Fundamentals of Electric Drives

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Lecture-31

Various types of synchronous motors, Equivalent circuit and phasor diagram of cylindrical synchronous motor, Speed-torque characteristics of cylindrical synchronous motor

Hello and welcome to this lecture on the fundamentals of electric drives. In our previous session, we delved into synchronous motors, exploring the two main categories: wound-field synchronous motors and permanent magnet synchronous motors. Today, we will begin by discussing these types in greater detail, examining their characteristics, applications, and operational principles. Let’s dive deeper into the various forms of synchronous motors to better understand how each functions and where they are most effectively employed.

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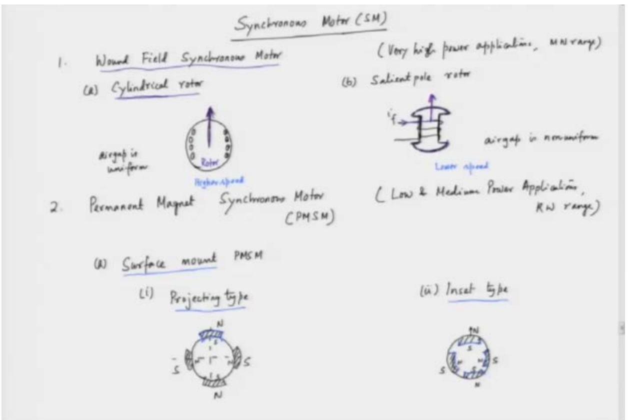

As we have already discussed, a wound-field synchronous motor can be categorized into two types: the cylindrical rotor and the salient pole rotor. In the case of a cylindrical rotor, the air gap is uniform, allowing for a consistent magnetic field. Here, the windings are placed around the rotor, which has a cylindrical shape, enabling the rotor to produce a magnetic flux effectively. This design is referred to as a cylindrical rotor synchronous motor.

Conversely, in a salient pole rotor, the windings are arranged around protruding poles, creating what are known as salient poles. When we apply the Ampère's thumb rule, we can determine that the current flowing through these windings generates a magnetic flux in a specific direction. Typically, cylindrical rotors are preferred for higher-speed applications due to their ability to withstand greater centrifugal forces. On the other hand, salient pole rotors are more suited for lower-speed applications, where their structure can be more effective.

In these motors, the rotor generates a direct current (DC) flux, as opposed to an induction motor, where the rotor operates differently. The DC flux is produced through DC windings on the rotor. If we replace these physical DC windings with permanent magnets, we create what is known as a permanent magnet synchronous motor.

Permanent magnet synchronous motors can take various forms, one of which is the surface mount permanent magnet synchronous motor. This type can be further divided into projecting and inset types. In a projecting type permanent magnet synchronous motor, the magnets are affixed to the surface of the rotor, projecting outward. These magnets are typically secured using epoxy glue and locking arrangements to ensure they remain in place during operation. For example, in a four-pole structure, we would see an arrangement of north and south poles, alternating as north, south, north, and south. However, it's important to note that permanent magnets cannot be achieved in a single pole configuration.

In the configuration of a projecting type permanent magnet synchronous motor, we observe a north pole situated above and a south pole positioned below. The arrangement alternates, with the south pole of the permanent magnet below the north pole. This setup is characteristic of the projecting type, where the magnets extend outward from the rotor surface.

On the other hand, in an inset type permanent magnet synchronous motor, the magnets are embedded within the rotor but still align with its surface. This design allows for slightly higher operational speeds since the magnets do not protrude outward, reducing potential drag. In this configuration, we see the north and south poles similarly positioned, with the north pole facing the surface to generate flux in a specified direction, while the corresponding south pole is located adjacent to it.

Additionally, we have another variation known as the interior permanent magnet synchronous motor. In this design, the magnets are buried deeper within the rotor, offering enhanced protection. The arrangement of the interior permanent magnets provides a distinct set of advantages, including improved efficiency and robustness in performance. This structure ensures that the magnets are shielded from external damage while maintaining optimal performance characteristics.

