Fundamentals of Electric Drives

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Lecture-28

Closed-loop Operation of Current Source Inverter (CSI) fed Induction Motor Drive, Control of Slip Ring of Induction Motor-Static Rotor Resistance Control

Hello and welcome to this lecture on the fundamentals of electric drives! In our previous session, we delved into the fascinating topic of current source inverter (CSI) fed induction motors and explored the relationship between stator current and slip frequency. Our goal was to understand how to adjust the stator current in order to maintain a constant air gap flux, or in other words, to keep the magnetizing current steady. Today, we will build upon that discussion as we revisit the curve we developed in the last lecture.

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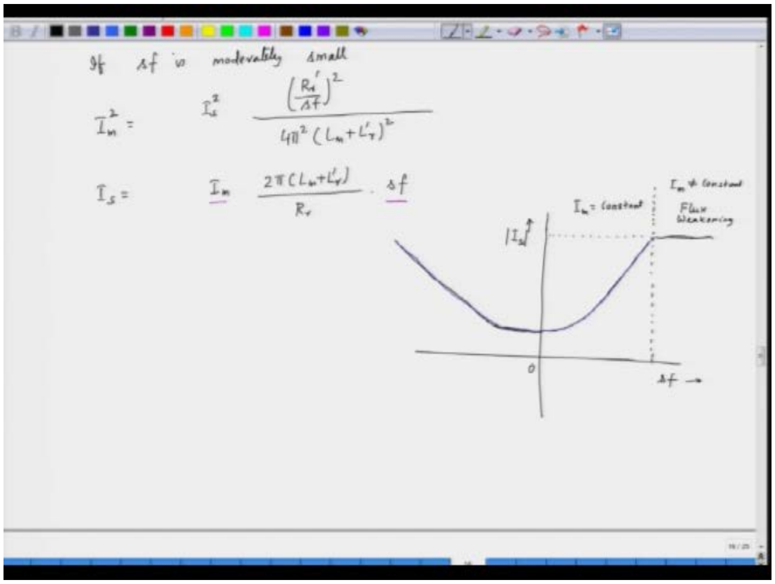

As we vary the slip frequency, it's essential that the stator current follows a specific profile to ensure that the magnetizing current, I_m, remains constant. Essentially, we are plotting the magnitude of the stator current here. The slip frequency can be either positive or negative, but our objective is to adjust the stator current in such a way that the magnetizing current remains nearly constant.

However, if we continue to increase the stator current, we will eventually reach a maximum value. Beyond this threshold, we cannot exceed the motor's rated capacity, which means the magnetizing current will no longer stay constant. At this point, we can categorize our operation into two distinct zones. Below a certain frequency, we maintain I_m as constant, a region known as the flux weakening or field weakening region.

Once we surpass this frequency, I_m is no longer constant; in fact, it begins to decrease. This behavior is practical and quite intentional. As we aim for higher slip speeds, we deliberately allow the magnetic flux to decrease, facilitating higher operational speeds. Now, let's delve into the closed-loop control of a CSI-fed induction motor drive.

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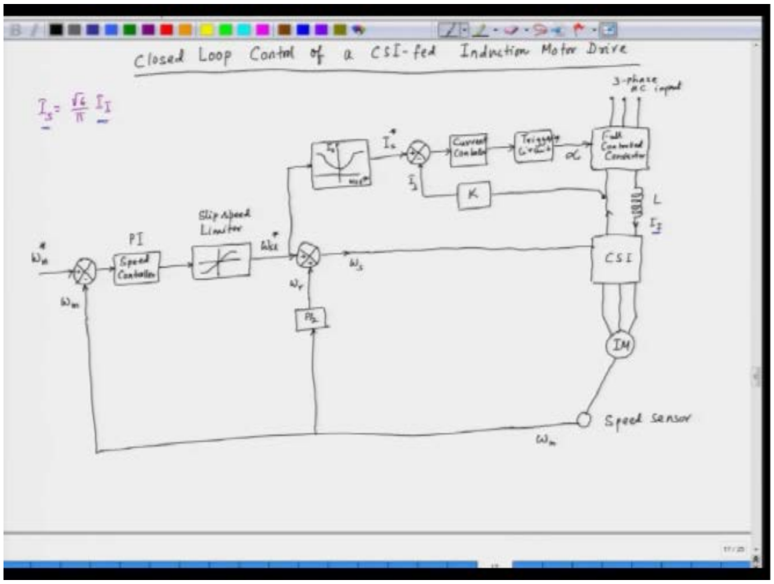

In this segment, we will be discussing the closed-loop control of a CSI-fed induction motor drive. To begin, let’s establish our reference speed, denoted as ω_n^*. We compare this reference speed with the actual speed of the motor. The result of this comparison is then fed into a speed controller, which is essentially a proportional-integral (PI) controller.

