Fundamentals of Electric Drives

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Lecture-29

Closed-loop Operation of Slip Ring Induction With Static Rotor Resistance Control, Slip Power Recovery in Slip Ring Induction Motor Drive-Static Kramer Drive

Hello, and welcome to this lecture on the fundamentals of electric drives. In our previous session, we explored the concept of static rotor resistance control for induction motors. The focus was on adjusting the motor's speed by manipulating the rotor resistance. In this case, we are working with a slip ring induction motor, which is ideal for this application since it allows us to insert resistance directly into the rotor circuit via the slip rings.

In the last lecture, we discussed how this resistance adjustment can be achieved using a chopper. The objective was to control the rotor resistance in a precise manner, thereby enabling us to effectively manage the motor's speed.

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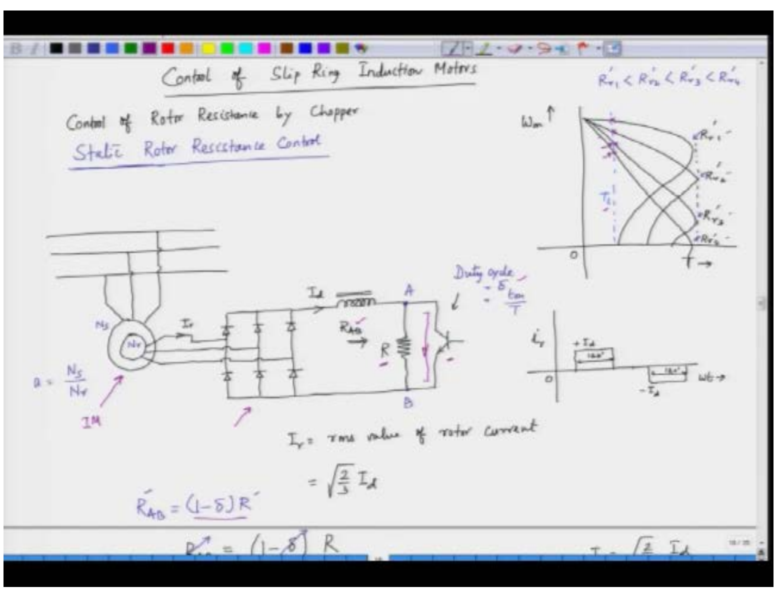

Let's briefly recap what we covered in the previous lecture. We were working with an induction motor, specifically a slip ring induction motor. In the rotor circuit, we introduced a non-controlled rectifier, which rectified the rotor current. Following this, we injected a resistance, denoted as R, into the rotor circuit. Additionally, we incorporated a switch that alternates between closed and open states to regulate the resistance.

What we observed is that the resistance seen from terminals A and B, R_{AB}, is given by the expression:

$$R_{AB} = (1 - \delta) \cdot R$$

Here, δ represents the duty cycle of the chopper switch, which modulates the connection in the circuit. Our goal is to control this system in a closed-loop configuration, where we aim to regulate the speed of the motor.

We then examined the characteristics for different values of rotor resistances R_{r1}, R_{r2}, R_{r3}, and R_{r4}. As the rotor resistance varies, the corresponding characteristic curve also shifts, leading to a change in motor speed. This occurs because the speed is determined by the intersection of two distinct characteristics: the motor torque and the load torque.

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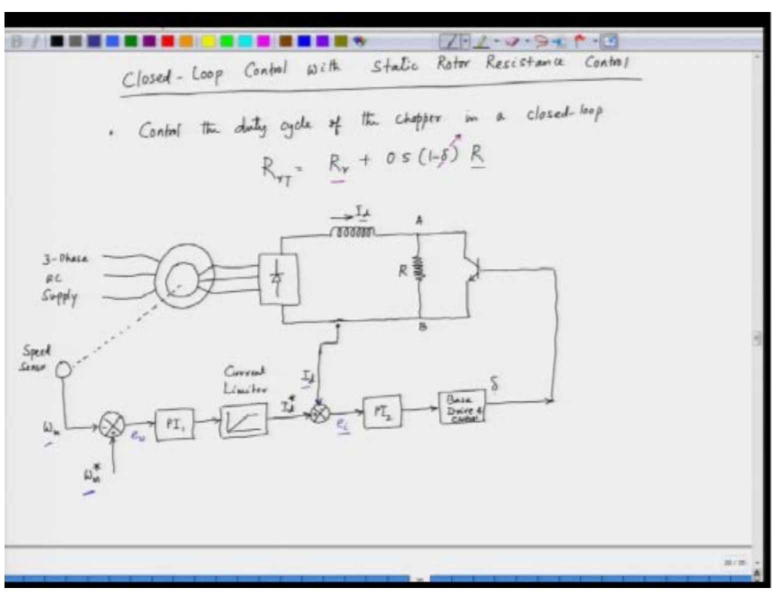