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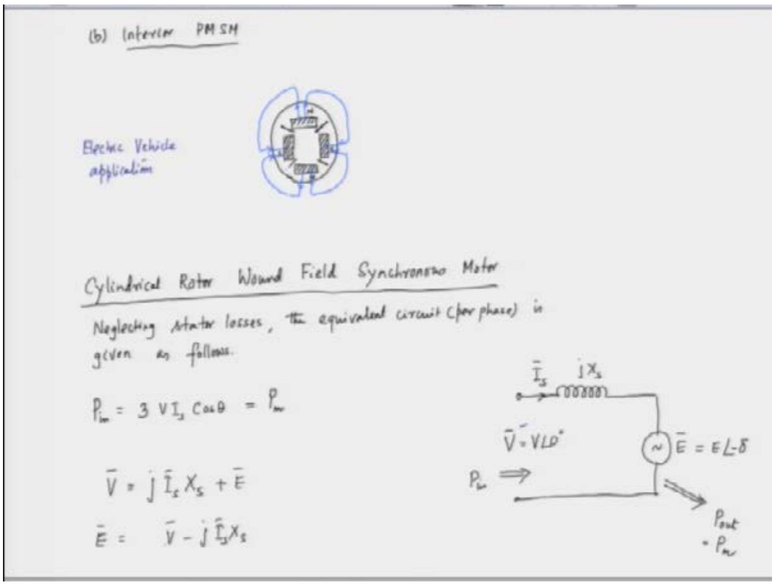

Now, let’s delve into the interior permanent magnet synchronous motor (IPMSM). In this design, we have the rotor structure prominently featuring the magnets embedded entirely within the rotor itself. Here, you can see one magnet positioned next to another, ensuring that all magnets remain contained within the rotor. For example, if we designate one end as the north pole and the other as the south pole, the arrangement of these magnets guarantees that they are securely housed, preventing any risk of them flying off during operation.

The interior permanent magnet synchronous motors are particularly well-suited for higher-speed applications. Since the magnets are enclosed within the rotor, they enjoy greater protection against external forces, making them less susceptible to demagnetization. Additionally, to facilitate efficient magnetic flux flow, we incorporate non-magnetic strips strategically placed to allow the flux to traverse the air gap. These non-magnetic strips ensure that the magnetic flux exits the north pole and enters the south pole seamlessly.

The flux path can be visualized as the magnetic flux emerging from the north pole and flowing into the south pole, similar to the flow pattern observed in the adjacent magnets. This effective magnetic circuit design significantly enhances the overall performance of the motor. Furthermore, the interior permanent magnet synchronous motors have gained immense popularity, especially in electric vehicle applications, where their efficiency and reliability are paramount.

With this understanding, let us now return to derive some fundamental equations that govern the operation of synchronous motors.

Let's begin our discussion with the cylindrical rotor synchronous motor, where the field configuration is cylindrical, and we have windings located in the field. Our goal is to derive the equations governing a cylindrical rotor wound field synchronous motor.

For simplicity, we will neglect stator losses in our analysis. Thus, the equivalent circuit per phase can be described as follows. In this equivalent circuit, we have omitted the stator losses, focusing instead on the synchronous reactance present in the stator. This leads us to consider the induced electromotive force (EMF) along with the applied voltage.

In this circuit, we denote the induced EMF as E, which lags behind the applied voltage V (represented as the voltage phasor) by an angle δ. It is important to remember that this phase lag occurs due to the nature of motor operation. Therefore, if we assume that the applied voltage V is at an angle of 0, the relationship can be expressed as:

$$E = E \angle -\delta$$

For input power calculations, we focus on the single-phase scenario first. The input power can be represented as:

$$P_{in} = 3V \cdot I_s \cdot \cos(\theta)$$

Here, θ is the angle between the voltage V and the stator current I_s. Given that we have neglected any losses in our system, the output power, denoted as P_{out}, is equivalent to the mechanical power P_m. In essence, we can conclude:

$$P_{in} = P_{out} = P_m$$

This indicates that the input power is equal to the mechanical output power, as we have assumed a lossless system, meaning there are no core losses and we can disregard friction associated with the mechanical load.

