2.3 Continuous conduction

Let us assume that the armature current is continuous over the whole range of operation. Typical voltage and current waveforms are shown in Fig for semi-converter and full-converter systems, respectively. The thyristors are symmetrically triggered. In the semi-converter system shown in Fig. thyristor Sl is triggered at an angle a and S2atan anglea+7T with respect to the supply voltage v. In the full-converter system shown in Fig. thyristors S,and S3 are simultaneously triggered at a, thyristors S2 and S4 are triggered at 7T +a.

In Fig. the motor is connected to the input supply for the period a<wt<7T through Sl and D2, and the motor terminal voltage ea is the same as the supply input voltage v. Beyond 7T, ea tends to reverse as the input voltage changes polarity. This will forward-bias the free-wheeling diode and DFW will start conducting. The motor current ia, which was flowing from the supply through Sl' is transferred to DFW (i.e., Sl commutates). The motor terminals are shorted through thefree-wheelingdiodeduring7T <wt <(7T+a), making eo zero. Energy from the supply is therefore delivered to the armature

Circuit when the thyristor conducts (a to7T). This energy is partially stored in the inductance, partially stored in the kinetic energy (K.E.) of the moving system, and partially used to supply the mechanical load. During the free-wheeling period, 7T to7T +a, energy is recovered from the inductance and is converted to mechanical form to supplement the K.E.in supplying the mechanical load. The free-wheeling armature current continues to produce electromagnetic torque in the motor. No energy is feedback to the supply during this period.

