Fundamentals of Electric Drives

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Module No # 04

Lecture No # 20

Single Phasing of Induction Motor, Braking of Induction Motor

Hello and welcome to this lecture on the fundamentals of electric drives. In our previous lecture, we discussed the operation of an induction motor under unbalanced voltage conditions. We observed that when the supply voltages are unbalanced, both the torque and power output of the motor decrease. As a result, the motor must be derated, meaning it can no longer operate at its full rated power and must run at a reduced power level.

Today, we will explore a specific scenario, when one of the three phases becomes open-circuited. This condition, known as single phasing, is a particular case of voltage unbalance. Let us now examine what happens to the motor's operation under this single-phasing condition and how it impacts the motor's performance.

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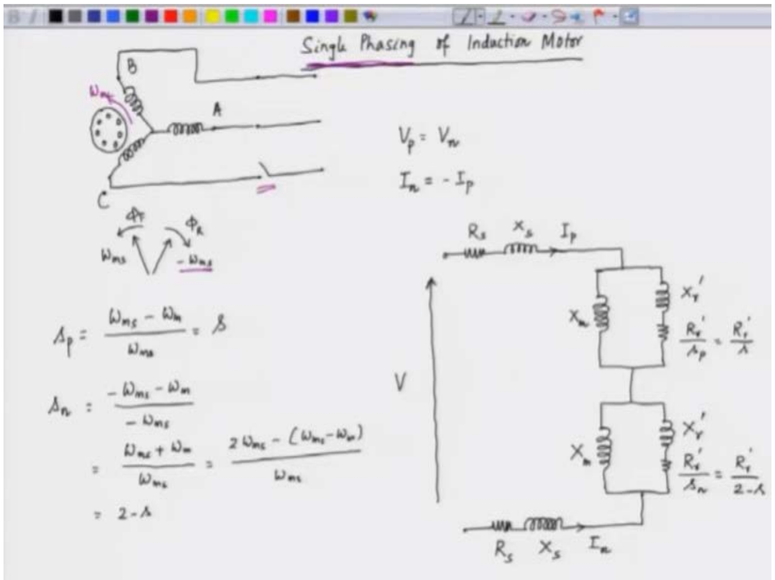

$V_p = V_n$

$I_n = -I_p$

$$s_p = \frac{\omega_{ms} - \omega_m}{\omega_{ms}} = s$$

$$s_n = \frac{-\omega_{ms} - \omega_m}{-\omega_{ms}} = \frac{\omega_{ms} + \omega_m}{\omega_{ms}} = \frac{2\omega_{ms} - (\omega_{ms} - \omega_m)}{\omega_{ms}} = 2 - s$$

$$\frac{R_r'}{s_p} = \frac{R_r'}{s}$$

$$\frac{R_r'}{s_n} = \frac{R_r'}{2-s}$$

In this scenario, we have a three-phase induction motor with stator windings labeled as phase A, phase B, and phase C. These windings are connected to a three-phase power supply. However, in this case, one of the phases, let’s assume phase C, becomes open-circuited. This condition is referred to as single phasing. Essentially, single phasing is a particular case of unbalanced voltage.

Now, when single phasing occurs, an important observation can be made: the positive sequence voltage becomes equal to the negative sequence voltage, i.e., $V_p = V_n$. Additionally, the current in the negative sequence component, I_n, is equal to the negative of the positive sequence current, I_p, so $I_n = -I_p$.

To analyze the motor under single phasing, we can represent the motor with two equivalent networks: one for the positive sequence and one for the negative sequence. In each case, the applied voltage is equally divided between the two networks.

In the positive sequence network, we have:

- Stator resistance, R_s
- Stator reactance, X_s
- Magnetizing reactance, X_m
- Rotor reactance, X'_r
- Rotor resistance divided by the positive sequence slip, R'_r / s_p

In the negative sequence network, the components are similarly represented, but the slip is now the negative sequence slip. The circuit includes:

- The same resistances and reactances as the positive sequence network, but adjusted for the negative sequence.

Now, an important point to note is that when one phase is open-circuited, the motor essentially behaves like a single-phase induction motor. This is because the three-phase symmetry is broken, and the motor has both a forward rotating field and a backward rotating field. The forward field, denoted as Φ_F, rotates in the forward direction, while the reverse field, Φ_R, rotates in the opposite (backward) direction. Initially, these fields have the same magnitude.