To control the speed in a closed-loop system, we need to regulate the current I_d, which is the current in the DC link. By controlling this current, we can effectively manage the torque, and consequently, the motor's speed. Now, let’s take a look at the closed-loop block diagram for the chopper-controlled rotor resistance in an induction motor drive.

Our total resistance consists of two components: R_r, the rotor resistance, and the external resistance. To control the motor's performance, we need to adjust the duty cycle of the chopper, denoted by δ. This is achieved through the following arrangement.

We have a slip ring induction motor with both rotor and stator windings. The stator is powered by a standard 3-phase AC supply, while the rotor is connected to a diode bridge rectifier. The rectifier configuration ensures that the rotor circuit is converted to DC. On the DC side of the circuit, we include an inductor and a resistor R, with a transistor-based chopper that controls the resistance between terminals A and B. The current flowing through the DC link is I_d, which is crucial for controlling the motor's behavior.

To regulate the motor's speed, we employ a speed sensor mounted on the rotor. This sensor measures the actual rotor speed, ω_m. The measured speed ω_m is then compared with the reference speed ω_m^*, which we want to maintain. The difference between these values, or the error, is processed by a Proportional-Integral (PI) controller. Since the PI controller includes an integrating action, its output must be constrained, so we introduce a current limiter. The output of this limiter is the reference current I_d^*, which directly influences the motor's torque.

The magnitude of I_d governs the motor's torque: to increase torque, I_d must be increased, and to reduce torque, I_d must be decreased. Hence, by managing I_d, we can effectively control the motor’s torque and consequently its speed.

The output of the PI controller, I_d^*, is compared with the actual current in the circuit, which is measured using a current sensor. The sensor feeds the actual current value back into the control loop. The difference between the reference current I_d^* and the actual current is then processed by a second PI controller (PI2). The output of PI2 controls the base drive of the transistor, adjusting the duty cycle δ of the chopper.

Thus, by controlling δ, we can regulate the resistance in the rotor circuit, ultimately managing the motor's speed. This forms the closed-loop control system for a chopper-controlled rotor resistance induction motor drive.

What we have here is a control system that starts by comparing the reference speed with the actual speed, resulting in a speed error. This speed error is then processed by a speed controller, which in this case could be a simple chopper-based controller. The output from the speed controller is the reference current, I_d^*. To manage this, we measure the actual current, I_d, using a current sensor and feed it back into the system.

The difference between I_d^* and the actual I_d is the current error, which is processed similarly to the speed error. This current error is fed into another PI controller, which generates a control signal. This control signal is then compared with a triangular wave to produce the gate signal required for the chopper. Ultimately, we control the chopper's duty cycle to adjust the current I_d, allowing for precise control over the motor's torque and speed.

This is essentially the closed-loop block diagram of the static rotor resistance control for a slip ring induction motor. Slip ring induction motors are commonly used in large power applications, and in such cases, maintaining high efficiency is critical. However, when using chopper-based resistance control, some energy is inevitably wasted in the resistors.