Next, we can illustrate the phasor diagram for this circuit. When constructing the phasor diagram, we must write down the vector equation reflecting the relationships among the applied voltage, current, and induced EMF. We can express this relationship using Kirchhoff's voltage law (KVL):

$$V = I_s \cdot jX_s + E$$

Alternatively, we can rearrange this to find the induced EMF:

$$E = V - jI_sX_s$$

This equation allows us to determine the induced EMF by subtracting the voltage drop across the synchronous reactance from the applied voltage. Through this process, we gain valuable insights into the operation of the cylindrical rotor synchronous motor.

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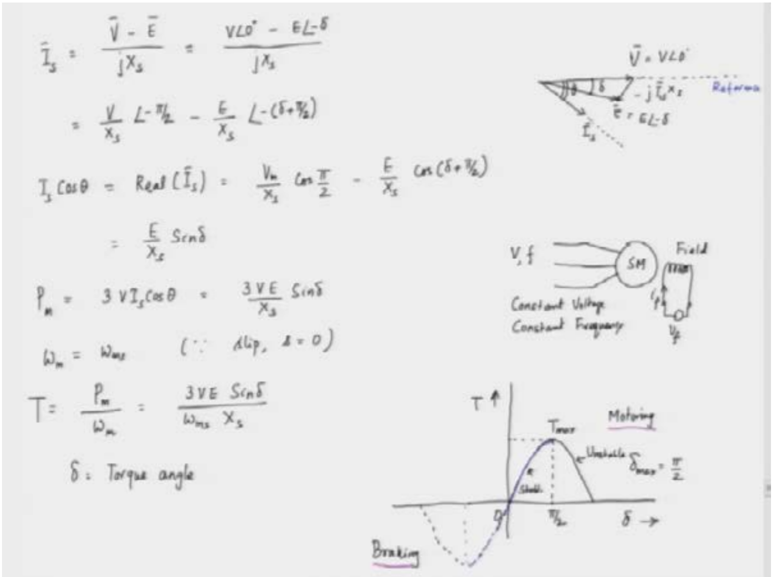

Let's delve into the details of our analysis. To illustrate this, let's assume we have a voltage phasor V and that the current I_s is lagging behind the voltage by an angle θ. In this scenario, we can visualize I_s as the current phasor, with θ representing the phase difference in our right-angled triangle. Our objective now is to determine the induced EMF, which we can express as -j I_s X_s.

To complete our phasor diagram, we denote the induced EMF as E, with the angle δ associated with it. Therefore, we can represent this as $E = E\angle - \delta$, illustrating that E lags behind the voltage by the angle δ.

The applied voltage V is our reference, positioned at an angle of 0 degrees. Given this setup, we can derive an expression for $I_s \cos\theta$. The current flowing in the circuit, I_s, can be formulated as:

$$I_s = \frac{V - E}{jX_s}$$

This equation signifies that the current phasor I_s is derived from the difference between the applied voltage V and the induced EMF E, divided by the reactance X_s.

Substituting our values into the equation, we find:

$$I_s = \frac{V\angle 0 - E\angle - \delta}{jX_s}$$

This gives us:

$$I_s = \frac{V}{X_s}\angle - \frac{\pi}{2} - \frac{E}{X_s}\angle - \delta + \frac{\pi}{2}$$

In this complex equation, we identify the real and imaginary components. The reference phasor represents the baseline from which we evaluate our other phasors.