Following the speed controller, we implement a limiter to constrain its output. This component is referred to as a slip speed limiter. It effectively regulates the output of the PI controller to ensure that the slip speed remains within acceptable limits. More appropriately, we can refer to it as a slip speed limiter.

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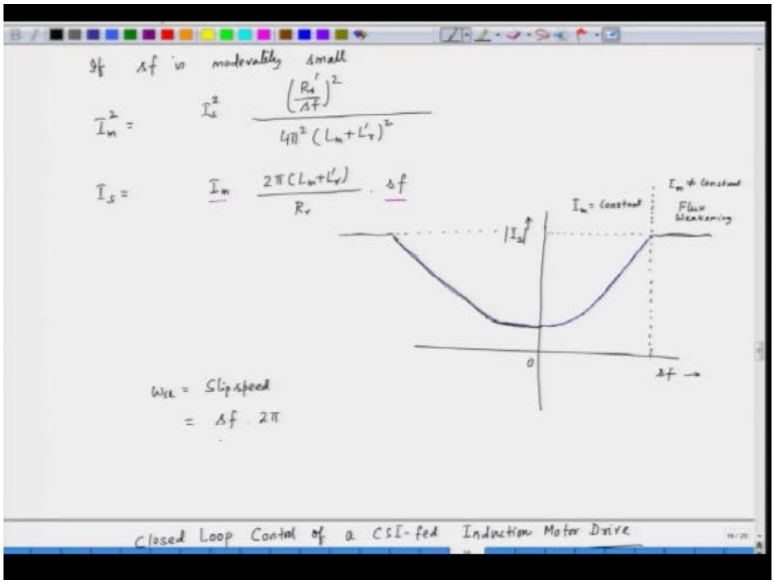

The slip frequency and slip speed are closely related concepts. In fact, the slip speed, denoted as ω_{sl}, is simply the slip frequency multiplied by 2π. This means that you take the slip frequency and multiply it by this constant factor to obtain the slip speed. It's important to note that constant current operation is also possible for negative values of the slip frequency.

Consequently, we have a symmetrical graph representing this relationship in both the first and second quadrants. Therefore, the slip speed output, ω_{sf}, can be expressed as $\omega_{sl} = 2\pi \cdot sf$, where ω_{sl} serves as our reference value.

Next, we need to relate this slip speed to the rotor speed, specifically the rotor electrical speed, in order to derive the fundamental frequency of the inverter. The CSI, or Current Source Inverter, employs Controlled Rectifiers (SCRs), which are quite robust and suitable for high-power applications. As we've discussed, the input to the CSI originates from a controlled rectifier, which is a fully controlled converter. The input supply is three-phase AC, and we have a DC link that contains large inductors. These inductors help maintain the current to the CSI nearly constant.

At the output of the CSI, we have the induction motor. To effectively control the system, we first need a speed sensor. This sensor detects the mechanical speed of the motor and provides feedback for the control system. The mechanical speed is then multiplied by the number of pole pairs to determine the electrical speed because, when we control the inverter, we are dealing with electrical frequency.

To clarify, we take the number of poles, denoted as p, and divide it by 2 to get the pole pairs, and this electrical speed, ω_s, is fed into the CSI for frequency control. Now, the slip speed, ω_{sl}, is directed to a function generator that produces a symmetrical waveform, as we just derived.

This essentially provides the relationship between the slip frequency, denoted as ω_{sl}, and the stator current, I_s. The slip frequency command is directed to a function generator, which produces the output I_s. This I_s is then compared with its actual value, which is obtained from a current sensor monitoring the inverter current.

We know from previous discussions that there is a derived relationship given by $I_s = \frac{\sqrt{6}}{\pi} I_i$. Thus, we can express I_s in terms of the input current I_i as follows:

$$I_s = \frac{\sqrt{5}}{\pi} I_i.$$

Here, I_i is converted into I_s using a constant gain block, which is followed by a current controller. The output from this triggering circuit is represented by α, which is the firing angle of the fully controlled converter.

We start with a three-phase AC input, and by controlling this angle α, the triggering angle of the input full-control bridge, we can effectively manage the DC link current. When we regulate the DC link current, we also influence the output of the CSI. This is significant because the DC link current is reflected as output, and we have established that the DC link current is proportional to the output of the CSI.

