Fundamentals of Electric Drives

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Lecture-26

Closed-loop Volt/Hz Control of Induction Motor With Slip Speed Regulation, Multiquadrant Operation of Induction Motor Drive

Hello and welcome to this lecture on the fundamentals of electric drives! In our previous session, we delved into the concept of slip speed control. We explored how we can adjust both the frequency and voltage while simultaneously regulating the slip speed. Now, as we focus on regulating the slip speed with an increase in frequency, denoted as K, we observe that various parameters change in the following ways. To begin with, the torque is initially maintained at a constant level.

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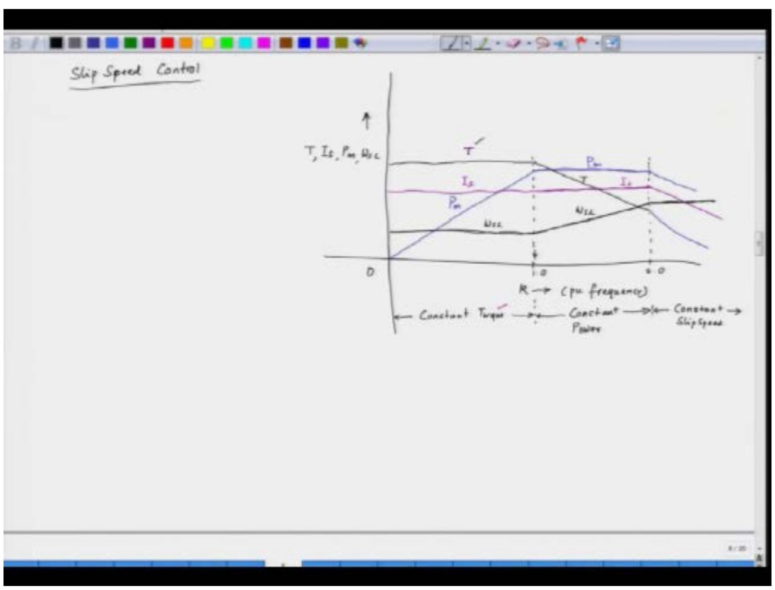

Initially, the torque is limited to a constant value, which is referred to as the constant torque region. During this phase, the current is also maintained at a steady level, while the power increases, and the slip frequency remains nearly constant. This behavior is observed in the region from 0 to 1 per unit frequency. As we approach the rated frequency, the torque reaches its rated value, and the current stabilizes at the rated current.

In this region, the power increases to its rated value, and the slip speed holds steady. Following this, we transition into the constant power region, where the torque begins to decrease. Although the power remains constant, denoted as P_m, the current continues to hold at approximately the same value, I_s, indicating that it does not change significantly. As a result, the slip speed must increase, linearly progressing until we reach a frequency of 2 per unit.

Once we exceed this frequency, the slip frequency hits its maximum value and becomes constant. In this constant slip speed region, both the power and the current begin to decrease, along with the torque, which diminishes in accordance with the factor $\frac{1}{K^2}$. All these relationships can be derived easily from the equations we discussed in the previous lecture.

So, we primarily have three distinct regions: the constant torque region, the constant power region, and the constant slip frequency region. Now, the question arises: how can we implement this system in a closed-loop fashion? We will maintain a constant volt-per-hertz control strategy while integrating slip regulation. Let’s take a closer look at the closed-loop block diagram of constant volt-per-hertz control with slip regulation.

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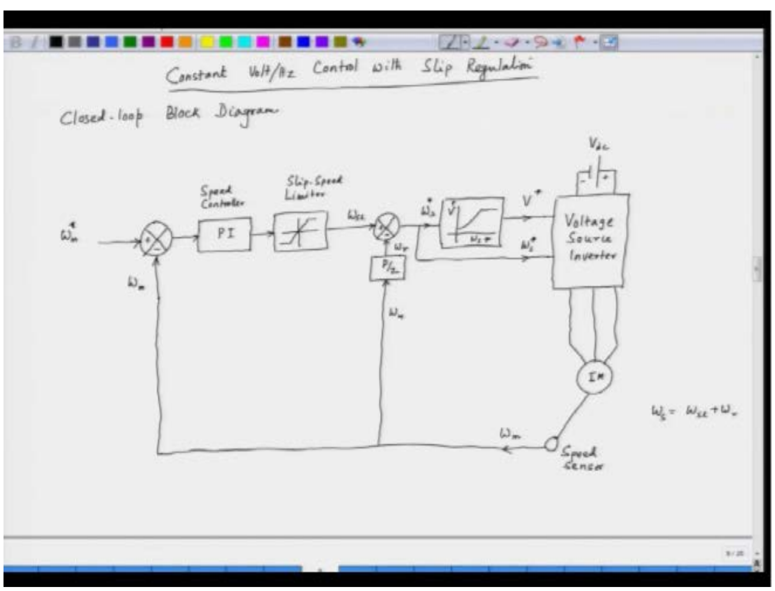

