Fundamentals of Electric Drives

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Lecture-30

Static Kramer Drive And its Closed-loop Control, Introduction to Synchronous Motor

Hello and welcome to this lecture on the fundamentals of electric drives. In our previous session, we delved into the slip power recovery scheme, where we explored one particular type of drive known as the static Kramer drive. The static Kramer drive is structured in a distinctive way, incorporating a rectifier in the rotor circuit. Let's take a closer look at how this configuration operates and its significance in controlling the rotor speed and enhancing system efficiency.

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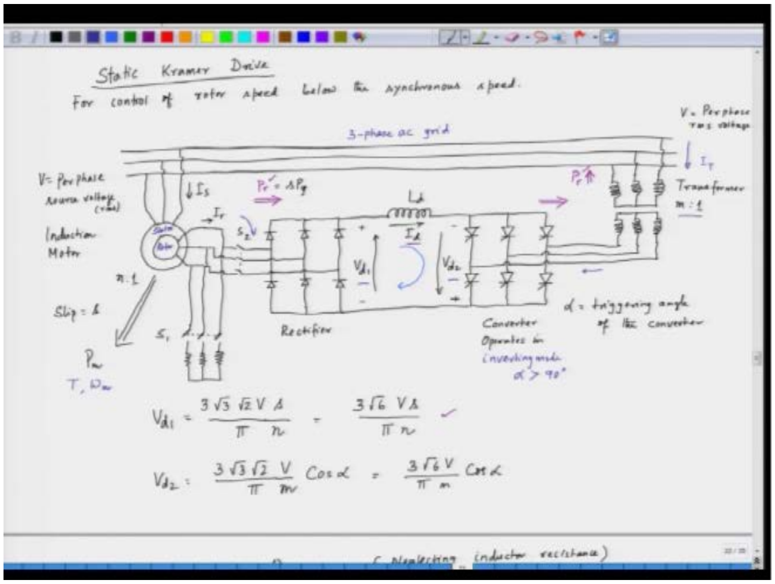

Then we are recovering this power PR and feeding this power back to the supply.

In this scenario, we observe that the slip can be controlled by adjusting the triggering angle, α, of the converter. Let’s derive a few key relationships to better understand this. By neglecting losses, such as rotor losses, resistance, and inductance, we simplify the system. We assume the inductor to be ideal, and the resistance can be taken as zero.

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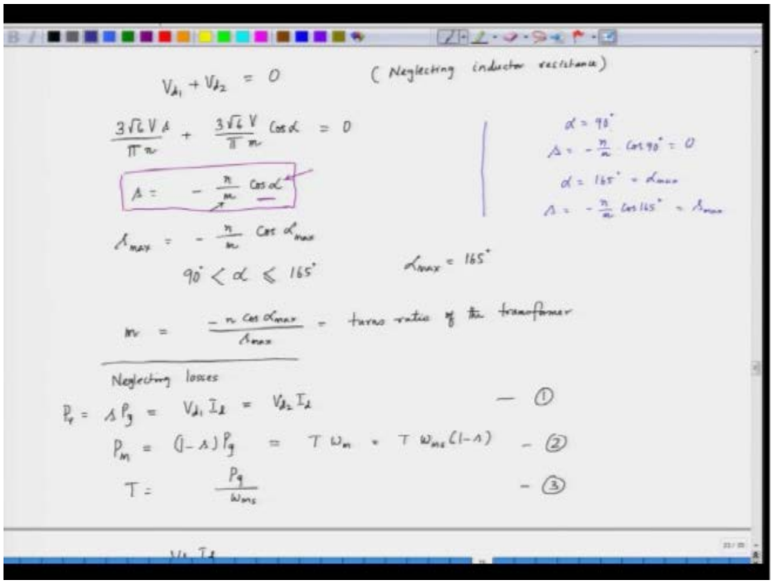

With this assumption, we can state that the slip power being recovered, denoted as slip power $S \cdot P_G$, is equal to the product of $V_{D1} \cdot I_d$ (which is the same as $V_{D2} \cdot I_d$. Therefore, the power recovered, P_R, is given by:

$$P_R = S \cdot P_G = V_{D1} \cdot I_d = V_{D2} \cdot I_d$$

This describes how the slip power is recovered in the system.