The synchronous speed of the forward field is ω_{ms}, while the reverse field rotates at $-\omega_{ms}$, as it moves in the opposite direction. The rotor speed, ω_m, remains in the forward direction.

We can calculate two slips for this situation:

1. Positive sequence slip, s_p, which is the slip for the forward field:

$$s_p = \frac{\omega_{ms} - \omega_m}{\omega_{ms}} = s$$

2. Negative sequence slip, s_n, which is the slip for the reverse field:

$$s_n = \frac{-\omega_{ms} - \omega_m}{-\omega_{ms}} = \frac{\omega_{ms} + \omega_m}{\omega_{ms}} = 2 - s$$

Hence, we now have two different slips:

- For the positive sequence, the slip is simply s.
- For the negative sequence, the slip is 2 - s.

In terms of current, the positive sequence current, I_p, and the negative sequence current, I_n, are equal in magnitude but opposite in direction due to the single-phasing condition. This effectively makes the motor operate like a single-phase induction motor.

Next, let’s consider the torque-speed characteristic of the motor under single-phasing. Since the motor is now running with both a positive and a negative sequence field, we will see the effects of both on the overall torque. The positive sequence field will produce a forward torque, while the negative sequence field will produce a counter-torque in the opposite direction. This interplay will alter the motor’s overall torque-speed characteristic, and we will analyze this behavior in detail to understand how single phasing impacts the motor's performance.

Let's analyze the torque-speed characteristics of the motor. On the y-axis, we have speed, and on the x-axis, torque. At the origin, the speed is zero. Now, remember that the motor has two fields: a forward field and a reverse field. The forward field corresponds to the positive sequence torque, and this increases as the speed approaches the synchronous speed, which is $+\omega_{ms}$.

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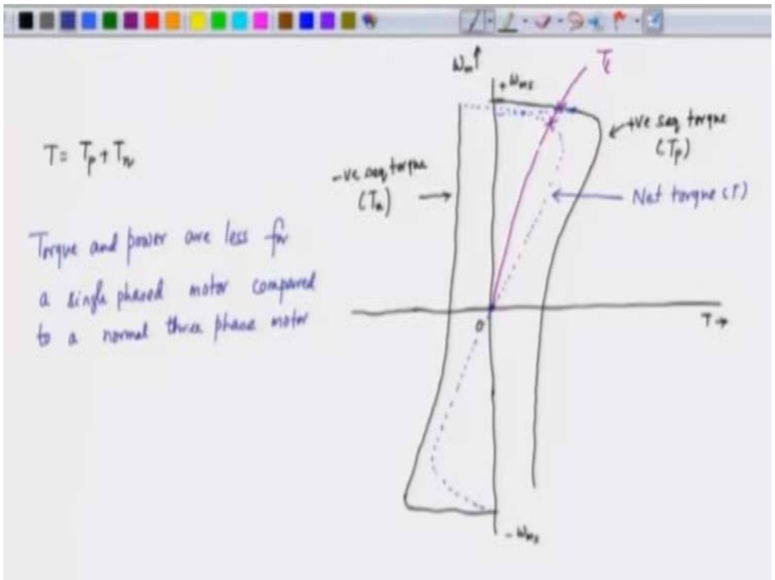

$T = T_p + T_n$

Torque and power are less for a single phased motor compared to a normal three phase motor

In contrast, the reverse field corresponds to the negative sequence torque, which occurs in the opposite direction. The negative synchronous speed is $-\omega_{ms}$. The negative sequence torque behaves similarly to the positive sequence torque but in reverse, creating a counteracting torque.

So, if we plot both torques, we can label the positive sequence torque as T_p and the negative sequence torque as T_n. The net torque, T, is the sum of these two components, $T_p + T_n$. When we combine them, the result is a net torque curve, which is reduced compared to the positive sequence torque alone. Since the magnitudes of the positive and negative sequence torques are equal at zero speed, the net torque at zero speed is also zero. This gives us the torque-speed characteristic of a single-phase motor.

From this, we can observe that the starting torque of a single-phase motor is zero, meaning the motor cannot start on its own without some external means, since there is no initial torque to get it going. However, once the motor begins to gain speed, it will pick up and eventually settle at a stable operating speed.

