Fundamentals of Electric Drives

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Lecture - 37

Construction and Operating Principle of Switched Reluctance Motor

Hello and welcome to this lecture on the fundamentals of electric drives! In our previous session, we introduced the fascinating topic of switched reluctance motors. These motors are renowned for their lightweight design, making them particularly well-suited for space applications, where the high torque-to-weight ratio and low rotor inertia are crucial advantages. However, as the name suggests, the operation of a switched reluctance motor requires careful switching at regular intervals, facilitated by a position sensor. This precise control is essential to optimize torque production effectively. Now, let's discuss the operating principle of the switched reluctance motor!

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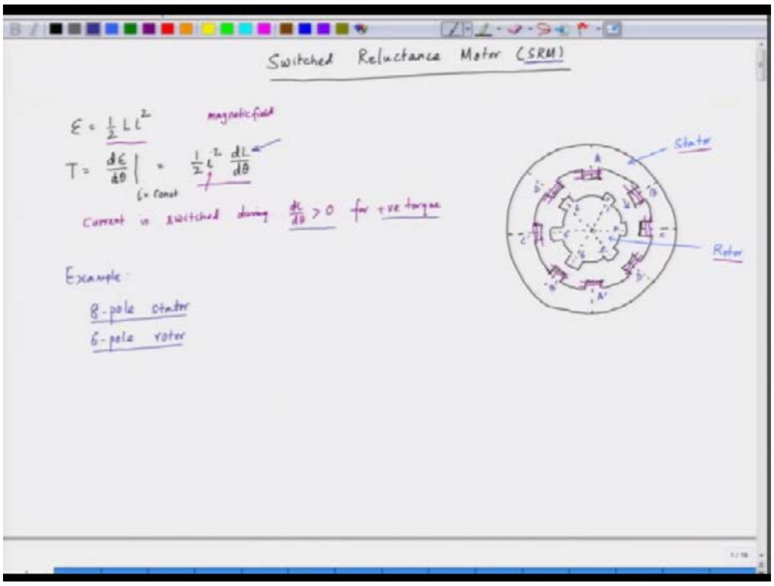

In our previous lecture, we discussed that the energy stored in an inductor is expressed by the formula $\frac{1}{2}Li^2$. This energy resides in the magnetic field, and if we differentiate this energy with respect to the rotor position, denoted as θ, while maintaining a constant current, we arrive at the expression $\frac{1}{2}Li^2\frac{dL}{d\theta}$.

Now, if the inductance is a function of θ, then any change in the inductance due to the relative motion between the stator and the rotor results in torque production. Thus, we can express the torque as $T = \frac{1}{2} i^2 \frac{dL}{d\theta}$. To optimize the torque, we need to focus on maximizing this expression.

But how do we achieve this optimization? The key lies in switching the current during intervals when $\frac{dL}{d\theta}$ is positive. This ensures that the torque remains positive. It's important to note that while the current i^2 will always yield a positive value regardless of its sign, the torque itself is influenced by $\frac{dL}{d\theta}$, which can be either positive or negative. Therefore, we must ensure that the current is switched when $\frac{dL}{d\theta} > 0$ to generate positive torque.

Now, let's take a closer look at the structure of the switched reluctance motor. The motor consists of a stator and a rotor. The stator features salient poles, and in this case, we can observe that there are a total of eight poles: 1, 2, 3, 4, 5, 6, 7, and 8. Both the rotor and the stator are equipped with windings, and each pole acts as an inductance, contributing to the overall functioning of the motor.

The rotor of the switched reluctance motor features six distinct poles, which we can label as 1, 2, 3, 4, 5, and 6. It's important to note that the rotor does not carry any windings; it is simply a plain, slotted rotor. As the rotor rotates, inductance variation occurs, which means we have $\frac{dL}{d\theta}$ where θ represents the rotor angle. This inductance variation across each phase as the rotor turns is what ultimately leads to torque production.

To achieve positive torque, we must switch the current when $\frac{dL}{d\theta}$ is greater than zero. This is the fundamental principle behind the operation of a switched reluctance motor. When we refer to "switching" the current, we are emphasizing the action that gives the switched reluctance motor its name.