Constant volt-per-hertz control, or V/f control, with slip regulation, also known as slip speed regulation, is crucial in maintaining efficient motor operation. To visualize this process, let's draw the closed-loop block diagram.

We begin with the reference speed, which is fed into a summation block. This block incorporates both positive and negative inputs, allowing us to compare the reference speed with the actual mechanical speed of the rotor. The output of this comparison is directed to a Proportional-Integral (PI) controller, which functions as the speed controller.

The output from the PI controller is then limited since it can potentially reach very high values. Thus, we impose a limit on this output. This output is specifically referred to as the slip speed. Consequently, we label this section as the slip speed limiter, where we are controlling the value of the slip speed.

It's essential to understand that the output of the speed controller corresponds to the slip speed. Torque is inherently a function of slip speed; therefore, if we wish to increase the torque, we need to increase the slip speed. Conversely, if we aim to decrease the torque, we must reduce the slip speed. Thus, the key control variable in this system is indeed the slip speed.

Moreover, if we want to increase the current, we increase the slip speed, and if we want to decrease the current, we reduce the slip speed. Therefore, by limiting the slip speed, we are essentially regulating both the torque and the current.

The output from the slip speed limiter provides the reference value for slip speed, denoted as ω_s. This reference value is then added to the electrical rotor speed, which is multiplied by the number of pole pairs. We denote the electrical rotor speed as ω_r. When we combine the rotor speed with the slip speed, we obtain the synchronous speed, represented as ω_s.

The synchronous speed, denoted as ω_s, is an electrical variable that feeds into a function generator. Here, we employ a V/f function generator, which we've discussed previously. In this configuration, the V/f function generates a relationship that maintains a constant voltage beyond the base speed. On a graph, we plot voltage on the y-axis and frequency on the x-axis, illustrating this relationship.

The output of this function generator is the reference voltage, labeled as V^*, and the frequency command is represented as ω_s in radians per second. This reference frequency is then directed to a voltage source inverter. The input to this inverter consists of a DC voltage, and the inverter's output is the converted AC voltage.

Connected to this system is an induction motor, which is powered by the inverter. Additionally, we have a speed sensor linked to the induction motor, possibly a tachogenerator, that provides us with the mechanical speed of the motor.

This speed sensor outputs ω_m, the mechanical speed, which is fed back into the system. This information is essential for calculating the synchronous speed, which is the sum of the rotor speed and the slip speed. Mathematically, we express this relationship as $\omega_s = \omega_{sl} + \omega_r$, where ω_{sl} represents the electrical slip speed, and ω_r denotes the electrical rotor speed.

Furthermore, we can relate this to the frequency as $\omega_s = 2\pi f$, indicating that any change we wish to make to the synchronous speed ω_s requires us to adjust the frequency. The information provided by ω^* also includes frequency details. Thus, when we have both the voltage amplitude and frequency, we can effectively feed this information into a controlled voltage source inverter.

The control system implemented here outputs the voltage in three-phase voltages, which are crucial for the operation of the induction motor. This represents a constant volt-per-hertz control scheme combined with slip regulation. One of the key advantages of this drive system is that it operates in a closed-loop configuration, providing feedback that ensures stability. By effectively regulating the slip speed, we are also able to limit both the torque and the current supplied to the motor.

This is particularly important because the motor's current must not exceed its rated value.

Now, let’s shift our focus to the multi-quadrant operation of an induction motor. An induction motor can function in various operational quadrants, including forward motoring, forward braking, reverse motoring, and reverse braking, similar to the behavior of a typical transmission system. However, to facilitate this versatility, we require two converters: one on the motor side and another on the input side, which connects to the AC source. Given that the motor itself is an AC motor, the use of these two converters is essential for effective operation.

