Fundamentals of Electric Drives

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Lecture-23

Self-excited Dynamic Braking of Induction Motor, Speed Control of Induction Motor Using Stator Voltage Regulator, Variable Voltage Variable Frequency Control

Hello and welcome to this lecture on the fundamentals of electric drives! In our previous session, we explored the concept of DC dynamic braking for induction motors. Today, we will delve into another fascinating method known as self-excited dynamic braking for induction motors.

In this approach, we utilize a capacitor bank to excite the induction motor. So, let's examine how we achieve self-excited dynamic braking in an induction motor!

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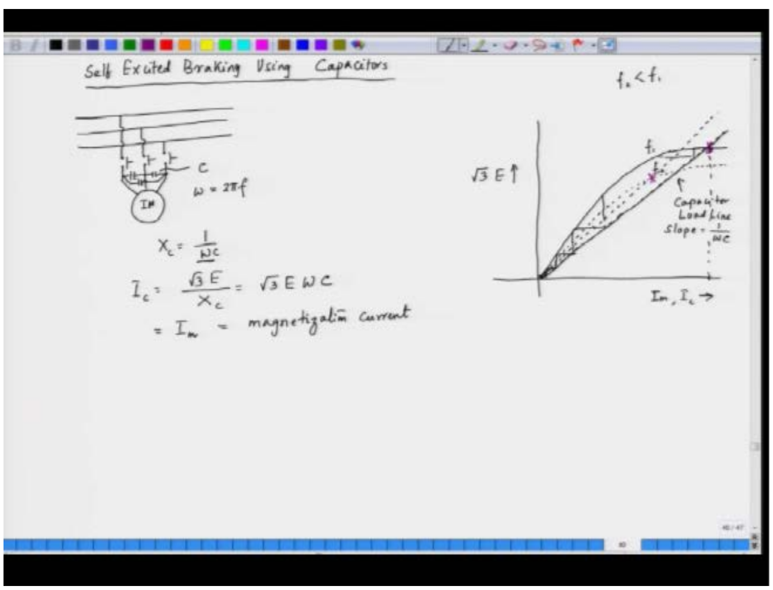

In this scenario, we have an induction motor that typically operates from a three-phase supply. However, when we wish to implement self-excited braking, we first disconnect the motor from the three-phase supply. Next, we connect a capacitor bank to the stator of the induction motor.

Here, we have our three-phase line supplying the induction motor, and we introduce three capacitors into the circuit, along with a switch that disconnects the motor from the mains. While the motor is running, it is no longer receiving a three-phase AC supply; instead, it is now connected to this bank of capacitors.

The capacitors provide the necessary excitation to the motor, resulting in an excited voltage known as self-excitation. This process of excitation is somewhat akin to the excitation of a sound generator. Let's take a closer look at how this excitation occurs.

We can visualize the magnetization characteristic, which typically features some residual magnetism. This curve represents the saturation characteristic of the core, which is a saturable core. Here, we denote E as the phase voltage, and we refer to the capacitor current's RMS value as I_C.

Upon connecting the capacitors, we establish a load line for the capacitors, which appears as a straight line on our graph. This line has a specific slope, given by $\frac{1}{\omega C}$, where C is the capacitance value. For our analysis, we can also plot the line voltage, represented as $\sqrt{3} \times E$. This gives us a clearer picture of the interactions between the capacitor load line and the motor's magnetization characteristics.

So, we are examining the relationship between capacitance, frequency, and reactance. The capacitive reactance X_C is given by the formula $\frac{1}{\omega C}$, where C represents the capacitance value and ω is the angular frequency. When the capacitors are connected in a delta configuration across the terminals, they experience the line voltage. The capacitive current can be expressed as the line voltage, which is $\sqrt{3}$ times the phase voltage, divided by the capacitive reactance X_C.

This results in the equation:

$$I_C = \frac{\sqrt{3}E}{X_C} = \sqrt{3}E \cdot \omega C$$

Here, I_C is the capacitive current, and when we draw a perpendicular from this current, we can identify it as the capacitive current flowing into the motor. Importantly, this current is a leading current, which means that the motor is supplying a leading current. This phenomenon is equivalent to the motor drawing a lagging current.

Consequently, we can say that this leading capacitive current corresponds to the line-to-line magnetizing current of the induction machine. Essentially, the motor is drawing an equivalent lagging current, denoted as I_m, which is known as the magnetization current of the induction motor.