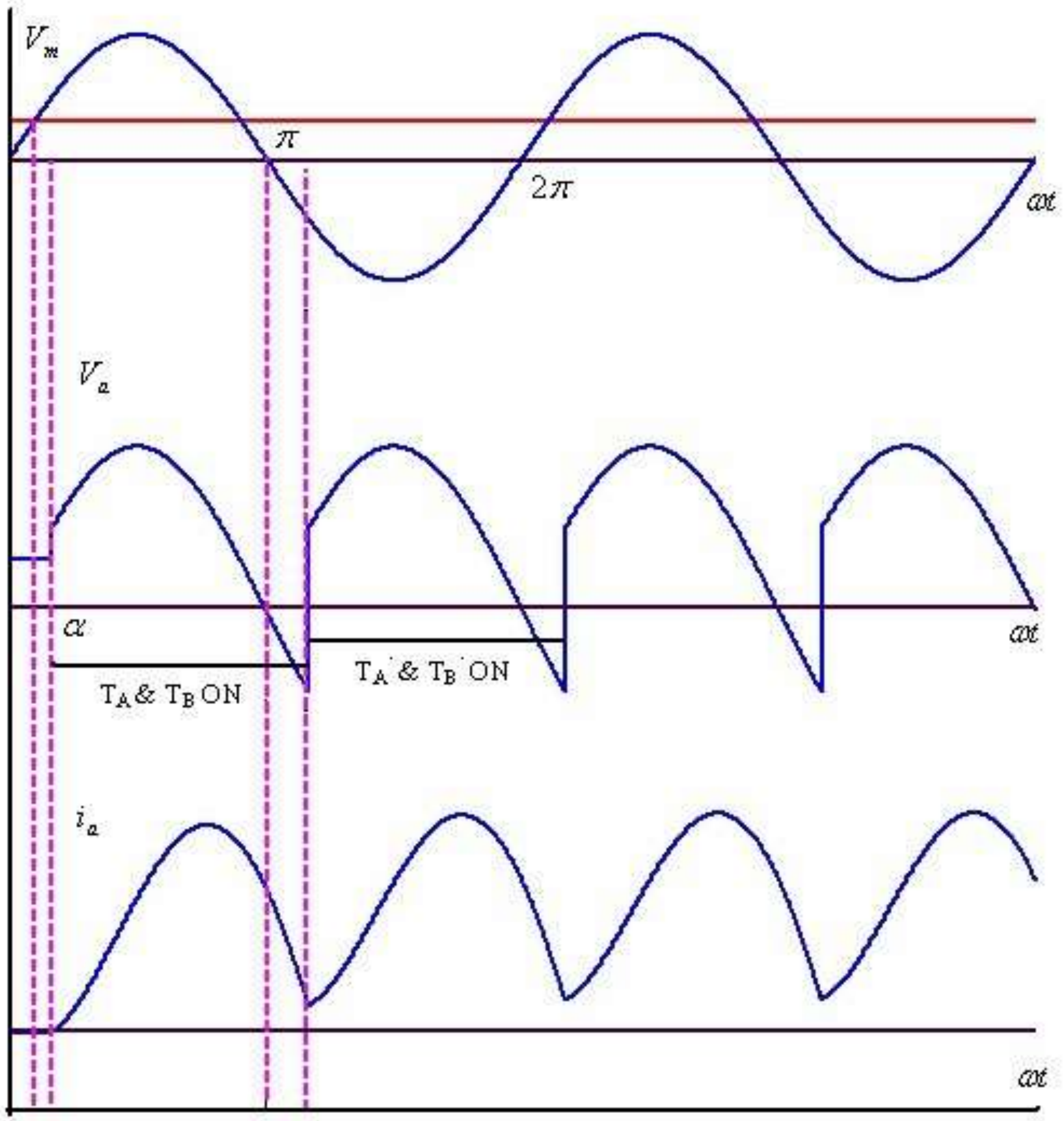


Figure 2.3.1 Continuous conduction waveform

(Source:"Fundamentals of Electrical Drives" by G.K.Dubey,page-108)

In Fig. the motor is always connected to the input supply through the thyristors. Thyristors Sl and S3conduct during the interval a<wt <(7T +a) and connect the motor to the supply. At 7T +a, thyristors S2 and S4aretriggered.Immediately the supply voltage appears across the thyristors Sl and S3asareverse- bias voltage and turns them off. This is called natural or line commutation. The motor current ia, which was flowing from the supply through Sl and S3'istransferred toS2and S4.During ato7T,energy flows from the input supply to the motor (both v and ia a re positive, and eo and io are positive, signifying positive power flow). However, during 7T to 7T +a, some of the motor system energy is feedback to the input supply(v and I have opposite polarities and likewise ea and io' signifying reverse power flow).voltage and current waveforms are shown for a firing angle greater than 90°.The average motor terminal voltage Eo is negative. If the motor back emf Eg is reversed, it will behave as a de- generator and will feed power back to the ac supply. This is known as the inversion operation of the converter, and this mode of operation is used in the regenerative braking of the motor.

2.5 Four Quadrant Operation of a Converters:

FirstQuadrant–Forwardmotoringmode

For first quadrant operation, thyristor S4 is kept on, thyristor S3 is kept off and thyristor switch S1 is operated. With S1, S4 ON, armature voltage $V_a = V_s$ and armature control I_a begins flow. Here both V_a and I_a are positive giving first quadrant operation, when S1 is turned off, positive current freewheels through S4, D2. In this manner, V_a, I_a can be controlled in this first quadrant, and operation gives forward motoring mode.