Now, what about the mechanical output? The mechanical output, P_m, is given by:

$$P_m = (1 - S) \cdot P_G$$

This mechanical output is also expressed in terms of torque and speed:

$$P_m = T \cdot \omega_m$$

where T is the torque, and ω_m is the rotor speed. Additionally, we know that:

$$\omega_m = \omega_{ms} \cdot (1 - S)$$

where ω_{ms} is the synchronous speed and S is the slip. From this, we can express torque T as:

$$T = \frac{P_G}{\omega_{ms}}$$

By substituting P_G from earlier, we get:

$$T = \frac{V_{D1} \cdot I_d}{S \cdot \omega_{ms}}$$

This gives us the relationship between torque, slip, and other parameters in the system. These equations highlight the interaction between slip, power recovery, and mechanical output, providing a clear understanding of how slip control affects the drive system.

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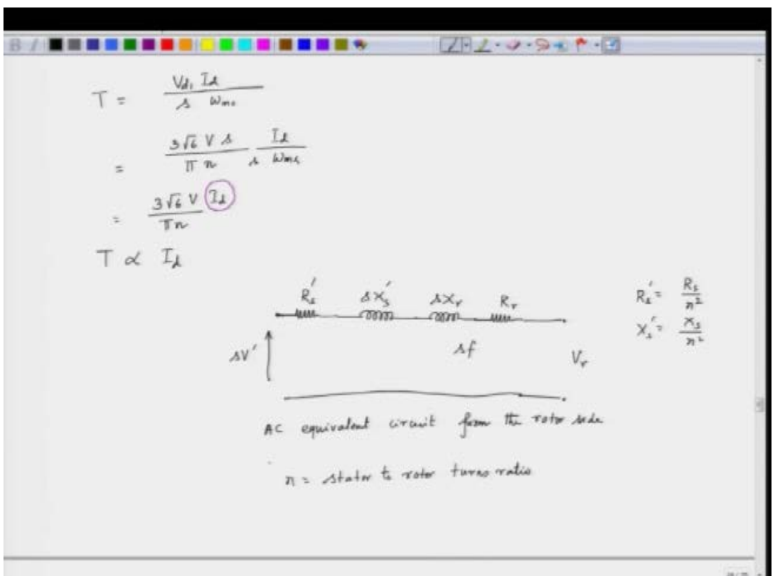

So, this is the situation we have here. Now, let's revisit V_{D1}, which we've already calculated earlier. From the equation, we know that:

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

We can now substitute this into the torque equation. So, the expression becomes:

$$T = \frac{3\sqrt{6} \cdot V \cdot I_d}{\pi n \cdot \omega_{ms}}$$

Here, the slip term S cancels out, leaving us with:

$$T = \frac{3\sqrt{6} \cdot V \cdot I_d}{\pi n}$$

This shows that the torque T is directly proportional to the DC link current I_d. Since $V, 3\sqrt{6}, \pi,$ and n are all constants, we can clearly see that:

$$T \propto I_d$$

This means that if we want to control the torque of the induction motor, and therefore control its speed, we need to regulate the DC link current I_d. By controlling I_d, we directly control the torque and, consequently, the speed of the motor.

Now, let's proceed to the AC equivalent circuit of the static Kramer drive, starting from the rotor side. The AC equivalent circuit will look like this:

- V_R represents the applied voltage to the rotor.
- We have the rotor resistance R_r.
- The rotor leakage reactance is represented by X_r, and its frequency is a slip frequency, $s \cdot f$. Thus, we multiply the reactance by S.
- Everything is referred from the rotor side, so the stator reactance becomes X_s', and the stator resistance becomes R_s'.

The stator reactance and resistance, when referred to the rotor side, are:

$$X_s' = \frac{X_s}{n^2}, \quad R_s' = \frac{R_s}{n^2}$$

where n is the turns ratio between the stator and rotor. So, this is the AC equivalent circuit from the rotor side. The voltage on the rotor side is denoted as $S \cdot V'$, and this equivalent circuit helps us calculate the current in the rotor circuit.

Now, let's move on to drawing the phasor diagram of the drive, which will provide a visual representation of the voltages and currents in the circuit. The phasor diagram for the static Kramer drive will help us understand the phase relationships between the different components in the AC equivalent circuit.

