**DC Choppers Applications in DC motor Drives and Renewable Energies**

Many industrial applications need a conversion of a voltage coming from a DC source into another DC level. Step up DC choppers are used for regenerative braking of dc motors. Step down DC choppers are used to control the speed of dc motor.

**Part I- Electric DC Motor Drives**

In many of the industrial applications, an **electric motor** is the most important component. A complete production unit consists primarily of three basic components;

- Electric motor,
- Energy-transmitting device and
- The working (or driven) machine.

An **electric motor** is the source of motive power.

An **energy transmitting device** delivers power from electric motor to the driven machine (or the load); it usually consists of shaft, belt, chain, rope etc.

A **working machine** is the driven machine that performs the required production process.

Examples of **working machine**:

① Lathes, ② Centrifugal Pumps, ③ Drilling Machines, ④ Lifts, ⑤ Conveyer Belts, ⑥ Food-Mixers, etc…

An electric motor together with its control equipment and energy-transmitting device forms an **electric drive**, as shown in the figure below:

![Electric Drive System Diagram](image)

A modern electric drive system using a feedback loop as shown in the figure below:
DC Motor Control: Variable Speed Drive

DC motors are used extensively in adjustable-speed drives and position control applications. The speed of a DC motor can be controlled by:

(i) Field-Flux Control Method
(ii) Armature-Voltage Control Method

DC choppers can be used for the speed control of DC motors.

Basic Equations of DC Motors

Motors are generally classified according to their methods of field excitation. Hence, the basic DC motor types are:

► Separately-excited DC Motors
► Shunt DC Motors
► Series DC Motors
► Compound DC Motor

The equivalent circuit for each DC motor type is shown below:
Basic performance equations for a separately-excited dc motor and is presented in this Lecture.

For the field circuit:

\[ V_f = I_f \cdot r_f \]

For armature circuit,

\[ V_a = E_a + I_a r_a \]

Motor back e.m.f.:

\[ E_a = K_a \phi \omega_m = K_m \omega_m \]
\[ T_e = K_a \phi I_a = K_m I_a \]
\[ T_e = D \omega_m + T_L \]
\[ V_f = \text{motor terminal voltage, V} \]
\[ I_a = \text{armature current, A} \]
\[ \phi = \text{field flux per pole, Wb} \]
\[ K_m = K_a \phi = \text{torque constant, Nm/A or, emf constant, V-sec/rad} \]
\[ r_a = \text{armature circuit resistance, } \Omega \]
\[ \omega_m = \text{angular speed of motor, rad/sec} \]
\[ r_f = \text{field circuit resistance, } \Omega \]
\[ D = \text{viscous friction constant, Nm-sec/rad.} \]

Electromagnetic power, \( P = \omega_m \cdot T_e \) watts

\[ E_a = K_m \omega_m = V_f - I_a r_a \]
\[ V_f - I_a r_a = V_a - I_a r_a \]
\[ \omega_m = \frac{V_f - I_a r_a}{K_m} \]

\[ \omega_m = \frac{K_m}{K_a \phi} \]
Where $T_e =$ electromagnetic torque and $T_L =$ load Torque

It can be seen that the speed of a DC motor can be controlled by changing Field-Flux Control and Armature-Voltage.

From the speed equation it can be seen that increasing the speed can be obtained by varying the flux field $\phi$ and decreasing the speed can be obtained by varying the terminal DC supply voltage $V_t$.

**DC-DC Buck Converter Drive**

When variable DC voltage is to be obtained from fixed DC voltage, DC chopper is the ideal.

Use of chopper in traction systems is now accepted all over the world. A chopper is inserted in between a fixed voltage DC source and the DC motor armature for its speed control below base speed.

Chopper drives are also used in battery-operated vehicle where energy saving is of prime importance.

Figure below shows the basic arrangement of a DC chopper feeding power to a DC series motor.