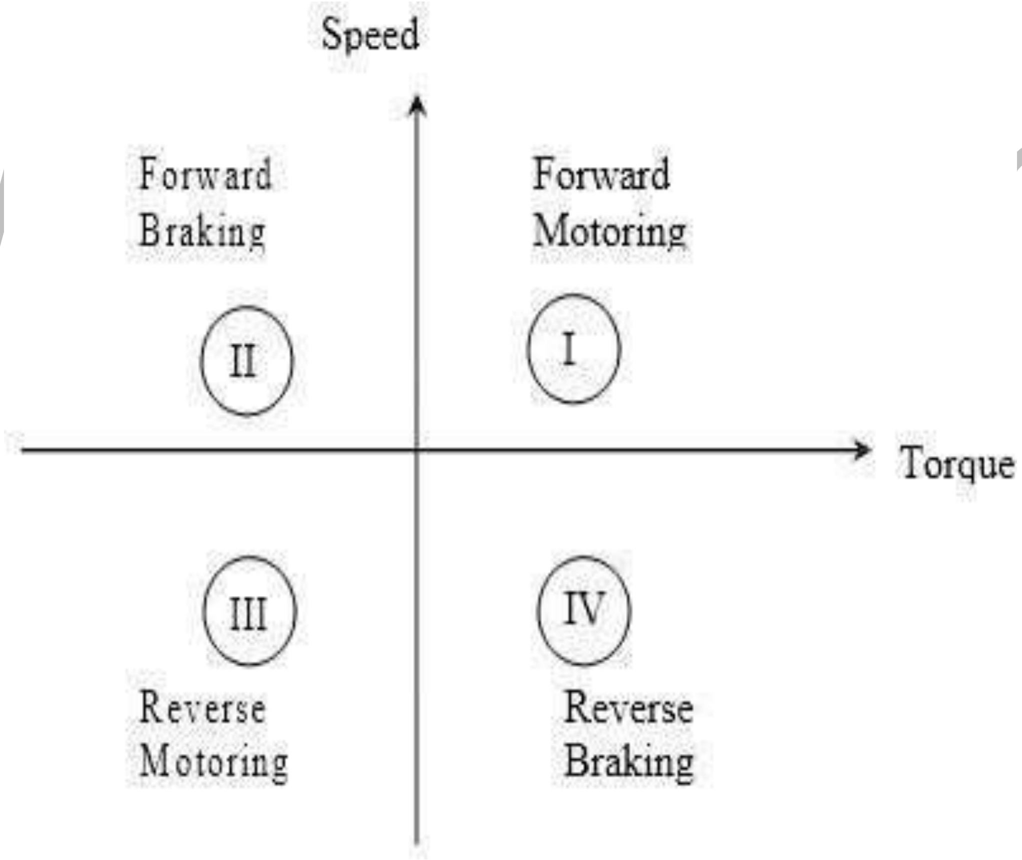


Figure 2.5.1 Four quadrant operation of drives

(Source:"Fundamentals of Electrical Drives" by G.K.Dubey,page-12)

SecondQuadrant–Forwardbrakingmode

Here thyristor S2 is operated and S1 , S3 and S4 are kept off. With S4 on, reverse or negative current flows through La, S2, D4 and Eb. During the operation time of S2, the armature inductance ‘La’ stores energy during the time S2 is on. When S2 is turned off, current is fed back to source through diodes D1 , D4 . Note that here (E+L(di/dt)) is more than the source voltage Vs .As the Vs is positive and Ia is negative, it is a second quadrant operation gives forward braking mode. In that power is fed back from armature to source.

ThirdQuadrant–Reversemotoringmode

For third quadrant operation, thyristor S1 is kept off, S2 is kept on and S3 is operated, polarity of armature back emf Eb must be reversed for this quadrant operation. With thyristor S3 is on, armature gets connected to source V. so that both Va , Ia are negative, leading to third quadrant operation. When S3 is turned off,negative current free wheels through S2,D4. In this manner only Va and Ia can be controlled in the third quadrant.

FourthQuadrant–ReverseBrakingmode

Here thyristor S4 is operated and other devices kept off, back emf Eb must have its polarity reversed as in third quadrant operation. With S4 on, positive current flows through S4,D2,La and Eb (armature). Armature inductance La stores energy during the time S4 is on. When S4 is turned off, current is fed back to source through diodes D2, D3.Here armature voltage Va is negative, but Ia is positive, leading to the chopper drive operation in the fourth quadrant. Also power is fed back from armature to source.

2.1 Steady state analysis of single phase converter fed separately excited DC motor drive:

INTRODUCTION

Direct-current motors are extensively used in variable-speed drives and position-control systems where good dynamic response and steady-state performance are required. Examples are in robotic drives, printers, machine tools, process rolling mills, paper and textile industries, and many others. Control of a dc motor, especially of the separately excited type, is very straightforward, mainly because of the incorporation of the commutator within the motor. The commutator brush allows the motor-developed torque to be proportional to the armature current if the field current is held constant. Classical control theories are then easily applied to the design of the torque and other control loops of a drive system.

DCMOTORS AND ITS CHARACTERISTICS

When a DC supply is applied to the armature of the dc motor with its field excited by a dc supply, torque is developed in the armature due to interaction between the axial current carrying conductors on the rotor and the radial magnetic flux produced by the stator. If the voltage V is the voltage applied to the armature terminals, and E is the internally developed motional e.m.f. The resistance and inductance of the complete armature are represented by R_a and L_a in Figure 2.1(a). Under motoring conditions, the motional e.m.f. E always opposes the applied voltage V, and for this reason it is referred to as 'back e.m.f.' For current to be forced into the motor, V must be greater than E, thearmature circuit voltage equation being given by

$$V= E \; I_a \; R_a \; L \; \frac{dI_a}{dt}$$

SinglePhase rectifierfed separatelyExcited DCmotor drive

The thyristor D.C. drive remains an important speed-controlled industrial drive, especially where the higher maintenance cost associated with the D.C. motor brushes is tolerable. The controlled (thyristor) rectifier provides a low-impedance adjustable 'D.C.' voltage for the motor armature, thereby providing speed control. For motors up to a few kilowatts the armature converter can be supplied from either single-phase or three-phase mains, but for larger motors three-phase is always used. A separate thyristor or diode rectifier is used to supply the field of the motor: the power is much less than the armature power, so the supply is often single-phase. Figure 2.9 shows the setup for single phase controlled rectifier fed separately excited dc motor drive. Field circuit is also excited by a dc source, which is not shown in the figure just for simplicity.

