Fundamentals of Electric Drives

Prof. Shyama Prasad Das

Department of Electrical Engineering

Indian Institute of Technology-Kanpur

Lecture-24

Variable Voltage Variable Frequency Control of Induction Motor, Open loop V/f Control

Hello and welcome to today's lecture on the fundamentals of electric drives! In our previous discussion, we focused on the variable voltage and variable frequency control of induction motors. Today, we'll pick up right where we left off.

When it comes to efficiently controlling the speed of an induction motor, it is essential to vary both the voltage and the frequency. By doing so, we can achieve a more effective and responsive control system. Now, let's take a closer look at the circuit diagram and the relevant equations that will guide our understanding of this concept.

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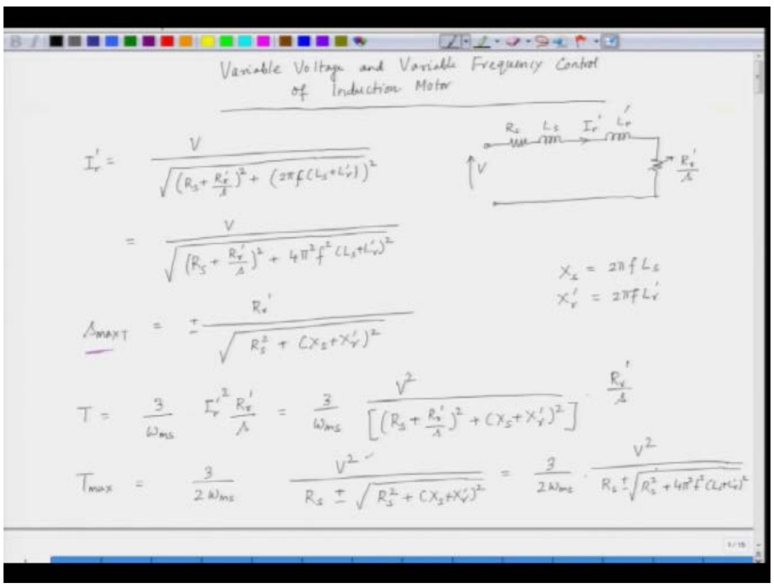

Now, let's delve into the concept of variable voltage and variable frequency control. The steady-state equivalent circuit we discussed previously is still applicable in this context. We can represent the equivalent circuit of an induction motor, which begins with the stator resistance (R_s), followed by the stator leakage inductance (L_s), the rotor leakage inductance (L_r', referred from the primary side), and the rotor resistance (R_r' divided by s).

The applied voltage in this circuit is denoted as V. It’s important to note that we have ignored the magnetizing reactance, as it does not directly factor into the torque equation. Now, focusing on the rotor current (I_r'), we can express it as:

$$I_r' = \frac{V}{\sqrt{R^2 + X^2}}$$

Here, the reactance X is given by:

$$X = 2\pi f(L_s + L_r')$$

If we simplify this expression, we arrive at:

$$I_r' = \frac{V}{\sqrt{R_s + \frac{R_r'}{s}^2 + \left(2\pi f(L_s + L_r')\right)^2}}$$

Now, our goal is to find the maximum torque, which occurs at a specific slip value, denoted as s_{maxT}. This value can be expressed as:

$$s_{maxT} = \frac{R_r'}{\sqrt{R^2 + X^2}}$$

Here, X_s represents the stator reactance, calculated as 2 π f L_s, while X_r denotes the rotor leakage reactance, expressed as 2 π f L_r'.

Substituting this expression into the torque equation, we find that torque is given by:

$$T = \frac{3}{\omega_{Ms}} I_r'^2 \frac{R_r}{s}$$

This leads to the overall equation for torque:

$$T = \frac{3}{\omega_{Ms}} \cdot \frac{V^2}{R_s + \frac{R_r'}{s}}^{2}$$

This comprehensive understanding allows us to explore the dynamics of variable voltage and frequency control in induction motors more effectively.