Now, considering that we have a certain amount of back EMF present, the system will self-excite, much like a homopolar generator, ultimately stabilizing at full speed and achieving the full value of the voltage. At this point, the motor is generating an induced EMF, which circulates current in both the rotor and stator. However, due to losses in the system, power will be dissipated in the form of I^2R losses, causing the motor to gradually decelerate.

This process is referred to as braking. As the motor speed decreases, the induced EMF also diminishes, leading to a reduction in frequency. Now, let's illustrate the magnetizing characteristic along with the capacitive load line for this reduced frequency. When the frequency decreases, we observe a shift in the magnetizing characteristic, indicating the behavior of the system under these altered conditions. This reflects the new characteristics associated with the lower frequency.

As we see a reduction in frequency, the magnetization characteristic also shifts downwards slightly. Let's denote the initial frequency as F_1 and the reduced frequency as F_2, where F_2 is less than F_1. With this decrease in speed or frequency, we observe a corresponding reduction in the induced EMF. Additionally, when the frequency decreases, the slope of the capacitance load line increases. Remember that this slope is inversely proportional to ω, where $\omega = 2\pi F$.

Thus, when the frequency diminishes, the capacitive reactance X_C increases, causing the load line to shift upwards. This means that the previous intersection point of the load line has changed; it was originally at a higher voltage, but now the operating point is at a reduced voltage. As a result, as frequency decreases, both voltage and current decline accordingly.

The effective current in this case is now lower than before. If we initially labeled the current as I_{m1}, it has now changed to I_{m2}, with $I_{m2} < I_{m1}$. Consequently, the current reduction leads to a decrease in losses, which, in turn, results in a diminished braking torque. As the motor continues to decelerate, it approaches zero speed. Below a certain threshold speed, self-excitation will cease.

This describes one method of braking an induction machine, known as self-excited braking. We've thoroughly explored the motoring and braking processes of a conventional induction machine. Now, let's shift our focus to the speed control of induction motors using solid-state devices. The first technique we will discuss involves utilizing a voltage regulator, also referred to as a voltage controller, for controlling the speed of an induction motor.

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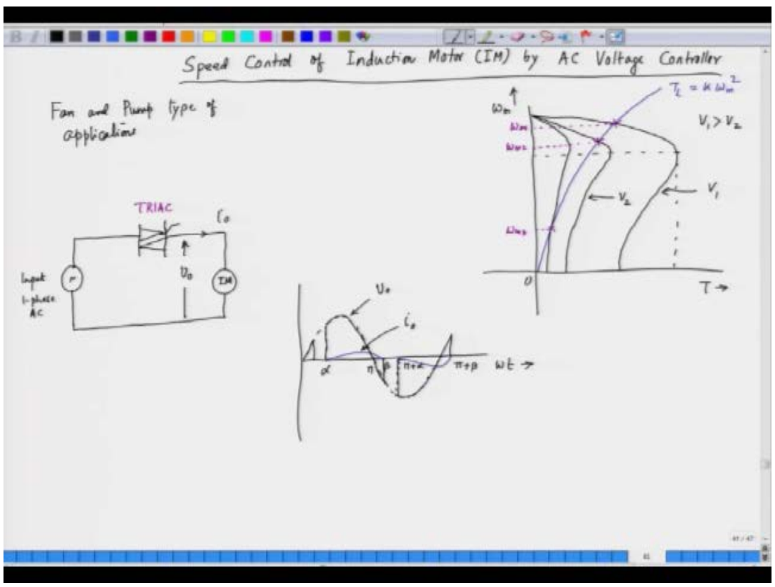

Speed control of an induction motor is often referred to as IM induction motor control using an AC voltage controller. Now, let's explore the applications of this type of speed control, which is typically utilized for fan and pump applications.

In this context, we analyze the speed-torque characteristics of the motor. On the vertical axis, we have the motor speed, while the horizontal axis represents torque, starting from the origin. This graph illustrates the normal speed-torque characteristics of an induction machine.

At a specific voltage V_1, we observe the maximum torque, denoted as $T_{\max}$. However, if we reduce the voltage, the torque will also decrease. This relationship arises from the fact that torque is proportional to the square of the voltage ($T \propto V^2$). Therefore, reducing the voltage results in a corresponding reduction in torque. Importantly, even as the voltage decreases to V_2 (where $V_1 > V_2$), the peak torque continues to occur at the same speed.

