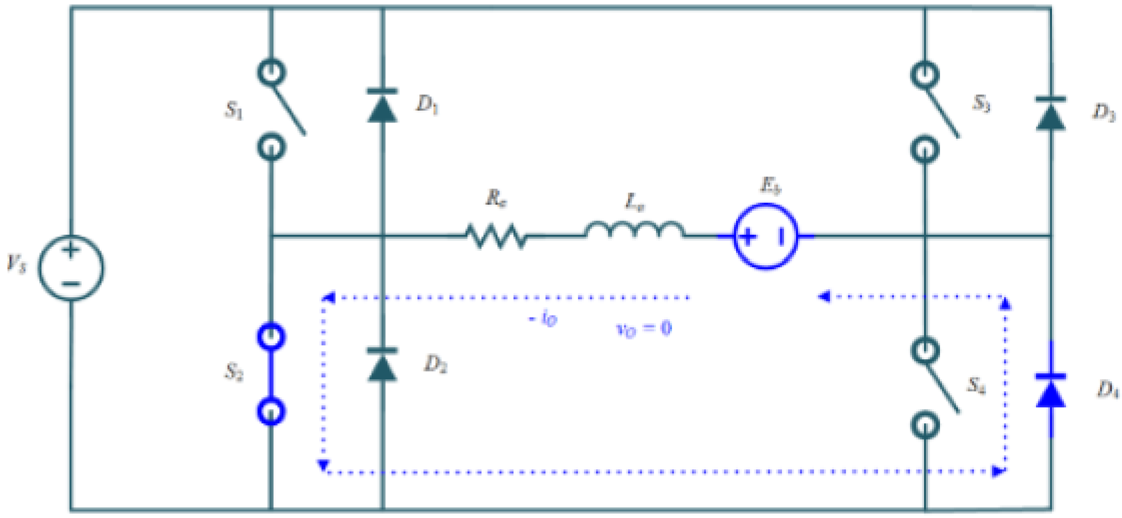
Resim-4: ileri yönde motor çalışma serbest geçiş

b) 2. Bölgede çalışma

- S2 ve D4 iletimde

Resim 5'te verilen eşdeğer devre şemasını incelerken motorun ileri yönde çalıştığı kabul edilecektir. Burada S2 anahtarı ve D4 diyodunun aktif olduğu durumda çıkış gerilimi v_o =0 ve

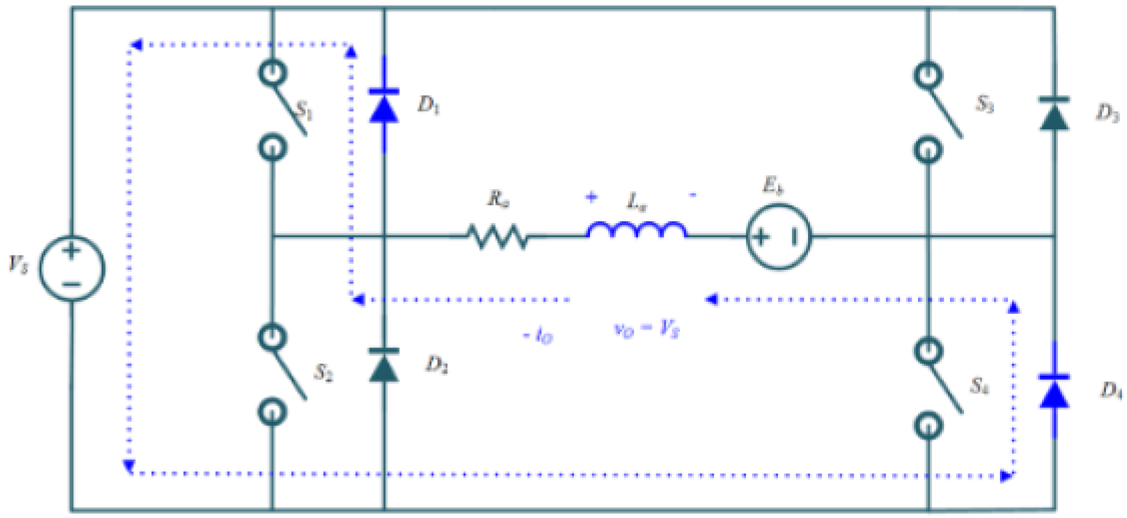
E_b ters elektromotor kuvvetinden dolayı çıkış akımı i_o negatif yönde olacaktır. Bu sebeple elektrik makinesi generatör olarak çalışmaktadır ve motor sargı endüktansı enerji depolar.



5: ileri yönde frenleme

- D1 ve D4 iletimde

Resim-6'da verilen eşdeğer devre incelenirse, burada S2 anahtarı kesim modundadır. D1 ve D4 diyotları iletime geçecektir. Burada çıkış gerilimi v_o pozitif ve çıkış akımı i_o negaiftir. Motor sargı endüktansında biriken enerji şebekeye aktarılır. Burada güç akışı yükten, kaynağa doğrudur. Bu çalışma moduna ileri yönde frenleme adı verilir.

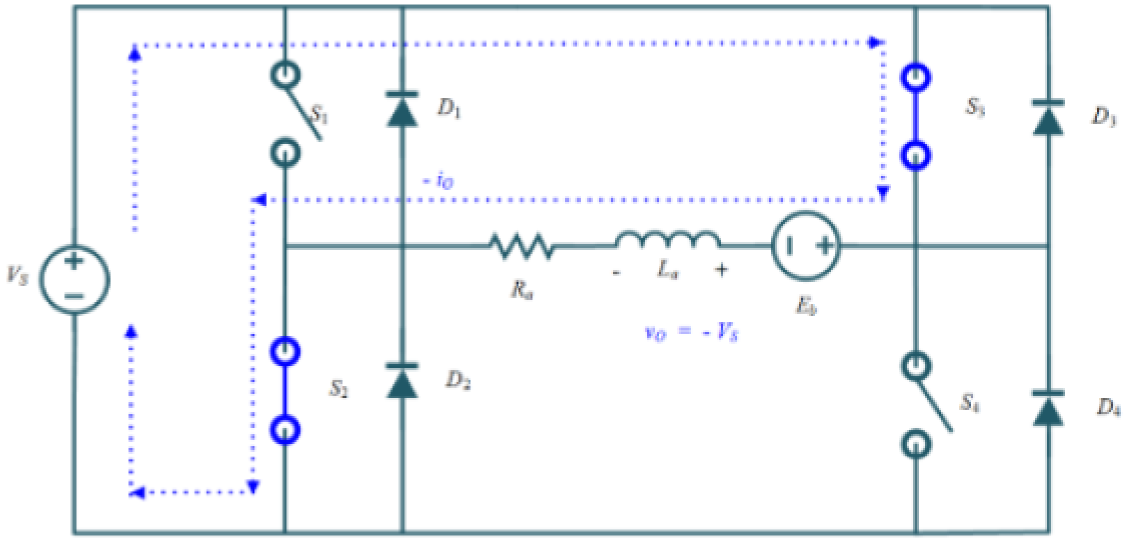


6: ileri yönde frenleme

c) 3. Bölgede Çalışma

- S3 ve S4 İletimde

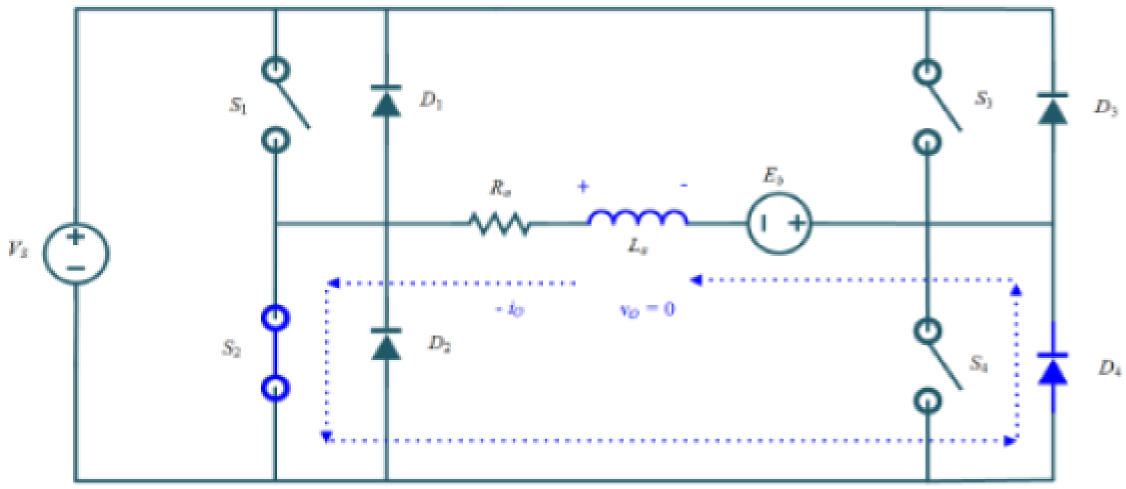
Resim-7'de verilen eşdeğer devreden de görüleceği üzere, S3 ve S4 iletimde iken ters elektro motor kuvveti negatiftir yönde olacaktır. Çıkış gerilim ve çıkış akımı i_o negatiftir, yük akışı kaynaktan yüke doğrudur. Motor sargı endüktansı enerji depolayacaktır ve motor ters yönde dönecektir. Buna geri yönde motor çalışma denir.



7: geri yönde motor

- S2 ve D4 iletimde

Resim-8'de verilen eşdeğer devreden de görüleceği üzere, S3 kesimde, S2 ve D4 iletimde iken ters elektro motor kuvveti negatiftir yönde olacaktır. Çıkış gerilimi v_o =0'dır ve çıkış akımı i_o negatiftir, kaynaktan yüke doğru bir yük akışı bulunmamaktadır. Motor sargı endüktansında depolanan enerji harcanacak ve motor ters yönde dönecektir. Buna da geri yönde motor çalışma denir.