Now, let's rewrite the torque equation in terms of the reactance, incorporating X_s and X_r' alongside R_r' divided by s. When we substitute the slip for maximum torque into this equation, we notice that the slip value for maximum torque can take on two forms: one is a positive value, indicating motoring conditions, and the other is a negative value, which corresponds to braking or generating conditions.

Upon substituting s_{maxT} into the equation and simplifying, we derive the expression for maximum torque. The maximum torque, T_{max}, is expressed as:

$$T_{max} = \frac{3}{2\omega_{Ms}} \cdot \frac{V^2}{R_s} \pm \sqrt{R^2 + X_s - X_r'^2}$$

This illustrates that the maximum torque is fundamentally related to the torque-speed characteristic of the induction motor. It's important to recognize that the maximum torque is dependent on the square of the applied voltage. Specifically, we see that T_{max} is proportional to V^2.

Now, in this context, if we further replace the reactance with frequency, we can express the maximum torque in another form. Thus, we arrive at:

$$T_{max} = \frac{3}{2\omega_{Ms}} \cdot \frac{V^2}{R_s} \pm \sqrt{R_a^2 + 4\pi^2 f^2 (L_s + L_r')^2}$$

Next, to streamline our expression, we can divide the entire equation by f^2. By doing so, we obtain the following equation, which illustrates the relationship between torque, voltage, and frequency more clearly.

What we have derived is that the maximum torque, T_{max}, can be expressed as:

$$T_{max} = K \cdot \frac{V}{f^2} \cdot \frac{1}{R_s/F} \pm \sqrt{\left(\frac{R_s}{F}\right)^2 + 4\pi^2(L_s + L'_r)^2}$$

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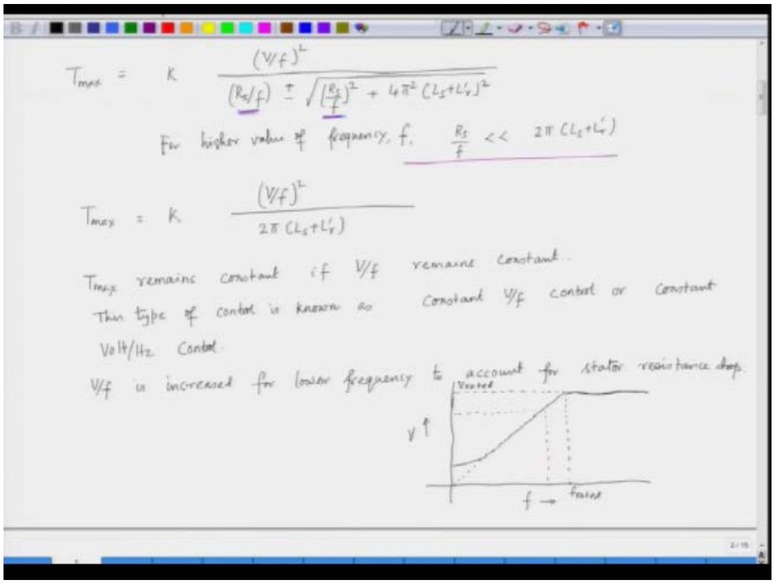

Let’s revisit our previous equation. We noticed that by dividing the entire expression by F, we effectively introduced F into both the numerator and denominator. When we perform this division, the term inside the square root becomes F^2, and we end up dividing other terms by F^2 as well. This leads to some cancellations, allowing F^2 in the numerator to cancel out with F^2 in the denominator.

It's important to recognize that ω_{Ms}, which is the synchronous speed, is indeed a function of frequency. Specifically, ω_{Ms} is calculated as:

$$\omega_{Ms} = \frac{2\pi F}{P/2}$$

This relationship indicates that the synchronous speed varies with frequency, and thus another frequency term arises from ω_{Ms}. Ultimately, we arrive at the expression $\frac{V}{f^2}$ multiplied by a constant K, which depends on factors such as the number of poles and includes the factor of 3.