Therefore, by controlling the DC link current, we can subsequently manage the stator current of the induction motor, which is also present in the system. Now, let’s visualize this with a closed-loop block diagram where we are controlling the slip frequency. By managing the frequency in this manner, we ensure that the flux remains within the rated value.

It's important to note that if we increase the slip frequency, the flux will decrease, but it will never reach saturation. Moreover, by implementing closed-loop control, we create a more stable overall system. Earlier, we observed that the motor was unstable during constant flux operation; however, with closed-loop feedback, we can stabilize the previously unstable induction motor system.

This discussion primarily revolves around squirrel-cage machines. However, we can also apply control techniques for slip ring induction motors, which are equally suited for high-power applications. Now, let's explore some of the control methods specifically designed for slip ring induction motors.

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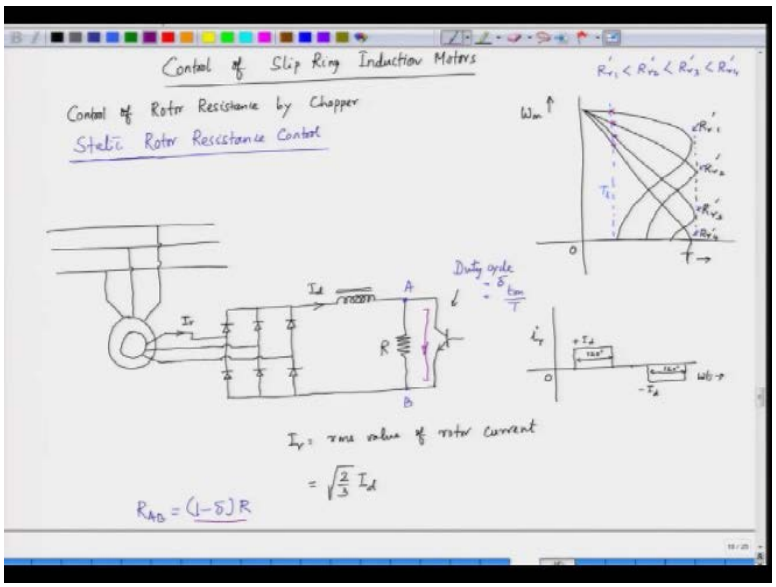

Let's begin our discussion on controlling slip ring induction motors, specifically focusing on the control of rotor resistance through the use of a chopper, which is commonly referred to as static rotor resistance control. If we recall the torque-speed characteristic of an induction motor, we can see that the speed of the motor can indeed be regulated by manipulating the rotor resistance. This is possible because the rotor is equipped with slip rings, allowing us to insert resistance directly into the rotor circuit.

Now, let's delve into the speed variation achieved through rotor resistance control. In this graphical representation of the torque-speed characteristic of an induction motor, we have the speed axis on the horizontal side and the torque axis on the vertical side. Here, we are examining the characteristics for a specific rotor resistance, denoted as R_{r1}'.

As we increase the rotor resistance, it's important to note that while the peak torque remains unchanged, the overall characteristic curve is altered. As we progressively increase the rotor resistance from R_{r1}' to R_{r2}', R_{r3}', and R_{r4}', the curves shift accordingly. This is visually represented here:

- For R_{r1}', the characteristic is at one point,
- For R_{r2}', it shifts to another,
- Continuing with R_{r3}' and R_{r4}', we observe a further change.

It's crucial to highlight that as we increase the rotor resistance, the values follow this relationship: $R_{r1}' < R_{r2}' < R_{r3}' < R_{r4}'$. In other words, we are progressively increasing the rotor resistance with each step.

Now, consider a scenario where we have a constant torque load, represented in our graph. As we adjust the rotor resistance, we can observe the corresponding changes in speed. For instance, in the case of low rotor resistance, the operating point is indicated here; as we move to the second case with increased resistance, the operating point shifts to this position; the third and fourth cases follow suit.

By increasing the rotor resistance, we effectively gain control over the speed of the induction motor. This control over rotor resistance is implemented using a chopper, which allows for precise adjustments and enhances the operational capabilities of slip ring induction motors.

This is why we refer to this method as static rotor resistance control. Now, let's explore how we implement this static rotor resistance control. We begin with three-phase lines supplying power to the induction motor through the slip ring. Typically, the stator is fed directly from the three-phase lines, while the rotor incorporates an uncontrolled rectifier.

The slip rings allow us to connect this uncontrolled rectifier, and within the DC link, we install a large inductance. To manage the rotor resistance, we need to insert a resistor followed by a switch, often referred to as a chopper switch. Since we have an inductor present, possibly an iron inductor, the resistance is placed here. The current passing through this inductor is denoted as I_d, and its purpose is to smooth out the current fluctuations. The role of the inductor is crucial; it ensures that the current remains almost constant and ripple-free.