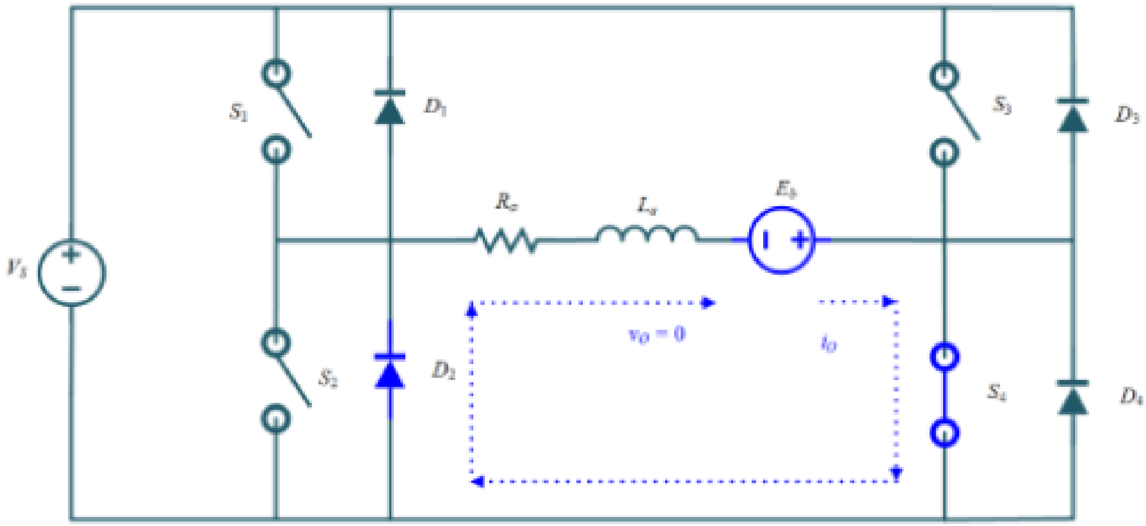


8: geri yönde motor

d) 4. Bölgede Çalışma

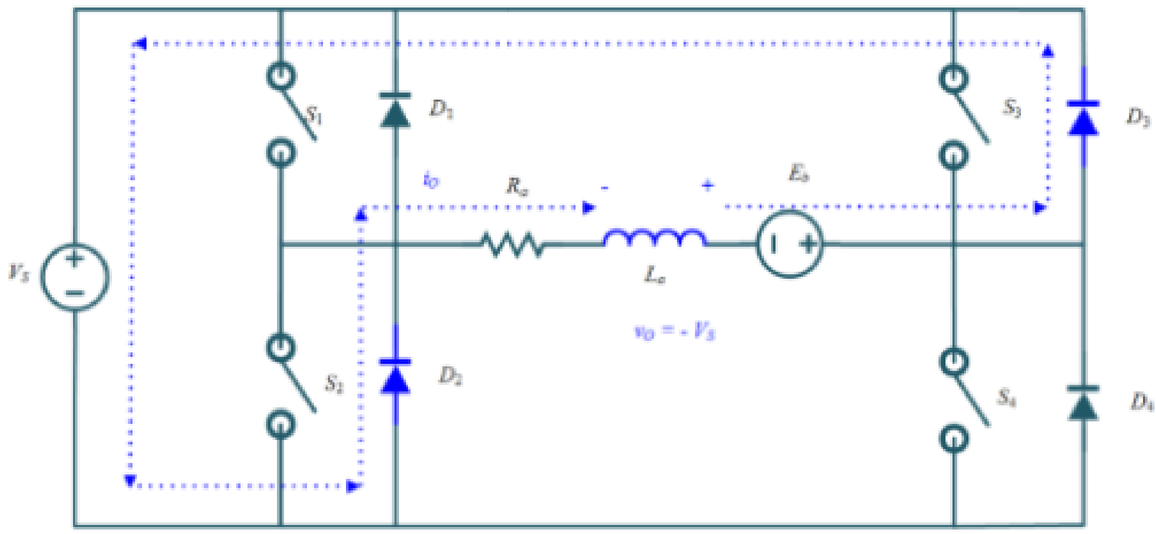
- S4 ve D2 İletimde

Resim-9’da verilen eşdeğer devreden de görüleceği üzere, S4 ve D2 iletimde iken ters elektro motor kuvveti negatiftir yönde olacaktır. Burada motorun geri yönde çalıştığını kabul edelim. S4 ve D2 iletimde iken, çıkış gerilimi v_o= 0 ve E_b çıkış akımını i_o pozitif olmasını sağlar. Elektrik makinası generatör olarak çalışır ve sargı endüktansı enerji depolar



Resim-9: geri yönde frenleme

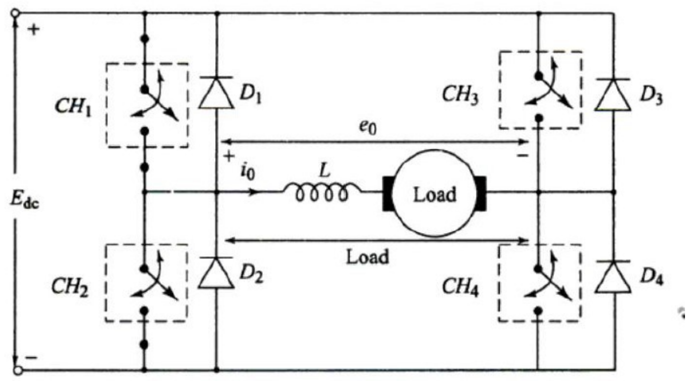
Resim-10’da verilen eşdeğer devre incelenirse, burada S3 anahtarı kesime geçtiğinde, D1 ve D4 diyotları iletime geçecektir. Burada çıkış gerilimi v_o negatif ve çıkış akımı i_o pozitif olacaktır. Motor sargı endüktansında biriken enerji D2 ve D3 diyotları üzerinden şebekeye aktarılır. Burada güç akışı yükten, kaynağa doğrudur. Bu çalışma moduna geri yönde frenleme adı verilir.



Resim-10: geri yönde frenleme

DÖRT BÖLGELİ KIYICI DEVRE

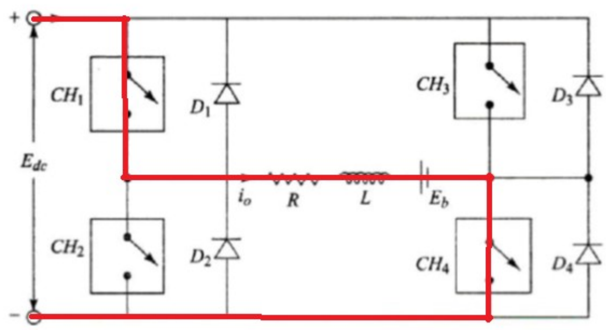
Aşagıdaki şekilde E şeklindeki kıyıcı güç devresi görülmektedir. 4 bölgeli kıyıcı C şekilindeki iki kıyıcının paralel kombinasyonu ile oluşturulur.



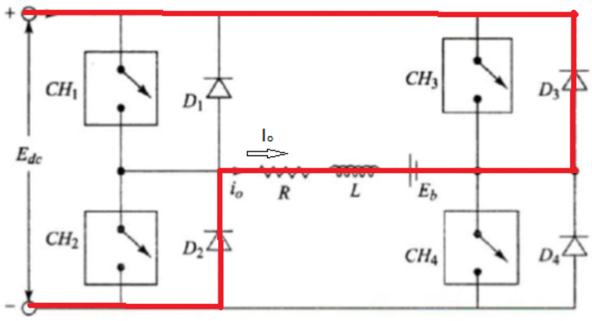
CH_4 anahtarı kesimde iken paralel bağlı onan D_4 diyodu kısa devredir ve üzerinden akım geçer. CH_3 anaharı kapalı iken CH_4 anahtarı kısa devre edilmiştir.

CH_4 anahtarı iletimde, CH_3 anahtarı kesimde iken; CH_1 ve CH_2 anahtarları E_0 geriliminin her zaman pozitif olmasını ve I_0 akımının iki yönlü olmasını sağlarlar. Yani 1. ve 2. bölgede motor çalışmayı gerçekleştirmemizi sağlarlar. Diğer taraftan CH_2 iletimde, CH_1 anahtarı kesimde iken; CH_3 veCH_4 E_0 geriliminin negatif ve I_0 akımının iki yönlü olmasını sağlarlar yani 3. ve 4. bölgede çalışma gerçekleşir.

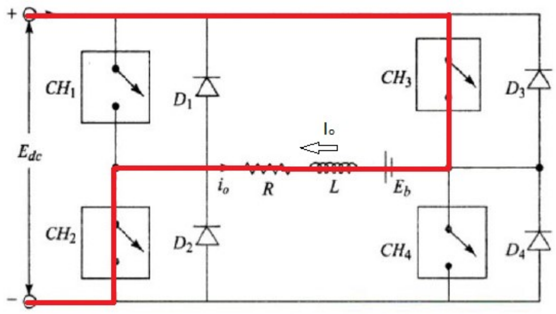
CH_1 ve CH_4 anahtarları iletimde olduğu durumda E_0 ve I_0 değerleri pozitif olur. Birinci bölgede çalışma sağlanır.



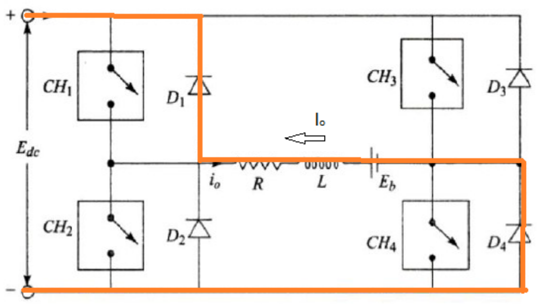
CH_1 ve CH_4 anahtarları kesimde olduğu durumda D_3 ve D_2 diyotları iletime girer ve I_0 pozitif ve E_0 negatif değer alır. Dördüncü bölgede çalışma sağlanır.



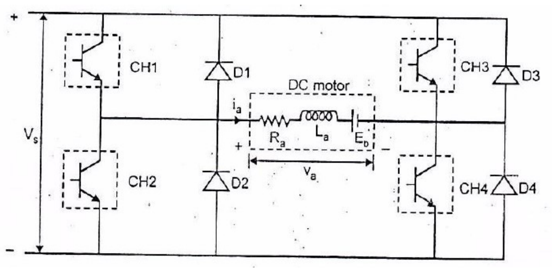
CH_2 ve CH_3 anahtarları iletimde olduğu durumda E_0 ve I_0 değerleri negatif olur. Üçüncü bölgede çalışma sağlanır.



CH_2 ve CH_3 anahtarları kesimde olduğu durumda D_1 ve D_4 diyotları iletime girer ve E_0 pozitif ve I_0 negatif değer alır. Dördüncü bölgede çalışma sağlanır.



Bölgeli çalışma devresi ileri ve geri yönlü olmak üzere iki köprünün birleşiminden oluşur. CH1 CH4 gibi anahtarlama elemanları ileri köprü dönüştürücüyü oluşturur ve energi kaynaktan yüke doğru akar ve yük beslenir. D1 ve D4 diyotları ise geri yönlü köprü dönüştürücü elemanlarıdır.Enerjinin yükten kaynağa doğru akmasını sağlarlar.



İleri yönlü Motor çalışma

CH_1 ve CH_4 anahtarları iletimde olduğu durumda yük gerilimi kaynak akımına eşit olur (Va=Vs) ve yükten İa akım geçer. Hem çıkış gerilimi hemde yük akımı pozitif değer alır. CH4 anahtarı kesime girerse onun serbest geçiş diyodu olan D4 diyodu iletime girer. Bu şekilde birinci bölgede hem çıkış gerilimi hemde yük akımı kontrol edilebilir.

İleri yönlü Frenleme Modu

CH2 çalışır durumda ve diğer üç anahtar kapalı tutulacaktır. CH2 negatif olduğu için indüktör L'den akmaya başlar. CH2, E ve D4. CH2 anahtarı iletimde enerji endüktansada depolanır. CH2 kapalıyken akım, D1 ve D4 diyotları aracılığıyla akım kaynağa doğru akar. Burada Vs kaynak voltajı (E + L.di / dt) daha fazla olacaktır. Güç yükten kaynağa doğru geri beslendiğinden, ikinci bölgede çalışma sağlanmış olacaktır.