Now, let's consider the type of load we are dealing with. In the case of fan or pump applications, the torque is directly proportional to the square of the speed. Let's illustrate the load characteristics for a fan-type load. We represent the load torque as T_L, which can be expressed as:

$$T_L = K \cdot \omega_M^2$$

where K is a constant and ω_M is the speed of the fan or pump. This indicates that as the speed of the fan or pump increases, the torque required also rises in proportion to the square of that speed.

Let's delve into the speed-torque characteristics of our system. We can observe that the first intersection occurs at a certain point in the graph, which corresponds to a specific speed. Now, when we reduce the voltage, the intersection moves to a new point on the graph. For example, if this initial speed is ω_{M1}, by reducing the voltage further, we can achieve a new speed denoted as ω_{M2}. Continuing this process, further voltage reduction yields additional characteristics, leading to yet another intersection point.

This next point is still stable and is identified as ω_{M3}. This demonstrates that we have a wide range of speed control available through voltage adjustment.

Now, how do we implement this voltage control? Voltage control can be applied in both three-phase and single-phase circuits. Let's first consider the single-phase circuit.

In this configuration, we begin with input AC power, and we utilize a TRIAC for control. This is a low-power circuit connecting our induction motor. The output voltage and current waveforms can be visualized as follows:

On the x-axis, we represent time with sinusoidal input expressed as ω t, while the y-axis displays voltage. Here, α represents the triggering angle. We trigger the TRIAC during both half-cycles of the waveform. In the positive half-cycle, we trigger it at the angle α, and in the negative half-cycle, the triggering occurs at π + α.

As a result, the current begins from zero, reaches a maximum, and then decreases to a value we can denote as β. When the current reverses, it represents the current in the negative half-cycle. The corresponding angle here is β, and in the negative cycle, it is π + β. This illustrates how we can effectively control the voltage supplied to the induction motor.

Let's take a closer look at the output voltage waveform. This is what the output voltage waveform appears like: it shows conduction beyond π as well, since the current continues to conduct up to the angle β. This results in a waveform that resembles this shape, which continues into the negative half-cycle. During this phase, the voltage reverses, and the conduction follows a similar pattern. Since this is a periodic waveform, we can expect the conduction to repeat in this manner. Thus, we denote this output voltage as V_0.

In this scenario, we also observe that both the output voltage and current are alternating in nature. However, by adjusting the triggering angle α, we can effectively control the RMS value of the output voltage. As we manage the RMS output voltage, the torque is consequently reduced, allowing us to control the speed of the motor.

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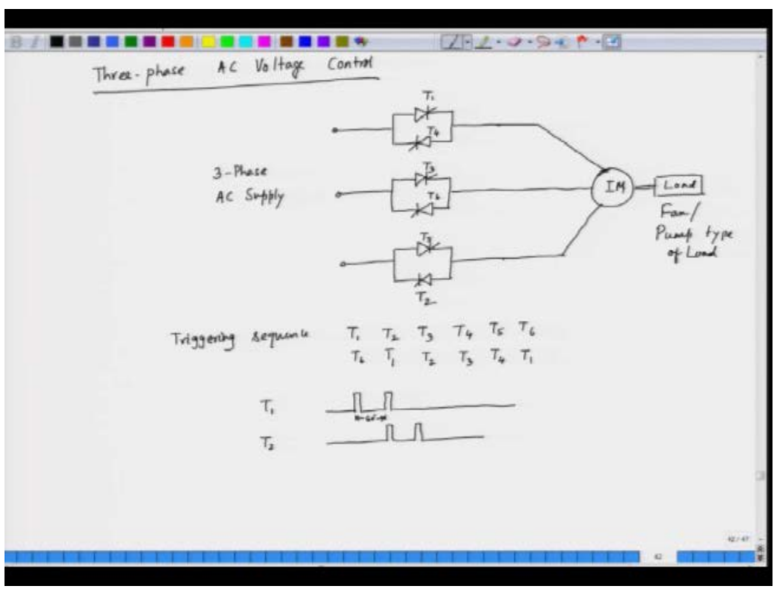

Now, let's extend this concept to a three-phase voltage controller, which is suitable for higher power applications. While a single-phase setup is commonly used for applications like fan motors, a simple TRIAC-based regulator suffices for controlling speed in single-phase systems. However, for higher power needs, we turn to a three-phase voltage controller, which utilizes not TRIACs but rather anti-parallel thyristors.

