Fundamentals of Electric Drives

Prof. Shyama Prasad Das

Department of Electrical Engineering

Indian Institute of Technology – Kanpur

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Two- quadrant DC Chopper, Four-quadrant DC Chopper

Hello and welcome to this lecture on the fundamentals of electric drives. In our previous session, we discussed DC chopper-fed DC motor drives. Today, we will explore how to achieve dynamic braking using a DC chopper.

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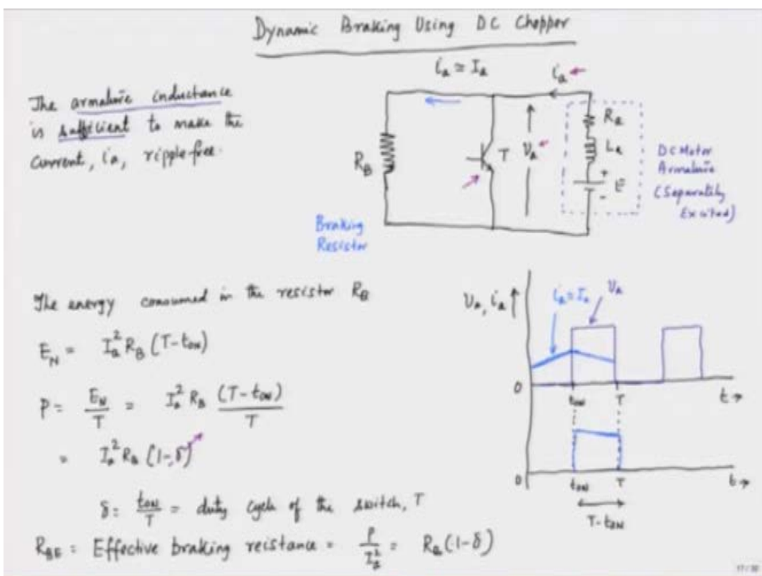

What we have here is the armature of the motor, which is represented by its resistance, inductance, and back EMF. Connected in parallel with the armature is a chopper switch, which interfaces with a braking resistor, denoted as R_B. This chopper switch is represented by the transistor T. We can define the armature voltage as V_a and the armature current as I_a.

This configuration illustrates the equivalent circuit of a separately excited DC motor. For our discussion, we will assume that the motor is actively rotating while driving a load, thereby possessing significant kinetic energy. To decelerate the motor electrically, we can engage in regenerative braking, which requires a DC source to absorb the motor's energy. However, if a DC source is not available, we can implement dynamic braking. This process involves dissipating the energy through the braking resistor, effectively transferring it away from the motor.

In this setup, we ensure that the switch, alongside sufficient armature inductance, allows for a nearly ripple-free current. We assume that the armature inductance is adequate to make the current I_a almost ripple-free, rendering it close to a steady DC current.

Now, let's illustrate the waveforms. We will plot time on the X-axis, while the armature voltage and armature current will be represented on the Y-axis, with the origin at the intersection.

When the switch is closed, the voltage V_a drops to zero, which we can represent with a horizontal line along the zero-voltage level. Conversely, when the switch is open and the transistor T is turned off, the voltage rises to a finite value, depicted as the armature voltage V_a.

As for the current, when the switch is closed, current flows through the switch, effectively short-circuiting the armature. We have also assumed that the armature inductance is sufficiently large to support this condition.

Now, since the armature inductance is sufficient, the current will charge the armature inductance, causing it to rise gradually. This is possible because the back EMF is sufficiently strong, allowing the current through the armature to increase exponentially. Once the switch is open, the current will flow through the braking resistor, denoted as R_B.

We have assumed that the current is ripple-free, which means that any ripple present is negligible. Consequently, the current will gradually decrease in a smooth manner. If we consider it to be ripple-free, it can be treated as nearly a constant DC current. Thus, the current through the armature can be regarded as almost a DC current, provided we ignore the ripple. While there may be some ripple, if the armature inductance is sufficiently large, we can indeed neglect it.

Next, we need to determine the power dissipated in the braking resistor. Let's examine the energy dissipated in R_B. To find the expression for energy, we can denote the energy consumed in the resistor as E_N. Assuming that the current I_a is almost ripple-free, we can express I_a as approximately equal to a constant I_A. This means that we can treat I_a as a constant current when we disregard the ripple.

