Fundamentals of Electric Drives

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Lecture-27

Current Source Inverter (CSI) fed Induction Motor Drive

Hello and welcome to this lecture on the fundamentals of electric drives! In today's session, we will be exploring the fascinating world of current source inverter-fed induction motor drives. Previously, we have delved into voltage source inverter-fed induction motor drives; however, for very high power applications, current sources are often preferred. This preference arises from their remarkable reliability compared to voltage sources. So, without further ado, let's dive into the intricacies of current source inverter-fed induction motor drives in today's lecture!

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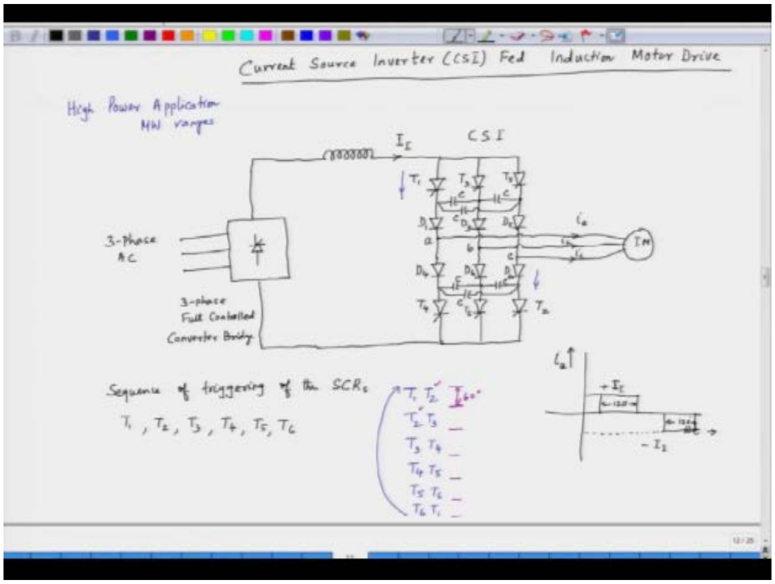

Current source inverter, commonly abbreviated as CSI, is widely utilized for high-power applications, particularly in the megawatt range. To illustrate, let's draw the circuit diagram of a typical current source, which is realized through the use of thyristors (SCRs) and diodes. The configuration will appear as follows: we have SCRs along with diodes, specifically, two sets of diodes, with additional diodes positioned accordingly.

At the heart of the design is the DC link, which incorporates a substantial inductance. Additionally, we have capacitors situated between the SCRs and the diodes; these are referred to as commutating capacitors. Following this setup, we connect the induction motor, which serves as the load. On the input side, we have a converter bridge, represented here in block diagram form. This converter bridge is a three-phase fully controlled converter, designed to accept a three-phase AC input.

In this configuration, the SCRs are designated as T1, T2, T3, T4, T5, and T6, while the diodes are labeled D1, D2, D3, D4, D5, and D6. The capacitors, denoted as C, are all of equal value. It's important to note that we will not delve into the detailed operation of this CSI, as that topic is typically covered in an introductory course on power electronics.

The capacitors facilitate forced commutation, enabling the SCRs to be triggered in a specific sequence, from T1 through T6. As this occurs, the capacitors become charged, and they play a crucial role in commutating one SCR when the next SCR is activated.

The sequence for triggering the SCRs is as follows: T1, T2, T3, T4, T5, and T6. At any given moment, if we disregard the commutation overlap, only two SCRs will be conducting at the same time. The conduction pairs will be T1 and T2, T2 and T3, T3 and T4, T4 and T5, T5 and T6, and so on.

To illustrate the SCR conduction, let's consider the scenario when T1 and T2 are active. Here, we have phase A, phase B, and phase C, which correspond to the phase currents I_A, I_B, and I_C. When T1 and T2 are conducting, the current flows from these phases and returns through phase C. After this, we transition to the next pairs: T2 and T3, T3 and T4, T4 and T5, T5 and T6, and T6 and T1, repeating the cycle back to T1 and T2.