Let's discuss the workings of a three-phase AC voltage controller.

A three-phase AC voltage controller is specifically designed for higher power applications. In this configuration, instead of using TRIACs, we utilize anti-parallel thyristors or thyristor-based electronic control relays (ECRs). For phase A, we have a set of anti-parallel thyristors; similarly, for phase B and phase C, we also have their respective sets of anti-parallel thyristors.

The input to this system is a three-phase AC supply, which feeds into our induction motor that drives a fan or pump type of load. The load, in this case, could either be a fan or a pump, connected to the motor.

The ECRs are triggered in a specific sequence, which we denote as T_1, T_2, T_3, T_4, T_5, and T_6. Each triggering pulse is deliberately delayed by 60 degrees. This means the delay between two successive triggering pulses is precisely 60 degrees. Therefore, the triggering sequence flows as follows: we first trigger T_1, then T_2, followed by T_3, T_4, T_5, and finally T_6.

To maintain continuity, when we trigger T_2, we also send a triggering pulse to T_1. This overlapping approach continues as we trigger T_2 and T_1, then T_3 and T_2, followed by T_4 and T_3, and so on, until we complete the cycle with T_6 and T_1. The reason for overlapping the triggering pulses is crucial; if we applied just a single pulse, the voltage controller might not initiate at all. Therefore, the controller provides a pair of triggering pulses to each ECR. For instance, T_1 is triggered by a specific pair of pulses, T_2 is also triggered by its own pair, and this continues, with the distance between these triggering events being 60 degrees.

This is the mechanism by which the AC voltage controller is triggered to effectively control the output voltage. Now, let's take a closer look at how we can determine the efficiency in the context of voltage control.

Let's calculate the efficiency of an induction motor operating under voltage control. For simplicity, we will neglect the stator impedance and focus on the equivalent circuit, which consists solely of the rotor. In this equivalent circuit, we represent the rotor's reactance as X_r' and its resistance as R_r'. By ignoring the stator resistances and leakage reactance, we can streamline our analysis.

In this configuration, the current flowing in the rotor circuit is denoted as I_r', and the input power,

P_{input}, is equivalent to the air-gap power, $P_{\text{air gap}}$. This leads us to the equation $P_{\text{input}} = P_{\text{air gap}} = 3I_r^2 \cdot R_r'/s$. Since our circuit contains only resistive elements, the power consumed occurs solely in the resistance, leading to rotor copper losses.

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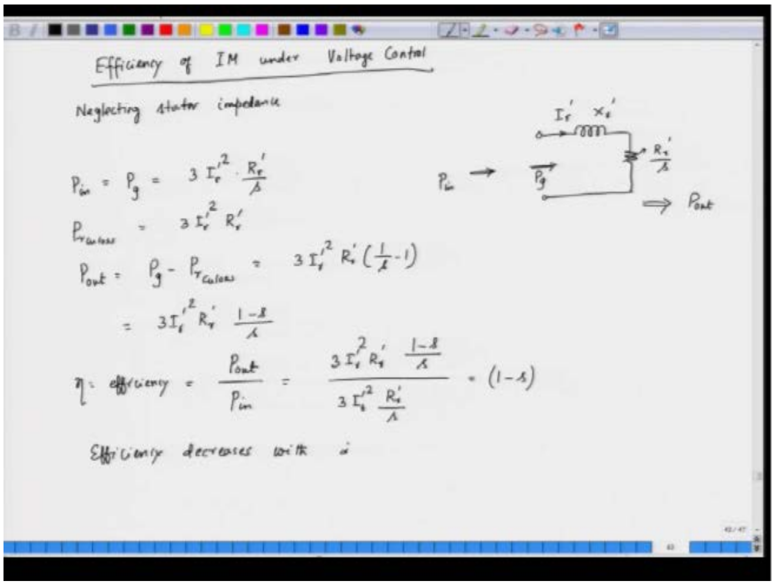

The rotor copper loss can be expressed as$P_{\text{copper loss}} = 3I_r^2 \cdot R_r'$. Therefore, the output power, denoted as P_{out}, can be calculated as follows:

$$P_{\text{out}} = P_{\text{air gap}} - P_{\text{copper loss}} = 3I_r^2 \cdot R_r' \cdot \left(\frac{1-s}{s}\right)$$