The energy consumed in the resistor can be calculated as:

$$E_N = I_a^2 R_B \cdot t_{ON}$$

This represents the power loss as I_s^2 R_B, and this loss occurs for a time duration t_{ON} over the time interval T.

Now, if we plot the current through the braking resistor, we will observe the current only during the off time of the switch. The time interval during which the current flows through the braking resistor is T - t_{ON}. This duration T - t_{ON} indicates the time for which the braking resistor is actively supplied with current.

To find the power dissipated in the braking resistor, we divide the energy by the time period. Since we are dealing with a repetitive waveform, the time period here is T because the same waveform repeats after a certain duration.

This waveform is periodic, and we need to calculate the power over one complete cycle. The power P can be expressed as:

$$P = \frac{E}{T} = \frac{I_a^2 R_B (T - t_{ON})}{T}$$

This expression can be simplified to:

$$P = I_a^2 R_B (1 - \delta)$$

where $\delta = \frac{t_{ON}}{T}$ represents the duty cycle of the switch. Now, what we need to determine is the effective braking resistance that the motor experiences.

By varying δ, we can adjust the braking power. This means that as we change the duty cycle, the braking power can also be modified. In essence, we can control the braking action on the motor by adjusting the duty ratio of the switch, which has a period of T. Although we have a fixed resistor in place, the chopper switch allows us to effectively convert that into a variable resistor, making the braking resistance perceived by the motor adjustable.

To express the effective resistance seen by the motor, we use the formula:

$$R_{effective} = \frac{P}{I_a^2} = R_B(1 - \delta)$$

Thus, by manipulating the duty cycle of the switch, we can change the braking resistance accordingly. This dynamic braking method is particularly useful in many applications where regenerative braking is not feasible; instead, we can achieve braking through a resistor.

Electrical braking offers several advantages. One significant benefit is that it results in no wear and tear on the wheels. Since the braking is accomplished electrically, the motion of the wheels is halted without frictional contact, thus enhancing the longevity of the mechanical components. This aspect is one of the key advantages of electrical braking systems.

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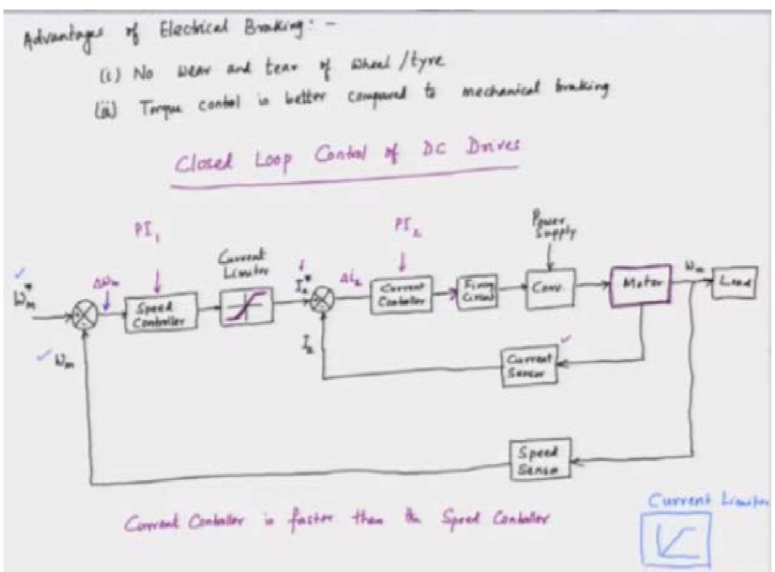

The advantages of electrical braking, whether through regenerative braking, plugging, or dynamic braking, are numerous. First and foremost, there is no wear and tear on the wheels or tires because the motion of the wheels is halted electrically. This means there is no friction between the wheel and the road or railway track, which significantly extends the life of these components.

Another notable advantage is that torque can be controlled smoothly. The control over torque is far superior compared to mechanical braking systems, allowing for more precise and efficient operation.