In our denominator, we have R_s/F for the motoring action, and the negative sign represents the generating action. This leads us to:

$$\sqrt{\left(\frac{R_s}{F}\right)^2 + 4\pi^2(L_s + L_r')^2}$$

Now, it's worth noting that when we consider a three-phase induction motor, the frequency is typically high; for instance, the normal rated frequency is 50 Hertz. When operating at this frequency, F assumes a large value. Although we can vary the frequency, if we find ourselves working with higher frequencies, we can effectively ignore R_s/F when compared to the reactive components. Thus, under conditions of elevated frequency, this simplifies our analysis considerably.

What we can conclude from our analysis is that $\frac{R_s}{F}$ becomes significantly smaller compared to 2π L_s + L_r' when the frequency F is large. This means that, since we are dealing with a substantial value of F, we can confidently state that $\frac{R_s}{F}$ is much less than $2\pi L_s + L_r'$. Consequently, in our denominator, we can ignore this term entirely because the resistance is typically small due to the nature of copper windings.

By disregarding $\frac{R_s}{F}$, we arrive at the following expression for maximum torque:

$$T_{max} = K \cdot \frac{V}{f^2} \cdot \sqrt{4\pi^2(L_s + L_r')^2}$$

This simplifies to 2π (L_s + L_r'). Therefore, this equation effectively gives us the maximum value of torque.

What's crucial to note is that the maximum torque remains constant as long as the ratio $\frac{V}{f}$ is maintained. This is precisely why we always strive to keep V/f constant while varying both voltage and frequency. This approach is commonly referred to as constant volts per hertz control, or simply constant V/f control.

Now, let's consider the implications if the frequency is low. In such cases, $\frac{R_s}{F}$ can no longer be neglected. When the frequency decreases, this term starts to dominate the behavior of the system. To maintain the same level of torque under these conditions, we need to increase V/f. So, while we keep V/f constant for higher frequencies, we must actually increase V/f for lower frequencies to compensate for the drop due to stator resistance. This adjustment ensures that we can still achieve the desired torque in situations where the frequency is low.

Let’s take a closer look at the characteristic curve we’re working with. On one axis, we have voltage, while on the other, we have frequency. By keeping the ratio $\frac{V}{f}$ constant, we ideally expect to move along a straight line that passes through the origin. However, at lower frequencies, we need to increase $\frac{V}{f}$ to account for the voltage drop caused by stator resistance. This is the function we need to follow.

Given a specific frequency, we can use this function to determine the corresponding voltage. As we approach the rated frequency, we also reach the rated voltage. This is because, as we increase the frequency, the voltage must also rise accordingly. When we hit the rated frequency of 50 Hertz, we achieve the rated voltage.

However, it's crucial to remember that once we reach this point, any further increase in frequency should not lead to an increase in voltage. Motors are designed with specific insulation ratings, and applying, for instance, 300 volts to a motor rated for 230 volts would put undue stress on the insulation. Thus, we must not exceed the voltage rating of the motor. When we increase the frequency beyond the rated frequency, the voltage is maintained constant; only the frequency is increased. This means that beyond the rated frequency F_{rated}, we keep the voltage at V_{rated} constant and do not increase it further.

Graphically, this is represented as a function where, initially, as we vary the frequency, we need to increase the voltage. After reaching the rated frequency, the voltage remains constant despite further increases in frequency. This understanding is critical when we implement constant V/f control for induction motors. Now, let’s explore how we can achieve this effectively.

Now, let's delve into the open-loop control system, as a closed-loop setup is not required in this scenario. Here, we provide a frequency command that is fed into a delay block. This delay block processes the command and generates the frequency reference. We also need to determine the corresponding voltage, which we obtain from the $\frac{V}{f}$ function we previously discussed. By inputting the frequency into this function, we derive the output, which is our reference voltage.