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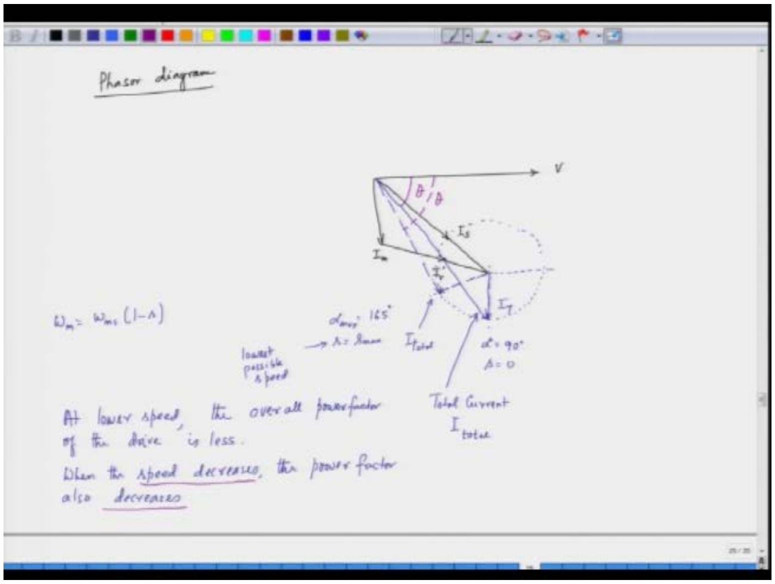

We begin by considering the phase voltage, denoted as V. This phase voltage supplies a magnetizing current I_m, which lags behind the voltage by approximately $\frac{\pi}{2}$. Now, if there is any resistive component, this will cause a slight shift in the magnetizing current. So, for simplicity, we assume I_m lags slightly due to this. Overlaid on this is the rotor current I_r, which is referred from the stator side. When we combine these two, we get the total current.

In this phasor diagram, the stator current is represented as I_s, while the rotor current I_r contributes to the overall current. Additionally, there is the magnetizing current I_m, and we also have the transformer current I_T, which is the current drawn by the converter from the transformer. The converter, in this setup, draws the transformer current I_T, and this current is controlled by the delay angle α.

Now, the delay angle α is crucial, and in this case, it is larger than 90 degrees. If we look closely at the phasor diagram, we observe that α starts at 90 degrees and can go up to a maximum of 165 degrees, denoted as $\alpha_{\max} = 165°$. Assuming the transformer current remains constant, its locus traces a circular path.

The range of α is from 90 to 165 degrees. When $\alpha = 90°$, the slip S becomes:

$$S = -\frac{n}{m} \cdot \cos(90°) = 0$$

This means that at $\alpha = 90°$, the converter is not recovering any slip power, and the rotor is operating at synchronous speed since the slip is zero.

When $\alpha = 165°$, which is the maximum angle, the slip S becomes:

$$S = -\frac{n}{m} \cdot \cos(165°)$$

This yields a negative value for S, which represents the maximum possible slip, S_{max}. So, when $\alpha = 165°$, the slip is at its highest, and the rotor speed is at its lowest. The relationship between slip and speed is governed by the equation:

$$\omega_m = \omega_s \cdot (1 - S)$$

Here, ω_m is the mechanical speed, and ω_s is the synchronous speed. When S = 0, the speed is equal to the synchronous speed. When $S = S_{\text{max}}$, the speed reaches its minimum.

Next, we consider the total current. The transformer current I_T, which corresponds to $\alpha = 165°$, is depicted as the current drawn by the transformer. Finally, the overall phasor, which represents the combined current in the system, looks like this in the phasor diagram, capturing the relationship between the stator current, rotor current, and transformer current in this setup.

This is the total current, denoted as I_{total}. Now, what exactly is I_{total}? It represents the combined current that is drawn from the grid. Specifically, I_{total} is the sum of the stator current I_s from the induction motor and the transformer current I_T, which is the current drawn by the converter. So, mathematically, we have:

$$I_{\text{total}} = I_s + I_T$$

This total current has a specific value, and now we also need to consider the power factor associated with it. The power factor angle, denoted as θ, is the angle between the total current I_{total} and the voltage V. This angle is crucial in understanding how efficiently the system operates.

When the motor is running at the lowest possible speed, we need to analyze what happens to the power factor. At maximum slip, or the minimum possible speed, the total current I_{total} reaches a certain value, which we can represent graphically in a phasor diagram. Along with this, the corresponding power factor angle θ also changes.

One key observation here is that as the motor speed decreases, the power factor becomes progressively worse. In other words, when the slip increases, the power factor deteriorates. So, we can conclude that at lower speeds, the motor operates with a reduced power factor. This is a critical takeaway: as the speed decreases, so does the overall power factor of the drive.

This holds especially true for the static Kramer drive. The reduction in power factor is directly tied to the reduced motor speed. Therefore, we must remember that when operating the motor at lower speeds, the overall drive performance, in terms of power factor, is compromised.