Now, let's assume the motor was previously running at a certain speed before single phasing occurred. Let's call this the motor's operating point. Once single phasing happens, the torque generated by the motor will drop significantly at the same speed. If the load torque remains constant, the operating point shifts. So, instead of operating at the previous speed and torque, the motor now operates at a new point where the reduced torque from the motor matches the fixed load torque, leading to a slight reduction in speed.

It’s important to note that even after single phasing, the motor continues to rotate, although at a lower speed and with reduced torque. The speed remains close to synchronous speed but is slightly reduced, depending on factors like the rotor resistance. If we assume the rotor resistance is low, the motor will continue to rotate with reduced power output. This means both torque and speed are reduced under single phasing conditions.

In conclusion, when a motor experiences single phasing, its torque and power output are significantly lower compared to its operation under balanced, three-phase conditions. The motor will still run but with reduced efficiency and capability. The motor operates at a different slip, and its overall performance diminishes.

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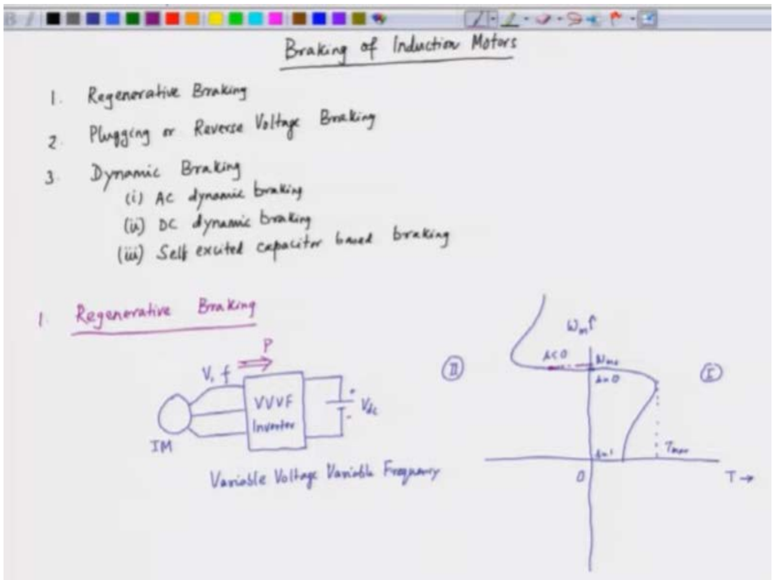

Braking of Induction Motors

1. Regenerative Braking
2. Plugging or Reverse Voltage Braking
3. Dynamic Braking
    (i) AC dynamic braking
    (ii) DC dynamic braking
    (iii) Self excited capacitor based braking

1. Regenerative Braking

Now that we’ve discussed motoring operation under single phasing, let's shift our focus to braking of the induction motor, specifically electrical braking. Electrical braking refers to methods where the motor is made to function as a generator, allowing power to be fed back into the supply grid or dissipated through resistors. In the next section, we will explore the different types of braking in induction motors and how they can be implemented.

When we talk about braking in induction motors, there are several types, each with its own distinct characteristics. The first type is known as regenerative braking, where power is fed back into the supply. The second type is called plugging, which is also referred to as reverse voltage braking. The third type is dynamic braking, which can be further classified into two main subcategories: AC dynamic braking and DC dynamic braking. There's also another type known as self-excited capacitor-based braking. These are the major types of braking techniques used in induction motors.

Let’s delve deeper into regenerative braking. To understand this, let’s first redraw the torque-speed characteristics of an induction motor. On the graph, we have the speed along the x-axis and the torque along the y-axis, with the origin at the center. The typical torque-speed characteristic of an induction motor falls in the first quadrant, where we observe the normal motoring behavior. At synchronous speed ω_{ms}, the slip s is zero, and at starting, slip is 1. The maximum torque T_{max} occurs at a specific point along this curve.

Now, what happens if we push the motor to rotate at a speed higher than the synchronous speed? When the motor's speed exceeds ω_{ms}, the system enters the second quadrant of the torque-speed characteristic. In this region, the slip becomes negative, which means the motor is operating with negative slip. When the slip is negative, both the torque and the power also become negative. This is crucial because negative power indicates that power is now being fed back to the supply – the motor is no longer consuming power; it’s returning energy to the system.

So, how do we get the motor to run at a speed higher than the synchronous speed? This can be achieved using an inverter, particularly a VVVF (Variable Voltage Variable Frequency) inverter. The VVVF inverter allows us to control both the voltage and the frequency of the motor's supply. We start with a DC voltage source, and by using the inverter, we can convert this DC into an AC signal with controllable voltage and frequency.

