Fundamentals of Electric Drives

Prof. Shyama Prasad Das

Department of Electrical Engineering

Indian Institute of Technology-Kanpur

Lecture-21

Dynamic Braking of Induction Motor, AC Dynamic Braking, DC Dynamic Braking

Hello, and welcome to this lecture on the fundamentals of electric drives. In our previous session, we began discussing the braking methods of induction motors, and today, we will continue that discussion. Specifically, we were talking about dynamic braking, where the kinetic energy of the motor is dissipated as heat through resistive elements. Now, let us discuss the first type of dynamic braking, known as AC dynamic braking of an induction motor.

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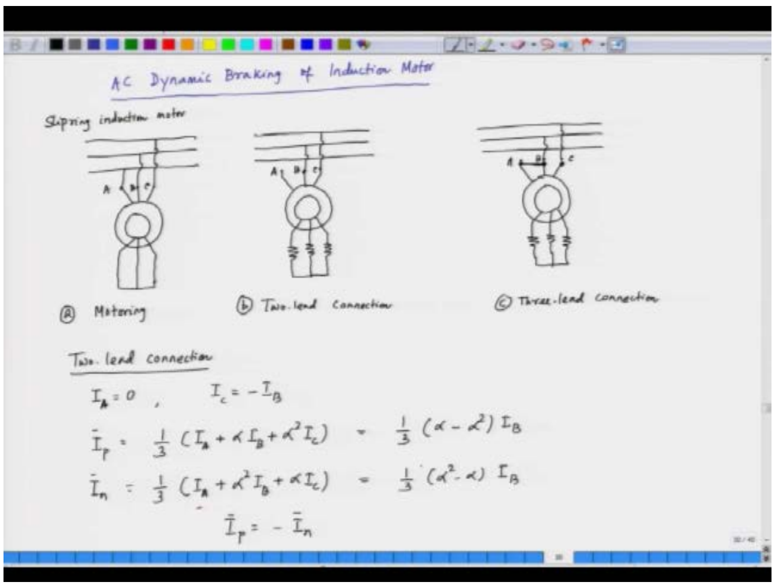

Now, let's discuss what happens in AC dynamic braking. Suppose we have a motor connected to a three-phase supply, this is a typical setup where the motor is powered by a three-phase supply, and in this case, it’s a slip ring induction motor. The slip rings are normally short-circuited and connected to the rotor, with phases A, B, and C powering the system.

This is what we call the motoring condition. When we apply AC dynamic braking, we disconnect or open-circuit one of the phases, allowing the kinetic energy of the motor to dissipate through the rotor resistance. For instance, if we open-circuit phase A, phases B and C remain connected while phase A is disconnected. This technique is primarily applied to slip ring induction motors, as it allows rotor resistance to be inserted via the slip rings.

In this scenario, when phase A is open, this is referred to as a two-lead connection, where only two phases (B and C) remain connected to the supply. Alternatively, there's another possibility: we open-circuit one of the phases and then connect it to one of the healthy phases, which can also be used for AC dynamic braking.

In this second method, we still have the three-phase supply connected to the stator, and the rotor has resistance inserted via the slip rings. In this case, phases B and C remain connected to the supply, while phase A is disconnected but short-circuited with phase B. This is referred to as a three-lead connection, as phases A, B, and C are still connected, but in a modified configuration. So, with this setup, if we want to transition from motoring to braking, we can either remove one of the phases and insert rotor resistance or remove one phase and connect it to a healthy phase, while also introducing rotor resistance.

Now, let’s explore the consequences of creating this unbalance by opening one of the phases. Suppose we label these methods: A refers to motoring, B refers to the two-lead connection, and C refers to the three-lead connection. First, we'll look at the two-lead connection, where we open-circuit one phase.

In a two-lead connection, when phase A is open, the current in phase A (I_A) becomes zero. As a result, currents in phases B and C (I_B and I_C) become equal and opposite, i.e., $I_C = -I_B$. This leads to an unbalanced condition in the motor. To analyze this unbalance, we can apply the sequence component method to calculate the positive and negative sequence currents.