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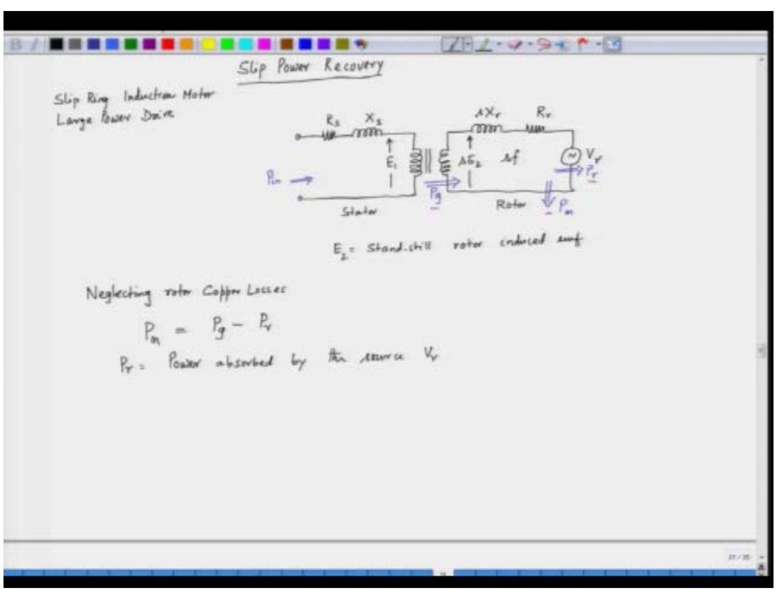

This brings us to the concept of slip power recovery. Instead of dissipating the rotor energy as heat in resistors, it is possible to recover and reuse this energy. This approach, known as the slip power recovery scheme, offers a more efficient alternative for controlling slip ring induction motors in high-power applications. So we will be discussing about the slip power recovery.

This slip power recovery scheme is typically used in slip ring induction motors, especially for large power drives. Now, let's delve into the concept of slip power recovery by analyzing the power phase equivalent circuit of an induction motor.

In this equivalent circuit, we have the stator side, which includes the stator resistance and stator leakage reactance. On the rotor side, we have the rotor leakage reactance and rotor resistance. To facilitate slip power recovery, we introduce a voltage source, V_r, at a specific frequency. As you know, the frequency of the rotor current depends on the slip, S, so the frequency in the rotor circuit is $S \cdot f$.

Let’s break it down further. In the stator, the induced EMF is denoted as E_1, while the rotor’s induced EMF is E_2. However, since the rotor is operating at slip S, the induced EMF in the rotor becomes $S \cdot E_2$. Here, E_2 is the standstill rotor EMF, while $S \cdot E_2$ is the EMF when the motor is running at slip S. The rotor reactance, X_r, is also scaled by slip, so the effective reactance is $S \cdot X_r$, with the rotor resistance denoted as R_r.

Now, let's consider the flow of power. From the stator, electrical power is supplied to the motor. Some of this power is lost in the stator, while the remaining power crosses the air gap between the stator and rotor, known as the air gap power, P_G. A portion of this air gap power is converted into mechanical power, P_m, while the rest is absorbed as slip power, P_r, by the voltage source V_r.

For simplification, if we neglect the rotor copper losses, we can express the mechanical power output P_m as the difference between the air gap power P_G and the rotor power P_r, which is being recovered. Therefore, we have the relationship:

$$P_M = P_G - P_R$$

In this context, P_r represents the power recovered by the voltage source V_r, which is the slip power that would otherwise be wasted in the rotor circuit. This recovered slip power is what gives the scheme its name , the slip power recovery scheme.

In earlier systems, mechanical methods like Schrage motors were employed to recover this slip power. However, modern applications use static converters for this purpose, offering more efficient and flexible recovery. Let’s now examine how static converters are used to recover slip power in contemporary configurations.

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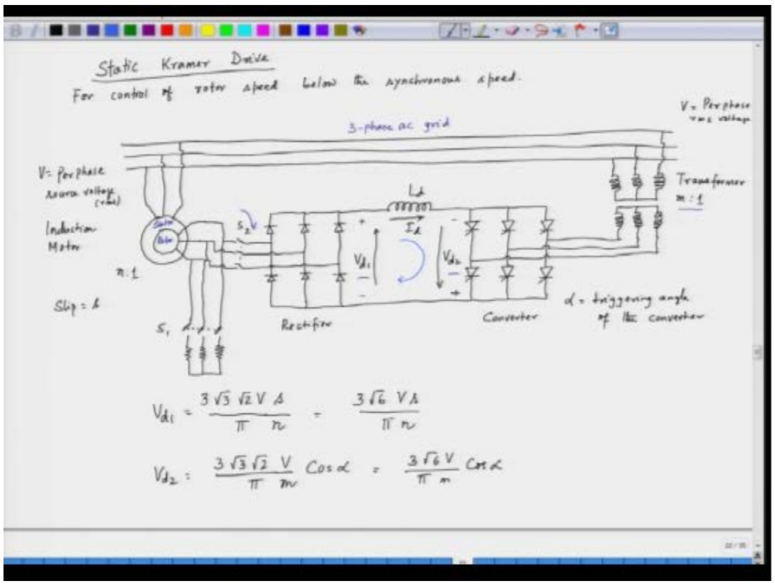

This configuration is known as the static Kramer drive, a system used for controlling the rotor speed of a slip ring induction motor below its synchronous speed. Let's take a closer look at how this system works.