Geri yönlü Motor çalışma Modu

CH1 anahtarı kapalı tutulacak, CH2 anahtarı açık olacak ve CH3 anahtarı çalıştırılacaktır. Bu çalışmada yükün uçlarındaki gerilim polaritesi ters çevrilmelidir. CH3 anahtarı açıkken, yüküne gerilimi kaynak Vs gerilimine eşit olur ve yük akımının değeri negatif olur. CH3 anahtarı kesime girdiğinde CH ve D4 elemanları iletimdedir.Bu yollan çıkış voltajı Va ve Yük akımı İa 3. çalışma bçlgesinde kontrol edilir.

Geri yönlü Frenleme Modu

CH4 çalıştırılacak ve CH1, CH2 ve CH3 kapalı olacaktır. Kıyıcı CH4 açıldığında pozitif akım CH4anahtarı ve D2diyodu üzerinden yüke doğru akmaya başlar ve L endüktansında enerji depolanır. CH4 kapatıldığında akım, D2 ve D3 diyotları aracılığıyla kaynağa geri döner, yük gerilimi negatif olduğur, ancak yük akımı pozitif olduğu için işlem dördüncü bölgededir. Güç yükten kaynağa geri döndüğünden geri yönlü frenleme modunda çalışma sağlanır.

Soru 5: 4 bölgeli kıyıcı devre ile dc motor kontrolü yapılmaktadır. Motor direnci R=1 ohm, L=10mH dir.200V dc kaynakla beslenmektedir. Motor akımı 10A iken

c) E_b =150 V iken kıyıcı devrenin doluluk oranı,
d) E_b = -110 V iken kıyıcı devrenin doluluk oranını bulunuz.

$$E_o = 2\,E_{dc}\,(\alpha - 0{,}5)$$

a) $i_o = \frac{E_o - E_b}{R} = \frac{2\,E_{dc}\,(\alpha - 0{,}5) - E_b}{R}$

$$10 = \frac{2\,x200x\,(\alpha - 0{,}5) - 150}{0{,}1}$$

$\alpha = 0{,}876$

$\alpha > 0{,}5$ oldugundan dolayı ileri yönlü motor çalışma modunda çalışır.

b) $i_o = \frac{E_o - E_b}{R} = \frac{2\,E_{dc}\,(\alpha - 0{,}5) - E_b}{R}$

$$10 = \frac{2\,x200x\,(\alpha - 0{,}5) - 110}{0{,}1}$$

$\alpha = 0{,}228$

$\alpha < 0{,}5$ oldugundan dolayı geri yönlü motor çalışma modunda çalışır.

Soru 6: Tek Bölgeli dc kıyıcı devresinde yükün direnci 10ohm ve giriş voltajı 230V dur. Kıyıcının frenkansı 1kHz ve T_{on}=0,4ms dir. Ortalama yük akımını ve çıkış gücünü bulunuz.

Doluluk oranı: k=0,4

Ortalama yük akımı: $V_o = V_s$ x k

V_o = 230 x 0,4 = 92V

Ortalama yük akımı: $I_{o,av} = V_o/R$

$I_{o,av}$ = 92/10 = 9,2 A

Çıkış güçü: $P_o = (V_{or})^2/R$

$$V_{or} = V_s\sqrt{k} = 230x\sqrt{0{,}4} = 145{,}46V$$

$P_o = 145{,}46^2/10 = 2115{,}85$ W

Soru 7: H köprü bağlantılı dc-dc kıyıcı devre ile direnci 10 ohm , endüktansı 50mH, ve back EMF değeri 55V olan motor beslenmektedir. Kaynak gerilimi 340V dur. Kıyıcı devrenin çalışma frekansı 200Hz ve doluluk oranı 0,25dir. Ortalama çıkış voltajı ve T1 anahtarının iletimde kalma süresini, rms çıkış voltajı ve ac voltaj dalgalanmasını, ortalama çıkış akımını ve kaçıncı bölgede çalışma gerçekleştiğini Motor tarafından üretilen elektriksel gücübulunuz. Ayrıca yük akımı yarıya düşürüldüğündeki doluluk oranını çıkış gücünü, gerilimini ve elektriksel gücü bulunuz?

- Ortalama çıkış voltajı ve T1 anahtarının iletimde kalma süresini

$$T_{periyot} = \frac{1}{f} = \frac{1}{200} 5\ ms$$

$$V_o = (2\lambda - 1)V_s = \left(2\frac{1}{4} - 1\right)x340 = -170V$$

$$T_{on} = 2\lambda T = 2x\frac{1}{4}x\frac{5}{2} = 1{,}25\ ms$$

$$T_{of} = 5 - 1{,}25 = 3{,}75\ ms$$

T1 ve T4 1,25ms iletimde kalırken, T2 ve T3 anahtarları 3,75 ms iletimde kalırlar.

- Rms çıkış voltajı ve ac voltaj dalgalanması

$$V_{rms} = \sqrt{1 - 2\lambda}\ x\ V_s = \sqrt{1 - 2\frac{1}{4}}\ x\ 340 = 240\ V$$

$$V_{ripple} = \sqrt{2}\ x\ V_s\ x\ \sqrt{\lambda(1 - 2\lambda)} = \sqrt{2}\ \ x\ 340x\ \sqrt{\frac{1}{4}\left(1 - 2\frac{1}{4}\right)} = 170V$$

- Ortalama çıkış akımını ve kaçıncı bölgede çalışma gerçekleştiğini bulunuz.

$$I_o = \frac{V_o - E}{R} = \frac{(2\lambda - 1)V_s - E}{R} = \frac{\left(2\frac{1}{4} - 1\right)x340 - 55}{10} = -22,5\ A$$

$V_o = -170V$, $I_o = -22,5\ A$ olduğundan ve ikisininde değerleri negatitif olmasından dolayı 3. Bölgede çalışma gerçekleşir.

- Motor elektriksel güç

$$P_E = I_o\ x\ E = 55\ x\ (-22,5) = -1237,5\ W$$

- $\lambda = 0,415$ olduğunda ortalama çıkış akımı

$$I_o = \frac{V_o - E}{R} = \frac{(2\lambda - 1)V_s - E}{R} = \frac{(2x0,415 - 1)x340 - 55}{10} = -11,25\ A$$

$$V_o = E + RxI_o = 55 - 11,25x10 = -57,5A$$

Doluluk oranı tekrar hesaplanır;

$$\lambda = \frac{1}{2}\left(1 + \frac{V_o}{V_s}\right) = \frac{1}{2}\left(1 + \frac{-57,5}{340}\right) = 0,415$$

T1 ve T4 anahtarlarının iletimde olduğu süre;

$$T_{on} = 2\lambda T = 2x0,415x\frac{5}{2} = 2,07\ ms$$

$$P_E = I_o\ x\ E = 55\ x\ (-11,25) = -618,75\ W$$

8.5.5 Four-Quadrant Chopper (or Class E Chopper)

Figure 8.25(a) shows the basic power circuit of Type E chopper. From Fig. 8.25, it is observed that the four-quadrant chopper system can be considered as the parallel combination of two Type C choppers. In this chopper configuration, with motor load, the sense of rotation can be reversed without reversing the polarity of excitation. In Fig. 8.25, CH_1, CH_4 D_2 and D_3 constitute one Type *C* chopper and CH_2, CH_3, D_1 and D_4 form another Type *C* chopper circuit. Figure 8.25(b) shows Class-E with *R–L* load.

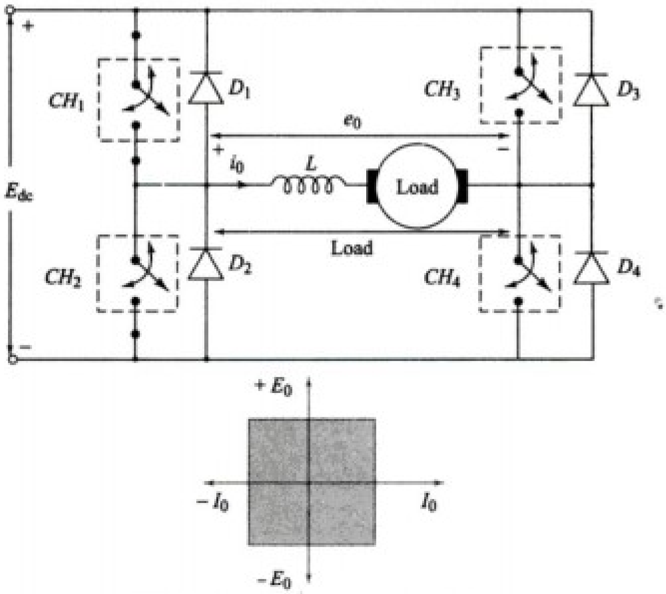


Fig. 8.25(a) *Type E chopper circuit and characteristic*

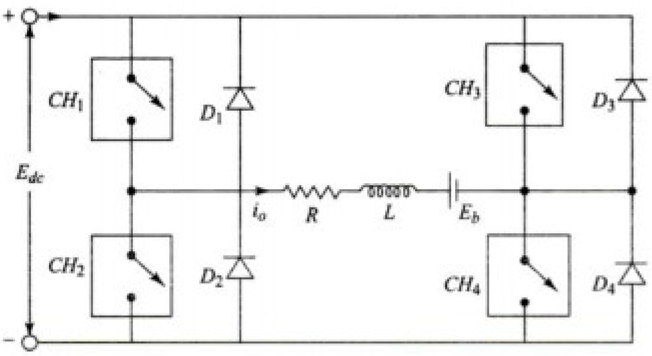


Fig. 8.25(b) *Class E chopper with R–L load*

If chopper CH_4 is turned on continuously, the antiparallel connected pair of devices CH_4 and D_4 constitute a short-circuit. Chopper CH_3 may not be turned on at the same time as CH_4 because that would short circuit source E_{dc}.

With CH_4 continuously on, and CH_3 always off, operation of choppers CH_1 and CH_2 will make E_0 positive and I_0 reversible, and operation in the first and second quadrants is possible. On the other hand, with CH_2 continuously on and CH_1 always off, operation of CH_3 and CH_4 will make E_0 negative and I_0 reversible, and operation in the third and fourth quadrants is possible.

The operation of the four-quadrant chopper circuit is explained in detail as follows:

When choppers CH_1 and CH_4 are turned-on, current flows through the path, $E_{dc+} - CH_1$ – load – $CH_4 - E_{dc-}$. Since both E_0 and I_0 are positive, we get the first quadrant operation. When both the choppers CH_1 and CH_4 are turned-off, load dissipates its energy through the path load–$D_3 - E_{dc+} - E_{dc-} - D_2$ – load. In this case, E_0 is negative while I_0 is positive, and fourth-quadrant operation is possible.