The positive sequence current I_P is given by the equation:

$$I_P = \frac{1}{3}(I_A + \alpha I_B + \alpha^2 I_C)$$

Substituting $I_A = 0$ and $I_C = -I_B$, we get:

$$I_P = \frac{1}{3}(\alpha - \alpha^2)I_B$$

Similarly, the negative sequence current I_n is calculated as:

$$I_N = \frac{1}{3}(I_A + \alpha^2 I_B + \alpha I_C)$$

Again, substituting $I_A = 0$ and $I_C = -I_B$, we get:

$$I_N = \frac{1}{3}(\alpha^2 - \alpha)I_B$$

From these two equations, we can see that the positive sequence current is equal in magnitude but opposite in direction to the negative sequence current. This is a key result that highlights the unbalanced nature of the current during AC dynamic braking with a two-lead connection.

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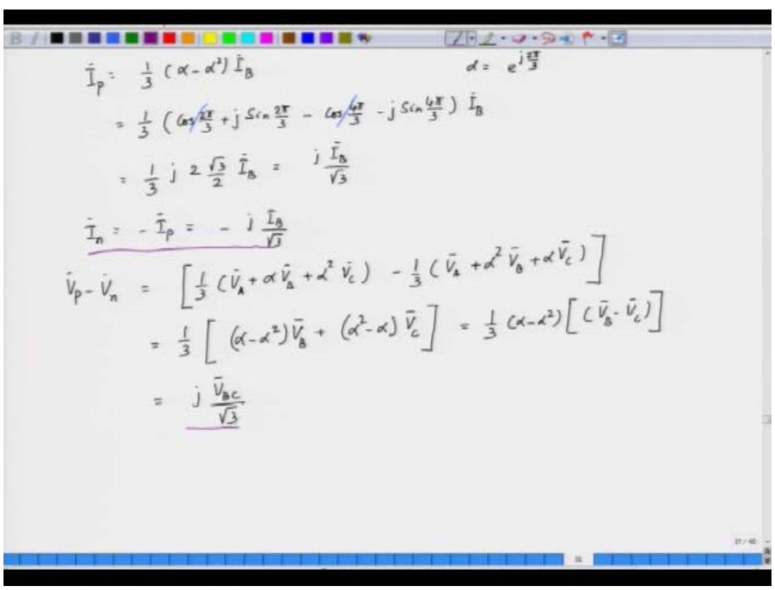

Let us now analyze the expression for I_p. We can rewrite I_p as:

$$I_P = \frac{1}{3}(\alpha - \alpha^2)I_B$$

To proceed, let's clarify what α represents. α is a complex operator defined as:

$$\alpha = e^{j\frac{2\pi}{3}}$$

Substituting this value, we expand α and α^2. So,

$$\alpha = cos\frac{2\pi}{3} + jsin\frac{2\pi}{3}$$

and similarly,

$$\alpha^2 = cos\frac{4\pi}{3} + jsin\frac{4\pi}{3}$$

Now, applying these to the expression for I_p:

$$I_P = \frac{1}{3}\left(\left(cos\frac{2\pi}{3} + jsin\frac{2\pi}{3}\right) - \left(cos\frac{4\pi}{3} + jsin\frac{4\pi}{3}\right)\right) I_B$$

With simplification, several terms cancel out. What remains after cancellation is:

$$I_P = \frac{j2sin\frac{2\pi}{3}}{3} I_B$$

This simplifies further to:

$$I_P = j\frac{I_B}{\sqrt{3}}$$

Similarly, for the negative sequence current I_n, we can find:

$$I_N = -I_P$$

Thus, I_n is:

$$I_N = -j\frac{I_B}{\sqrt{3}}$$

Now, let's analyze the voltages. We are interested in the difference between the positive and negative sequence voltages, V_p - V_n. From the sequence component method, we know:

$$V_P = \frac{1}{3}(V_A + \alpha V_B + \alpha^2 V_C)$$

$$V_N = \frac{1}{3}(V_A + \alpha^2 V_B + \alpha V_C)$$

Subtracting these, the V_A terms cancel out, leaving:

$$V_P - V_N = \frac{1}{3}(\alpha - \alpha^2)(V_B - V_C)$$

We already know $\alpha - \alpha^2 = j$, so the expression becomes:

$$V_P - V_N = j\frac{V_{BC}}{\sqrt{3}}$$

This gives us the line voltage as:

$$V_{BC} = j\frac{V_{BC}}{\sqrt{3}}$$

Now, returning to the relationship between current and voltage, we find that the current I_n is equal to $-I_p$, meaning:

$$I_N = -j\frac{I_B}{\sqrt{3}}$$

Using this, we can deduce the equivalent circuit. Since the positive sequence current is equal and opposite to the negative sequence current, the positive and negative sequence networks must be connected in series. Therefore, when drawing the equivalent circuit, the positive and negative sequence networks should be placed in series to accurately reflect the system's behavior.