Let’s delve into the multi-quadrant operation of the induction motor. Here, we have two voltage source inverters, which we can refer to as Converter 1 and Converter 2. The first stage, Converter 1, functions as an AC to DC converter, while the second stage, Converter 2, acts as a DC to AC converter. These two converters are connected on the DC side, and there is a capacitor present in this configuration. The voltage on the DC side is denoted as V_{DC}.

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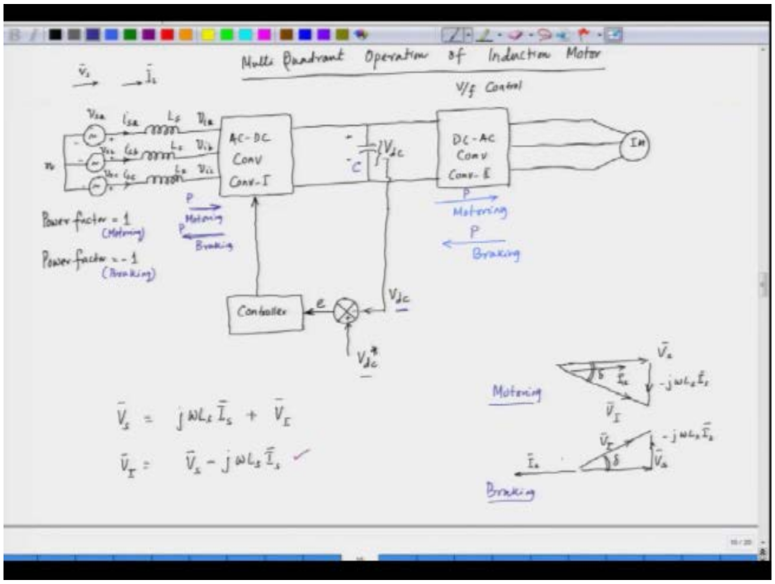

The output from Converter 2, the DC to AC converter, provides the AC supply to the induction motor. Specifically, we have a three-phase induction motor powered by this converter. Now, regarding Converter 1, it receives power from the AC supply through inductors. Each phase of the converter is equipped with inductors, and the input in this case is three-phase AC.

We have a three-phase supply with a neutral line. The inductors play a crucial role in this system, and the input side is defined by the supply voltages: V_a for phase A, V_b for phase B, and V_c for phase C. Correspondingly, the currents flowing through these phases are I_{SA}, I_{sb}, and I_{sc}.

The second converter can utilize a volt-per-hertz (V/f) control strategy. It is essential that the first converter maintains a constant DC link voltage. When the motor enters the motoring region, power flows from the DC side to the AC side. In this scenario, the capacitor discharges, as the power transfer occurs from the DC link to the motor. This discharge process is a vital aspect of the operation, allowing the system to function effectively during motoring conditions.

Now, let’s discuss the braking operation of the induction motor, which involves a significant reversal of power flow. During braking, the motor essentially acts as a generator, and the power flow shifts from the motor back to the DC link. As a result, the voltage in the DC link increases, necessitating careful monitoring of this voltage.

To achieve this, we employ a sensor that continuously monitors the DC link voltage, referred to as V_{DC}. This voltage is fed back into the system, where it is compared with a reference DC link voltage, denoted as V_{DC}^*. The comparator subtracts the feedback voltage V_{DC} from the reference voltage V_{DC}^*, producing an error signal. This error signal is then processed by a controller, which generates a command signal for Converter 1.

During motoring, the DC link voltage will discharge, resulting in a positive error since the feedback voltage is lower than the reference voltage. Conversely, if the motor is in the braking region, the DC link voltage will increase, leading to a negative error because V_{DC} will be greater than V_{DC}^*.

By monitoring this error, the controller adjusts the input power accordingly. It can either supply power in the forward direction for motoring or reverse the power flow for braking. Essentially, this means that while the motor is running in motoring mode, power flows from the AC supply, is converted to DC, and then transformed into variable voltage and variable frequency AC to drive the motor.

In contrast, during braking, power is returned back to the source, a process known as regenerative braking. Thus, in braking conditions, power must flow back to the source, effectively reversing the direction of power flow. Conversely, in motoring conditions, power flows from the source to the motor in a forward direction. This seamless transition between motoring and braking operations highlights the efficiency and versatility of regenerative braking in induction motor systems.