It's important to note that at any given time, two SCRs are conducting, with each SCR conducting for 120 degrees. This conduction interval lasts 60 degrees, and there are a total of six conduction changes within one complete cycle. Consequently, each SCR conducts for two segments, which also totals 120 degrees.

As we observe the output current, let's plot I_A against ω t at an angle. The resulting waveform for I_A will resemble a classic rectangular wave. Each segment corresponds to 120 degrees, which is consistent in both directions. Here, the input current is denoted as I_i, while the output current is I_A.

For the negative side, we have $-I_r$. If we analyze the fundamental component of this, we find that it represents the phase current I_A. Similarly, the currents for phases B and C will be shifted from phase A by 120 degrees, continuing this sequence. Thus, what we see here is the characteristic behavior of phase A current.

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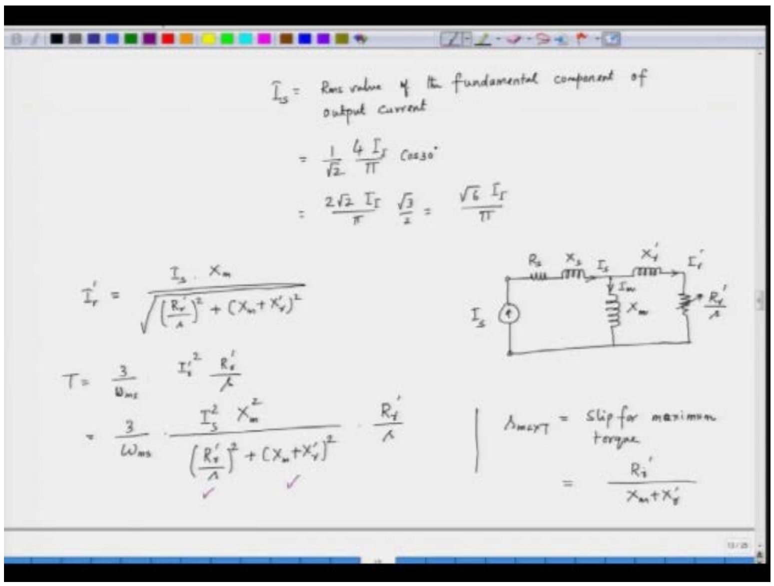

Let's delve into the RMS value, particularly focusing on the fundamental component. The RMS value of the output current, denoted as I_s, is equal to $\frac{4I_i}{\pi}\cdot\cos(30°)$. Here, I_i represents the peak value of the current. Since we are calculating the RMS value, we need to divide by $\sqrt{2}$. This gives us $\frac{2\sqrt{2}I_i}{\pi}$, and recognizing that $\cos(30°)\ is\ \frac{\sqrt{3}}{2}$, we arrive at the final expression of $\frac{\sqrt{6}I_i}{\pi}$.

This means that if we know the inverter's input DC current, we can easily calculate the RMS value of the stator current, which is the output current of the inverter. This current flows in the induction motor and is crucial for torque production.

With an inverter at our disposal, we can vary both the output current and the output fundamental frequency. The fundamental frequency can be analyzed by examining the fundamental current component, which can be determined using the Fourier series method. Thus, we have the capability to change not only the RMS value of the current but also the frequency by adjusting the switching speed. This makes it a variable current and variable frequency source, allowing us to manipulate the stator current and frequency.

Now, applying this principle to the induction motor, we can sketch the equivalent circuit of the induction motor. In this circuit, we include the stator resistance and reactance, the rotor reactance, and the rotor resistance. This equivalent circuit is quite detailed and accurately reflects the system, incorporating losses in the output.

Thus, the equivalent circuit consists of the stator resistance, stator leakage reactance, rotor leakage reactance, rotor resistance referred to the primary side, and the magnetizing reactance. This comprehensive approach ensures that we account for all essential parameters in the analysis of the induction motor's performance.

In our equivalent circuit, we have a current source instead of a voltage source. The current source has a value of I_s, which represents the RMS value, measured in amperes. The rotor current is denoted as I_R, while the current in the magnetizing branch is I_m.