Now, to find the real part of I_s, we recognize that $I_s \cos\theta$ represents this real component. Hence, we can express it as:

$$I_s \cos\theta = \frac{V_m}{X_s}\cos\left(\frac{\pi}{2}\right) - \frac{E}{X_s}\cos\left(\delta + \frac{\pi}{2}\right)$$

Simplifying this, we know that $\cos\left(\frac{\pi}{2}\right) = 0$, leading us to focus on the second term. The cosine of $\delta + \frac{\pi}{2} equals - \sin\delta,$ thus yielding:

$$I_s \cos\theta = -\frac{E}{X_s}\sin\delta,$$

Now that we have this relationship, we can apply it to calculate the output power P_{output}. Recall that:

$$P_{output} = 3VI_s \cos\theta,$$

In this way, we prepare to substitute $I_s \cos\theta$ back into our equation to find the output power of the system.

This leads us to the expression for mechanical output power in a cylindrical rotor synchronous machine, which can be represented as:

$$P_m = \frac{3VE\sin\delta}{X_s}$$

To derive the torque from the mechanical power, we divide this mechanical power by the rotor speed. It’s important to note that the rotor speed is equivalent to the synchronous speed, as there is no slip in a synchronous machine. Therefore, we can state that the rotor speed is equal to the synchronous speed, denoted as ω_s, given that the slip is zero.

Now, let’s express the torque T:

$$T = \frac{P_m}{\omega_s} = \frac{3VE\sin\delta}{X_s\omega_s}$$

In this equation, V represents the applied voltage, which remains constant, and E signifies the excitation EMF or the induced EMF, which is also constant as long as the field is maintained at a constant level.

When we operate the synchronous motor, we supply it with a constant voltage and a constant frequency from the source. In the case of a wound field synchronous motor, maintaining these constants is crucial for predictable performance.

Now, if we consider the torque T, we can explore how it varies with respect to the torque angle δ. As we manipulate δ, the torque will change accordingly, while keeping the voltage, field, frequency, and speed constant. This gives us the opportunity to visualize this relationship graphically.

In this scenario, we can plot the torque T against the torque angle δ. On the x-axis, we have δ, and on the y-axis, we plot the torque T. As δ varies, we can observe how the torque responds, illustrating the dynamic relationship between these two parameters in a synchronous machine. This graphical representation allows us to better understand the operational characteristics of the synchronous motor.

As we observe the torque curve, we notice that it resembles a sine wave. When we adjust the value of the torque angle δ, the torque increases. In fact, as we increase δ, the torque continues to rise until it reaches its maximum value at $\delta = \frac{\pi}{2}$. This point represents the peak torque achievable by the synchronous motor. Beyond this maximum, if we continue to increase δ, the torque begins to decline. Thus, it’s important to recognize that there is a limit to how much torque we can generate; if we increase δ past this threshold, the torque will decrease.

Furthermore, it’s noteworthy that δ can also take on negative values. This negative range is typically associated with braking and generating operations. In motoring mode, we operate with positive δ, but to switch to braking mode, we need to make the torque negative, which entails setting δ to a negative value. This transition effectively turns the motor into a generator, allowing for energy recovery during braking.

Now, let’s discuss the benefits of having a separate field winding for our synchronous motor. The field winding is excited by a direct current (DC) source, denoted as V_f, which enables us to produce a consistent DC flux. This feature allows us to operate the synchronous motor under a variety of power factor conditions. Unlike induction motors, which always operate under a lagging power factor, a synchronous motor can be adjusted to operate at different power factors. By controlling the field current, we can achieve lagging, unity, or even leading power factors.

Next, let's examine the phasor diagrams corresponding to these various power factor conditions, as they will provide valuable insight into the motor's operational characteristics.