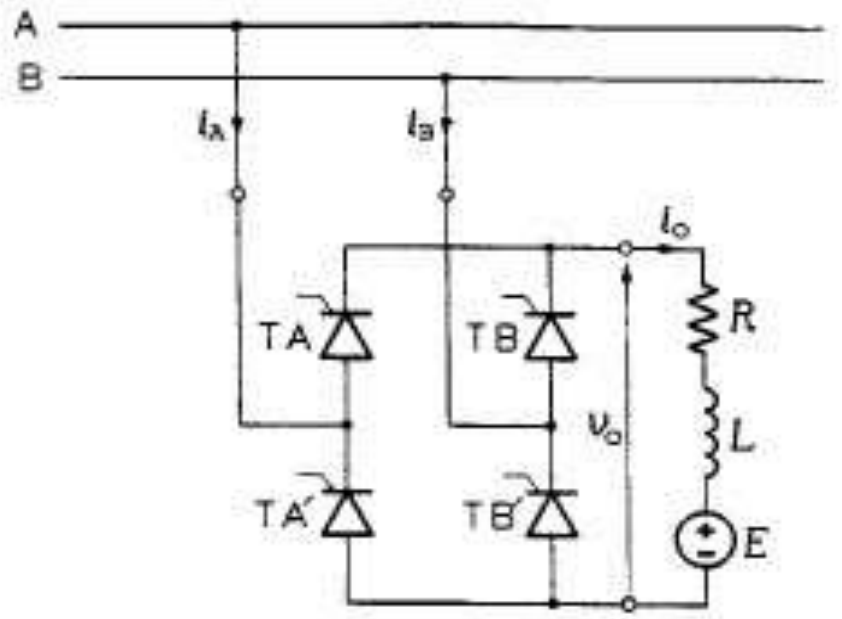


Figure 2.1.1 SinglePhase rectifierfed DCmotor drive

(Source:"Fundamentals of Electrical Drives" by G.K.Dubey,page-108)

The basic circuit for a single-phase separately excited dc motor drive is shown in Fig. The armature voltage is controlled by a semi-converter or full-converter and the field circuit is fed from the ac supply through a diode bridge. The motor current cannot reverse due to the thyristors in the converters. If semi-converters are used, the average output voltage (Ea)is always positive. Therefore power flow (Ea1a) is always positive, that is, from the ac supply to the dc load. In drive system semi-converters, regeneration or reverse power flow from motor to ac supply is not possible. In semi-converters free- wheel (i.e., dissipation of armature inductance energy through the free-wheeling path) takes place when the thyristor blocks.

Single-phase full-wave drives are used for low and medium-horsepower applications as indicated infig2.1.Suchdriveshavepoor speed regulation on open-loop firing angle control. However, with armature voltage or tachometer feedback, good regulation can be achieved.

Basic Equation I

The armature circuit of the de motor is represented by its back voltage eg, armature resistance Ra, and armature inductance La as showninFig.

Back voltage:

$$e_g = K_a \Phi n$$

Average Back Voltage

$$E_g = K_a \Phi N$$

The armature circuit voltage equation is

$$e_a = R_a i_a + L_a \frac{di_a}{dt} + e_g$$

Interms of average values,

$$E_a = R_a I_a + E_g$$

Note that the inductance La does not absorb any average voltage. From equations 2 and 6, the average speed is

$$N = \frac{E_a - R_a I_a}{K_a \Phi}$$

In single-phase converters, the armature voltage ea and current t, change with time. This is unlike the M-G set drive in which both ea and t, are essentially constant. In phase-controlled converters, the armature current ia may not even be continuous. In fact, for most operating conditions, t, is discontinuous. This makes prediction of performance difficult. Analysis is simplified if continuity of armature current can be assumed.

2.2 Steady state analysis of three phase converter fed separately excited DC motor drive:

Three phase controlled rectifiers are used in large power DC motor drives. Three phase controlled rectifier gives more number of voltage per cycle of supply frequency. This makes motor current continuous and filter requirement also less.

The number of voltage pulses per cycle depends upon the number of thyristors and their connections for three phase controlled rectifiers. In three phase drives, the armature circuit is connected to the output of a three phase controlled rectifier.

Three phase drives are used for high power applications up to megawatts power level. The ripple frequency of armature voltage is greater than that of the single phase drives and its requires less inductance in the armature circuit to reduce the armature current ripple.Three phase full converter are used in industrial application up to 1500KW drives. It is a two quadrant converter.