To induce regenerative braking, we reduce the frequency of the supply, causing the motor's mechanical speed to surpass the synchronous speed. At this point, the motor enters the second quadrant, and the torque becomes negative, indicating that the motor is now acting as a generator. This reversal of energy flow means that the power generated by the motor is fed back to the supply.

In this configuration, the induction motor (denoted as I_m) is connected to the inverter, and the motor behaves like a generator. The power generated is sent back to the DC supply, which could be a battery. The battery, in turn, is charged by the power fed back from the motor. This entire process is what we call regenerative braking, and it requires a variable voltage and variable frequency source, such as the VVVF inverter, to function properly.

Thus, regenerative braking allows us to take advantage of the motor's ability to act as a generator when its speed exceeds the synchronous speed, feeding energy back into the system, which can be used to charge a battery or return power to the grid. This technique is not only efficient but also allows energy recovery, which is particularly useful in applications like electric vehicles and industrial systems.

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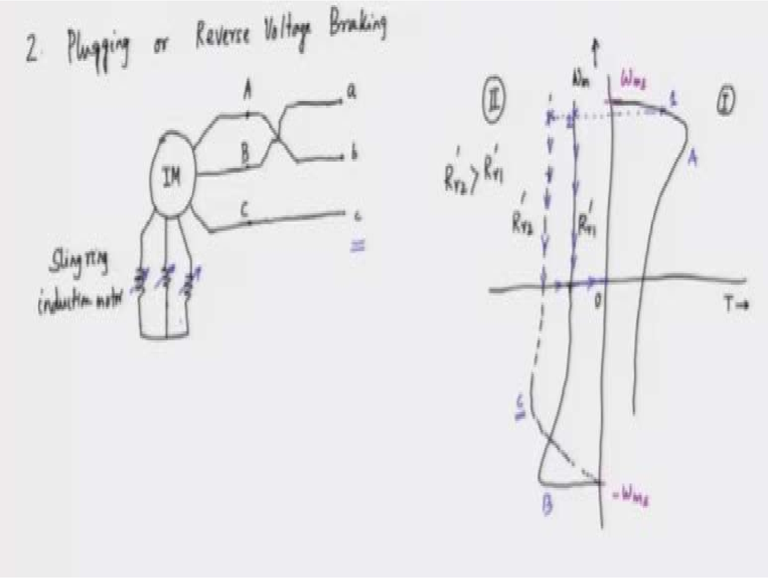

Now let’s move on to the second type of braking, known as plugging or reverse voltage braking. In this method, we alter the phase sequence of the supply applied to the stator of the induction motor. What happens here is that by changing the phase sequence, the direction of the rotating magnetic field also changes. Essentially, the sequence of the voltage phases is reversed, and this reversal is what we refer to as plugging.

Here’s how it works: we have an induction motor connected to a three-phase supply. Typically, the phase sequence applied to the motor is something like a, b, and c. But in the case of plugging, we swap this sequence. For example, instead of supplying the phases in the usual order of a, b, c, we supply them in the order b, a, c. By doing this, the phase sequence of the supply is altered, which in turn changes the direction of the rotating magnetic field within the motor. This is the essence of how plugging works: reversing the phase sequence causes the rotating field to move in the opposite direction.

Now, let’s examine the torque-speed characteristic to better understand the effect of plugging. Imagine a graph with speed ω_m on the y-axis and torque on the x-axis. In normal operation, the motor runs in the first quadrant, with positive torque and positive speed. At synchronous speed, the motor reaches $+\omega_{ms}$, the positive synchronous speed. This is the point where slip is zero, and the motor operates efficiently.

However, when we reverse the phase sequence, the synchronous speed also reverses, turning into $-\omega_{ms}$. This means that the direction of the rotating field is now reversed, and the motor enters the second quadrant of operation. The synchronous speed is now negative, and the motor operates with a negative torque, effectively braking the rotor. This characteristic curve shifts to reflect this reversed operation.

For motors like slip-ring induction machines, plugging can be further controlled by introducing additional resistance into the rotor circuit. These machines are designed with slip rings that allow external resistances to be inserted into the rotor circuit. By adjusting the rotor resistance, we can control the braking effect more precisely, making plugging an even more effective braking method in these types of motors.