When choppers CH_2 and CH_3 are turned-on, current flows through the path, $E_{dc+} - CH_3$ – load – $CH_2 - E_{dc-}$. Since both E_0 and I_0 are negative, we get the third-quadrant operation. When both choppers CH_2 and CH_3 are turned-off, load dissipates its energy through the path load– $D_1 - E_{dc+} - E_{dc-} - D_2$ – load. In this case, E_0 is positive and I_0 is negative, and second-quadrant operation is possible.

This four-quadrant chopper circuit consists of two bridges, forward bridge and reverse bridge. Chopper bridge CH_1 to CH_4 is the forward bridge which permits energy flow from source to load. Diode bridge D_1 to D_4 is the reverse bridge which permits the energy flow from load-to-source. This four-quadrant chopper configuration can be used for a reversible regenerative d.c. drive.

Example 8.16 A four-quadrant chopper is driving a separately excited d motor load. The motor parameters are $R = 0.1$ ohm, $L = 10$ mH. The supply voltage i 200 V d.c. If the rated current of the motor is 10 A and if the motor is driving the rate torque. Determine:

(i) the duty cycle of the chopper if $E_b = 150$ V.

(ii) the duty cycle of the chopper if $E_b = -110$ V.

Solution:

For a four-quadrant chopper, the average voltage in all the four-modes is given by

$$E_0 = 2\,E_{dc} \cdot (\alpha - 0.5)$$

(i) The average current, $i_0 = \dfrac{E_0 - E_b}{R} = \dfrac{2\,E_{dc} \cdot (\alpha - 0.5) - E_b}{R}$

$$10 = \frac{2 \times 200\,(\alpha - 0.5) - 150}{0.1} \quad \therefore\ \alpha = 0.876$$

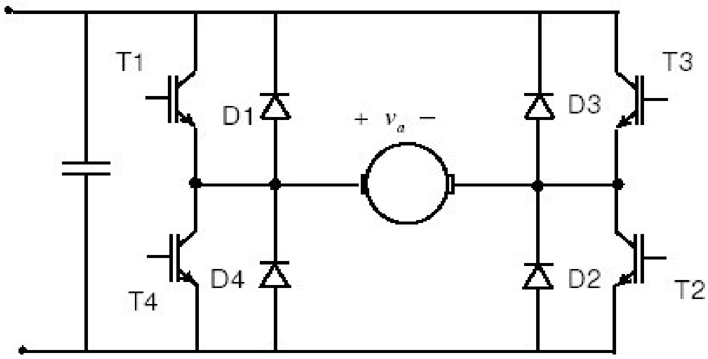
Since, $\alpha > 0.5$, this mode is forward-motoring

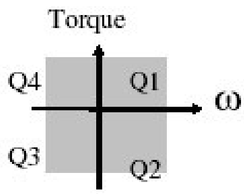
(ii) Now, $10 = \dfrac{2 \times 200\,(\alpha - 0.5) - 110}{0.1}, \quad \therefore\ \alpha = 0.228$

As $\alpha < 0.5$, this mode is reverse motoring mode.

4 Quadrant DC drives

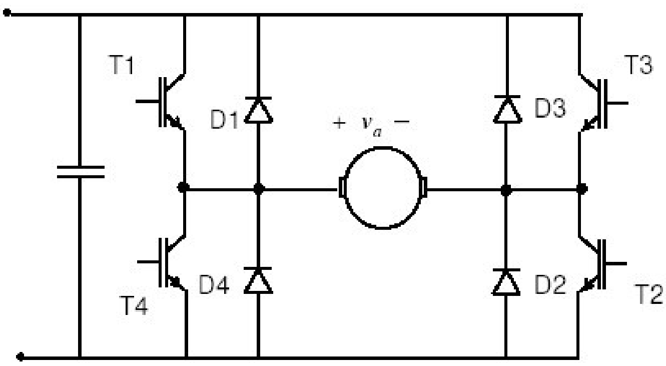
A full-bridge DC-DC converter is used.



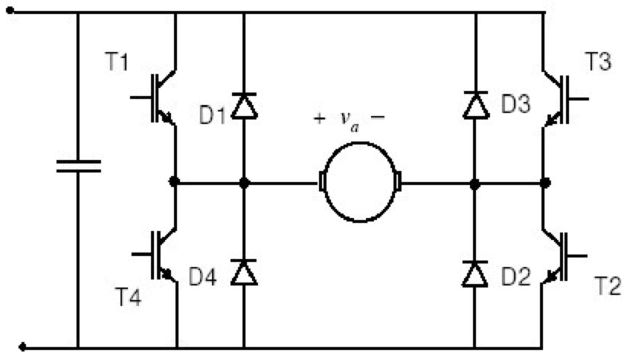


4-quadrant: Forward motoring

- T1 and T2 operate; T3 and T4 off.
- T1 and T2 turn on together: the supply voltage appear across the motor terminal. Armature current rises.
- T1 and T2 turn off: the armature current decay through D3 and D4

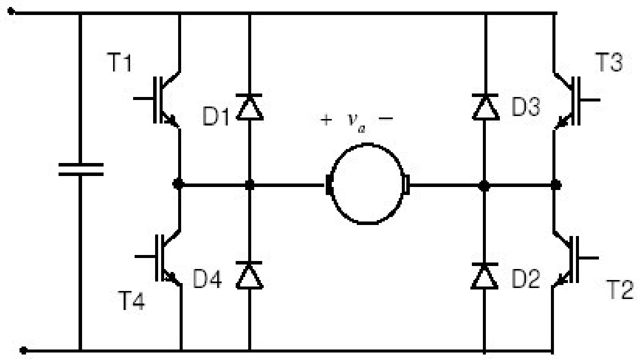


Regeneration



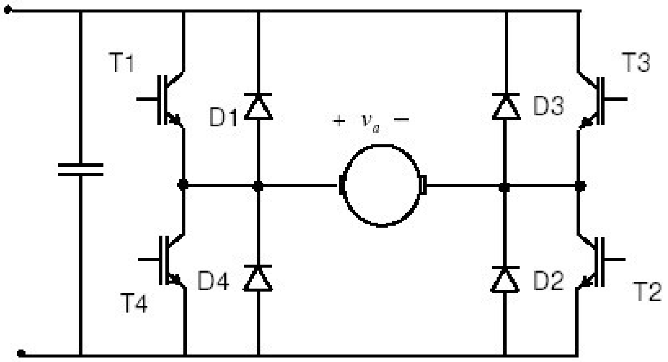
- T1, T2 and T3 turned off.
- When T4 is turned on, the armature current rises through T4 and D2.
- When T4 is turned off, the motor, acting as a generator, returns energy to the supply through D1 and D2.

Reverse Motoring



- T3 and T3 operate; T1 and T2 off.
- When T3 and T4 are on together, the armature current rises and flows in reverse direction.
- Hence the motor rotates in reverse direction.
- When T3 and T4 turn off, the armature current decays through D1 and D2.

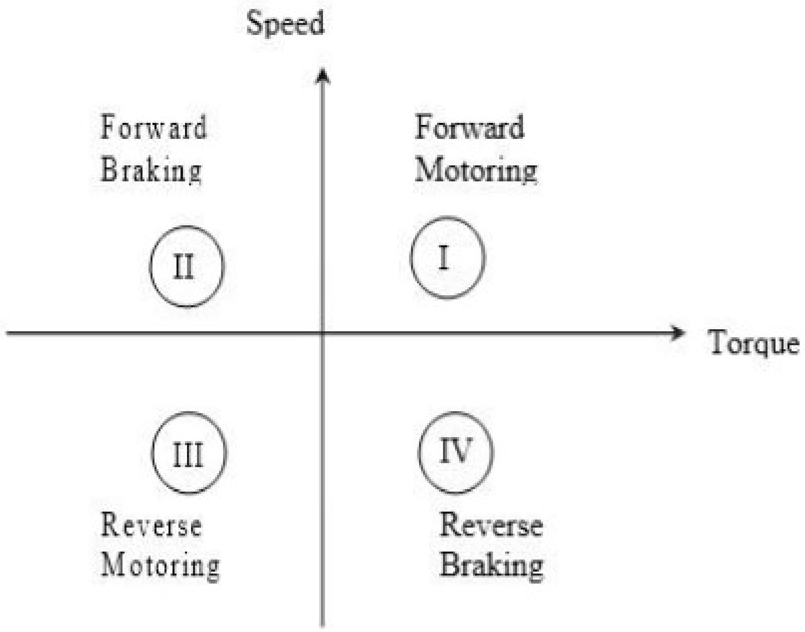
Reverse Generation

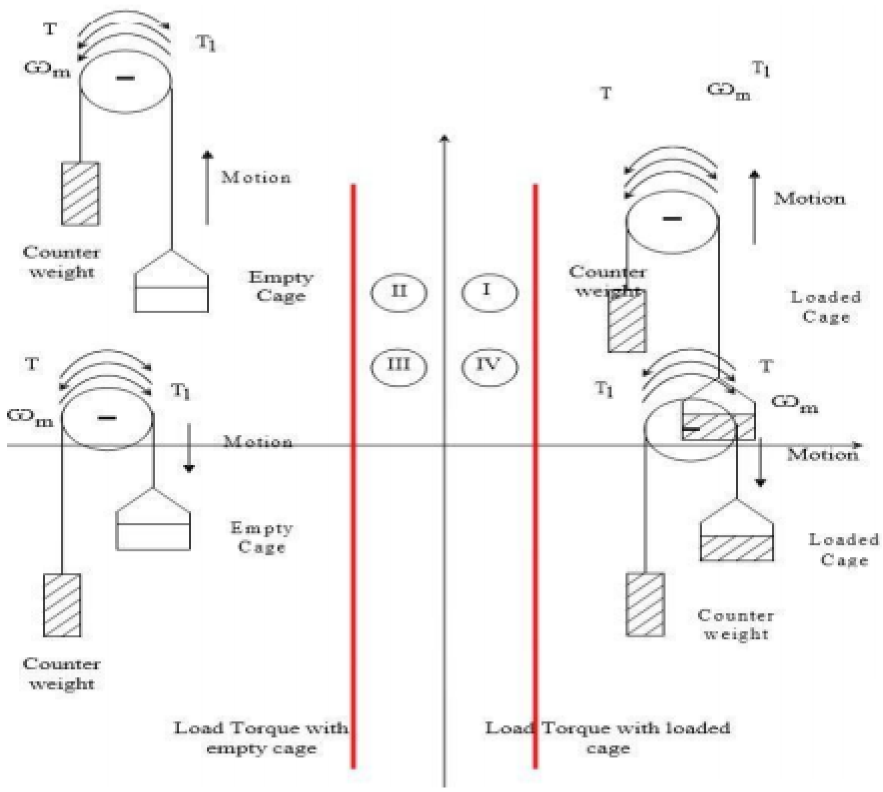


- ✓ T1, T3 and T4 are off.
- ✓ When T1 is on, the armature current rises through T2 and D4.
- ✓ When Q2 is turned off, the armature current falls and the motor returns energy to the supply through D3 and D4.