Motoring and braking operations are distinguished by the behavior of the DC link voltage, often referred to as the DC link voltage. When the DC link voltage increases, we can infer that the system is in the braking region. Conversely, if the DC link voltage decreases, the system is operating in the motoring condition. Based on this feedback, the controller will generate the appropriate triggering signal for Converter 1, which functions as an AC to DC converter.

Now, let's illustrate the phase diagram. In this diagram, we represent the inverter phase voltages as V_{SA}, V_{SB}, and V_{SC}, corresponding to the source phase voltages. Meanwhile, the inverter output voltages are denoted as V_{IA}, V_{IB}, and V_{IC}. We can express this relationship using a vector equation.

If we define V_S as the source voltage, this phasor can be equated to the voltage drop across the inductor, represented as j ω L_s I_S, where I_S is the phasor indicating the input current. Additionally, we have the inverter input voltage V_I. Therefore, we can derive the inverter input voltage as:

$$V_I = V_S - j\omega L_s I_S.$$

This scenario describes an AC to DC converter, or, more specifically, an inverter converting DC to AC. Our objective now is to synthesize V_{IA}, V_{IB}, and V_{IC} as phasors. To do this, we utilize the equation we derived earlier.

Let's proceed to draw the phasor diagram. In this diagram, we represent the input voltage V_S. For optimal performance, we aim for a power factor of unity, which implies that the input current should be in phase with the input voltage. Thus, both the input current I_S and the input voltage V_S will align perfectly in phase, illustrating a power factor of 1. This means that the phasor diagram reflects that the input voltage and input current are in complete alignment, achieving the desired unity power factor.

Now, let's delve into the vector equation V_S - j ω L_s I_S. Here, the term j ω represents a rotation of +90 degrees, while -j ω indicates a reverse rotation. By incorporating these two components, we arrive at the inverter input voltage V_I. This entire process illustrates the power flow from the source to the load, and the angle between these vectors is referred to as the power angle or torque angle. This explanation pertains specifically to the motoring condition.

For the braking operation, however, the power factor shifts to -1. In other words, the power factor is +1 during motoring and transitions to -1 during braking. This negative power factor signifies that the power flow is reversed, returning energy to the supply. When the power factor is -1, the voltage and current are in opposition, creating an angle of 180 degrees, where $\cos(180°) = -1$.

Continuing with our phasor diagram, we represent the term -j ω L_s I_S. When we complete the phasor diagram, we observe that it encapsulates the relationship $V_S - j\omega L_S I_S = V_I$. The angle between these vectors is the torque angle, denoted as δ. This configuration illustrates the braking condition.

So, we have established that during motoring, the power factor is +1, whereas during braking, it is -1. The goal is to synthesize the inverter phase voltages appropriately, enabling us to control the voltages of Converter 1 effectively. Let's explore how we can achieve this through a block diagram representation.

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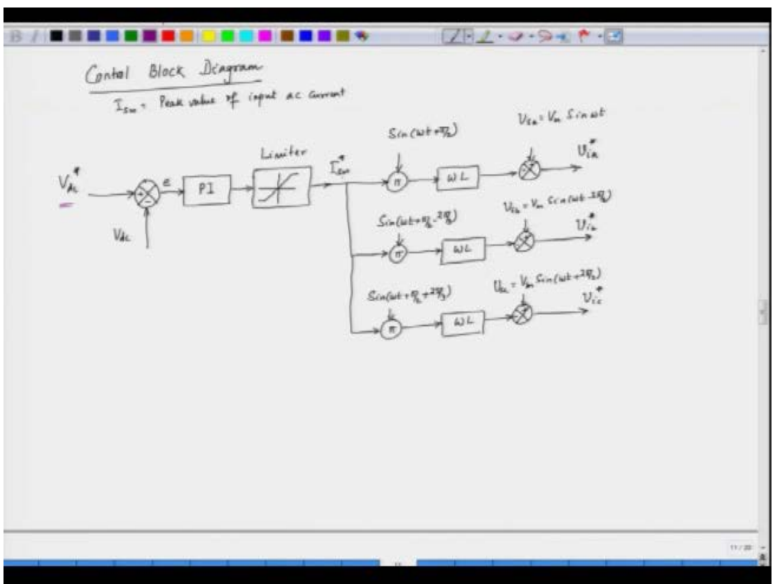

Let's delve into the control block diagram. Our objective here is to maintain a constant d.c. link voltage, which we denote as V_{DC}^*. We will compare this reference value with the actual d.c. link voltage to determine the error. This error signal is then fed into a Proportional-Integral (PI) controller. The output from the PI controller goes to a limiter, where we constrain the output to prevent excessive values.