As shown in lecture 6, the output voltage is

$$V_{oAV} = V_{in}D$$

The output DC current is:

$$I_{oAV} = I_{AV} = I_{AV} \frac{T}{t_{on}} = I_{AV} \frac{1}{D}$$

where the switch duty ratio can be expressed as

$$D = \frac{t_{on}}{T}$$

As shown in the waveforms below the switching frequency $f$ is $1/T$, where $T$ is the time for one-cycle and equal to $T_{on} + T_{off}$
Power delivered to motor = (Average motor voltage) (average motor current)

\[ P_{dc} = DV_s \times I_a \]

Input power to chopper = (average input voltage) (average source current)

\[ P_{in} = V_s \times DI_a \]

For the motor armature circuit,

\[ \omega_m = \frac{DV_s - I_a(r_a + r_s)}{K_m} \]

**Example 1:** A DC series motor is fed from 600 V DC source through a chopper. The DC motor has the following parameters:

\[ r_a = 0.04 \, \Omega, \quad r_s = 0.06 \, \Omega, \quad k = 4 \times 10^{-3} \, Nm/amp^2 \]

The average armature current of 300 A is ripple free. For a chopper duty cycle of 60%, determine: input power from the source, motor speed and motor torque

**Solution**

a- Power input to motor = D.V_s.I_a=0.6\times600\times300=108kW

b- For a DC series motor, the terminal voltage \( V_t \) which is the DC output voltage of the chopper \( V_o \) is equal to:

\[ DV_s = E_a + I_a R = k I_a \omega_m + I_a R \]

\[ 0.6 \times 600 = 4 \times 10^{-3} \times 300 \times \omega_m + 300 (0.04 + 0.06) \]

\[ \omega_m = \frac{360 - 30}{1.2} = 275 \text{ rad/sec or 2626.1 rpm} \]

c- Motor torque,

\[ T_e = k I_a^2 = 4 \times 10^{-3} \times 300^2 = 360 \text{ Nm}. \]
Example 2: The chopper used for on-off control of a DC separately-excited motor has supply voltage of 230V DC, an on-time of 10msec and off-time of 15msec. Neglecting armature inductance and assuming continuous conduction of motor current, calculate the average load current when the motor speed is 1500 rpm and has a voltage constant of $K_m = 0.5 \text{ V/rad per sec}$. The armature resistance is $3\Omega$.

Solution:

Chopper duty cycle $D$ is

$$D = \frac{t_{on}}{T} = \frac{t_{on}}{t_{on} + t_{off}} = \frac{10 \times 10^{-3}}{10 \times 10^{-3} + 15 \times 10^{-3}} = 0.4 \text{ or } 40\%$$

For the motor armature circuit,

$$V_{oAV} = V_{in}D = V_t = E_a + I_aR_a = K_m\omega_m + I_aR_a$$

$$V_{in}D = K_m\omega_m + I_aR_a$$

$$230 \times 0.4 = 0.5 \frac{2\pi \times 1500}{60} + I_a \times 3$$

Motor load or armature current

$$I_a = \frac{230 \times 0.4 - 0.5 \frac{2\pi \times 1500}{60}}{3} = 4.48A$$

Example 3: A DC chopper is used to control the speed of a separately-excited DC motor. The DC supply voltage is 220 V, armature resistance $R_a = 0.2\Omega$ and motor constant $K_a \times \phi = 0.08 \text{ V/rpm}$.

This motor drives a constant torque load requiring an average armature current of 25A. Determine (a) the range of speed control (b) the range of duty cycle $D$. Assumed the motor current to be continuous.

Solution:

For the motor armature circuit,

$$V_t = E_a + I_aR_a$$

As motor drives a constant torque load, motor torque $T_e$ is constant and therefore armature current remains constant at 25A.

Minimum possible motor speed is $N = 0 \text{ rpm}$. Therefore,

$$V_{in}D = K_m\omega_m + I_aR_a$$

$$220 \times D = 0.08 \times 0 + 25 \times 0.2$$

$$\Rightarrow$$

$$D = \frac{25 \times 0.2}{220} = 0.0227 = 2.27\%$$
Maximum possible motor speed corresponds to \( D = 1 \) or 100\% (i.e. when 220 V DC is directly applied and no chopping is done).

\[
V_{in}D = K_m \omega_m + I_a R_a \\
220 \times 1 = 0.08 \times n_m + 25 \times 0.2 \\
n_m = \frac{220 - 25 \times 0.2}{0.08} = 2687.5 \text{ rpm}
\]

Range of speed control: \( 0 < N < 2687.5 \text{ rpm} \) and corresponding range of duty cycle: \( 2.27\% < D < 100\% \)

**Example 4:** Suppose a trolley bus is driven by a DC series motor as shown in Figure below.

The speed of the motor is controlled by a DC chopper fed by the 750V DC trolley wires. The operating frequency of the chopper is 500Hz and the ON time of the chopper switch is 0.5 msec. The total armature circuit resistance of the series motor is 0.4Ω and the current drawn by the series motor \( (I_o) \) has average value of 50A and peak-to-peak ripple of 2A.