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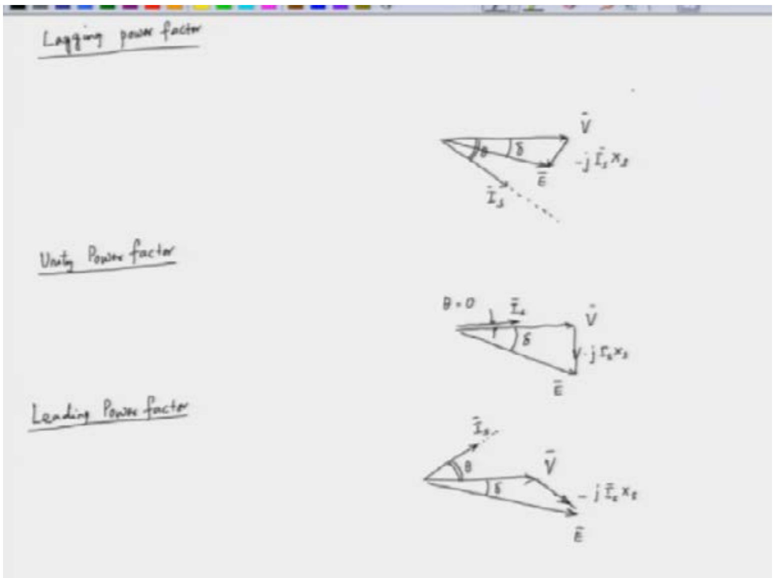

Let's discuss the scenario of lagging power factors first. When we have a lagging power factor, we observe that the applied voltage is represented here, and the current I_s lags behind this voltage. Our objective is to determine the induced electromotive force (EMF), denoted as E. The induced EMF can be calculated using the expression -j I_s X_s, where all quantities are represented as phasors. In this context, E is generated by the field winding, and we have the torque angle, δ. For the motor, the induced EMF E lags behind the voltage by this angle δ.

Now, let's consider the case where the power factor is unity. In a unity power factor scenario, the voltage and current are perfectly in phase. This means that we have a voltage phasor here, and the current phasor I_s aligns exactly with it. The induced EMF E remains consistent, and in this case, the torque angle δ represents the angle between the voltage and the induced EMF. For unity power factor operation, the angle θ is 0, indicating that V and I_s are in phase.

Next, we can explore how the motor operates under a leading power factor. For leading power factor operation, we need to over-excite the field winding, which increases the field current. Here, we have the voltage V, and the current I_s now leads the voltage by an angle θ. It's important to note that this creates a 90° phase angle drop across the reactance. Again, we can express this as -j I_s X_s. If we connect these two points, we can determine the induced EMF E, and once more, the torque angle δ indicates that E lags behind the voltage by this angle.

What we observe here is quite interesting: when the value of E is relatively low, we operate under a lagging power factor. As the value of E increases to a moderate level, we approach unity power factor. Finally, when E becomes significantly higher, essentially when we have over-excitation, we operate under a leading power factor.

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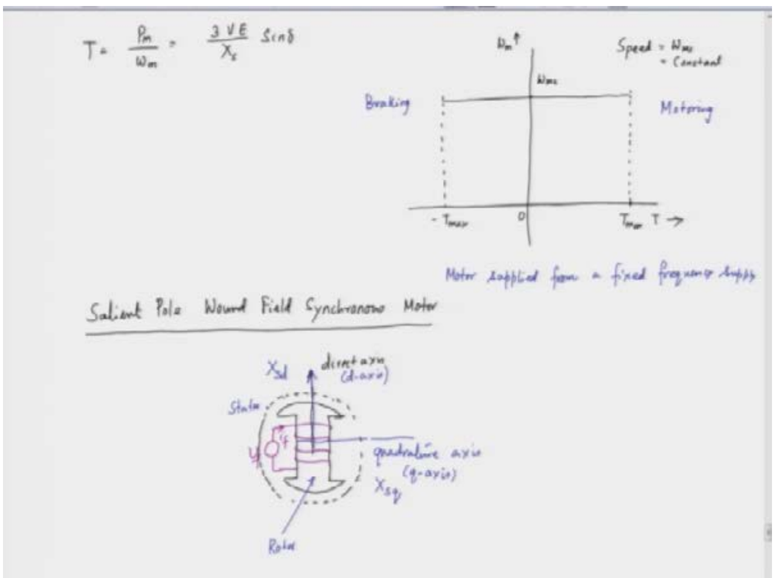

This flexibility in power factor operation is a distinct advantage of using a wound field synchronous machine. Now, let's move on to examine the speed-torque characteristics of a wound field synchronous machine.