Now, if we shift our focus to the input side and examine the rotor current, we can analyze its characteristics. When we plot the rotor current for one phase through an uncontrolled rectifier, we observe the nature of the rotor current. If we chart the rotor current against time, we designate time on the horizontal axis and rotor current (I_r) on the vertical axis, with the instantaneous value represented.

The shape of this current waveform is essentially quasi-rectangular in nature. We can visualize it like this: the waveform spans a width of 120 degrees. This is crucial to note; we marked this 120-degree interval for our analysis. The positive peak of this waveform reaches $+I_d$, while the negative peak dips to $-I_d$.

To calculate the RMS value of this current, we refer to the rotor current I_r. The RMS value of the rotor current reflects the quasi-rectangular nature of the input current from the bridge, characterized by its 120-degree duration. Understanding these waveform dynamics is fundamental to effectively controlling the slip ring induction motor.

Now, if we want to determine the RMS value of the rotor current, we need to compute the root mean square (RMS). The conduction period lasts only 120 degrees, which is two-thirds of 180 degrees. Therefore, when we calculate the root mean square, we arrive at the final value of $\sqrt{\frac{2}{3}} \cdot I_d$.

This indicates that the RMS value of the input current is $\sqrt{\frac{2}{3}} \cdot I_d$.

Next, we consider the operation of the chopper, which functions with a duty cycle denoted as δ. Essentially, we operate the chopper with a duty cycle equal to δ, which can be defined as the ratio of T_{on} to the total period T. When the chopper is in the "on" state, the resistance is bypassed; conversely, when the chopper is off, the resistance is included in the circuit. Thus, the duty cycle is represented as δ.

Now, let's analyze the resistance between two points, which we can label as point A and point B.

The resistance seen by the chopper at this junction, denoted as R_{AB}, can be expressed as $R_{AB} = (1 - \delta) \cdot R$. This formula reflects the fact that when the switch is closed, the resistance effectively becomes zero.

If we consider the scenario where we permanently close the switch by setting $\delta = 1$, then T_{on} equals the total period T. In this case, the resistance is completely bypassed, which means that the current will flow exclusively through the switch, rendering the resistance irrelevant. This corresponds to $\delta = 1$. Therefore, in general, we can summarize the relationship for the resistance as $R_{AB} = (1 - \delta) \cdot R$.

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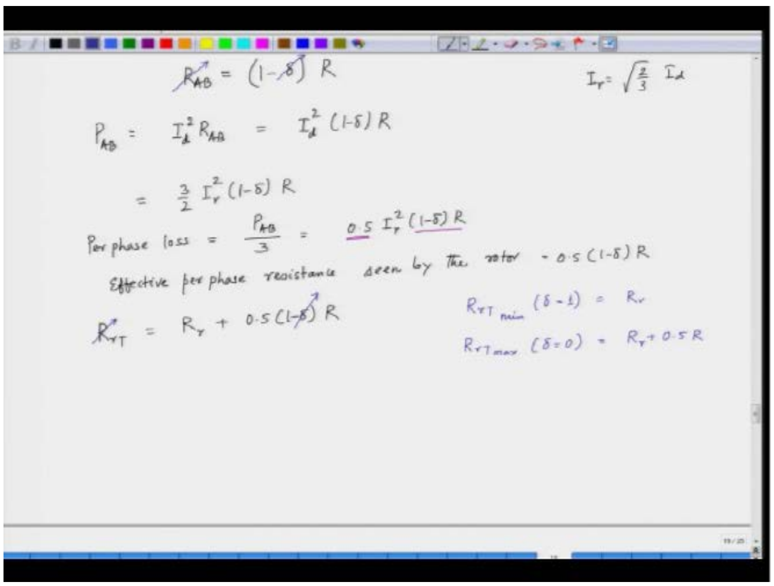

Let's summarize this effectively. As we manipulate R_{AB}, we are doing so through the chopper, which is our primary control strategy. By adjusting the duty cycle δ, we can achieve a variable resistance. This adjustment of δ directly influences the resistance reflected on the rotor side.

Now, let's examine the power loss, denoted as P_{AB}. This power loss is expressed mathematically as $P_{AB} = I_d^2 \cdot R_{AB}$. Referring back to our circuit, we note that I_d is the current flowing through the looking resistance R_{AB}. Thus, we can conclude that the loss is $I_d^2 \cdot R_{AB}$. By substituting R_{AB} with $(1 - \delta) \cdot R$, we can reformulate our expression for losses observed from the AB segment of the circuit.