In this setup, we can determine the value of the effective rotor current, denoted as I_R'. The magnitude of I_R' is equivalent to the input current I_s flowing through this path. To express this mathematically, we have:

$$I_R' = \frac{I_s \cdot X_M}{\sqrt{\left(\frac{R_R'}{S}\right)^2 + (X_M + X_R')^2}}$$

Here, X_M represents the magnetizing reactance, R_R' is the rotor resistance referred to the primary side, and S is the slip.

Now, let's move on to the torque equation for the induction motor. The torque (T) is given by:

$$T = \frac{3}{\omega_{Ms}} \cdot I_s^2 \cdot \frac{R_R'}{S}$$

This expression allows us to calculate the torque based on the slip. If we substitute I_R' into the torque equation, we get:

$$T = \frac{3}{\omega_{Ms}} \cdot I_S^2 \cdot \frac{X_M^2}{\left(\frac{R_R'}{S}\right)^2 + (X_M + X_R')^2} \cdot \frac{R_R'}{S}$$

This reveals the relationship between torque and slip. To find the slip at which torque reaches its maximum value, we can analyze this expression further. The slip for maximum torque, denoted as $S_{max\,T}$, can be derived from the condition where the denominator reaches its optimum.

Mathematically, we find that:

$$S_{max\,T} = \frac{R_R'}{X_M + X_R'}$$

In this equation, we see that the slip for maximum torque is contingent upon the rotor resistance and the total reactance, which includes both the magnetizing reactance and the rotor reactance referred to the primary side. When these two quantities are equal, we achieve the condition for maximum torque, providing a clear insight into the operation of the induction motor under varying slip conditions.

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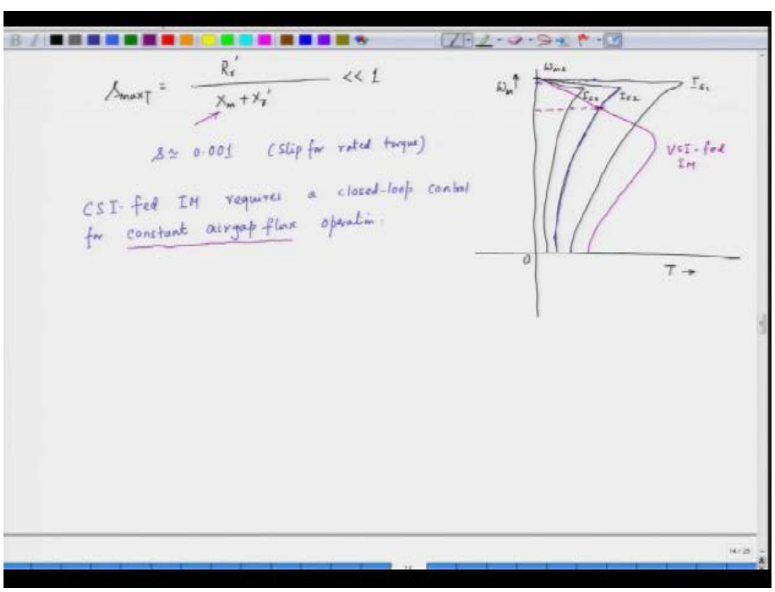

Let's analyze the value of $S_{max\,T}$. What we observe is that $S_{max\,T}$ can be expressed as:

$$S_{max\,T} = \frac{R_R'}{X_M + X_R'}$$

This ratio represents a very small quantity, significantly less than 1. This is due to the fact that the magnetizing reactance X_M is quite large, while the leakage reactance X_R' is relatively small. Therefore, we can expect the slip to be on the order of approximately 0.001 or 0.002.

Now, let's consider the torque-slip characteristic of a Current Source Inverter (CSI) fed machine. In this characteristic, if we plot the relationship between the rotor speed ω_m and the torque, we notice a distinctive behavior. At very low values of slip, the torque-speed characteristic demonstrates that the torque starts at a low value, and as we vary the input current I_s, we obtain a family of torque curves. For instance, we can denote these curves as I_{s1}, I_{s2}, and I_{s3}.