Introduction to four quadrant operation: Motoring operations

- For consideration of multi quadrant operation of drives, it is useful to establish suitable conventions about the signs of torque and speed.
- A motor operates in two modes – Motoring and braking. In motoring, it converts electrical energy into mechanical energy, which supports its motion. In braking it works as a generator converting mechanical energy into electrical energy and thus opposes the motion.
- Now consider equilibrium point B which is obtained when the same motor drives another load as shown in the figure. A decrease in speed causes the load torque to become greater than the motor torque, electric drive decelerates and operating point moves away from point B.
- Similarly when working at point B and increase in speed will make motor torque greater than the load torque, which will move the operating point away from point B
- Similarly operation in quadrant III and IV can be identified as reverse motoring and reverse braking since speed in these quadrants is negative.


Speed
Forward Braking
Forward Motoring
II
I
Torque
III
IV
Reverse Motoring
Reverse Braking


Motion
Counter weight
Empty Cage
II
I
III
IV
Loaded Cage
Motion
Empty Cage
Counter weight
Loaded Cage
Counter weight
Load Torque with empty cage
Load Torque with loaded cage

For better understanding of the above notations, let us consider operation of hoist in four quadrants as shown in the figure. Direction of motor and load torques and direction of speed are marked by arrows.

A hoist consists of a rope wound on a drum coupled to the motor shaft one end of the rope is tied to a cage which is used to transport man or material from one level to another level . Other end of the rope has a counter weight. Weight of the counter weight is chosen to be higher than the weight of empty cage but lower than of a fully loaded cage.

Types of Braking

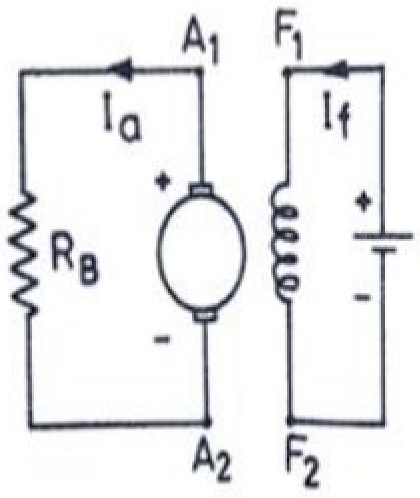
- Brakes are used to reduce or cease the speed of motors. We know that there are various types of motors available (DC motors, induction motors, synchronous motors, single phase motors etc.) and the specialty and properties of these motors are different from each other, hence this braking methods also differs from each other. But we can divide braking in to three parts mainly, which are applicable for almost every type of motors.

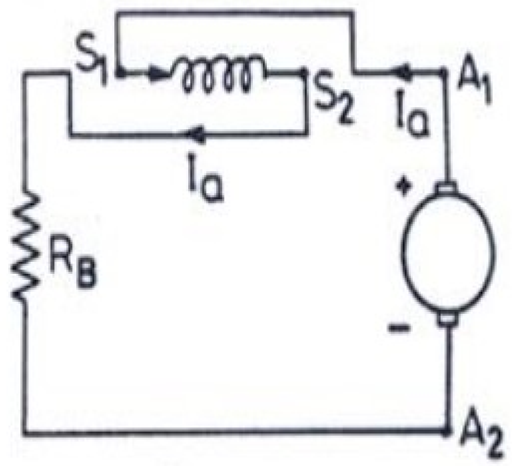
  i) Regenerative Braking

  ii) Plugging type braking

  iii) Dynamic braking

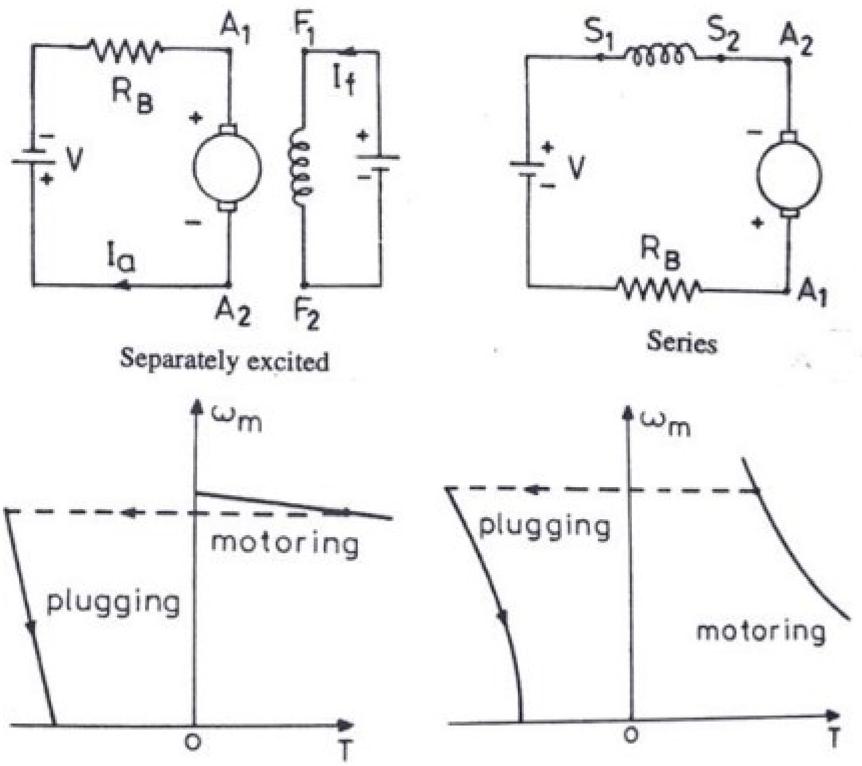
Another method of reversing the direction of torque and braking the motor is dynamic braking. In this method of braking the motor which is at a running condition is disconnected from the source and connected across a resistance. When the motor is disconnected from the source, the rotor keeps rotating due to inertia and it works as a self –excited generator. When the motor works as a generator the flow of the current and torque reverses. During braking to maintain the steady torque sectional resistances are cut out one by one.





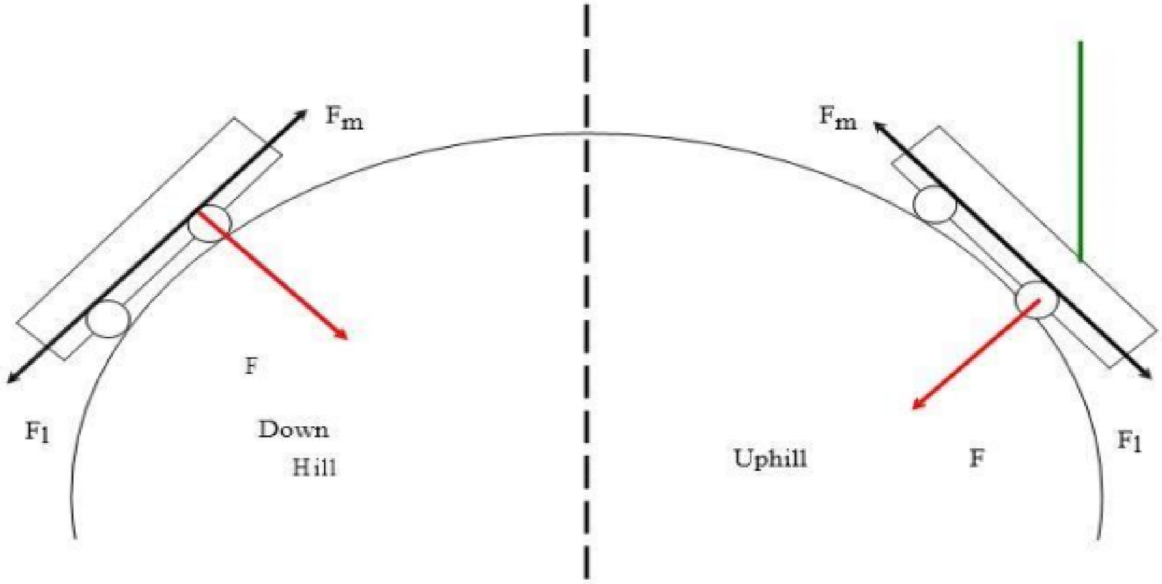
Plugging Type Braking

- Another type of braking is plugging type braking. In this method the terminals of supply are reversed, as a result the generator torque also reverses which resists the normal rotation of the motor and as a result the speed decreases. During plugging external resistance is also introduced into the circuit to limit the flowing current. The main disadvantage of this method is that here power is wasted.

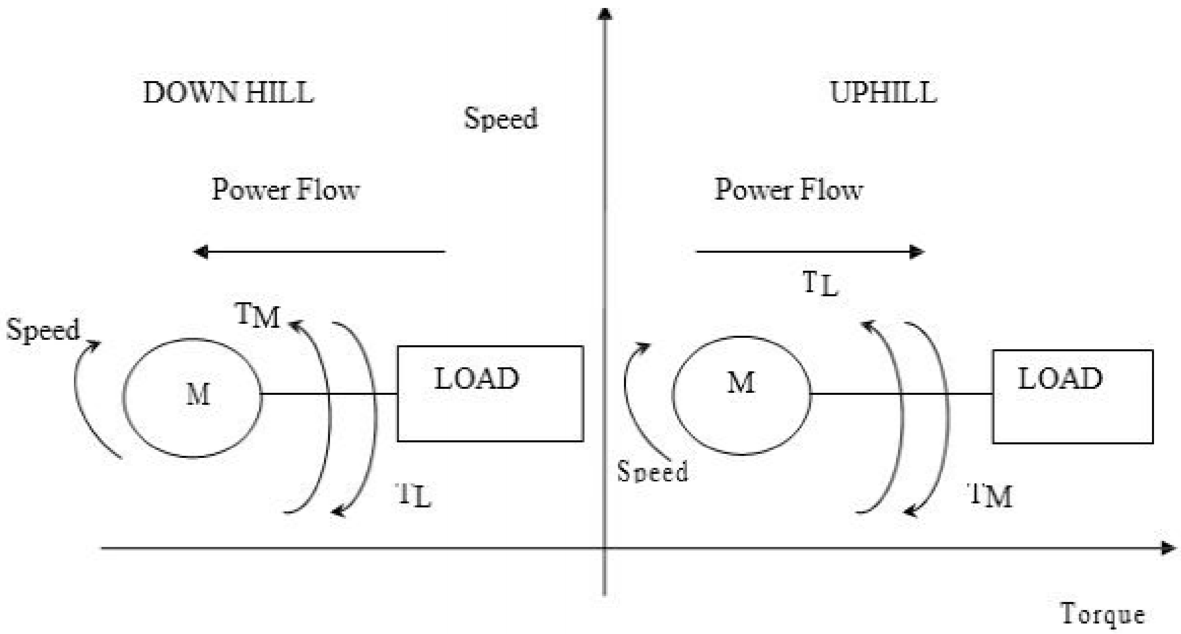


Regenerative braking operations

- Regenerative braking takes place whenever the speed of the motor exceeds the synchronous speed. This baking method is called regenerative braking because here the motor works as generator and supply itself is given power from the load, i.e. motors. The main criteria for regenerative braking is that the rotor has to rotate at a speed higher than synchronous speed, only then the motor will act as a generator and the direction of current flow through the circuit and direction of the torque reverses and braking takes place.