Now, as we delve into the topic of converter-fed and chopper-fed DC drives, it is essential to note that these drives are often operated in a closed-loop configuration. What do we mean by a closed loop? When we aim to maintain accurate speed control, we need to implement a speed feedback mechanism. For instance, in a textile mill, it might be crucial to ensure that the motor speed remains at a precise 900 RPM. To achieve this, we incorporate speed feedback, which is integral to closed-loop speed control.

Let's take a look at the block diagram representing this system. We start with a reference speed, denoted as ω_m^*. This reference speed is fed into a summing junction where we compare it with the actual speed of the motor. The difference between the reference speed and the actual speed is processed in the speed controller.

The output from the speed controller produces a reference current for the motor. This is where the current limiter comes into play, ensuring that the current remains within safe limits. We denote this reference armature current as I_a^*.

Additionally, we incorporate a current controller into the system. This controller monitors the armature current, allowing for further refinement in the control process. Following this, we have the firing circuit, which activates the converter. The output of the converter then drives the motor, which is typically mechanically coupled to a load. The load itself represents a mechanical load that the motor is tasked with driving.

Thus, this closed-loop control structure not only enhances the accuracy of speed regulation but also integrates various components to ensure smooth operation and optimal performance in DC drive systems.

In our system, the motor current is continuously changing, and we have a current sensor in place to monitor this motor current. The sensor feeds the motor current data back to the control system, which regulates the current flowing through the motor. Meanwhile, the converter provides the necessary power supply for these operations.

Within this setup, we have an inner loop dedicated to current control, and an outer loop responsible for speed control. The speed sensor detects the mechanical speed of the motor, denoted as ω_m, and feeds this information back to the input side of the controller as the feedback speed. This configuration represents the closed-loop block diagram of the DC drive system.

It's important to note that sometimes the converters are unidirectional. For instance, if we are using a fully controlled converter, it can only supply current in one direction. In this scenario, the current limiter is designed to accommodate only positive current limits. This means that the current limiter operates within a unidirectional range.

However, if we utilize a converter capable of supplying current in both directions, such as a dual converter or a four-quadrant chopper, the current limiter can manage both positive and negative values. Now, let's explore how the control mechanism is accomplished.

We start with a reference speed, which is compared to the actual speed of the motor. If the actual speed is less than the reference speed, a speed error arises, denoted as $\Delta\ \omega_m$. This speed error is then fed into the speed controller, which is typically a Proportional-Integral (PI) controller. The PI controller integrates and amplifies this speed error, allowing for more precise control.

To prevent the output from reaching excessively high values, we implement the current limiter. This current limiter constrains the current value to both a maximum positive limit and a maximum negative limit, ensuring safe and effective operation of the motor control system.

The current flowing through the DC motor remains well within its operational limits. In fact, a DC motor can typically handle approximately three times its rated current for brief periods. Therefore, the current limit is often set to about 1.5 to 2 times the motor's rated value. In this context, I_a^* represents the reference current, which is the output of the current limiter. This reference current is then compared with the actual motor current using a feedback loop facilitated by the current sensor. The sensor measures the actual current and feeds this information back into the system, resulting in a current error denoted as $\Delta\ I_a$.

This current error is subsequently inputted into a current controller, which is typically a Proportional-Integral (PI) controller. The output from this controller is sent to the firing circuit as the control voltage. This firing circuit is responsible for generating the triggering signal for either a converter or a chopper converter, which, in turn, supplies power to the armature of the DC motor.

It is crucial to maintain the current limit because we want to prevent the motor current from reaching dangerously high levels, which could potentially damage the windings. By establishing an appropriate current limit based on the motor's capabilities, we ensure that the motor operates safely. With an inner current controller in place, we not only protect the motor but also effectively control the torque, as torque is directly related to current. Thus, by managing the current, we inherently manage the torque of the motor as well.

When we compare the current controller to the PI controller used for speed control, we find that the current controller generally acts more quickly. This is because the current controller regulates an electrical variable, which requires a fast response. In contrast, the speed controller manages a mechanical variable, which can be adjusted more slowly compared to an electrical variable. As a result, the speed controller is typically the slower of the two, while the current controller is designed to respond more rapidly.

This concludes our overview of closed-loop control for DC drives. Depending on the specific converter and drive configuration, we can tailor the closed-loop control system, including the design of the speed and current controllers.