Now, with this understanding, let's move on to discussing the closed-loop speed control scheme for the static Kramer drive.

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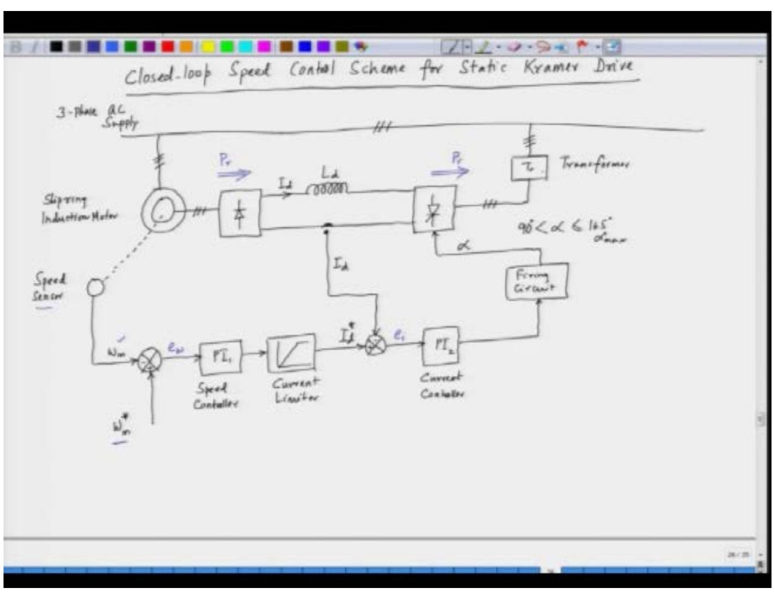

Let's now delve into the closed-loop speed control scheme for the static Kramer drive. Here, we are specifically dealing with a motor operating at speeds below the synchronous speed. To begin, we have a 3-phase AC supply that powers the slip ring induction motor, which consists of a 3-

phase stator and a 3-phase rotor. On the rotor side, we incorporate a converter system designed to recover the slip power.

The rotor circuit includes an uncontrolled rectifier followed by a fully controlled converter, which is responsible for transferring the recovered power back to the grid. Between these components, we have a DC link with current I_d, and an inductor L_d that smooths the current. Additionally, a transformer connects the 3-phase converter to the grid, thus enabling the recovery of the slip power.

Now, to effectively control the speed of the motor, a feedback system is implemented. A speed sensor is mounted on the rotor to monitor its speed, denoted as ω_m. This real-time speed feedback is compared to the reference speed ω_n^*, which represents the desired speed set by the user. The difference between these two values forms the speed error, which is then processed by a PI (Proportional-Integral) controller, labeled as PI 1.

The output of this PI controller is the reference value for the DC current, denoted I_d^*. This reference current is then passed through a current limiter to ensure the system operates within safe limits. A current sensor measures the actual DC link current, and this feedback value is compared with I_d^*. The result is fed into another PI controller, which then regulates the firing circuit.

The firing circuit controls the triggering angle α of the converter, adjusting the power flow accordingly. By controlling α, we directly influence the rotor speed, maintaining the motor's speed below synchronous operation.

So, this closed-loop control system uses feedback from both the rotor speed and DC link current to regulate the slip ring induction motor’s speed. By adjusting the converter's triggering angle, the system ensures precise speed control, keeping the motor’s operation below synchronous speed, while efficiently recovering the slip power and feeding it back to the grid.

In this setup, we deal with a dynamic speed control system where the reference speed, denoted as ω_n^*, is compared with the actual speed detected by a speed sensor. The difference between these two values generates a speed error, which is then processed by a PI (Proportional-Integral) speed controller. This speed controller is followed by a current limiter that outputs the reference value for the DC link current.

This reference current is then compared to the actual DC link current, and the resulting current error is sent to another PI controller, which acts as the current controller. The output from this current controller drives the firing circuit of the converter. The converter operates within a firing angle α range, where α is greater than 90° and up to a maximum of 165°. Within this range, the converter functions in inverting mode, allowing it to recover the slip power from the rotor side of the motor.

Assuming a lossless DC link, the recovered slip power is then transferred back to the grid. This forms the basis of the closed-loop control for the static Kramer drive. By manipulating the triggering angle α of the converter, we can precisely control the motor's speed. In this closed-loop system, adjusting the reference speed ω_n^* enables direct control of the motor’s speed.

This process covers the control of the slip ring induction motor. Next, we’ll move on to explore the control of synchronous motors and how their speed is regulated.