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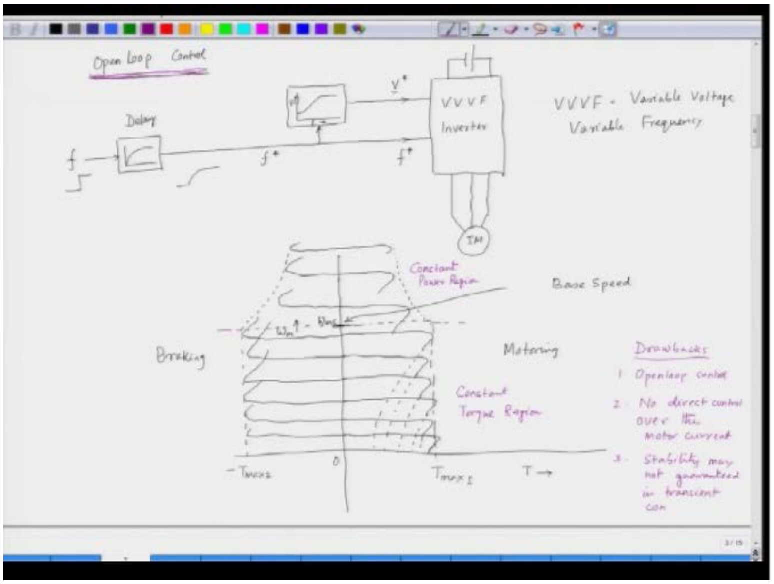

This reference voltage, along with the reference frequency, is then supplied to a variable voltage and variable frequency (VVVF) inverter. The inverter takes in a DC input voltage and converts it into an AC voltage suitable for driving the induction motor. In this case, we are dealing with a three-phase induction motor, and the output of the inverter produces a three-phase AC signal.

As we change the frequency, it's essential to do so gradually. Abrupt changes in frequency can lead to instability in the machine. That's precisely why we incorporate a delay block. When we apply a step change to the frequency, the actual change is delayed, allowing the machine's inertia to respond appropriately.

As we vary the frequency, represented by our frequency command, the voltage is adjusted in accordance with the relationship we established earlier. We strive to maintain a constant $\frac{V}{f}$ ratio, except in low-speed or low-frequency regions, where we increase $\frac{V}{f}$ to compensate for the voltage drop due to stator resistance. This approach ensures that the torque of the motor remains constant throughout the operation.

Let’s take a closer look at the torque-speed characteristic of this drive. On the graph, we place speed on the y-axis and torque on the x-axis, with the origin serving as our reference point. The resulting characteristic curve captures the behavior of the motor during both motoring and regenerative braking operations. As we adjust the frequency, we observe a series of parallel characteristics, with the peak torque, also known as the maximum torque, remaining consistent throughout these variations.

This torque-speed characteristic reveals the unique relationship we see as frequency is reduced while maintaining a constant $\frac{V}{f}$ ratio. The result is a family of curves that exhibit this behavior. Even in the generating region, we observe a similar trend, where the peak torque remains nearly constant. We designate the maximum torque as T_{max}, while the corresponding torque for braking or generating is represented as the negative of the maximum torque.

To clarify, if we refer to the peak torque as T_{max1}, the negative peak torque during braking would be labeled as $-T_{\text{max2}}$. Here, the torque is negative, indicating the braking or generating phase, while the positive torque reflects the motoring phase.

This family of curves emerges when we apply variable voltage and variable frequency control while keeping $\frac{V}{f}$ constant. The base speed, denoted as ω_{Ms}, represents the synchronous speed. Beyond this rated synchronous speed, we need to adjust our approach: we keep the voltage constant but increase the frequency. Consequently, the $\frac{V}{f}$ ratio decreases, leading to a reduction in torque.

As we transition to higher speeds, we observe a gradual decline in torque, as depicted in this characteristic curve. Up to the base speed, we maintain a constant torque; however, once we exceed the base speed, our critical point, we begin to see the torque reduce. This dynamic behavior is crucial in understanding the operation of the motor under varying conditions.

Beyond the base speed, we transition into a region characterized by variable torque, where torque begins to decrease even as speed increases. This phenomenon is referred to as the constant power mode or constant power region. Prior to reaching the base speed, we observe what is known as the constant torque region. This entire behavior illustrates the torque-speed characteristic of an induction motor when it is supplied by a variable voltage and variable frequency inverter, with the $\frac{V}{f}$ ratio maintained constant up to the base speed.

Once we exceed the base speed, the voltage remains constant while the frequency is increased. As a result, the $\frac{V}{f}$ ratio decreases, leading to a reduction in torque in accordance with our established equations, which aligns with the behavior seen in the constant power mode.