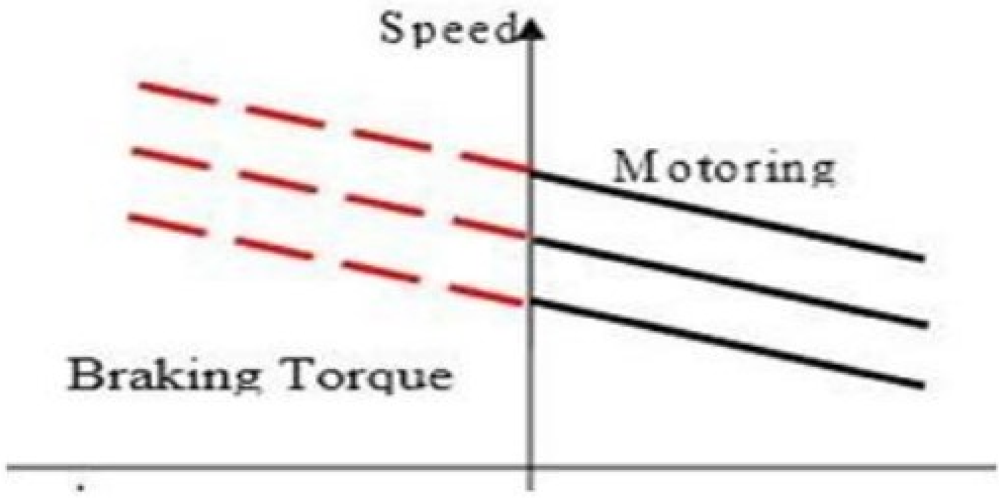
Regenerative braking of electric vehicle



Regenerative Braking for DC motor:

In regenerative braking of dc motor, generated energy is supplied to the source. For this the following condition is to be satisfied.

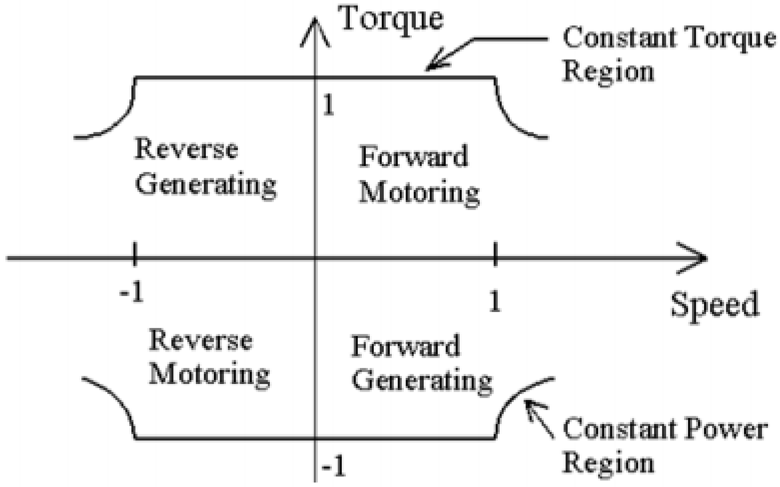
$E > V$ and I_a should be negative



Regenerative braking speed torque characteristics of dc shunt motor

Four quadrant operation of DC motors by dual converters

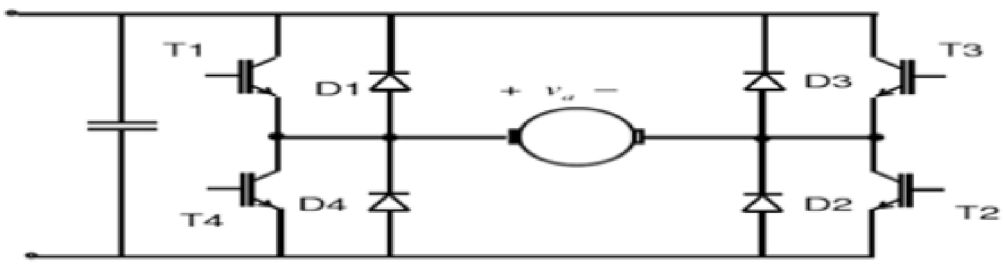
- Separately-excited dc shunt motor can be operated in either direction in either of the two modes, the two modes being the motoring mode and the regenerating mode.
- It can be seen that the motor can operate in any of the four quadrants and the armature of the dc motor in a fast four-quadrant drive is usually supplied power through a dual converter. The dual converter can be operated with either circulating current or without circulating current.
- If both the converters conduct at the same time, there would be circulating current and the level of circulating current is restricted by provision of an inductor.

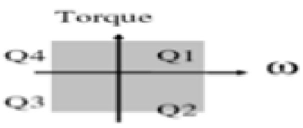


Four quadrant operations

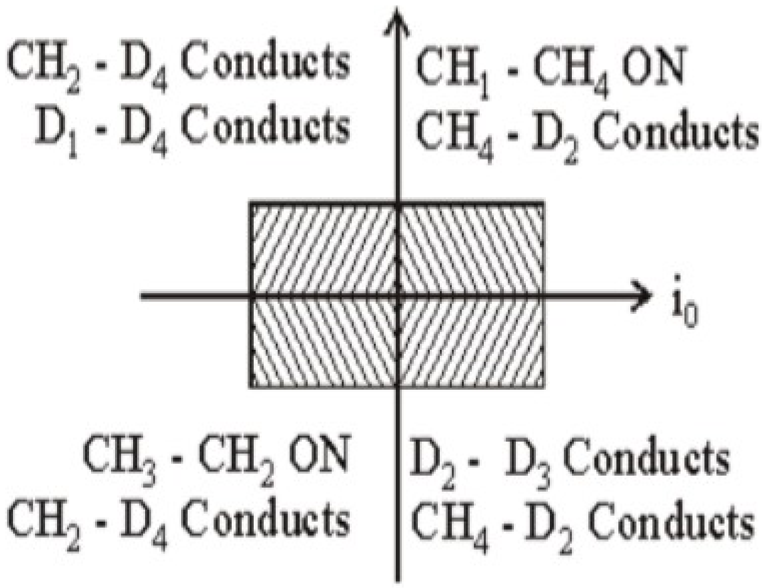
Four quadrant chopper fed DC separately excited and series motors with continuous current operation:

A full-bridge DC-DC converter is used.





- Class E is a four quadrant chopper
- When CH1 and CH4 are triggered, output current i_O flows in positive direction through CH1 and CH4, and with output voltage $v_O = V$.
- This gives the first quadrant operation.
- When both CH1 and CH4 are OFF, the energy stored in the inductor L drives i_O through D2 and D3 in the same direction, but output voltage $v_O = -V$.
- Therefore the chopper operates in the fourth quadrant.
- When CH2 and CH3 are triggered, the load current i_O flows in opposite direction & output voltage $v_O = -V$.
- Since both i_O and v_O are negative, the chopper operates in third quadrant.
- When both CH2 and CH3 are OFF, the load current i_O continues to flow in the same direction D1 and D4 and the output voltage $v_O = V$.
- Therefore the chopper operates in second quadrant as v_O is positive but i_O is negative.



4.7.3 Four-Quadrant Control

The four-quadrant operation can be obtained by using the class E chopper shown in 4.15. The chopper can be controlled using the following methods.

Method I. If S_2 is kept closed continuously and S_1 and S_4 are controlled, one gets a two-quadrant chopper as shown in figure 4.12a. This provides a variable positive terminal voltage and the armature current in either direction, giving the motor control in quadrants I and II.

Now if S_3 is kept closed continuously and S_1 and S_4 are controlled, a two-quadrant chopper is obtained, which can supply a variable negative terminal voltage and the armature current in either direction, giving motor control in quadrants III and IV.

For the changeover from forward motoring to reverse motoring, the following sequence of steps is followed.

In the first quadrant S_2 is on continuously, and S_1 and S_4 are being controlled. For the changeover, δ is reduced to its minimum value. The motor current reverses [equation (4.33)] and reaches the maximum permissible value. The current control

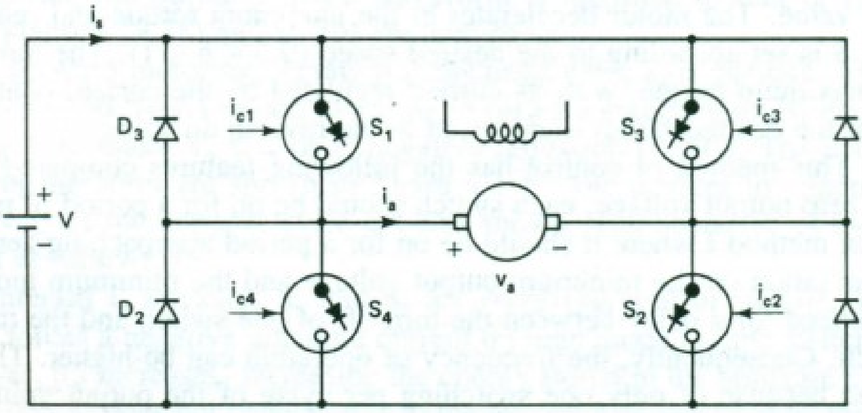


Figure 4.15 Class E four-quadrant chopper.

loop restricts it from exceeding the maximum permissible value. The motor decelerates at the maximum torque and reaches zero speed. Now S_2 is opened, S_3 is continuously closed and δ for the pair S_1, S_4 is adjusted corresponding to the desired speed. The motor now accelerates at the maximum torque in the reverse direction and its current is regulated by the current-control loop. Finally it settles at the desired speed.

This method of control has the following features: The utilization factor of the switches is low due to the asymmetry in the circuit operation. Switches S_3 and S_2 should remain on for a long period. This can create commutation problems when the switches are realized using thyristors. The minimum output voltage depends directly on the minimum time for which the switch can be closed. Since there is always a restriction on the minimum time for which the switch can be closed, particularly in thyristor choppers, the minimum available output voltage, and, therefore, the minimum available motor speed, is restricted.

To ensure that the switches S_1 and S_4, and S_3 and S_4 are not on at the same time, some fixed time interval must elapse between the turn-off of one switch and the turn-on of another switch. This restricts the maximum permissible frequency of operation. It also requires two switching operations during a cycle of the output voltage.

Method II. Switches S_1 and S_2 with diodes D_1 and D_2 provide a circuit identical to the chopper of figure 4.13. This chopper can provide a positive current and a variable voltage in either direction, thus allowing motor control in quadrants I and IV. Switches S_3 and S_4 with diodes D_3 and D_4 form another chopper, which can provide a negative current and a variable voltage in either direction, thus allowing the motor control in quadrants II and III.