This method of braking is particularly effective if you're using a slip-ring induction motor. In such motors, we have the ability to introduce resistance into the rotor circuit. By doing so, we can adjust the rotor resistance, which significantly affects the motor's braking characteristics, especially during negative synchronous speed. For instance, if we increase the rotor resistance, the torque-speed characteristic changes accordingly. Let’s assume we have two different resistance values: R_{r1}' and R_{r2}', where R_{r2}' is greater than R_{r1}'. In this case, the motor’s behavior will vary, as shown by a series of different characteristic curves, with the higher resistance value yielding a more pronounced braking effect, represented by a dotted line.

Now, suppose the motor was operating at a certain speed prior to braking. When we suddenly change the phase sequence, the torque-speed characteristic shifts from its normal operation (let’s call this curve 'a') to a new braking characteristic (curve 'b'). During this transition, the mechanical speed, being a physical variable, cannot change instantaneously. Instead, the motor’s operating point moves from position 1 (on curve 'a') to position 2 (on curve 'b'), where the torque immediately becomes negative. This negative torque causes the motor to decelerate, reducing its speed.

As the speed decreases, it follows the braking characteristic until it eventually reaches zero speed. However, even at zero speed, the torque remains negative, which means the motor will begin to accelerate in the reverse direction unless we intervene. To prevent this, we must disconnect the motor from the supply to stop it at zero speed.

If we increase the rotor resistance further, the braking torque becomes even more pronounced. For example, the motor might shift from curve 'b' to a new curve 'c', corresponding to an increased rotor resistance. Under these conditions, the motor will decelerate more quickly, and even at zero speed, there will still be significant negative torque unless the power supply is removed. Without this disconnection, the motor will continue into reverse motoring, entering the third quadrant of the torque-speed curve.

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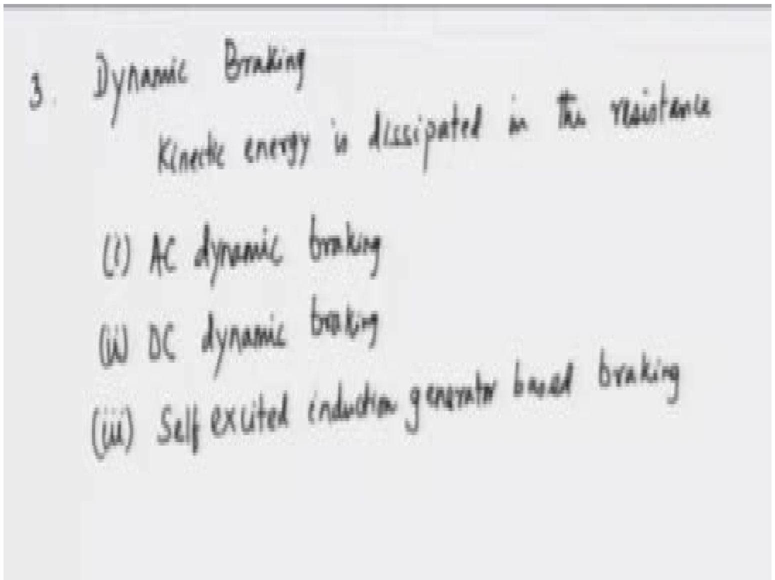

3. Dynamic Braking

Kinetic energy is dissipated in the resistance

(i) AC dynamic braking

(ii) DC dynamic braking

(iii) Self excited induction generator based braking

It's important to note that during plugging, the current drawn by the motor is extremely high because we are effectively reversing the phase sequence. This large current necessitates the introduction of rotor resistance to limit the current and prevent potential damage. Therefore, plugging is typically only attempted in slip-ring induction motors, where we can insert sufficient rotor resistance to control the current and achieve effective braking.

Now, let’s explore the third type of braking, which is dynamic braking. As we’ve discussed, in dynamic braking, the kinetic energy of the motor is dissipated as heat through resistors. This energy dissipation helps to slow down the motor effectively. There are several forms of dynamic braking: AC dynamic braking, DC dynamic braking, and self-excited induction generator-based braking.

In each case, the objective is to convert the motor's kinetic energy into heat, which is then dissipated through either internal rotor resistance or some external resistive load. Whether we're dealing with rotor resistance or an external resistor, the principle remains the same, the kinetic energy of the motor is dissipated to bring the machine to a stop.. So we stop here for today’s lecture we will continue this dynamic braking of induction motor in the next lecture.