Now, it's important to note that this is an open-loop control system. The absence of closed-loop feedback means we lack direct control over the motor current, raising some potential drawbacks. These drawbacks include the following: since we are operating in an open-loop mode, there is no direct feedback mechanism to monitor the motor current, and stability may not be guaranteed during transient conditions. Our adjustments are limited to changing the frequency, and while the voltage changes in accordance with that frequency, we cannot ascertain the actual motor current. It is possible, for instance, that the motor could become overloaded and draw excessive current, yet we would have no indication of this condition.

Moreover, if we were to vary the frequency too rapidly, the motor could potentially enter an unstable region. To address these concerns, we turn to slip frequency control, which offers a more robust and reliable approach compared to the open-loop $\frac{V}{f}$ control system. In our next discussion, we will delve deeper into the principles and advantages of slip frequency control.

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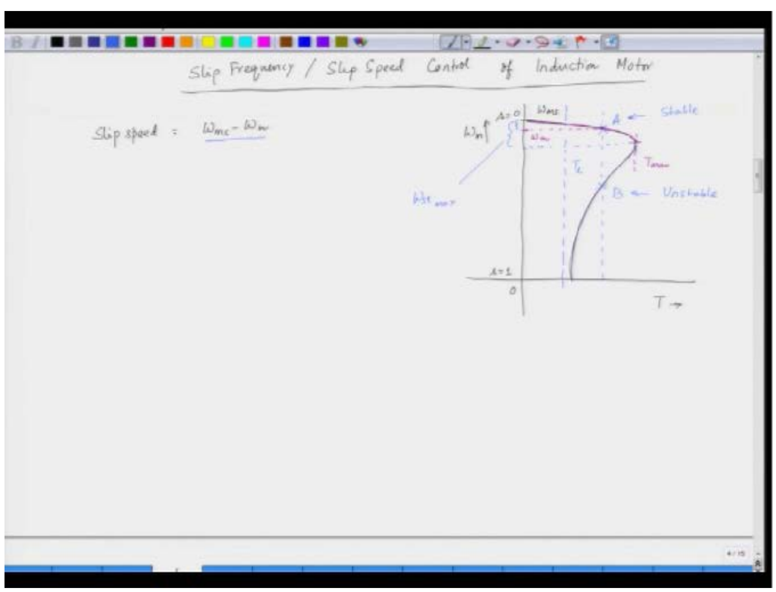

This is referred to as slip frequency or slip speed control of the induction motor. But why should we opt for slip frequency control? To understand this, let's delve into the underlying philosophy of slip frequency or slip speed control.

First, let's clarify what slip speed is. If we were to plot the torque-speed characteristic of an induction motor, we would observe the following curve, with speed on the y-axis and torque on the x-axis. The synchronous speed marks the point where slip equals zero, while at the origin, the slip equals one. For example, if the motor is operating at a certain speed, let's denote this speed as ω_M. The slip speed is defined as the difference between the synchronous speed and the motor speed:

$$\text{Slip speed} = \text{Synchronous speed} - \omega_M$$

Now, let's consider a constant torque load. This load is represented as T_L, and within this region, we refer to it as the conventional stable region. This stable region is where we can find the maximum torque, $T_{\max}$. The distinction between stable and unstable regions is defined with respect to a torque profile. For a constant torque load, the area we discussed is the stable region, while any area beyond this threshold becomes unstable.

When we analyze a torque that exceeds the constant torque load, we notice that it intersects the torque-speed characteristic at two distinct points: one at point A and the other at point B. Here, point A represents a stable operating point, while point B signifies an unstable point. It is essential to operate the motor within the stable region to ensure reliable performance.

This stability can be achieved by effectively controlling the slip speed, which, as mentioned, is the difference between the synchronous speed and the motor speed. By managing this slip speed, we can ensure that the motor operates within the maximum allowable slip speed, denoted as $\omega_{Sl_{\max}}$. This is the primary rationale behind the adoption of slip speed control or slip frequency control, as it guarantees the stability of the induction motor drive.

We will conclude our discussion for today. In the next lecture, we will explore slip frequency control in greater detail.