1. Name the circuit shown in the figure above which is used to drive the DC motor
2. Sketch the waveforms of \( I_S \) and \( I_O \) and \( I_D \).
3. Determine the average armature voltage \( (E_a) \),
4. The average switch current \( (I_S) \),
5. The average current of the freewheeling diode \( (I_D) \),
6. the maximum and minimum values of armature current
7. The ON time and duty cycle of the chopper switch at starting with motor starting current limited to 100A.

**Solution:**

1. The circuit is a Buck or step-down DC-DC converter
2. The waveforms of \( I_S \) and \( I_O \) and \( I_D \) are shown below
\[ E_a = V_t - I_a R_a = V_o - I_a R_a = V_{in} D - I_a R_a \]
\[ D = \frac{t_{on}}{T} = \frac{t_{on}}{T} = \frac{0.5 \times 10^{-3}}{1/500} = 0.25 \]
\[ E_a = V_{in} D - I_a R_a = 750 \times 0.25 - 50 \times 0.4 = 167.5V \]

(4) \[ I_s = I_{inAV} = DI_o = 0.25 \times 50 = 12.5A \]

(5) The diode current is the difference between output and input currents

\[ I_D = I_o - I_s = 50 - 12.537.5A \]

(6) The maximum and minimum armature current or output chopper current can be obtained as:

\[ I_{i\text{max}} = I_{oAV} + \frac{1}{2} \Delta I_L = 50 + \frac{1}{2} \times 2 = 51A \]
\[ I_{i\text{min}} = I_{oAV} - \frac{1}{2} \Delta I_L = 50 - \frac{1}{2} \times 2 = 49A \]
At starting of the motor the applied emf voltage $E_a$ is equal to zero $\Rightarrow$

$t_{on} = DT$

$E_a = V_{in}D - I_aR_a = 0$

$\Rightarrow$

$V_{in}D = V_a = V_t = I_aR_a$

$\Rightarrow$

$D = \frac{I_aR_a}{V_{in}} = \frac{100 \times 0.4}{750} = \frac{100 \times 0.4}{750} = 0.0533$

$t_{on} = DT = D \frac{1}{f} = 0.0533 \times \frac{1}{500} = 106.67 \, \mu\text{sec}$

**Exercise 1**: An electronic chopper is placed between a 600 V DC trolley wire & the armature of a series motor, as shown in the figure below.

![Circuit Diagram](image)

The switching frequency is 800 Hz and each power pulse width is 400$\mu$s. If the DC current in the trolley wire is 80A and the total armature circuit resistance of the series motor is 0.5$\Omega$, calculate: a. the armature current (Ans.: 192V) b. the armature voltage (Ans.: 67V).

**Exercise 2**: A step-down chopper is used to supply power from a DC 600V overhead wire to the armature of a DC motor on a trolley bus. The armature inductance is large enough to give a smooth current and the armature resistance is 0.4$\Omega$. The frequency of the chopper is set at 500Hz. Determine, with the aid of a circuit diagram, (a) The ON time of the chopper to provide a motor current of 100A when the bus is stopped. (Ans.: 0.134 msec) (b) The maximum possible generated voltage of the motor for an armature current of 100A, (Ans.: 560V) (c) The average value of the supply current for the conditions of (a) and (b). (Ans.: 6.7A, 100A)

**Exercise 3**: A 600-V, separately-excited, DC motor has an armature resistance of 1.2$\Omega$. The armature draws a current of 25A at 600V when the motor is driving a load at 1000 rpm.

(i) Determine the back EMF of the motor (Ans.: 570V)
If the armature is connected to the supply through a step-down chopper operating at 400Hz with an ON time of 1.5 \textit{msec}, determine,

(ii) The duty cycle of the chopper (\textbf{Ans.:60\%}),
(iii) The output voltage of the chopper (\textbf{Ans.: 360V}),
(iv) The back EMF of the motor (\textbf{Ans.: 330V}),
(v) The motor speed (\textbf{Ans.: 578.9 rpm}).

It is assumed that the load torque and the flux remain constant.