Now, let's consider an example of a switched reluctance motor (SRM) with a six-pole rotor and an eight-pole stator. In this configuration, the stator is equipped with windings, while the rotor remains winding-free. Moving forward, we will delve into further specifications of this motor configuration, which are as follows.

In this section, we will discuss the construction of a typical switched reluctance motor (SRM). Let's begin by outlining the key construction parameters. We have eight stator poles, which we can also refer to as stator teeth, and six rotor poles, or rotor teeth. Additionally, there is a critical ratio known as the tooth-to-tooth pitch, which is equivalent to the pole arc to pole pitch ratio, and is given as 0.4.

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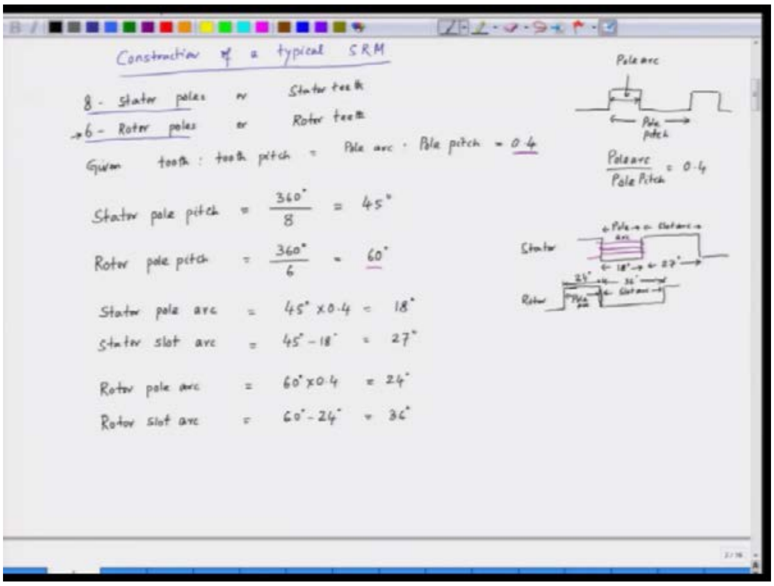

What does this ratio mean? It signifies the relationship between the pole arc and the pole pitch. In simpler terms, if we consider the geometry of the motor, 40% of the pole pitch is occupied by the pole arc. This applies to both the stator and the rotor.

Now that we have defined our eight stator poles and six rotor poles, let's calculate the stator and rotor pole pitches. To find the stator pole pitch, we take the total circle of 360 degrees and divide it by the number of stator poles, which is 8. Thus, the pole pitch for the stator is:

$$\text{Stator Pole Pitch} = \frac{360^\circ}{8} = 45^\circ.$$

Next, we calculate the rotor pole pitch in a similar manner. Since there are six rotor poles, the rotor pole pitch is:

$$\text{Rotor Pole Pitch} = \frac{360^\circ}{6} = 60^\circ.$$

We've also established that the pole arc to pole pitch ratio is 0.4. Therefore, we can determine the stator pole arc as follows:

$$\text{Stator Pole Arc} = \text{Pole Pitch} \times 0.4 = 45° \times 0.4 = 18°.$$

Subsequently, the stator slot arc can be calculated by subtracting the pole arc from the pole pitch:

$$\text{Stator Slot Arc} = \text{Pole Pitch} - \text{Stator Pole Arc} = 45° - 18° = 27°.$$

What does this mean in practical terms? In the context of the stator and rotor, the stator pole arc measures 18 degrees, while the remaining slot arc measures 27 degrees. This visual representation indicates how the stator's design interacts with the rotor, as illustrated in this diagram: the stator, shown on one side, features an 18-degree pole arc and a corresponding slot arc, while the rotor occupies the adjacent space.

Here, we can see the winding configuration, with the stator windings positioned prominently, while the rotor lies just below. The rotor features a slotted structure, and as we analyze the stator, we note that the stator slot arc is determined to be 27 degrees, calculated as follows: $45° - 18° = 27°$.