What we have here is a comprehensive view of the positive and negative sequence networks. In the positive sequence network, we encounter several key components: the stator resistance, the stator leakage reactance, and the magnetizing reactance. Additionally, we have the rotor leakage reactance and the rotor resistance contributing to the overall dynamics of the system.

Moving on to the negative sequence network, we again find the magnetizing reactance, rotor leakage reactance, and rotor resistance. The configuration of the circuit elements is as follows: we denote the stator resistance as R_s and the stator leakage reactance as X_s. The magnetizing reactance is represented as X_m, while the rotor leakage reactance is X_r', and the rotor resistance is R_r'.

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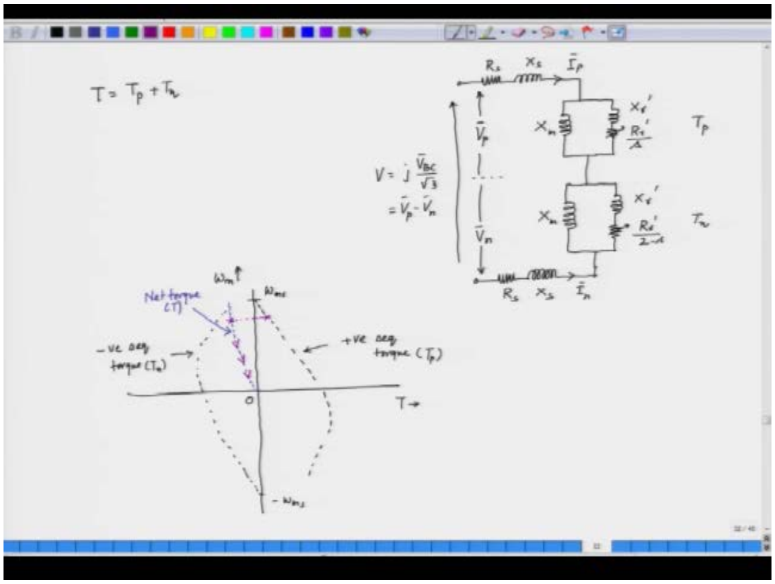

For the positive sequence slip, we have $\frac{R_r'}{s}$, where s is the slip. In contrast, for the negative sequence slip, it's expressed as $\frac{R_r'}{2-s}$. Thus, we observe these variable resistances at play.

Next, we identify the positive sequence current, I_p, and the negative sequence current, I_n. Notably, these two currents are equal in magnitude but opposite in direction. The applied voltage in this scenario has been derived as:

$$V = j\frac{V_{BC}}{\sqrt{3}}$$

This relationship represents V_p - V_n, where V_p is the voltage drop across the positive sequence network and V_n is the voltage drop across the negative sequence network. Consequently, the net voltage can be expressed as:

$$V_{net} = V_P - V_N = j\frac{V_{BC}}{\sqrt{3}}$$

With the voltage established and the networks clearly defined, we can now calculate the torque as well as the corresponding currents. The positive sequence network will yield the positive sequence torque, while the negative sequence network will contribute to the negative sequence torque.

Ultimately, the net torque can be calculated as the sum of the positive sequence torque and the negative sequence torque.

Now, let's visualize this with the torque-speed characteristic. When plotting the torque-speed characteristic, we place the speed (ω) on the y-axis and the torque on the x-axis. This representation allows us to analyze the performance and behavior of the induction motor under different operational conditions.

At the origin, we can observe the positive sequence torque depicted in the graph. It's important to note that this torque has been plotted with a relatively high rotor resistance. We've introduced this rotor resistance through the slip rings to enhance the effectiveness of the motor braking. By incorporating sufficient rotor resistance, we achieve this particular characteristic for the positive sequence torque.

Now, when we examine the negative sequence torque, we find it corresponding to $-\omega_{ms}$. This curve exhibits a similar shape to that of the positive sequence torque. For clarity, let's label the positive sequence torque as T_p and the negative sequence torque as T_n. Given that the rotor resistance is quite substantial, we observe that the sum of T_p and T_n yields a negative value for positive speeds.