The switch-over from quadrant I to quadrant III can be carried out using the following sequence of steps. In quadrant I, the switches S_1 and S_2 are controlled with $0.5 < \delta < 1.0$. The armature current has the direction shown in figure 4.15. For the changeover, S_1 and S_2 are turned off. The armature current now flows through diode D_1, source V, and diode D_2, and quickly falls to zero. The motor back emf has the polarity with the left terminal positive. Now the switches S_3 and S_4 are controlled with δ in the range $0 < \delta < 0.5$, but approaching 0.5. The motor current flows in the reverse direction and reaches the maximum value [equation (4.39)]. The current-control loop regulates δ to keep the current from exceeding the maximum permissible value. The motor decelerates at the maximum torque and reaches zero speed. Now δ is set according to the desired speed ($0.5 < \delta < 1$). The motor accelerates at the maximum torque, with its current regulated by the current-control loop and settles at the desired steady-state speed in the reverse direction.

This method of control has the following features compared to method I: At near-zero output voltage, each switch should be on for a period of nearly T sec., unlike in method I where it should be on for a period approaching zero. Thus, there is no limitation on the minimum output voltage and the minimum motor speed. There is no need for a delay between the turn-off of one switch and the turn-on of another switch. Consequently, the frequency of operation can be higher. The switching loss is less because of only one switching per cycle of the output voltage compared to two in method I. Due to the symmetrical operation, the switches have a better utilization factor.

Method III. This method is a modification of method II. In method II, switches S_1 and S_2 with diodes D_1 and D_2 form one chopper, which allows motor control in quadrants I and IV. The second chopper, providing operation in quadrants II and III is formed by switches S_3 and S_4, and diodes D_3 and D_4. In method II, these choppers are controlled separately. In the present method, these choppers are controlled simultaneously as follows.[9]

The control signals for the switches S_1–S_4 are denoted by i_{c1}, i_{c2}, i_{c3}, and i_{c4}, respectively. As with the convention adopted, a switch conducts if its control signal is present and it is forward biased; otherwise it remains open. The control signal i_{c1} to i_{c4}, and the waveform of v_a, i_a, and i_s for forward motoring and forward regeneration are shown in figure 4.16a and b, respectively. Switches S_1 and S_2 are given control signals with a phase difference of T secs. Switch S_1 receives a control signal from $t = 0$ to $t = 2\delta T$, where $\delta = t_{on}/2T$. The control signal for switch S_2 is present from $t = T$ to $t = T + 2\delta T$. Switches S_1 and S_4, and S_2 and S_3 form complementary pairs in the sense that the switches of the same pair receive control signals alternately. Usually some interval must elapse between the turn-off of one switch and the turn-on of another switch of the same pair to ensure that they are not on at the same time. This interval has been neglected in drawing the waveforms of figure 4.16.

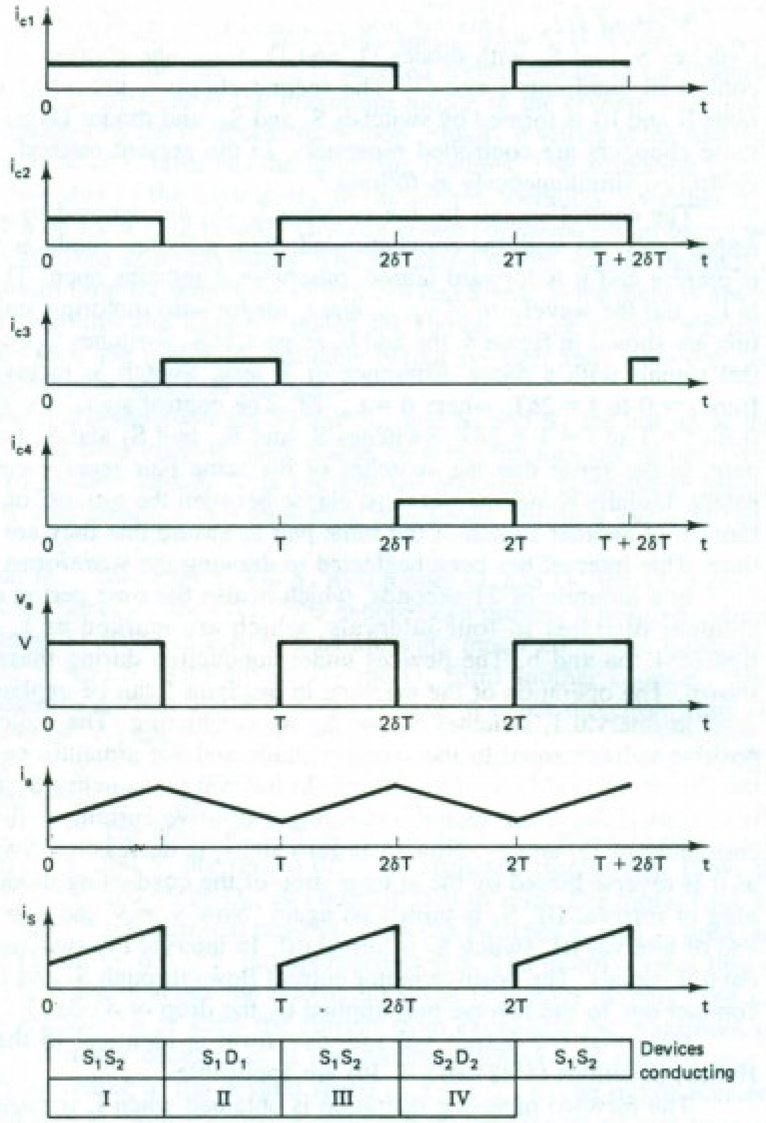
In a duration of 2T seconds, which is also the time period of each switch, the chopper operates in four intervals, which are marked as I, II, III, and IV in figures 4.16a and b. The devices under conduction during these intervals are also shown. The operation of the machine in quadrant I can be explained as follows.

In interval I, switches S_1 and S_2 are conducting. The motor is subjected to a positive voltage equal to the source voltage and the armature current increases. At the end of interval I, S_2 is turned off. In interval II, switches S_1 and S_3 receive control signals. Since the motor is carrying a positive current, it flows through a path consisting of D_1 and S_1. Now v_a is zero and i_a is decreasing. Switch S_3 remains off as it is reverse biased by the voltage drop of the conducting diode D_1. At the beginning of interval III, S_2 is turned on again. Now $v_a = V$ and i_a is increasing. At the end of interval III, switch S_1 is turned off. In interval IV, switches S_2 and S_4 receive control signals. The positive motor current flows through S_2 and D_2, and S_4 does not conduct due to the reverse bias applied by the drop of diode D_2.

Note that the output voltage waveform is identical to that of figure 4.14a. Hence, equations (4.38) and (4.39) are applicable.

The forward motoring operation is obtained when I_a is positive. The operation can be transferred from forward motoring to forward regeneration by decreasing δ or increasing E to make $V_a < E$ or I_a negative [equation (4.39)]. The waveforms for forward regeneration are shown in figure 4.16b. The devices in conduction in the four intervals of the chopper cycle are also shown. The operation of the chopper is explained as follows.

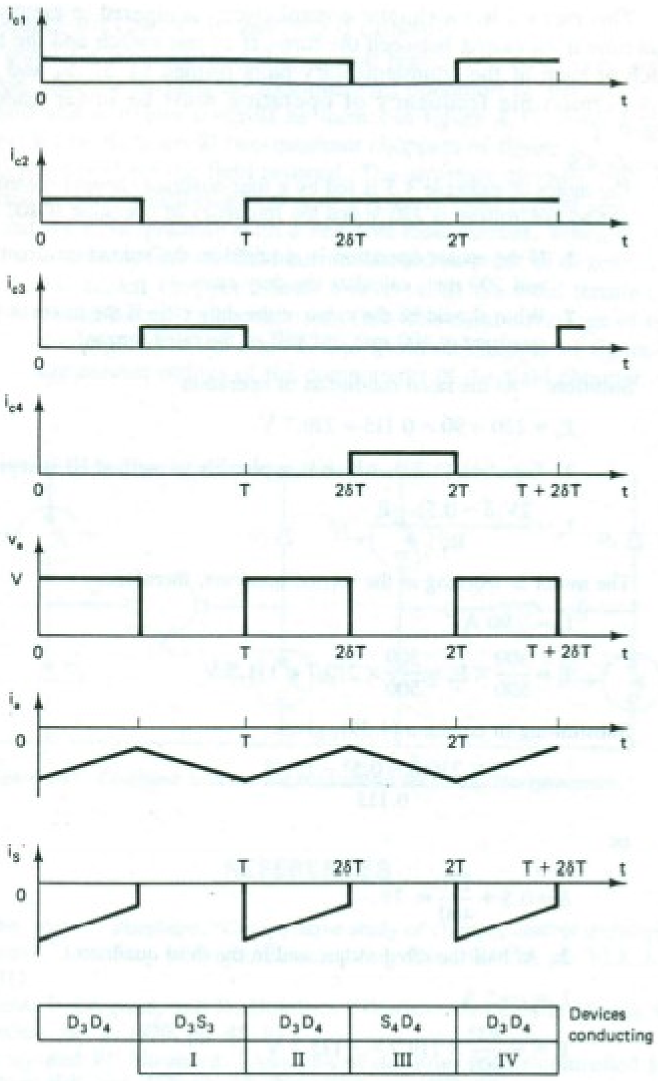
In interval I, switches S_1 and S_3 are receiving control signals. The positive back emf forces a negative armature current through diode D_3 and switch S_3. During this interval, $|i_a|$ increases, increasing the energy stored in the armature circuit inductance. Switch S_1 does not conduct due to the reverse bias provided by the drop of the conducting diode D_3. Switch S_3 is opened at the end of interval I. The armature current is forced through diode D_3, source V, and diode D_4, and the energy is fed to the



(a) Forward motoring, $0.5 \leq \delta \leq 1.0$ and $V_a > E$

Figure 4.16 Waveforms of the four quadrant chopper of Fig. 4.15 using *method III* *(continued on next page)*.

source. Although switches S_1 and S_2 are receiving the control signals, they remain open due to the reverse bias provided by the voltage drops of diodes D_3 and D_4. The motor terminal voltage is now V and $|i_a|$ is decreasing. S_4 is turned on in interval III. The armature current now flows through switch S_4 and diode D_4. Switch S_2 also receives a control signal; however, it does not conduct due to the reverse bias applied by diode D_4. The armature current magnitude again builds up. S_4 is turned off at the



(b) Forward regeneration, $0.5 \leq \delta \leq 1.0$ and $V_a < E$

Figure 4.16 (continued).

end of interval III. The armature current is forced again through diode D_3, the source, and diode D_4, and the energy is fed to the source.

The motoring and regenerative braking operations in the reverse direction are obtained when $0 < \delta < 0.5$, for which V_a is negative. Reverse motoring is obtained by setting δ such that $|V_a| > |E|$ and reverse regeneration is realized when $|E| > |V_a|$.

This method has a simpler control circuit compared to methods I and II. Since some time must elapse between the turn-off of one switch and the turn-on of another switch of each of the complementary pairs formed by S_1, S_4 and S_2, S_3, the maximum permissible frequency of operation must be lower compared to that of method II.