We've previously established that the torque is given by the relationship $T = \frac{P_m}{\omega_m} = \frac{3VE}{X_s} \sin \delta$. This holds true in a constant frequency application. Now, let's visualize this by plotting the torque characteristics on a graph, where we have the speed axis and the torque axis.

In this scenario, the torque is independent of speed, which remains constant. Since we are working with a synchronous motor supplied from a constant frequency source, the motor speed, denoted as $\omega_{m\,s}$, remains stable. Thus, we have a constant speed motor in operation. This means that under these conditions, the speed of the motor does not vary; it is not a variable speed operation.

The torque, however, can take on both positive and negative values. As we've discussed, a positive torque indicates motoring, while a negative torque indicates braking. The maximum torque, $T_{\max}$, corresponds to a maximum angle δ of $\frac{\pi}{2}$. This defines the operating range for the motor; beyond this angle, we enter an unstable region. So, we have a stable operational area and an unstable one.

The maximum torque that can be achieved is denoted as $T_{\max}$. This value can also be applicable when the motor is in braking mode, allowing operation down to -$T_{\max}$, which corresponds to $\delta = -\frac{\pi}{2}$. To summarize, for $\delta = +\frac{\pi}{2}$, we operate at +$T_{\max}$, and for $\delta = -\frac{\pi}{2}$, we operate at $-T_{\max}$. This range of operation, from $T_{\max}$ to -$T_{\max}$, defines our first quadrant of torque characteristics.

We refer to this operation as motoring, while the operation occurring in the second quadrant is designated as braking. In both cases, the speed remains constant, as we are dealing with a motor supplied from a fixed frequency source. Now, let's delve into the analysis of a salient pole synchronous motor.

For a salient pole synchronous motor, which is essentially a wound field synchronous motor, we need to draw the equivalent circuit. This is crucial because the air gap in this type of motor is non-uniform due to the presence of salient poles. In this configuration, we have one direct axis (d-axis) and one quadrature axis (q-axis).

The rotor construction is distinctly different; it features salient poles, and the stator surrounds this structure. This setup gives us a clear distinction between the direct axis, where the windings are located in the rotor, and the DC voltage applied through slip rings, denoted as V_f. The current flowing in the field winding is represented by I_f, producing flux along the direct axis due to its alignment with the poles.

In addition to the direct axis, we have a quadrature axis, which lies at a right angle to the direct axis. This means that the air gap is smaller along the direct axis compared to the quadrature axis. To illustrate, we can envision the rotor encased within a cylindrical stator. Consequently, the air gap is reduced along the direct axis while being larger along the quadrature axis.

In this context, we have two synchronous reactances: one aligned with the direct axis, labeled $X_{s\,d}$, and the other aligned with the quadrature axis, denoted $X_{s\,q}$. This is in contrast to a cylindrical machine, where there is only a single synchronous reactance, X_s. In a salient pole synchronous machine, the presence of non-uniform air gaps necessitates two distinct synchronous reactances.

As a result, we cannot derive a single equivalent circuit for a salient pole synchronous machine. Instead, we must utilize two equivalent circuits to analyze the machine's performance. We will resolve the magnetomotive force (MMF) along both the d-axis and the q-axis to ascertain the respective fluxes and calculate the induced EMF.

We will conclude our discussion here for today’s lecture, and in our next session, we will explore further details regarding the salient pole synchronous machine.