Fundamentals of Electric Drives

Prof. Shyama Prasad Das

Department of Electrical Engineering

Indian Institute of Technology-Kanpur

Lecture-25

Slip Speed Control of Induction Motor, Constant Volt/Hz Control With Slip Speed Regulation

Hello and welcome to this lecture on the fundamentals of electric drives! In our previous discussion, we focused on the concept of slip speed control in induction motors. When we refer to slip speed, we are essentially talking about the differential between the synchronous speed and the actual motor speed. To better illustrate this concept, let’s take a closer look at its graphical representation.

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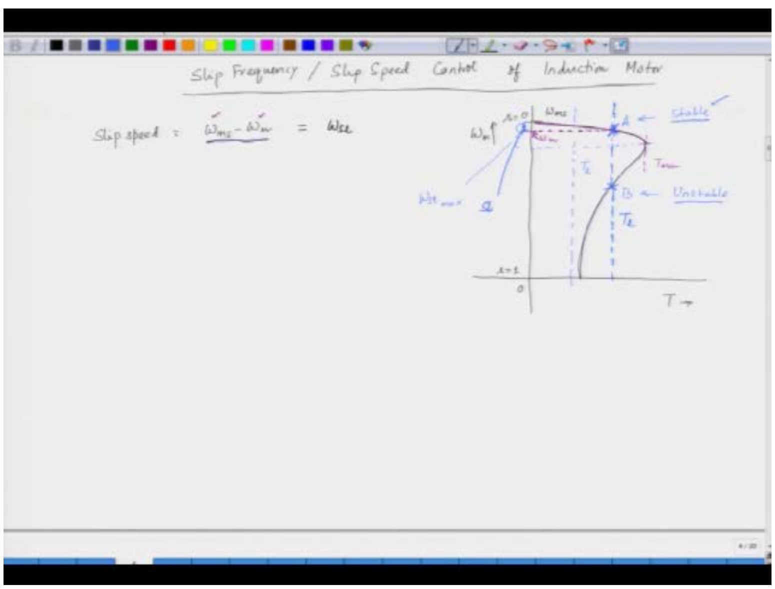

As we discussed in the last lecture, slip speed is defined as the difference between the synchronous speed, denoted as ω_{Ms}, and the rotor speed, represented as ω_M. To illustrate this, let’s assume that our operating point speed is ω_M. In this scenario, the corresponding synchronous speed is ω_{Ms}. The differential speed between these two, ω_{Ms} and ω_M, is what we refer to as the slip speed, designated as ω_{sl}.

Now, when we consider a constant torque load, represented by the torque-load profile T_L, we can observe that it intersects the motor characteristic at two distinct points: point A and point B. Here, point A is identified as a stable operating point, while point B is an unstable operating point. This indicates that operating at point B could lead to instability.

Therefore, it is crucial to maintain operation at the stable equilibrium point, which is point A. We can achieve this stability by effectively controlling the slip speed. While we will continue to implement variable voltage and variable frequency control of the induction motor, varying both voltage and frequency as we previously discussed, this time, we will also incorporate slip speed control. Now, let's delve into the concept of constant volt/hertz control in conjunction with slip speed control.

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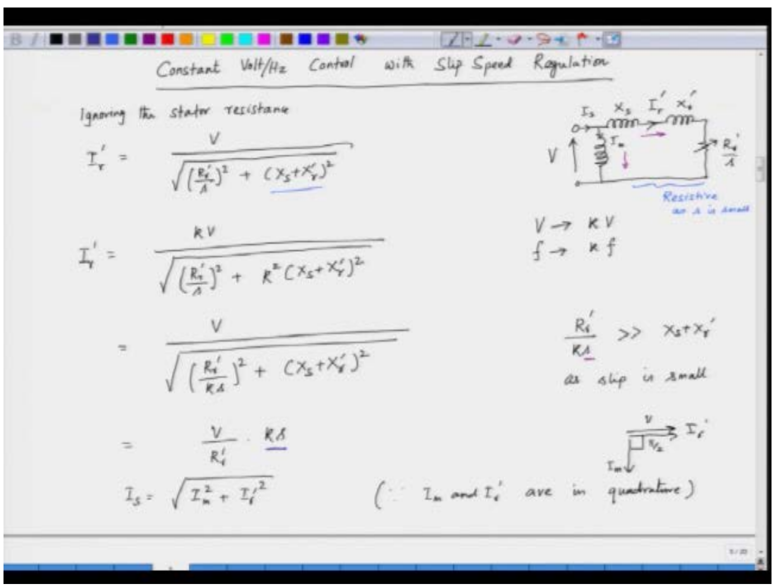