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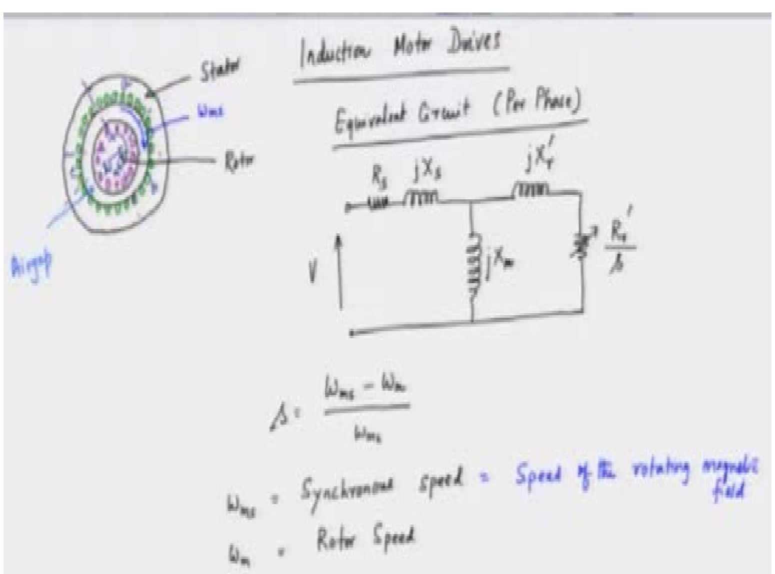

Now, let's delve into induction motor drives. Induction motors are a type of AC motor and are often referred to as the workhorses of the industry. In fact, approximately 60 to 70% of electric drives are induction motors, highlighting their immense popularity. They find applications across a vast array of sectors, from domestic appliances to industrial setups, making induction motors an integral part of everyday life.

The construction of an induction motor is quite simple. It consists of two main components: the rotor and the stator. The rotor is equipped with conductive bars or windings, while the stator houses the AC windings. Importantly, there is an air gap between the stator and the rotor, which plays a crucial role in the operation of the motor. In a three-phase induction motor, the stator is designed to accept three-phase power, enabling it to generate a rotating magnetic field.

To analyze the performance of the motor, particularly in terms of speed and torque, we need to draw the equivalent circuit. This equivalent circuit can be represented for both single-phase and three-phase systems. Within this circuit, we include components such as the armature, stator resistance (R_s), stator leakage reactance (X_s), rotor leakage reactance (X_r' referred from the stator side), and rotor resistance (R_r', also referred from the stator side).

In essence, the motor comprises both resistances and reactances. When we apply a specific voltage, known as the power phase voltage, the equivalent circuit captures these parameters. The components represented in the circuit are as follows: R_s represents the stator resistance, X_s denotes the stator leakage reactance, X_r' indicates the rotor leakage reactance as seen from the stator side, R_r' is the rotor resistance referred from the stator, and X_m represents the magnetizing reactance. It's important to note that the rotor resistance is divided by a parameter known as "slip," which is essential for determining the motor's operational characteristics.

When the rotor rotates, slip is generated, which is defined by the equation $S = \frac{\omega_{ms}-\omega_m}{\omega_s}$. Here, ω_{ms} is referred to as the synchronous speed, while ω_m represents the rotor speed. For instance, if the rotor is rotating in a clockwise direction at a speed of ω_m, and the stator is equipped with three-phase windings, we can identify three distinct phases: Phase A, Phase B, and Phase C.

The stator generates a rotating magnetic field that revolves at the synchronous speed, ω_{ms}. As this rotating magnetic field is produced, the rotor will endeavor to catch up with it. This interaction occurs because the rotor contains conductive bars that become short-circuited, resulting in an induced electromotive force (EMF). This induced EMF generates a current that circulates within the rotor.

The current interacts with the rotating magnetic field, producing torque in the process. This torque attempts to propel the rotor forward, aiming to synchronize with the rotating magnetic field. The difference in speed, denoted by ω_{ms} - ω_m, establishes a finite value of slip, which is essential for the operation of the motor.

Thus, we utilize the equivalent circuit to analyze and derive the torque and speed characteristics of the induction motor. In conclusion, this wraps up our discussion for today's lecture. We will continue our exploration of induction motor drives in the next session.