This error signal effectively provides insight into the current magnitude. In essence, the current is determined by the performance of the PI controller. The output of the limiter corresponds to the peak value of the input current, denoted as I_{SM}, which represents the peak value of the input AC current. If the error is substantial, the current will be higher; conversely, if the error is minimal, the current will also decrease. Thus, the error serves as a direct measure of the required current.

Next, this current is multiplied by the term $\sin\left(\omega t + \frac{\pi}{2}\right)$. The frequency information, ω, is sourced from a phase-locked loop, which tracks the input supply frequency. The addition of $\frac{\pi}{2}$ indicates a phase shift of 90 degrees, essentially simulating a rotation by j, which corresponds to a $\frac{\pi}{2}$ shift. Notably, we also have a negative sign here. After this multiplication, we proceed to multiply the result by the reactance, further integrating this information into our control strategy.

Let's delve into the intricacies of our control system. We begin by considering the reactance, which is represented by ω L. This information is then fed into a subtractor, where we have both a negative and a positive sign. We apply the input voltage V_{SA} in this context. But what exactly is V_{SA}? It is defined as $V_M \sin(\omega t)$.

To obtain this supply voltage V_{SA}, we can utilize a sensor that accurately measures it. This sensor senses V_{SA} and feeds the information into our system. Essentially, we are striving to realize the equation $V_S - j\omega L_S I_S = V_I$, where V_I represents the inverter output voltage in the first stage.

In our scenario, we have a three-phase system, which necessitates three different control strategies for the inverter. Starting with phase A, we denote its reference voltage as V_{IA}. Moving on to phase B, we again introduce a multiplier, denoted as π, and apply the sine function. However, this time, we adjust the phase to $\omega t + \frac{\pi}{2} - \frac{2\pi}{3}$, accounting for the phase shift associated with phase B.

The voltage for phase B, denoted as V_{SB}, is similarly sensed. Given that we are dealing with a three-phase system, we must control each phase of the inverter. Thus, for phase B, we measure the phase voltage, which is shifted from phase A by 120 degrees. The expression for this phase is $V_{SB} = V_M \sin\left(\omega t - \frac{2\pi}{3}\right)$, and the output of this measurement yields the reference voltage V_{IB}.

In a similar manner, we need to derive the reference voltage for phase C. For phase C, the expression becomes $V_{SC} = V_M \sin\left(\omega t + \frac{\pi}{2} + \frac{2\pi}{3}\right)$. This systematic approach ensures that we can effectively control all three phases of the inverter with precision.

We proceed by multiplying with the reactance ω L, and then we use a subtractor to process the data. At this point, we obtain V_{AC} through a sensor, which measures $V_M \sin\left(\omega t + \frac{2\pi}{3}\right)$. From this subtraction, we derive the reference voltage for phase C, denoted as V_{IC}. Thus, we have established the reference voltages V_{IA}, V_{IB}, and V_{IC} for the three legs of the inverter.

The inverter can operate using sine triangle pulse-width modulation (PWM). These three sine references control the operation of the three legs of the inverter effectively. When the first inverter, or converter 1, is triggered, the input currents are managed carefully. The objective here is to maintain a closed-loop control system that keeps the dieseling voltage constant.

As the motor operates, any changes in its performance are automatically sensed, resulting in a current denoted as I_{SM}. Notably, I_{SM} could be positive during motoring conditions, while it could become negative, indicating that the power factor is -1 during braking conditions.

This leads us to our control block diagram, which illustrates how to implement this system experimentally in a closed-loop drive. Importantly, the drive is capable of operating in all possible quadrants. We have two converters, converter 1 and converter 2, that function independently. Depending on the operational demands of the drive, we can seamlessly transition between motoring, braking, and operate in both the forward and reverse directions.

Thus, we have thoroughly explored the multi-quadrant operation of the induction motor in today's discussion. With that, we conclude this lecture. We will continue our examination of induction motor drives in the next session.