Next, we turn our attention to the rotor. It is important to note that the rotor current behaves differently; we previously established that the RMS value of the rotor current is given by $\frac{\sqrt{2}}{3} I_d$. We will substitute this value into our power loss equation. Thus, substituting I_d yields:

$$P_{AB} = \frac{3}{2} \cdot I_d^2 \cdot (1 - \delta) \cdot R$$

This formulation indicates that the rotor is subjected to losses analogous to $I_d^2 \cdot R_{AB}$. Given that our motor is a three-phase induction motor, the rotor also consists of three phases. To determine the total losses, we must divide by 3 to obtain the power losses per phase. Consequently, the power phase losses can be expressed as:

$$P_{\text{phase}} = \frac{P_{AB}}{3} = 0.5 \cdot I_r^2 \cdot (1 - \delta) \cdot R$$

This signifies that the effective resistance seen by the rotor, which influences the power loss, can be represented as:

$$\text{Effective Resistance} = 0.5 \cdot (1 - \delta) \cdot R$$

The rotor has its own inherent resistance, denoted as R_r' or R_r. Consequently, the total rotor resistance, which includes the external resistance, can be expressed using the following formula:

$$R_{rT} = R_r + 0.5 \cdot (1 - \delta) \cdot R$$

This equation indicates that we have the ability to increase the rotor resistance by adjusting δ. By manipulating this parameter, we can effectively control the total rotor resistance. The minimum total rotor resistance, $R_{T\,\text{min}}$, occurs when δ = 1, which results in:

$$R_{T\,\text{min}} = R_r$$

Conversely, the maximum total rotor resistance, $R_{T\,\text{max}}$, is observed when δ = 0. In this case, substituting δ = 0 into the equation gives us:

$$R_{T\,\text{max}} = R_r + 0.5 \cdot R$$

This sets the limits for the variation of rotor resistance, allowing us to adjust it from a value of R_r up to $R_r + 0.5R$.

Now, when dealing with an induction motor, it is essential to consider the turns ratio between the stator and the rotor. For instance, the stator may have a turns ratio N_s, while the rotor will have its own turns ratio N_r. Thus, the referred value is established through the turns ratio, represented as $\frac{N_s}{N_r}$.

As we proceed with our calculations, it is imperative to account for this turns ratio in order to develop the equivalent circuit accurately.

Now, let's take a closer look at the block diagram representing the static rotor resistance control of the induction motor.

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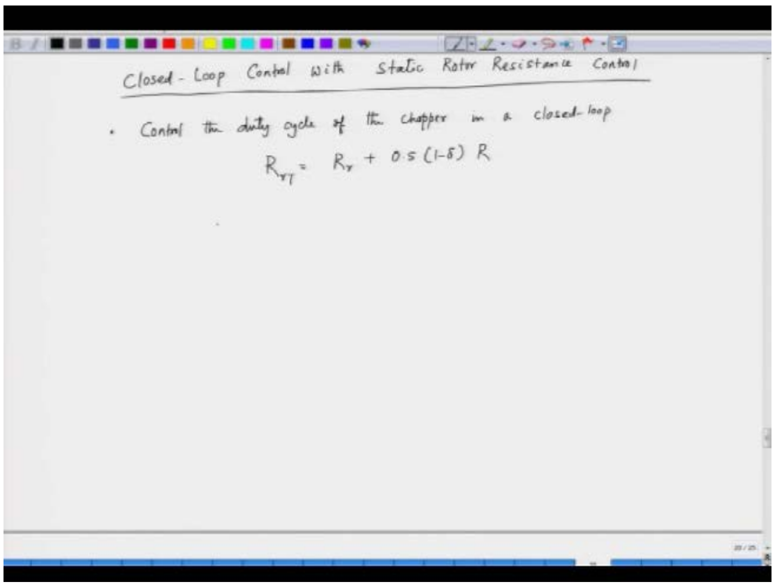

We have begun our discussion on rotor resistance, and now our primary objective is to control the duty cycle of the chopper in a closed-loop system. The total rotor resistance can be expressed as:

$$R_{rT} = R_r + 0.5 \cdot (1 - \delta) \cdot R$$

By managing the rotor resistance in this closed-loop configuration, we can effectively adjust the total rotor resistance R_r'.

In our next lecture, we will delve into the details of this control block diagram. For today, we have established how rotor resistance can be regulated using a chopper-controlled resistor. Our discussion on this topic will continue in the upcoming lecture.