To calculate efficiency, we use the ratio of output power to input power:

$$\text{Efficiency} = \frac{P_{\text{out}}}{P_{\text{input}}} = \frac{3I_r^2 R_r' \cdot (1-s)}{3I_r^2 R_a'} = 1 - s$$

From this relationship, we observe that the efficiency of a voltage-controlled induction motor is 1 - s. This means that as the slip increases, efficiency decreases; when the slip is close to 1, the efficiency is quite low. Conversely, if the slip approaches 0, the efficiency is high. Therefore, when operating a fan controlled by a voltage regulator, it is crucial to run it at a higher speed to achieve better efficiency.

In summary, efficiency declines with a reduction in speed, making voltage control suitable for low-power applications, primarily for fan operation where efficiency is not a critical concern. However, for high-power applications, voltage control is not preferred. This is because as the speed decreases, the efficiency diminishes as well.

For higher power needs, it's advisable to employ more effective speed control methods, specifically voltage and frequency control, where both parameters are managed. Let's delve into the details of voltage and frequency control for an induction motor.

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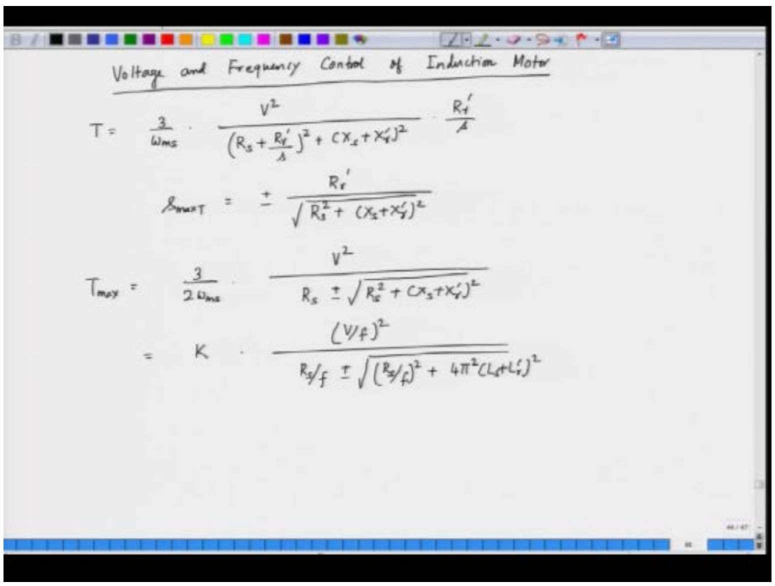

Let's examine the torque equation for an induction motor, which is expressed as:

$$T = \frac{3}{\omega_m s} \cdot \frac{V^2}{R_s + \frac{R_e}{s}} + \frac{X_s + X_r^2 \cdot R_r'}{s}$$

From our analysis, we know that the maximum torque occurs at a specific slip, denoted as s_{maxT}. This value can be calculated using the formula:

$$s_{maxT} = \frac{R_r'}{R_s^2 + X_s + X_r'^2}$$

In this context, we have a positive sign representing the motoring action and a negative sign for the generating action. This characteristic defines the behavior of the induction motor, with the maximum torque reaching its peak value at the slip $s_{max\,T}$. If we substitute this value into our torque equation, we can derive the maximum torque, T_{max}, as follows:

$$T_{max} = \frac{3}{2} \cdot \omega_m \cdot \frac{V^2}{R_s} \pm \sqrt{R_e^2 + X_s + X_r^2}$$

Furthermore, we can reformat this expression into a more specific form:

$$T_{max} = K \cdot \frac{V}{f^2} \cdot \frac{R_s}{f} \pm \frac{R_s}{F} \sqrt{4\pi^2 \cdot L_s + L_{st}}$$

This equation allows us to express the torque-speed characteristic of an induction motor in terms of voltage and frequency.

By varying both the voltage and frequency, we engage in what's known as variable voltage and variable frequency control of the induction motor. This approach offers significant advantages: by adjusting both parameters, we can maintain the peak torque at a constant level while also achieving higher efficiency.

In our upcoming lecture, we will discuss the concept of variable voltage and variable frequency control for induction motors, exploring its implications and benefits in greater detail.