If we trace the arcs representing these torques, we find the resultant torque curve appearing somewhat like this. This curve indicates the net torque acting on the motor. Suppose the motor was initially operating at a certain speed. When we engage in AC dynamic braking, we disconnect one of the phases and introduce the rotor resistances. Consequently, the characteristic curve transitions from one point to another within this characteristic framework.

We see both the positive sequence torque and the negative sequence torque at play here. While the original speed-torque characteristic may have appeared differently, the final outcome leads us into the second quadrant of operation. This transition is significant, as it means that braking will commence due to the presence of negative torque, causing the motor's speed to decrease until it reaches zero.

Naturally, at zero speed, the braking torque vanishes completely. Thus, there is no possibility of reversing the speed since the torque diminishes to zero at that point. Now, let's explore what occurs in a three-lead connection.

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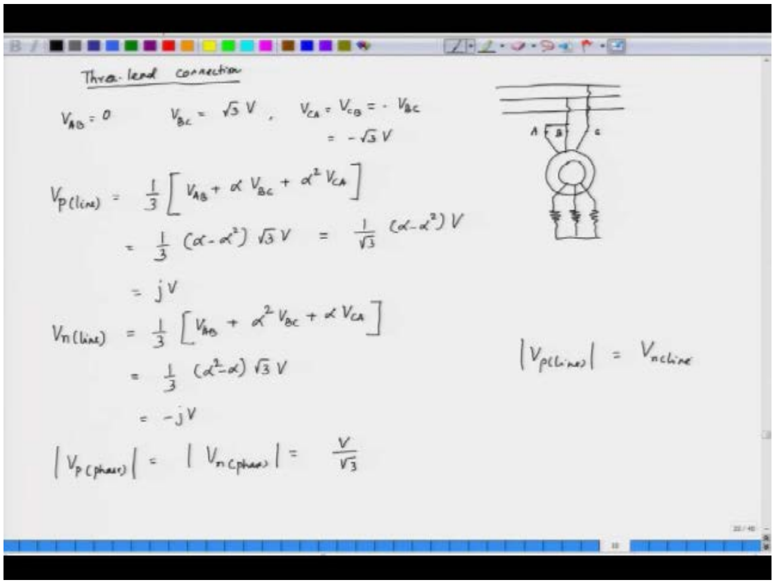

In a three-lead connection, we encounter a different scenario altogether. Here, we have three leads connected to our system. When discussing this three-lead connection, we have an AC supply linked to the stator of the motor, and we also have the rotor in the setup. In this case, we've introduced sufficient resistance within the rotor, as we are working with a slip ring induction motor equipped with appropriate rotor resistance.

Let's label the phases: we have phase C, then phase B, and finally phase A, which is connected to phase B. So, we can clearly identify phase A, phase B, and phase C in our configuration. Notably, phases B and C are short-circuited, while phase A is disconnected but linked to phase B.

Now, when we analyze this three-lead connection, we can easily conclude that the line voltage $V_{AB} = 0$. Moving on to V_{BC}, if we consider only the amplitude component, we find that $V_{BC} = \sqrt{3} \cdot V$, where V represents the phase voltage. Similarly, V_{CA} can be analyzed; it will yield the same result as V_{CB} because phases A and B are short-circuited. Thus, $V_{CB} = -V_{BC} = -\sqrt{3} \cdot V$.

In summary, we have established that $V_{BC} = \sqrt{3} \cdot V$ and $V_{CA} = -\sqrt{3} \cdot V$. Now, we can apply the sequence component method to analyze this unbalanced line voltage further. The positive sequence line voltage can be calculated as follows:

$$V_p = \frac{1}{3}(V_{AB} + \alpha V_{BC} + \alpha^2 V_{CA}) = \frac{1}{3}(0 + \alpha V_{BC} + \alpha^2 V_{CA}).$$

This equation allows us to systematically analyze the behavior of the system under these specific conditions.