In this discussion, we will focus on constant volt/hertz control combined with slip speed regulation, allowing us to effectively manage the slip speed. Let’s start by writing the equation for the rotor current. The rotor current, denoted as I_r, can be expressed as the applied voltage divided by the square root of the sum of the squared rotor resistance divided by slip and the squared sum of the stator reactance and rotor leakage reactance. Mathematically, this is represented as:

$$I_r = \frac{V}{\sqrt{R_r/s^2 + X_s + X_r'^2}}$$

In this expression, we have chosen to ignore the stator resistance for simplification.

Now, if we consider an approximate equivalent circuit, we can depict it as follows: we have the stator leakage reactance, the rotor leakage reactance, and the rotor resistance, R_r/s. The applied voltage here is V, representing the phase voltage, while I_r is the rotor current observed from the primary side.

Next, we will modify both the voltage and the frequency by a factor of K. Consequently, the voltage transforms to $K \cdot V$, and the frequency adjusts to $K \cdot F$. This adjustment ensures that the ratio V/f remains constant.

Substituting these values, we can rewrite our expression as:

$$R_r' = \frac{K \cdot V}{\sqrt{(R_r/Ks)^2 + (X_s + X_r')^2}}$$

In this case, the reactance will include the frequency term, leading us to observe that the reactance modifies by multiplying by K^2 in the expression $X_s + X_r'$.

Now, to simplify further, we divide both the numerator and denominator by K:

$$I_r = \frac{V}{\sqrt{R_r/s^2 + (X_s + X_r')^2}}$$

Assuming the slip of the machine is relatively small, we can assert that R_r'/K s is significantly greater than the reactance, $X_s + X_r'$. Hence, we conclude that:

$$\frac{R_r'}{Ks} \gg X_s + X_r'$$

In essence, under conditions of small slip, R_r'/K s remains quite substantial compared to the reactances involved.

By applying this approximation, we arrive at the expression for the rotor current, which can be represented as:

$$I_r = \frac{V}{R_r' \cdot Ks}$$

This equation provides us with a clear understanding of the rotor current in the system. Typically, we also consider the magnetizing branch, where the magnetizing current I_M and the stator current I_s are present. Given that the slip s is very small, the rotor circuit behaves predominantly as a resistive circuit. This resistive nature arises because I_s is significantly small, approaching zero, making the value of I_M quite large in comparison.

As the slip s approaches zero, the leakage reactance becomes negligible, confirming that the circuit is mainly resistive. In this context, we observe that the rotor current I_r and the magnetizing current I_M are orthogonal, or in quadrature, to each other. Therefore, we can express the stator current I_s as:

$$I_s = \sqrt{I_M^2 + I_r^2}$$

Here, I_M is primarily constant, indicating that if the rotor current I_r remains constant, the stator current will also remain constant. It is important to note that the rotor current is influenced by the product of the constant K and the slip s, while the voltage V is maintained as a given constant. The rotor resistance R_r' also plays a critical role in this relationship. If we can keep K constant, we can thus ensure that I_r remains stable.

Let’s explore the expression for torque in our system. The torque expression can be given as:

$$T = \frac{3}{\omega_{Ms}} \cdot K \cdot I_r^2 \cdot \frac{R_r}{s}$$

Since we are adjusting the frequency, we must multiply by a factor of K. Now, substituting the value of I_r^2 into this equation, we find:

$$I_r^2 = \frac{V^2}{R_r' \cdot K \cdot s^2}$$

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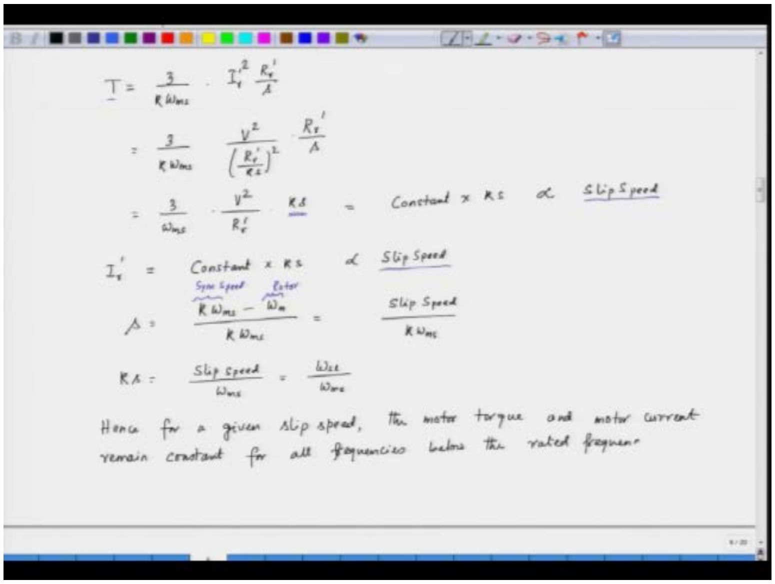

So, simplifying this gives us:

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

From this expression, we can see that torque is proportional to K · s. To maintain a constant torque, it is essential to keep K · s constant. We previously established the relationship for the rotor current:

$$I_r = \text{constant} \cdot K \cdot s$$

This means that the rotor current is directly proportional to K · s as well, indicating that both K and the rotor resistance R_r' are constant values. Similarly, we can express torque as:

$$T = \text{constant} \cdot K \cdot s$$

Now, let's analyze what K · s represents. In this context, slip s is defined as:

$$s = \frac{K \cdot \omega_{Ms} - \omega_M}{\omega_{Ms}}$$

Where ω_{Ms} is the synchronous speed, and ω_M is the rotor speed. The term K · ω_{Ms} - ω_M is referred to as the slip speed. Essentially, this is the difference between the synchronous speed and the rotor speed, scaled by the factor K. This helps us understand the dynamics of the system and how adjustments in speed and current can affect torque.

The rotor speed, denoted as ω_M, is an essential factor in our analysis. The difference between the synchronous speed, ω_{Ms}, and the rotor speed is referred to as the slip speed. By rearranging our equation, we can bring K to the left side, resulting in:

$$K \cdot s = \frac{\text{slip speed}}{\omega_{Ms}} = \frac{\omega_{Sl}}{\omega_{Ms}}.$$

This tells us that K · s is proportional to the slip speed. Therefore, if we wish to increase the slip speed, we must also increase K · s. In this context, we can also assert that torque is directly proportional to slip speed. Similarly, the current is also proportional to the slip speed.

These derivations are crucial because they indicate that both torque and current are related to the slip speed. For a given slip speed, both torque and current remain constant, regardless of the frequency of operation. This means that even if the frequency changes, maintaining a particular slip speed will ensure that both the torque and the current remain unchanged.

Thus, for any given slip speed, the motor torque and motor current will remain constant for all frequencies below the rated value. This is a significant conclusion, as it highlights the consistency of motor performance under varying conditions.

Now, let's consider what happens when the frequency exceeds the rated value. When the frequency surpasses the rated value, the voltage no longer serves its initial purpose; in fact, the voltage remains constant beyond this point. This is a critical aspect to understand as we continue our exploration of motor control and performance.

Let's delve into the scenario where the frequency increases beyond the rated value. When this happens, we consider the case where $K > 1$. At $K = 1$, we are at the rated frequency, and once K exceeds 1, the voltage remains constant; in other words, the voltage V does not increase beyond the rated frequency. Therefore, for $K > 1$, V remains constant.

In this case, we also need to consider the rotor current. Since we will continue to ignore the stator resistance, we can express the rotor current I_r as follows:

$$I_r = \frac{V}{\sqrt{\left(\frac{R_r'}{s}\right)^2 + (X_s + X_r')^2}}.$$

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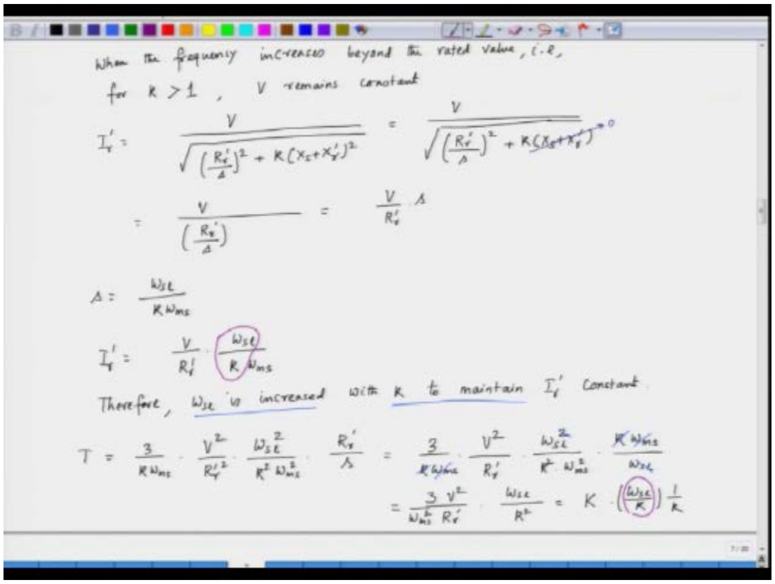