At the synchronous speed ω_{MS}, which is our reference point, we find the origin of the torque-speed characteristic. The slip corresponding to the rated torque is exceedingly small, emphasizing that the operating slip is quite minimal. For example, if we choose to operate at I_{s1}, the slip will be around 0.001, which is indeed a very small value, indicating the condition for rated torque.

Moreover, when we examine the equivalent circuit at this small slip, we notice that the slip resistance becomes quite large. As a result, this large resistance influences the circuit behavior, causing the current to predominantly flow towards the magnetizing reactance. This is a crucial aspect of the operation, as it underscores how the circuit dynamics change under low slip conditions, leading to enhanced magnetizing currents in the system.

This brings us to the concept of saturation in induction machines. At this point, even when we attempt to operate at maximum rated torque, the machine is significantly under-saturated. Therefore, it is not advisable to operate in this region.

Now, if we examine the corresponding characteristics of a Voltage Source Inverter (VSI) fed induction motor, we observe that the rated slip is much higher. This indicates that the operation aligned with the rated flux value for a VSI fed induction motor is considerably different. It's crucial to understand that if we aim to operate with a rated value of flux using a Current Source Inverter

(CSI), the characteristic curve positions us in what is known as the unstable region of the CSI.

The CSI characteristic presents us with this instability. This means that if we intend to maintain a constant air gap flux while operating the CSI, we must implement a closed-loop control system to stabilize this inherently unstable CSI. It's essential to note that a CSI-driven induction motor is never operated under open-loop conditions. Instead, a CSI-fed induction motor requires closed-loop feedback for effective control, ensuring the stability of the air gap flux during operation.

To maintain constant air gap flux, our operation must take place within a specific range, necessitating closed-loop feedback due to the CSI's tendency to function in the unstable region. Now, let's delve into the operation of the CSI while maintaining a constant air gap flux.

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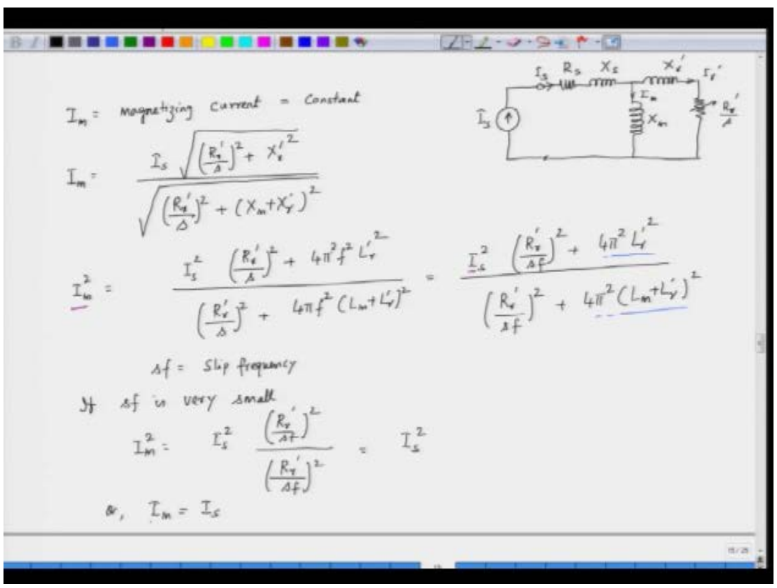

Let's consider the equivalent circuit we discussed earlier. Here, we have the stator and rotor components, along with the air gap represented by the magnetizing branch, denoted as X_m. We also have the rotor resistance $R_{r'}$, the slip s, the stator reactance X_s, and we are feeding this setup with a Current Source Inverter (CSI), represented by a current source. In this configuration, the rotor current is I_r, while the stator current is denoted as I_s.

Now, if we want to determine the magnetizing current, I_m, we must keep this current constant to ensure stable operation with a constant air gap flux. To express I_m, we can relate it to the stator current I_s flowing into the circuit. The formula for the magnetizing current can be defined as follows:

$$I_m = \frac{I_s \cdot \sqrt{\frac{R_r}{s}^2 + X_{r'}^2}}{\sqrt{R_{r'}^2 + (X_m + X_{r'})^2}}$$

Squaring both sides yields:

$$I_m^2 = I_s^2 \cdot \left(\frac{R_r}{s}\right)^2 + \frac{4\pi^2 s^2 L_{r'}^2}{R_s^2 + 4\pi^2 f^2 (L_m + L_{r'})^2}$$

In this equation, $s \cdot f$ represents what we call the slip frequency. Controlling the slip frequency of a CSI-fed induction motor is crucial, as it can vary from zero up to a certain value.