Now, turning our attention to the rotor, the rotor pole pitch is 60 degrees. To find the rotor pole arc, we apply the same ratio, resulting in:

$$\text{Rotor Pole Arc} = 60° \times 0.4 = 24°.$$

Consequently, the rotor slot arc can be calculated by subtracting the rotor pole arc from the rotor pole pitch:

$$\text{Rotor Slot Arc} = 60° - 24° = 36°.$$

Visualizing the rotor, we can identify the rotor pole arc, which measures 24 degrees, alongside the rotor slot arc at 36 degrees. Thus, we are expressing all parameters and distances in terms of angles, providing clarity on the rotor's configuration.

Next, let’s delve into how inductance varies as the rotor moves beneath the stator. When the rotor rotates and its pole aligns with a stator pole, there is a gradual increase in inductance. Conversely, as the rotor moves away, the inductance begins to decrease. To illustrate this concept more clearly, we will draw several diagrams to aid our understanding.

Here we have our stator, which features an 18-degree pole arc, clearly indicated here, while the slot arc measures 27 degrees. It's important to note that this pattern is periodic, meaning it repeats consistently throughout the structure. To illustrate this further, we have taken a quarter of the stator and opened it up, allowing us to visualize the angles as linear distances.

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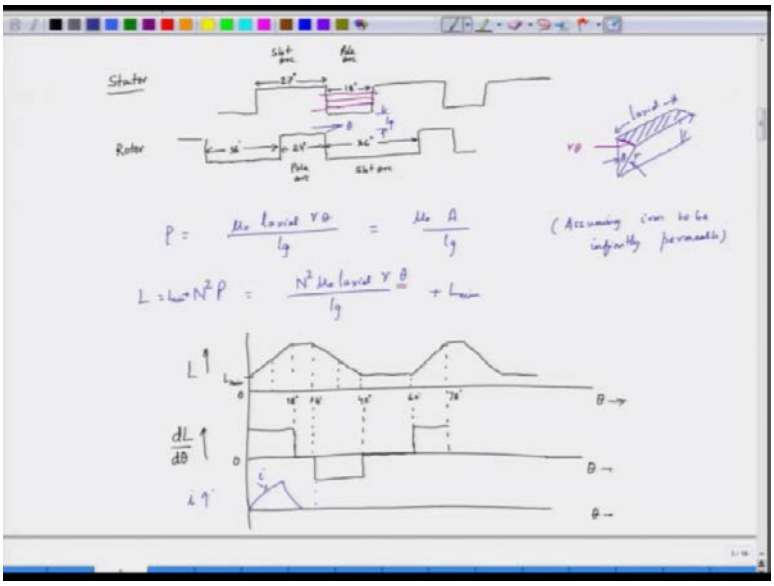

This is the stator we've discussed, with its distinctive pole arc and slot arc. Below the stator lies the rotor, which has a pole arc of 24 degrees and a slot arc of 36 degrees. Just like the stator, this rotor pattern also repeats. It's essential to point out that the stator is equipped with windings; each stator pole is adorned with these windings, while the rotor slot arc is defined at 36 degrees.

As the rotor moves in a designated direction, it rotates and makes an angle θ with respect to its original position. This motion occurs beneath the stator. As the rotor aligns with the stator, we observe a gradual, linear increase in inductance. This inductance can be defined as the product of the permeance, which is given by $\mu_0 \cdot l_{\text{axial}} \cdot r_\theta / l_g$, where l_g represents the air gap.

Now, considering the rotor's pattern, it essentially resembles a section of a cylinder. As the rotor moves, it's crucial to determine the area of overlap between the rotor and the stator. This overlap occurs when the rotor is positioned directly beneath the stator. In this configuration, the air gap length is denoted as l_g. Additionally, l_{axial} refers to the axial length, which is the length measured along the rotor's axis.

Here we have the axial length of the motor, specifically referring to the axial length of the rotor. The angle θ is illustrated in a linear fashion, representing the overlap angle between the stator and rotor. The area of overlap can be expressed as $A = l_{\text{axial}} \cdot r \cdot \theta$, where r denotes the radius of the rotor. Therefore, this overlapping arc is determined by the product of the radius and the angle θ.