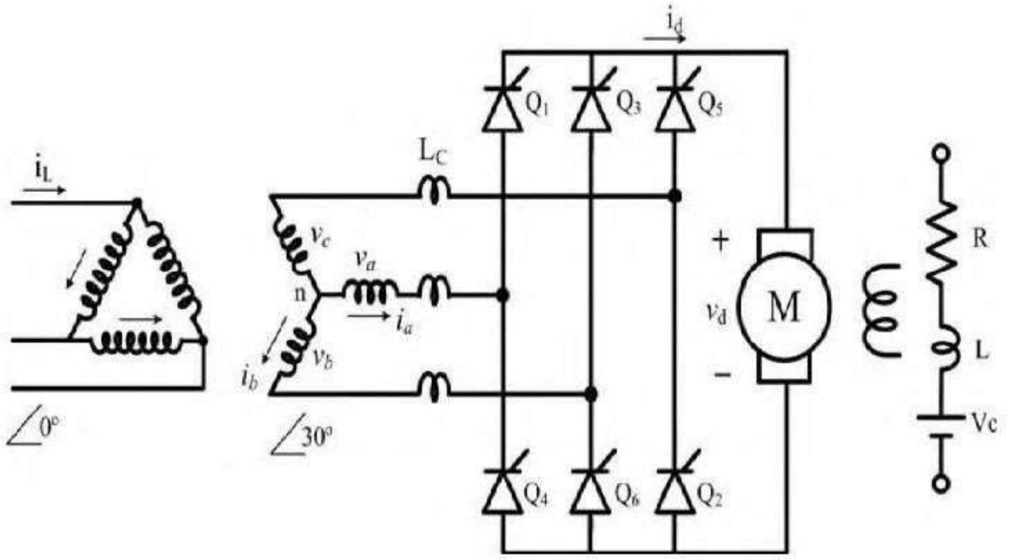


Figure 2.2.1 Three Phase rectifierfed DCmotor drive

(Source:"Fundamentals of Electrical Drives" by G.K.Dubey,page-111)

Three phase full converter bridge circuit connected across the armature terminals is shown fig. The voltage and current waveforms of the converter. The circuit works as a three AC to DC converter for firing angle delay $0^0 < \alpha < 90^0$ and as a line commutated inverter for $90^0 < \alpha < 180^0$. A three full converter fedDC motor is performed where generation of power is required.