Let's dive into the calculations involving the line voltages. From our previous discussion, we established that one-third of the contributions from V_{BC} and V_{CA} are opposite to each other. Therefore, we can express this as:

$$V_p = \frac{1}{3}(\alpha - \alpha^2) \cdot \sqrt{3}V.$$

Upon simplification, this reduces to:

$$V_p = \frac{1}{\sqrt{3}}(\alpha - \alpha^2) \cdot V.$$

This results in J times $\sqrt{3}$, and ultimately we find:

$$V_p = j \cdot V.$$

Next, we can determine the negative sequence line voltage. The expression for V_n line is given by:

$$V_n = \frac{1}{3}(V_{AB}) + \alpha^2 V_{BC} + \alpha V_{CA}.$$

Since $V_{AB} = 0$, we can rewrite this as:

$$V_n = \frac{1}{3}(\alpha^2 V_{BC} + \alpha V_{CA}).$$

Substituting in our previous results, we find:

$$V_n = \frac{1}{3}(\alpha^2 - \alpha) \cdot \sqrt{3}V,$$

which simplifies to:

$$V_n = -jV.$$

Thus, we have successfully calculated both the positive sequence line voltage and the negative sequence line voltage. Now, turning our attention to the phase voltages: in this scenario, the magnitude of the phase voltage will be consistent. The phase voltage, the positive sequence phase voltage, and the negative sequence phase voltage will all be equal. This leads us to conclude that the magnitude is:

$$V_{\text{phase}} = \frac{3}{\sqrt{3}} V.$$

In this case, since the magnitudes of the positive and negative sequence line voltages are the same, it follows that the phase voltages will also share this same magnitude. While there may be some phase differences, the magnitudes remain equal.

With these calculations in hand, we can now proceed to draw the equivalent circuit for the three-lead connection. The equivalent circuit will be structured as follows: it will clearly reflect the interactions among the components, allowing us to visualize the dynamics of this particular setup.

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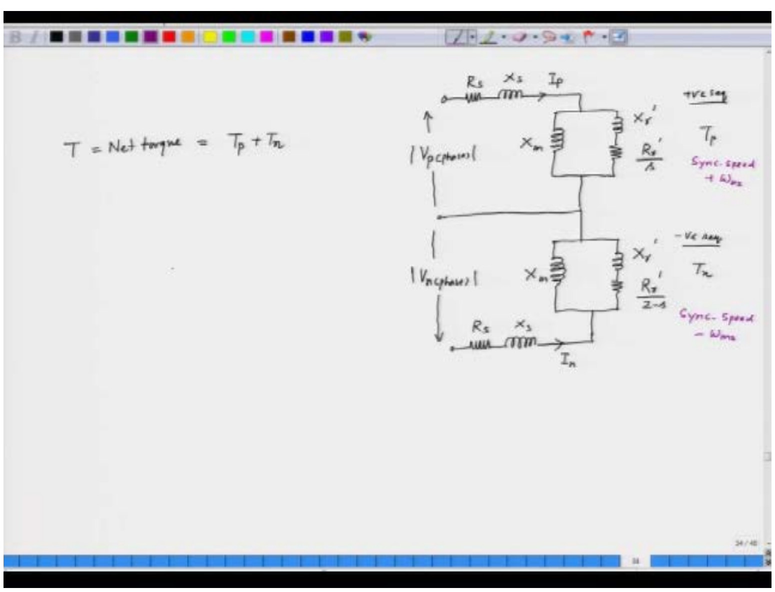

Here we have the components of our equivalent circuit clearly laid out. First, let's look at the positive sequence network, which consists of the stator resistance, the stator leakage reactance, the magnetizing reactance, the rotor leakage reactance, and the rotor resistance. We can denote these as X_m, X_r', and $\frac{R_r'}{s}$.

In this scenario, it's important to note that the two phase voltages are equal, so we equate them accordingly. Now, moving on to the negative sequence network, we see similar components: X_m, X_r', and $\frac{R_r'}{2-s}$. This gives us a clear picture of the three-lead connection we are analyzing.

For both networks, we have the resistance and the leakage reactance defined. Specifically, R_s and X_s apply to the positive sequence network. As for the phase voltages, both the positive sequence phase voltage and the negative sequence phase voltage are equal in magnitude, indicating symmetry in this system.