With the increase in frequency, the reactance terms will be influenced by the factor K, resulting in $K \cdot X_s + X_r'$. Simplifying this expression gives us:

$$I_r = \frac{V}{\sqrt{\left(\frac{R_r'}{s}\right)^2 + (K \cdot X_s + X_r')^2}}.$$

Now, if we assume that the resistance $\frac{R_r'}{s}$ is very large, we can neglect the reactance with respect to the resistance. This leads us to the simplified expression:

$$I_r \approx \frac{V}{\frac{R_r'}{s}}.$$

Now substituting s with its definition gives us:

$$I_r = \frac{V}{R_r' \cdot \frac{\text{slip speed}}{K \cdot \omega_{Ms}}} = \frac{V \cdot K \cdot \omega_{Ms}}{R_r' \cdot \text{slip speed}}.$$

As K increases, which corresponds to an increase in frequency, the slip speed also must increase in order to maintain a constant rotor current. This is crucial because every motor has a specified rated current; for example, if a motor is rated for 10 amperes, exceeding this current could potentially damage the windings.

Thus, when the rated frequency is exceeded and K is greater than 1, it is essential to increase the slip speed along with K to keep the rotor current constant at its rated value. This careful management ensures that the motor operates efficiently and safely, avoiding potential damage due to excessive current.

What we are examining here is the relationship between the slip speed ω_{sl} and the factor K to maintain a constant rotor current. As ω_{sl} increases, it becomes essential to also increase K to ensure that the current remains constant. Now, let's take a closer look at the torque equation.

The torque can be expressed as:

$$T = \frac{3V^2}{K \cdot R_r} \cdot \frac{\omega_{sl}}{K^2 \cdot \omega_{Ms}^2} \cdot \frac{R_r}{s}.$$

In this scenario, the frequency is increased by a factor of K, while the voltage remains constant. So we rewrite this expression considering s, which is defined as:

$$s = \frac{\omega_{sl}}{K \cdot \omega_{Ms}}.$$

Substituting this back into the equation, we have:

$$T = \frac{3V^2}{R_r} \cdot \frac{\omega_{sl}}{K^2 \cdot \omega_{Ms}^2} \cdot \frac{K \cdot \omega_{Ms}}{R_r}.$$

Here, R_r cancels out, simplifying our equation significantly. Now, let's examine the cancellation steps closely. The term ω_{Ms} cancels with another ω_{Ms} in the denominator, leaving us with just one ω_{sl}. Additionally, we can see that we have one K in the numerator and one K in the denominator.

As a result, we derive the following expression for torque:

$$T = \frac{3V^2 \cdot \omega_{sl}}{K^2 \cdot R_r \cdot \omega_{Ms}^2}.$$

This equation reveals that the torque is inversely proportional to K. As K increases, meaning we are operating beyond the rated frequency, the torque will decrease.

Now, let's consider the implications of maintaining the ratio of $\frac{\omega_{sl}}{K}$ constant. By keeping this ratio steady, we ensure that the current remains constant as well. Therefore, while K increases, which affects torque, this constant ratio allows us to manage the slip speed and maintain stable operation.

Finally, let’s plot the various parameters, power, torque, and slip speed, against the variations of K to visualize how these relationships interact as we adjust the frequency. This graphical representation will help us better understand the dynamics at play in our electric drive system.