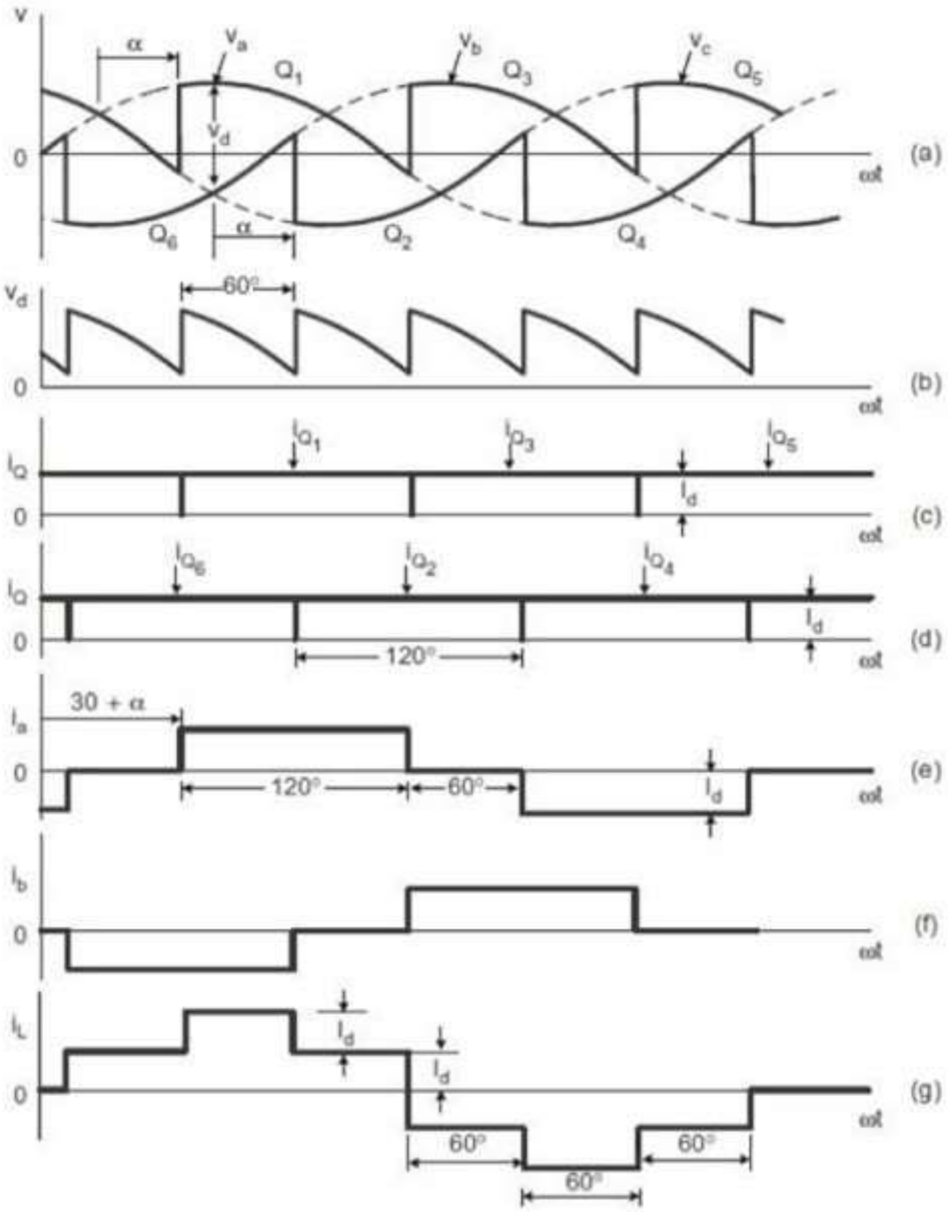


Figure 2.2.2 Three Phase rectifierwaveforms

(Source:"Fundamentals of Electrical Drives" by G.K.Dubey,page-111)

The average motor armature voltage is given by

$$V_a = \frac{3}{\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha} V_{ab}\, d(\omega t)$$

In the above substitute $V_{ab} = \sqrt{3}V_m \sin\left(\omega t + \frac{\pi}{6}\right) d(\omega t)$

We have $V_a = \frac{3\sqrt{3}}{\pi} V_m \cos\alpha$

Speed Torque Relations:

The drive speed is given by

$$V_a = E_b + I_a R_a \qquad \text{Where } E_b = K_a \phi \omega$$

Then $V_a = K_a \phi \omega_m + I_a R_a$

$$\omega_m = \frac{V_a - I_a R_a}{K_a \phi}$$

In separately excited DC motor $K_a \phi I_a = T$ therefore (2.52) becomes

$$\omega_m = \frac{V_a}{K_a \phi} - \frac{R_a}{(K_a \phi)^2} T$$

2.4 Time-ratio Control

In the time ratio control the value of the duty ratio, D is varied. There are two ways, which are constant frequency operation, and variable frequency operation.

Constant Frequency Operation

In this control strategy, the ON time, TON is varied, keeping the frequency , or time period (f=1/T) constant. This is also called as pulse width modulation control (PWM). Two cases with duty ratios, as (a) 0.25 (25%), and (b) 0.75 (75%) are shown. Hence, the output voltage can be varied by varying TON.