Now, let's discuss the concept of permeance. Permeance is defined as μ_0, the permeability of air, multiplied by the area and divided by the air gap length. We assume that the iron material is infinitely permeable for this calculation. Consequently, the permeance of the air gap can be expressed as:

$$\text{Permeance} = \mu_0 \cdot \frac{A}{l_g}$$

Moving on to inductance, it is given by the equation $L = N^2 \cdot \text{Permeance}$. This results in:

$$L = N^2 \cdot \mu_0 \cdot \frac{l_{\text{axial}} \cdot r \cdot \theta}{l_g}$$

As the rotor aligns under the stator, we observe a gradual increase in inductance. This inductance can be formulated as:

$$L = N^2 \cdot \mu_0 \cdot \frac{l_{\text{axial}} \cdot r \cdot \theta}{l_g} + L_{\text{min}}$$

Here, L_{min} represents the minimum inductance value when the rotor slot r is facing the stator pole arc. As the rotor pole arc moves under the stator pole arc, we can see a progressive increase in inductance, which is a function of the angle θ.

If we visualize the variation in inductance, we can depict it starting from an initial position. As the rotor rotates and comes under the stator for an overlap of 18 degrees, the inductance will experience a notable increase throughout this range. The graphical representation of this inductance variation illustrates the relationship between the rotor's angular position and the resulting inductance changes.

So, here we have the angles represented: 9 degrees, 18 degrees, and then the overlap extends to 24 degrees. This means that we have a continuous overlap for a total of 24 degrees, starting from 18 degrees and extending to 24 degrees. After this point, the rotor begins to move away from the stator. As the rotor slot approaches the slot arc, which spans 36 degrees, we can see that for the next 18 degrees, the inductance will gradually decrease.

This means that as we move from 24 degrees further to 18 degrees, which brings us to a total of 42 degrees, the inductance will continue to drop. The inductance will maintain this lower value until it reaches 60 degrees, at which point the pattern will repeat itself. Thus, the inductance variation can be illustrated in a trapezoidal waveform.

On the x-axis, we have the angle θ plotted against the inductance, which varies as a function of θ. It's crucial to understand that the inductance should change with the rotor's position. As the rotor moves beneath the stator and the overlap occurs, we observe the maximum inductance. Conversely, as the rotor moves away from the stator, the inductance decreases to its minimum value.

This behavior continues due to the repetitive nature of the slots and poles, resulting in a periodic waveform. Now, since the stator inductance is a function of θ, we can consider $\frac{dL}{d\theta}$. We will plot $\frac{dL}{d\theta}$ against θ.

In this context, we need to determine what the derivative of the inductance with respect to θ is. Initially, $\frac{dL}{d\theta}$ will be zero, indicating a steady state. From 0 to 18 degrees, $\frac{dL}{d\theta}$ remains constant because the inductance is increasing in this range. This demonstrates a linear rise until we reach the maximum inductance, emphasizing the relationship between rotor position and inductance variation.

From 18 to 24 degrees, the inductance remains constant, resulting in $\frac{dL}{d\theta} = 0$. As we move from 24 to 42 degrees, however, the inductance begins to decrease, indicating that $\frac{dL}{d\theta}$ takes on a negative value. This describes the variation of $\frac{dL}{d\theta}$.

Continuing from 42 to 60 degrees, we again find that the inductance stabilizes, so $\frac{dL}{d\theta}$ returns to 0. This behavior will repeat itself in the next cycle, from 60 to 78 degrees, where the inductance gradually increases again, resulting in a positive but constant $\frac{dL}{d\theta}$.

This illustrates the variations in the slope, specifically the derivative of L with respect to θ. Our key objective here is to recognize that since $\frac{dL}{d\theta}$ can shift between positive and negative values, we need to switch the current during the periods when $\frac{dL}{d\theta}$ is positive. Therefore, the current should predominantly flow in these intervals.

If we were to visualize this as a current waveform or signal, it would be important for the current to be present only when $\frac{dL}{d\theta}$ is positive, and not when it is negative. Now, let's explore what happens when we implement this strategy.