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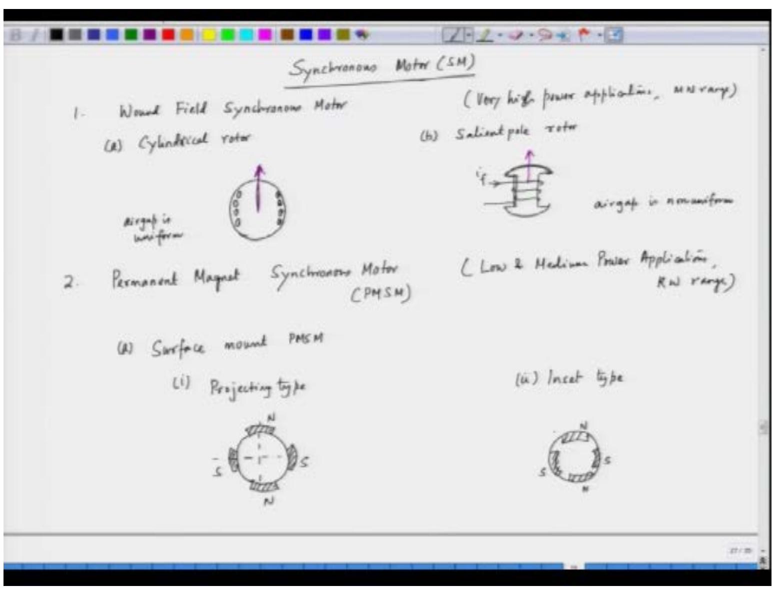

Next, we will discuss synchronous motors, which come in two primary types: wound rotor (or wound-field) synchronous motors and permanent magnet synchronous motors (PMSMs). The first type, wound-field synchronous motors, are typically used in high-power applications, generally in the megawatt range. These motors are less common compared to PMSMs but are indispensable for large-scale, high-power systems. On the other hand, permanent magnet synchronous motors are more suited for low to medium power applications, typically ranging in the kilowatt scale.

Within the category of wound-field synchronous motors, there are two types of rotors: cylindrical rotor types and salient pole types. Let’s first look at the cylindrical rotor type. As the name suggests, the rotor has a cylindrical shape, and the conductors are placed in the rotor in such a way that they carry current across the structure, generating a magnetic field along the axial direction. This results in a rotor with a smooth, cylindrical profile, providing a uniform air gap between the stator and the rotor.

The second type of rotor is the salient pole rotor. In this design, the rotor poles protrude outward, creating a visibly distinct pole structure. The windings, carrying direct current (denoted as I_F), are placed on these poles, producing magnetic flux in a non-uniform pattern. As a result, the air gap in salient pole rotors is non-uniform, unlike in the cylindrical rotor type where the air gap remains consistent and uniform throughout.

Now, moving on to permanent magnet synchronous motors (PMSMs), these motors also have two subtypes. The first is the surface-mounted permanent magnet motor, where the magnets are mounted on the surface of the rotor. These surface-mounted motors can be further classified into projecting type and inset type designs. The projecting type has the magnets mounted such that they stand out from the surface, while the inset type has magnets embedded slightly within the rotor's surface.

In summary, synchronous motors vary greatly depending on the application, with wound-field types used in high-power systems and PMSMs catering to medium and low-power applications. The specific rotor design, whether cylindrical, salient pole, or permanent magnet-based, determines the motor's characteristics and suitable applications.

In a permanent magnet synchronous motor (PMSM), the rotor is made of permanent magnets, eliminating the need for field windings. The rotor flux is generated by these permanent magnets. In the projecting pole type rotor, the magnets are positioned on the surface of the rotor, so they visibly project outward. This creates a distinct rotor structure where the magnets, such as the north and south poles, are prominently placed around the rotor, ensuring a strong magnetic field.

On the other hand, in the inset type rotor, the magnets are embedded just beneath the surface of the rotor, aligned with its outer edge. The magnetic poles (north and south) are arranged within the rotor in a more integrated fashion compared to the projecting type, where the magnets are external.

In summary, we have broadly covered two key types of synchronous motors: the wound-field synchronous motor and the permanent magnet synchronous motor. Wound-field synchronous motors are designed for high-power applications, typically in the megawatt range, while permanent magnet synchronous motors are better suited for low to medium power applications.

In the next lecture, we will dive into the control techniques for synchronous motors. For now, we conclude today's session and will continue our discussion on synchronous motor control in the following lecture.