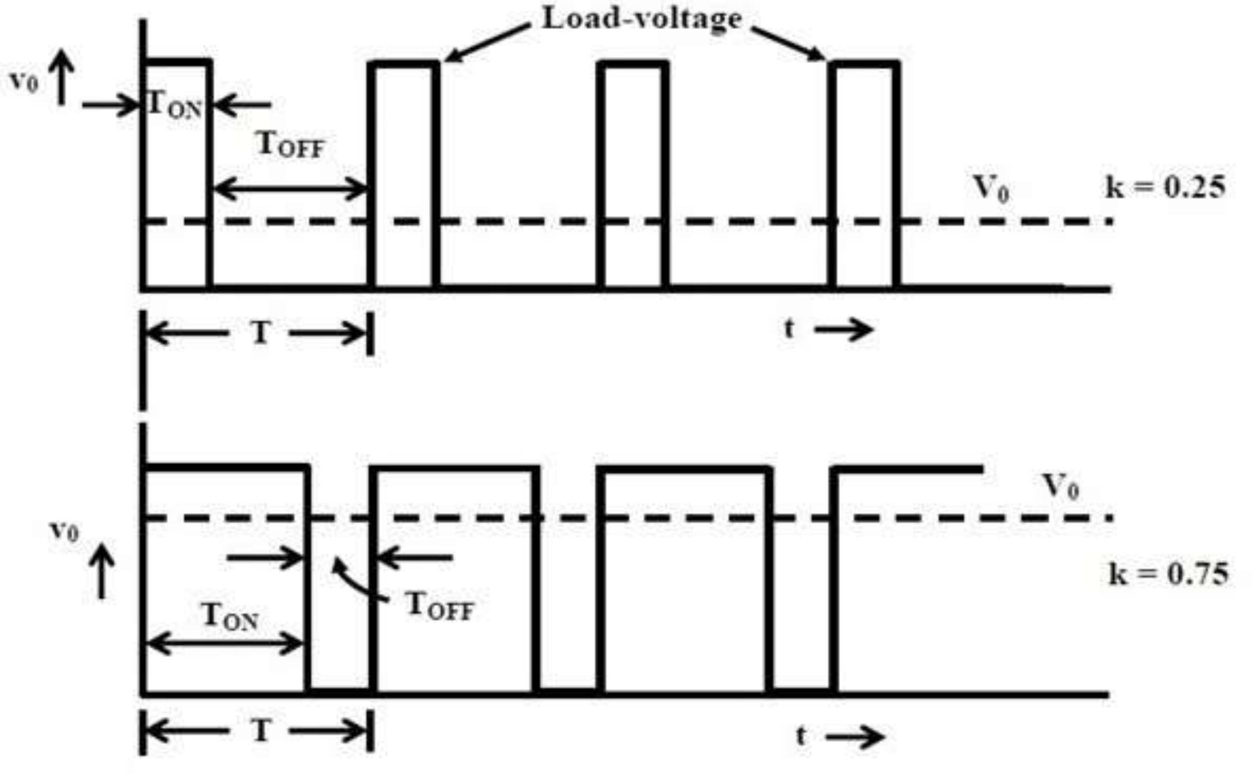
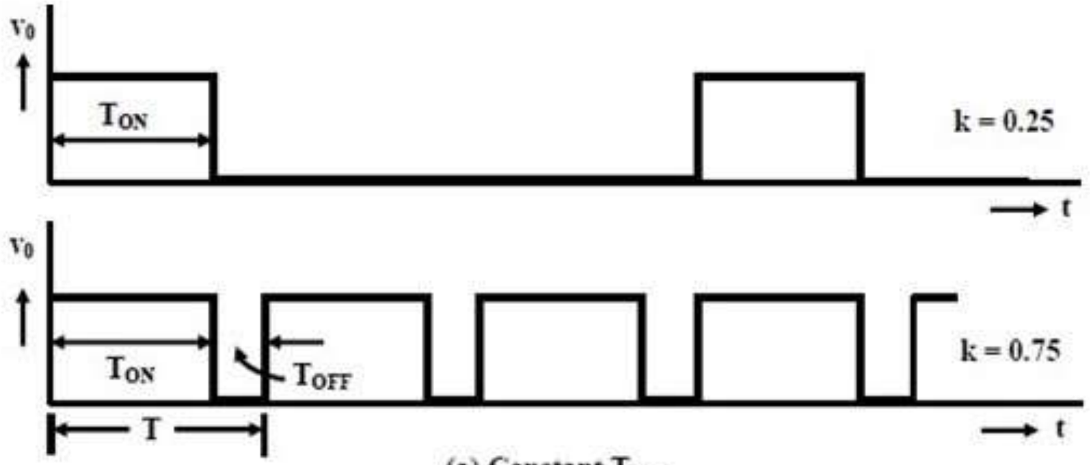


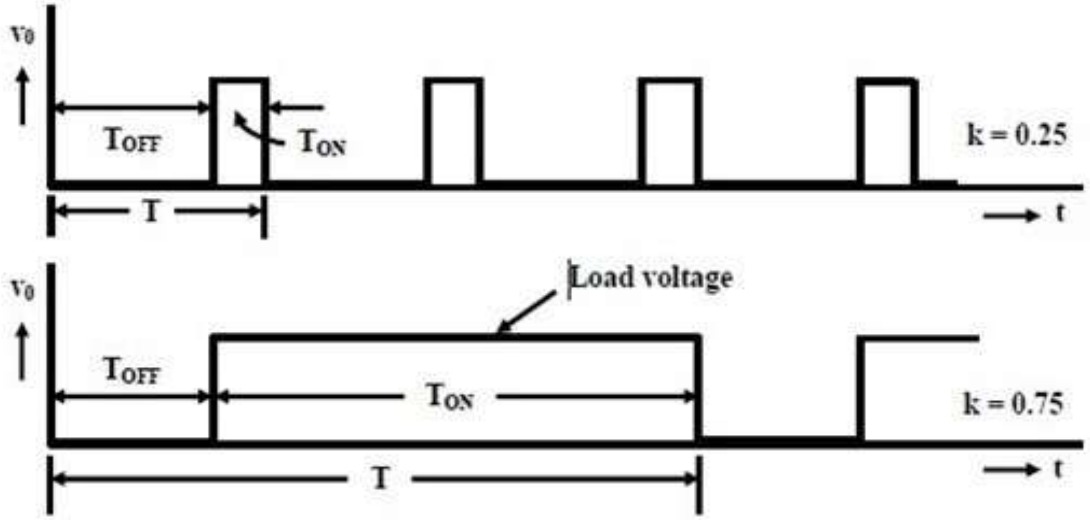
Fig. 2.4.1 : Pulse-width modulation control (constant frequency)

Variable Frequency Operation

In this control strategy, the frequency (f=1/T), or time period *T* is varied, keeping either (a) the ON time, constant, or (b) the OFF time, constant. This is also called as *frequency modulation control*. Two cases with (a) the ON time, constant, and (b) the OFF time, constant, with variable frequency or time period are shown in Fig. The output voltage can be varied in both cases, with the change in duty ratio.