Next, we define the positive sequence current as I_p and the negative sequence current as I_n. With these currents established, we can now calculate the corresponding torque for each network. The net torque will be the summation of these two torques:

$$\text{Net Torque} = T_P + T_N.$$

It's crucial to note that the negative sequence torque will indeed be negative, as it corresponds to rotation in the opposite direction. Here, the synchronous speed for the positive sequence is denoted as $+\omega_{ms}$, while for the negative sequence, it will be $-\omega_{ms}$. Therefore, since the synchronous speed is negative, it follows that the negative sequence torque will also be negative.

By combining these two torques, T_p from the positive sequence network and T_n from the negative sequence network, we can determine the net torque in this system. This methodology allows us to effectively analyze the equivalent circuit and find the torque for both the two-lead and three-lead connections.

Now, let's shift our focus to understanding DC dynamic braking and its implications in our system.

The next type of braking we will discuss is DC dynamic braking, specifically for induction motors. One notable drawback of DC dynamic braking, compared to AC dynamic braking, is that AC dynamic braking is typically employed for slip ring induction motors. This requirement arises because, without a slip ring induction motor, we cannot introduce rotor resistance. Introducing sufficient rotor resistance is crucial for generating negative torque in the second quadrant; however, this limitation does not apply to DC dynamic braking.

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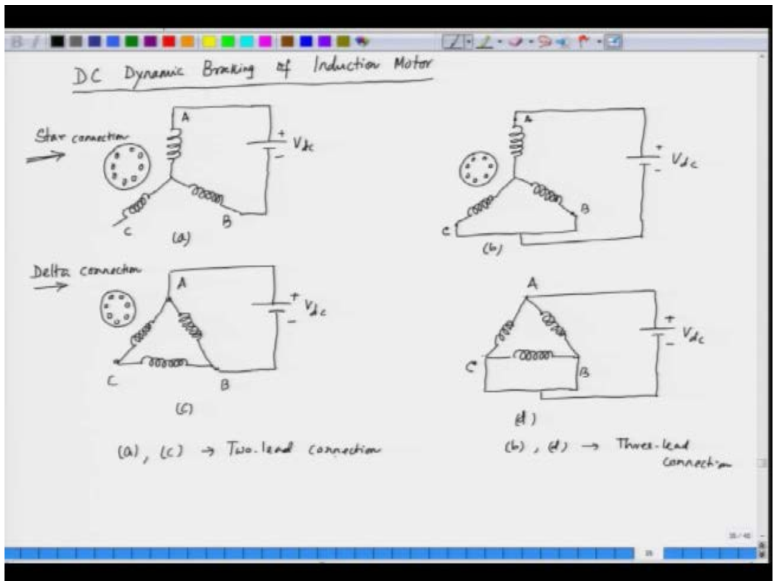

In DC dynamic braking, we start with the stator windings of the induction motor, which consist of phases A, B, and C. We then apply a DC supply to the stator of the induction motor. Now, let's consider the rotor. It could be a squirrel cage rotor, but regardless of its type, the key is that the stator is supplied with DC voltage.

For a star-connected stator, we can apply the DC supply in a couple of ways. One method is to directly connect the DC supply across one phase and the other two phases, which have been short-circuited. This setup allows us to effectively harness the benefits of DC dynamic braking.

In the case of a delta-connected stator, the approach is slightly different. We can apply the DC voltage between any two phases while keeping the rotor in place. This means we could have phase A, phase B, and phase C configured in a delta connection, and the DC voltage is applied between two of these phases. In both configurations, the rotor continues to rotate, ensuring that the braking action is effectively applied.

We have phases A, B, and C in our configuration. By short-circuiting phases B and C, we can apply the DC voltage, denoted as V_{dc}, between one phase and the two short-circuited phases. This setup is representative of the delta connection. Now, if we consider the star connection, we have our first two phases: let's label them as A and B, while C and D are our other two phases. Here, A and C form what we call a two-lead connection because we are simply connecting two leads to the DC supply. In contrast, the connection between phases B and D represents a three-lead connection, where we connect three leads to the DC supply, with phases B and C being short-circuited.

When we apply DC to the stator, we are effectively producing a DC magnetic field. While the rotor continues to rotate, the stator's production of this DC field induces currents in the rotor. These induced currents, in turn, lead to the braking action of the induction motor. Unlike when we have a rotating field, we now have a static DC field that plays a crucial role in slowing the rotor down to a stop.

With this understanding, we will pause here for today’s lecture. In our next session, we will discuss the topic of dynamic braking.