We begin with a three-phase power supply, which feeds the stator of the slip ring induction motor. The rotor, in turn, is connected to an uncontrolled rectifier, specifically a three-phase bridge rectifier. This rectifier is linked to the rotor windings via the slip rings, allowing us to control the rotor circuit.

Each of the rotor's three phases, Phase A, Phase B, and Phase C, are connected to separate switches. These switches are typically used to connect the rotor windings to starting resistors, which help in the initial phase of starting the motor. The switches are designated as S_1 and S_2, and they play a crucial role in controlling the operation of the motor.

Now, we introduce a transformer into the system, which has a turns ratio of n:1. The rotor circuit is connected to the transformer through a DC link, which includes a large inductor L_d to smooth the DC current I_d. Additionally, a three-phase silicon-controlled rectifier (SCR) bridge is connected to the DC link. This SCR bridge is responsible for converting the recovered slip power back into AC, which is then fed back to the supply through the transformer.

Here's how the system operates:

1. Normal Operation (No Speed Control): When the motor is running without any speed control, switch S_1 is closed, and switch S_2 is open. In this state, the stator is directly connected to the three-phase AC supply, and the rotor is connected to resistances through the slip rings. The motor operates normally, rotating as expected without any slip power recovery.

2. Slip Power Recovery and Speed Control: When we want to recover the slip power and control the rotor speed, we switch the configuration. Switch S_1 is opened, and switch S_2 is closed, connecting the rotor circuit to the rectifier bridge. The slip power generated in the rotor, instead of being wasted in the resistors, is now fed through the SCR bridge and transformed back into the AC grid via the transformer.

In this configuration, the power from the rotor is rectified into DC voltage, denoted as V_{D1}, which flows through the DC link inductor L_d as the current I_d. The output of the SCR bridge produces a second DC voltage V_{D2}, and both V_{D1} and V_{D2} contribute to the recovery of the rotor's slip power. This recovered power is then transformed through the transformer and returned to the three-phase AC grid.

By adjusting the duty cycle of the SCRs in the bridge, we control the amount of slip power recovered and, consequently, the motor's speed. This system allows for efficient speed control and energy recovery, making it an ideal solution for large power applications.

The static Kramer drive is a significant improvement over older mechanical methods of slip power recovery, as it employs static converters (like the SCR bridge) to recover and feed the slip power back into the grid, enhancing overall efficiency.

In this setup, the rectifier is connected to the rotor of the induction motor. At this stage, switch S_2 is closed, while switch S_1 is open. The output voltage of the rectifier is denoted as V_{D1}. Now, what exactly is V_{D1}?

The output of a three-phase rectifier is given by:

$$V_{D1} = \frac{3V_m}{\pi}$$

where V_m is the peak phase voltage. If we express the phase voltage V as the RMS value of the power source voltage, we can derive the following. The peak phase voltage $V_m is \sqrt{2}V$, and the line-to-line voltage is $\sqrt{3}$V. Thus, the output voltage V_{D1} becomes:

$$V_{D1} = \frac{3 \times \sqrt{3} \times \sqrt{2} \times V}{\pi}$$

Since the rotor operates at a slip speed S, we incorporate the slip factor into the equation, and also account for the transformer turns ratio n:1. Ignoring any minor voltage drops and considering the turns ratio, the output voltage at V_{D1} can be expressed as:

$$V_{D1} = \frac{3 \times \sqrt{6} \times V \times S}{\pi n}$$

Next, let's consider V_{D2}, the voltage coming through the transformer. The transformer has a turns ratio of m:1. Applying the same logic, the expression for V_{D2} becomes:

$$V_{D2} = \frac{3 \times \sqrt{6} \times V}{\pi m}$$

However, since V_{D2} is obtained through a controlled rectifier, we must introduce the firing angle α of the converter. The output is modulated by multiplying with cos α, where α is the triggering angle. Thus, the final expressions for V_{D1} and V_{D2} are:

$$V_{D1} = \frac{3 \times \sqrt{6} \times V \times S}{\pi n}$$

$$V_{D2} = \frac{3 \times \sqrt{6} \times V}{\pi m} \times \cos \alpha,$$

To control the system, we apply Kirchhoff's Voltage Law (KVL) to the circuit. When KVL is applied to this loop, the resulting equation provides the basis for controlling the overall output voltage, enabling efficient control of the motor's operation through the converter system.