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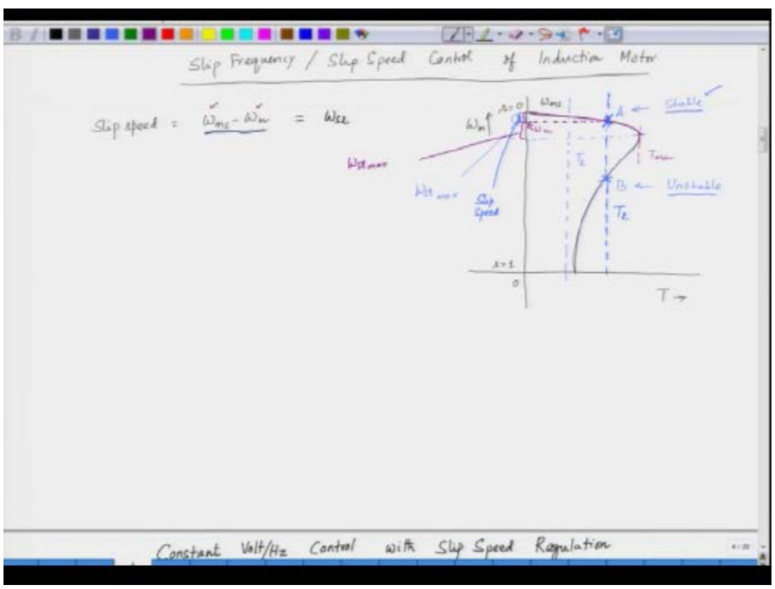

Let’s visualize the relationships among various parameters by plotting them against the factor K on the x-axis. Here, we’ll mark K = 1 as the rated frequency, and then perhaps we will consider a point where K = 2. This K = 1 corresponds to the base frequency, which is our reference point.

Now, let’s examine the behavior of the system up to the rated frequency. During this range, we keep the torque constant. This means that while the torque remains unchanged, the slip speed is also held constant as we approach the rated frequency.

As we consider the power, it's crucial to note that power is the product of torque and speed. When we increase the frequency, the speed naturally rises as well, resulting in an increase in mechanical power. Thus, we see that the power increases linearly with K up to the rated frequency.

Once we surpass the rated frequency, our strategy shifts. In this case, we need to increase the slip speed to maintain the rotor current at a constant level. The rotor current, denoted as I_s, is the stator current that we want to keep steady.

To achieve this constant current, we must increase the slip speed (ω_{sl}) in proportion to K. This means that as the frequency increases, represented by the growing value of K, we also need to increase the slip speed to maintain that crucial ratio constant.

Thus, while torque remains steady and power increases with frequency, our focus on keeping the stator current constant necessitates an adjustment in slip speed as we increase K.

As we continue our discussion, we reach even higher speeds, specifically at 2 per unit, where we find the maximum value of slip speed. Beyond this point, the slip speed is maintained at a constant level. Consequently, if we keep this slip speed constant while increasing K, the current will actually decrease. Therefore, as K rises beyond 2, the current decreases while maintaining the constant slip speed.

Now, let's talk about power. The power remains constant after we exceed the rated frequency because power is defined as the product of voltage and current. Since the voltage remains constant and we also keep the current steady, the power will similarly remain constant. We assume a power factor of 1, indicating that we are dealing with a purely resistive circuit. Thus, with both V and I remaining constant, power stays unchanged.

However, the torque behaves differently; as K increases, the torque decreases. Beyond the rated frequency and particularly after 2 per unit, we see a further decline in torque, which decreases with the square of K. The current, too, follows suit and decreases in this scenario.

Now, let's visualize this relationship by plotting torque, current (P_m), and slip speed (ω_{sl}) on the y-axis against the power unit frequency K on the x-axis. This graph illustrates how various parameters change with the power unit frequency K.

Initially, as we increase the frequency, we find ourselves in a constant torque region, which extends up to the rated frequency or speed. This segment is designated as the constant torque region because the torque remains relatively constant between 1 and 2. Beyond this, we enter what we call the constant power region, where power remains steady.

When we go past the value of 2, we transition into the constant slip frequency region. This means that in this region, the slip frequency has reached its maximum allowable value. It’s essential to note that we cannot exceed this maximum value of slip frequency. If we examine the torque-speed characteristic, we see that this point represents the upper limit for slip speed, denoted as $\omega_{sl\,\max}$. Going beyond this point would lead us into an unstable region, which we must avoid by regulating slip speed appropriately.

In summary, we have defined three critical regions: the constant torque region, the constant power region, and the constant slip frequency region. Within this framework, when slip frequency is regulated, both current and torque are also effectively managed. This results in a more efficient drive system compared to the traditional open-loop voltage/frequency (V/f) control drive.

That concludes today’s lecture. We will continue our exploration of slip regulation in the next session.