(a) Constant T_{ON}



(b) Constant T_{OFF}

Fig. 2.4.2 : Output voltage waveforms for variable frequency system

(Source:"Fundamentals of Electrical Drives" by G.K.Dubey,page-123)

There are major disadvantages in this control strategy. These are:

(a) The frequency has to be varied over a wide range for the control of output voltage in frequency modulation. Filter design for such wide frequency variation is, therefore, quite difficult.

(b) For the control of a duty ratio, frequency variation would be wide. As such, there is a possibly of interference with systems using certain frequencies, such as signaling and telephone line, in frequency modulation technique.

(c) The large OFF time in frequency modulation technique, may make the load current discontinuous, which is undesirable.

Thus, the constant frequency system using PWM is the preferred scheme for dc-dc converters.

Current Limit Control

As can be observed from the current waveforms for the types of dc-dc converters described earlier, the current changes between the maximum and minimum values, if it (current) is continuous. In the current limit control strategy, the switch in dc-dc converter (chopper) is turned ON and OFF, so that the current is maintained between two (upper and lower) limits.

When the current exceed upper (maximum) limit, the switch is turned OFF. During OFF period, the current freewheels in say, buck converter (dc-dc) through the diode, , and decreases exponentially. When it reaches lower (minimum) limit, the switch is turned ON. This type of control is possible, either with constant frequency, or constant ON time, . This is used only, when the load has energy storage elements, i.e. inductance, L. The reference values are load current or load voltage. This is shown in Fig. In this case, the current is continuous, varying between and , which decides the frequency used for switching. The ripple in the load current can be reduced, if the difference between the upper and lower limits is reduced, thereby making it minimum. This in turn increases the frequency, thereby increasing the switching losses.

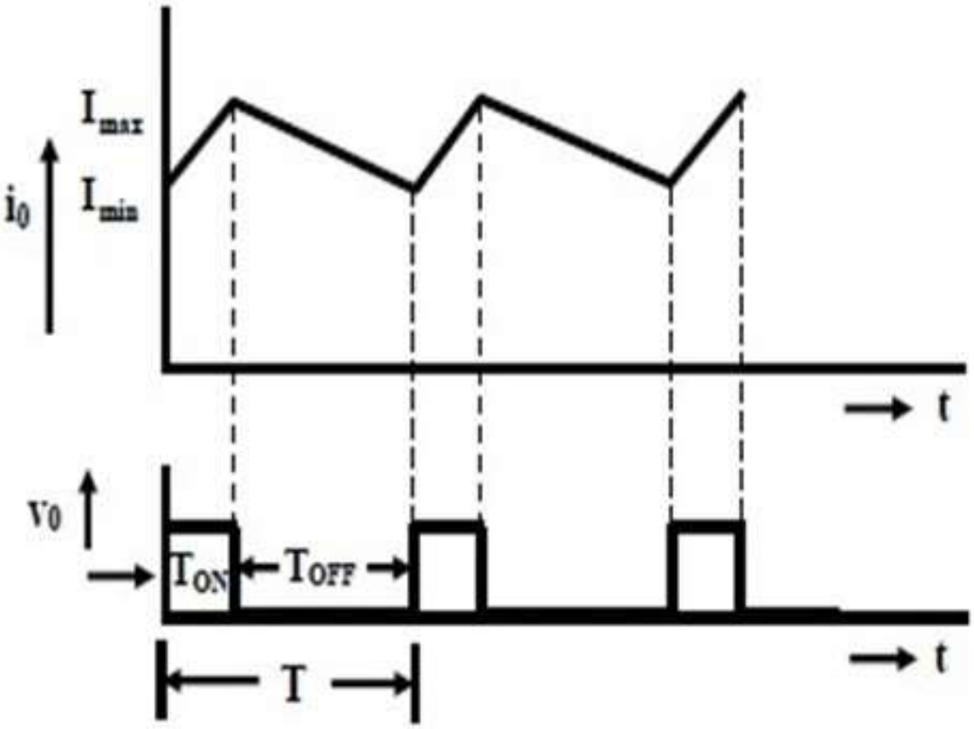


Fig. 2.4.3 : Current limit control

(Source:"Fundamentals of Electrical Drives" by G.K.Dubey,page-125)