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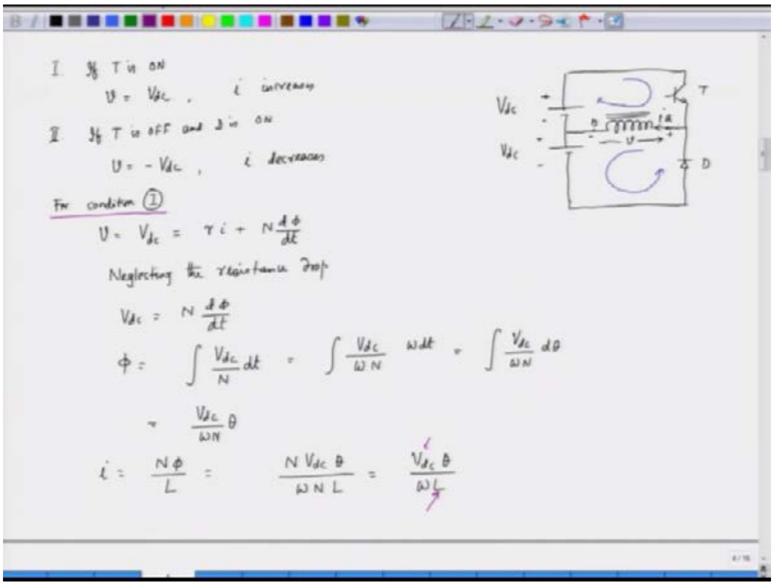

Now, let's implement this using a simple inverter setup, a half-bridge inverter. Imagine we have the half-bridge structure, where the stator winding is configured as shown, complete with a power transistor responsible for switching the voltage, as well as a diode integrated into the circuit. In this straightforward arrangement, we apply V_{dc} across the system.

When the transistor T is turned on, let's analyze what happens. If we designate the terminals as a and b, we can consider the voltage v in this scenario. With T activated, the voltage v becomes positive, equating to V_{dc}. Consequently, the current flows as illustrated, moving from the battery through the transistor and into the winding. Thus, we can conclude that when T is on, v equals V_{dc}.

Conversely, if T is off and the diode D is on, the current, which previously flowed from the battery through the winding, now changes direction. When we switch T off, the diode conducts, allowing the current to circulate freely. In this case, we denote the voltage as $v = -V_{dc}$, resulting in a decrease in current.

To summarize, when the transistor is on, $v = V_{dc}$ and the current i, the current flowing through the winding, increases. On the other hand, if T is off and D is on, then $v = -V_{dc}$ and i decreases.

Now, let’s express this mathematically. Considering the inductance in this scenario, we can formulate the equation as follows:

$$v = V_{dc} = ri + N\frac{d\Phi}{dt}$$

Here, we neglect the resistance drop because it is relatively small, given that we are dealing with copper windings which have a low resistance. Thus, we simplify our equation to:

$$V_{dc} = N\frac{d\Phi}{dt}$$

So, what does Φ represent here? The flux Φ can be expressed as:

$$\Phi = \frac{V_{dc}}{N}dt$$

To relate this to our angular displacement, we can manipulate our equation by dividing by ω (the angular speed) and then multiplying by ω:

$$\Phi = \frac{V_{dc}}{N}dt = \int \frac{V_{dc}}{\omega N}d$$

Let’s delve into the first condition we’ve established, which will guide our analysis. For Condition 1, we can describe the flux using the equation derived from our earlier discussions. The flux is expressed as:

$$\Phi = \int \frac{V_{dc}}{\omega N}d$$

Upon integrating this, we find that:

$$\Phi = \frac{V_{dc}}{\omega N}$$

This indicates that the flux increases linearly with respect to the angle θ. Therefore, we conclude that as θ increases, the flux also rises in a linear fashion. Conversely, if we apply a negative voltage, $-V_{dc}$, the flux will decrease linearly with respect to θ.

Now, let’s shift our focus to the current. The current can be expressed as:

$$I = \frac{N\Phi}{L}$$

Substituting our expression for flux, we have:

$$I = \frac{N \cdot \frac{V_{dc}}{\omega N}\theta}{L}$$

The N terms cancel out, simplifying our equation to:

$$I = \frac{V_{dc}\theta}{\omega L}$$

This equation provides us with the current flowing through the winding of the switched reluctance motor. Importantly, we can observe that the current is directly proportional to θ, the rotor angle, and inversely proportional to the inductance L.

By carefully controlling the applied voltage V_{dc}, we can manipulate the current in the winding. This control over current is vital, as it ultimately enables us to manage the torque produced by the motor.

That concludes our lecture for today. We will continue our exploration of switched reluctance motors in our next session. Thank you for your attention!