Four-quadrant Operation with Field Control

When field control is required for getting speeds higher than base speed and the transient response need not be fast, the four-quadrant operation is obtained by a combination of field and armature controls as shown in figure 4.17. Both armature and field are supplied by the class D two-quadrant choppers of figure 4.13. The reversal switch RS is employed for the field reversal. The armature chopper provides operation in the first and the fourth quadrant with a positive field current and operation in the second and the third quadrant with a negative field current. When the field connection is to be reversed, first the field current should be reduced to zero. The use of the class D two-quadrant chopper allows a reversal of the field terminal voltage, which forces the field current to become zero fast. The main advantage of this circuit is the lower cost compared to the class E four-quadrant chopper of figure 4.13, because of the lower current ratings of the components of the field chopper.

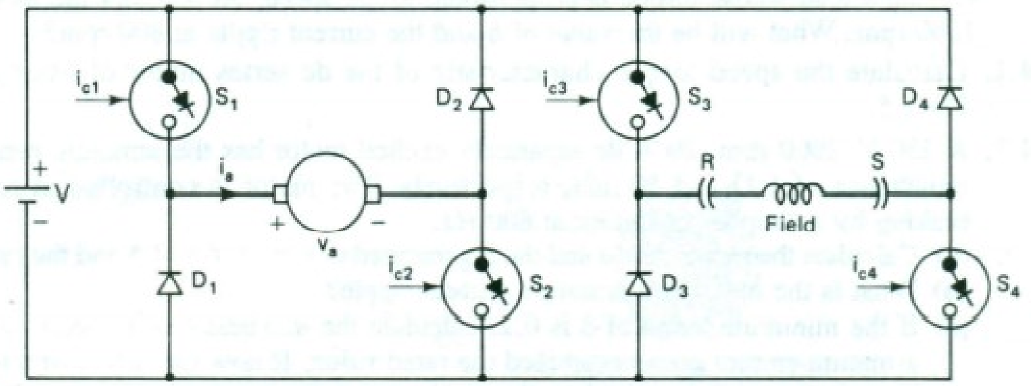


Figure 4.17 Combined armature and field control for four-quadrant operation.

Example 4.5

The motor of example 4.3 is fed by a four-quadrant chopper controlled by method III. The source voltage is 230 V and the frequency of operation is 400 Hz.

1. If the motor operation is required in the second quadrant at the rated torque and 300 rpm, calculate the duty ratio.
2. What should be the value of the duty ratio if the motor is working in the third quadrant at 400 rpm and half of the rated torque?

Solution: At the rated conditions of operation

$$E_r = 230 - 90 \times 0.115 = 219.7 \text{ V}$$

1. Equation (4.39), which is applicable to method III is reproduced here:

$$I_a = \frac{2V(\delta - 0.5) - E}{R_a} \tag{4.39}$$

The motor is working in the second quadrant, therefore,

$$I_a = -90 \text{ A}$$

$$E = \frac{300}{500} \times E_r = \frac{300}{500} \times 219.7 = 131.8 \text{ V}$$

Substituting in equation (4.39), gives

$$-90 = \frac{2 \times 230(\delta - 0.5) - 131.8}{0.115}$$

or

$$\delta = 0.5 + \frac{121}{460} = .76\,.$$

2. At half the rated torque and in the third quadrant

$$I_a = -45 \text{ A}$$

$$E = -\frac{400}{500} \times 219.7 = -175.7 \text{ V}$$

Substituting in equation (4.39), gives

$$-45 = \frac{2 \times 230(\delta - 0.5) + 175.7}{0.115}$$

or

$$\delta = 0.5 - \frac{181}{460} = 0.11\,.$$

6.5. THE FOUR-QUADRANT CHOPPER

A d.c. brush motor with separate excitation is fed through a four-quadrant chopper (Table 6.1e). Show the waveforms of voltage and current in the third and fourth quadrants.

<u>Solution</u>:

The basic circuit of a four-quadrant chopper is shown in Figure 6.9.

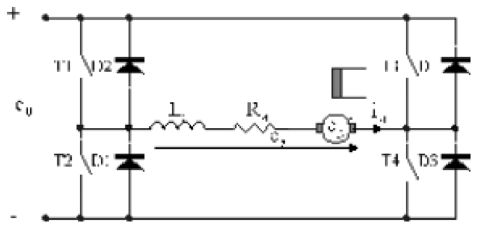


Figure 6.9. D.c. brush motor fed through a four-quadrant chopper

If T_4 is on all the time, T_1-D_1 and T2-D2 provide first- and (respectively) second-quadrant operations as shown in previous paragraphs. With T_2 on all the time and T_3-D_3 and, respectively, T_4-D_4 the third- and fourth-quadrant operations is obtained (Figure 6.10). So, in fact, we have 2 two-quadrant choppers acting in turns.

However, only 2 out of 4 main switches are turned on and off with the frequency f_{ch} while the third main switch is kept on all the time and the fourth one is off all the time.

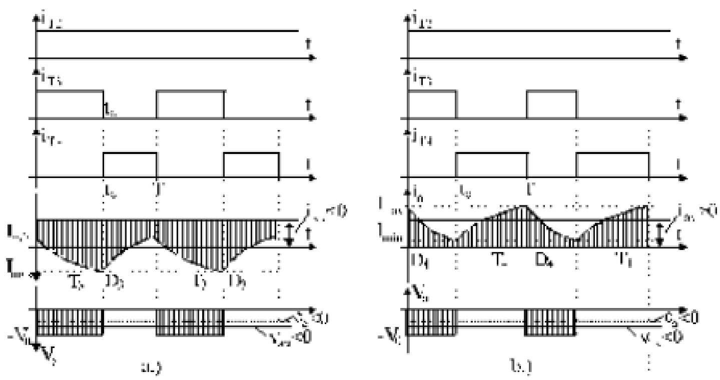


Figure 6.10. Four-quadrant chopper supplying a d.c. brush motor

a.) Third quadrant: iav<0, Vav<0; b.) Fourth quadrant: iav>0, Vav<0.

Four-quadrant operation is required for fast response reversible variable speed drives.

As expected, discontinuous current mode is also possible but it should be avoided by increasing the switching frequency f_{ch} or adding an inductance in series with the motor.

Let us assume that:

A d.c. brush motor, fed through a four-quadrant chopper, works as a motor in the third quadrant (reverse motion). The main data are $V_0 = 120V$, $R_a = 0.5\Omega$, $L_a = 2.5mH$, rated current $I_{an} = 20A$; rated speed $n_n = 3000$ rpm; separate excitation.

a. Calculate the rated e.m.f., e_g, and rated electromagnetic torque, T_e.

b. For $n = -1200$ rpm and rated average current ($i_{av} = -I_{an}$) determine the average voltage V_{av}, $t_c / T = \alpha_{on}$, and maximum and minimum values of motor current I_{max} and I_{min} for 1kHz switching frequency.

<u>Solution</u>:

a. The motor voltage equation for steady state is:

$$V_{av} = R_a i_a + e_g \tag{6.54}$$

for rated values $V_{av} = V_0 = 120V$, $i_a = i_{an} = 20A$, thus

$$e_{gn} = K_e \lambda_p n_n = V_{av} - R_a i_a = 120 - 20 \cdot 0.5 = 110 \text{ V} \tag{6.55}$$

$$K_e \lambda_p = \frac{e_{gn}}{n_n} = \frac{110}{50} = 2.2 \text{ Wb} \tag{6.56}$$

b. The motor equation in the third quadrant is

$$V_{av} = R_a i_a + e_g = 0.5 \cdot (-20) + 2.2 \cdot (-20) = -54 \text{ V}, \tag{6.57}$$

the conducting time t_c for T_3 (Figure 6.10a) is

$$\frac{t_c}{T} = \frac{V_{av}}{-V_0} = \frac{-54}{-120} = 0.45 \tag{6.58}$$

$$t_c = T \cdot 0.45 = \frac{1}{f_{ch}} \cdot 0.45 = \frac{1}{10^3} \cdot 0.45 = 0.45 \cdot 10^{-3} \text{ s} \tag{6.59}$$

Form ((6.40)-(6.41)) the motor current variation (Figure 6.10a) is described by

$$i_a = \frac{V_0' - e_g}{R_a} + A \cdot e^{-t\frac{R_a}{L_a}}; \quad 0 < t \le t_c \tag{6.60}$$

$$i_a' = -\frac{e_g}{R_a} + A' \cdot e^{-(t-t_c)\frac{R_a}{L_a}}; \quad t_c < t \le T \tag{6.61}$$

The current continuity condition ($i_a(t_c) = i_a'(t_c)$) provides

$$t_c = -\frac{L_a}{R_a} \cdot \ln\left[\left(A' - \frac{V_0'}{R_a}\right) / A\right] \tag{6.62}$$

The second condition is obtained from the average current expression

$$i_{av} = \frac{1}{T}\left[\int_0^{t_c} i_a dt + \int_{t_c}^{T} i_a' dt\right] =$$

$$\frac{1}{T}\left\{\frac{V_0' - e_g}{R_a} t_c - \frac{e_g}{R_a}(T - t_c) + \frac{L_a}{R_a}\left[\left(1 - e^{-t_c\frac{R_a}{L_a}}\right)A + A'\left(1 - e^{-(T-t_c)\frac{R_a}{L_a}}\right)\right]\right\} \tag{6.63}$$

From (6.62) and (6.63) we obtain:

$$\left(A' - \frac{V_0'}{R_a}\right) / A = e^{-t_c\frac{R_a}{L_a}};$$

$$V_0' = -V_0; \quad e_g = K_e \lambda_p n = 2.2 \cdot (-20) = -44 \text{ V}$$

$$\left(A' + \frac{(-120)}{0.5}\right) / A = e^{-0.45 \cdot 10^{-3} \frac{0.5}{2.5 \cdot 10^{-3}}} = 0.914 \tag{6.64}$$

$$-20 = 10^3\left\{\frac{-120-(-44)}{0.5}0.45\cdot 10^{-3} - \frac{(-44)}{0.5}0.55\cdot 10^{-3} + \frac{2.5\cdot 10^{-3}}{0.5}\left[\left(1-e^{-0.45\cdot 10^{-3}\frac{0.5}{3.5\cdot 10^{-3}}}\right)A + A'\left(1-e^{-0.55\cdot 10^{-3}\frac{0.5}{3.5\cdot 10^{-3}}}\right)\right]\right\} \quad (6.65)$$

$$-20 = -20 + 0.43A + 0.5205A' \quad (6.66)$$

$$0.43A + 0.5205A' = 0 \quad (6.67)$$

$$A' + 240 = 0.914A \quad (6.68)$$

$$A = 137.62;\ A' = -113.92 \quad (6.69)$$

Now we may calculate $I_{min} = i_a(0)$

$$I_{min} = A + \frac{V_0' - e_g}{R_a} = 137.92 + \frac{-120-(-44)}{0.5} = -15.08 \text{ A} \quad (6.70)$$

Also $I_{max} = i_a'(t_c)$

$$I_{max} = A' - \frac{e_g}{R_a} = -113.92 + \frac{-(-44)}{0.5} = -25.92 \text{ A} \quad (6.71)$$