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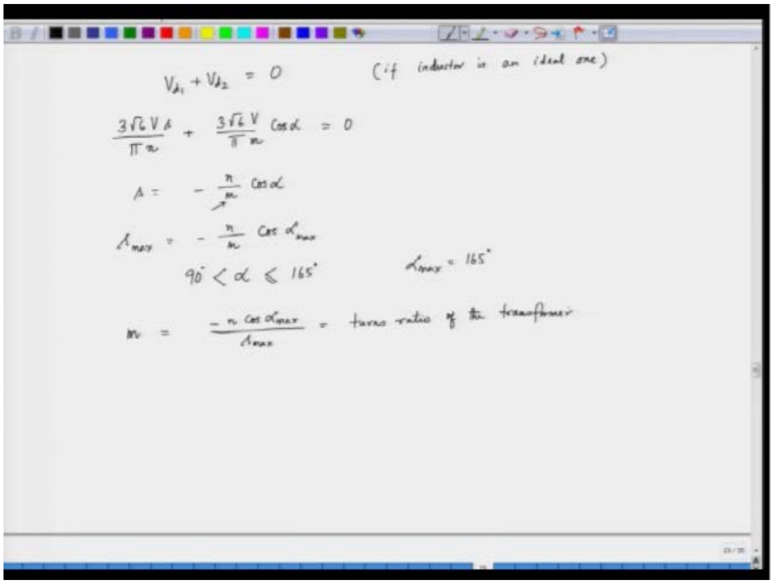

So, we can state that $V_{D1} + V_{D2} = 0$, assuming the inductor is ideal, meaning there is no voltage drop across it. In this ideal scenario, we obtain the equation:

$$V_{D1} + V_{D2} = 0$$

Expanding this, we have:

$$\frac{3 \times \sqrt{6} \times V \times S}{\pi n} + \frac{3 \times \sqrt{6} \times V}{\pi m} \times \cos\alpha = 0$$

This equation simplifies to:

$$S = -\frac{m}{n} \times \cos\alpha,$$

Thus, the slip S of the induction motor is directly proportional to the cosine of the triggering angle α and the ratio of the transformer turns $\frac{m}{n}$. By adjusting the triggering angle α, we can effectively control the slip of the induction motor.

To design the transformer, let's consider the maximum value of the slip, denoted as $S_{\max}$. At the maximum slip, we can express the equation as:

$$S_{\max} = \frac{m}{n} \times \cos \alpha_{\max}$$

Now, let's explore the range of α. Since this converter operates in inverting mode, the triggering angle α is greater than $\frac{\pi}{2}$ or 90°. Typically, the range of α is between 90° and 165°, with $\alpha_{\max}$ approximately 165°. The reason for choosing 165° as the maximum is due to the need for successful turn-off of the converter's components, which requires a margin below 180°. Therefore, the converter operates from 90° to 165°, controlling the power fed back to the source.

In terms of power flow, the rotor power P_r is recovered and fed back to the supply through the transformer. This is why this method is referred to as the slip power recovery scheme. The power flowing from the rotor is directed back into the grid, improving the system's efficiency.

To design the transformer, the turns ratio $\frac{m}{n}$ is given by:

$$\frac{m}{n} = \frac{-S_{\max}}{\cos \alpha_{\max}}$$

Thus, the turns ratio of the transformer can be determined based on the maximum slip $S_{\max}$ and the maximum firing angle $\alpha_{\max}$.

Thus, by controlling the triggering angle α, we can regulate the slip of the induction motor. This allows the motor to operate at speeds below synchronous speed, as slip S remains between 0 and 1. This concludes today's discussion, and in the next session, we will continue exploring the slip power recovery scheme in further detail.