Now, let’s analyze what happens when the slip frequency is very small. When s_f is negligible, the contributions from the slip components become less significant compared to the dominant terms. Therefore, we can neglect these smaller terms, leading us to the simplified equation:

$$I_m^2 \approx I_s^2 \cdot \left(\frac{R_{r'}}{s_f}\right)^2$$

This implies that:

$$I_m = I_s$$

Thus, when the slip frequency is very small, the RMS value of the stator current I_s is essentially equal to the magnetizing current I_m. This relationship highlights the direct correlation between the stator and magnetizing currents in the context of slip frequency control.

Now, let's consider the scenario where the slip frequency, s_f, is moderately small. In this case, we can neglect certain quantities in our equations. Specifically, if s_f is moderately small, we can set the negligible terms to zero. However, it’s important to note that while some quantities may be small, they still hold some significance and dominate the analysis. Thus, we can disregard the less significant parts.

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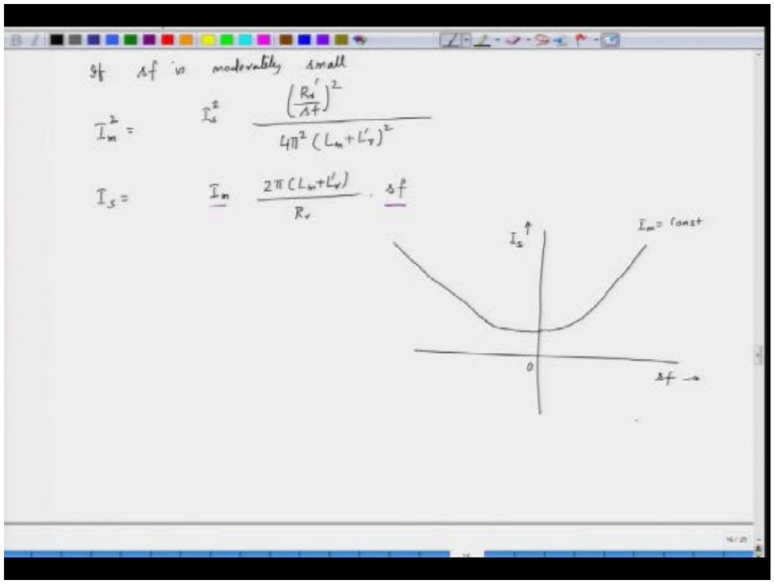

By neglecting the denominator $4\pi^2 L_r^2$ and simplifying the numerator where R_r' divided by s_f is small, we arrive at the following relationship:

$$I_m^2 = I_s^2 \cdot \frac{{R_{r'}}^2}{s_f}$$

This simplifies to:

$$I_s = I_m \cdot \frac{2\pi(L_m + L_{r'})}{R_r \cdot s_f}$$

What we see here is that the stator current, I_s, varies linearly with the slip frequency s_f. This relationship shows that if we maintain the magnetizing current I_m constant, the stator current I_s is directly proportional to the slip frequency.

If we graph this relationship between slip frequency and the RMS value of the stator current, we find that when s_f is very small, I_s remains constant. As s_f increases, the stator current also rises accordingly. We can represent this trend graphically, showing that both positive and negative increases in slip frequency correspond to a similar increase in stator current.

This observation is critical because it indicates that to adjust the slip frequency, we must also change the stator current to maintain a constant magnetizing current, or in other words, to keep the air gap flux stable.

With this understanding, we can move forward in our discussions on controlling a CSI-fed induction motor by adjusting the slip frequency while simultaneously modifying the stator current to ensure consistent magnetizing current and air gap flux.

This concludes today's lecture, and we will continue this discussion in our next session.