Fundamentals of Electric Drives

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Lecture – 38

Current/Voltage Control for Switched Reluctance Motor, Operating Modes of Switched Reluctance Motor, Introduction to Traction Drives

Hello and welcome to this lecture on the fundamentals of electric drives! In our last session, we delved into the fascinating world of switched reluctance motors, and today, we'll be continuing from where we left off.

We established that in a switched reluctance motor, the rotor features a slotted design, which plays a crucial role in its operation. Our primary focus is on the strategic switching of the stator current at positive $\frac{dL}{d\theta}$ to maximize torque. This approach is essential for achieving optimal performance from the motor. Let’s explore this concept further!

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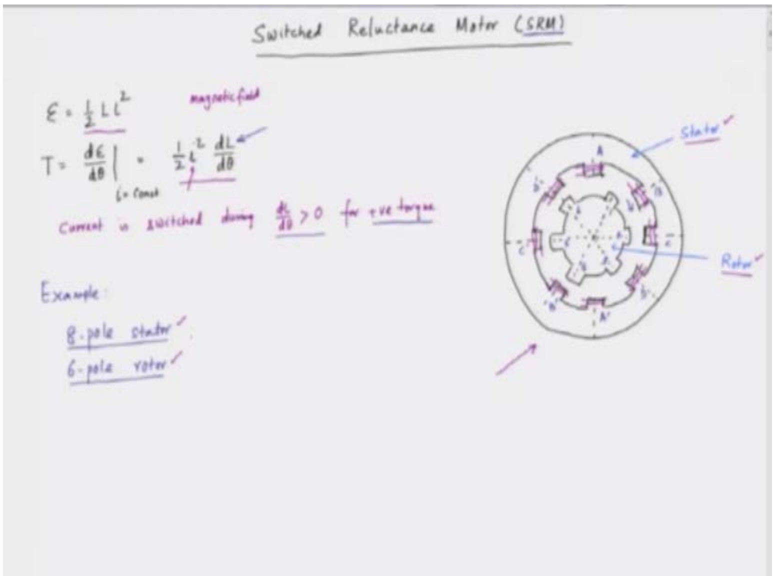

In our previous lecture, we explored the intriguing workings of a switched reluctance motor. Let’s recap what we discussed.

We have a stator and a rotor; the rotor features a slotted design and notably does not contain any windings, while the stator is equipped with windings. For this particular example, we are examining an 8-pole stator, labeled as AA', BB', CC', and DD', paired with a 6-pole rotor, identified as poles 1 through 6. This setup serves as a valuable foundation for our understanding of the motor's operation and characteristics.

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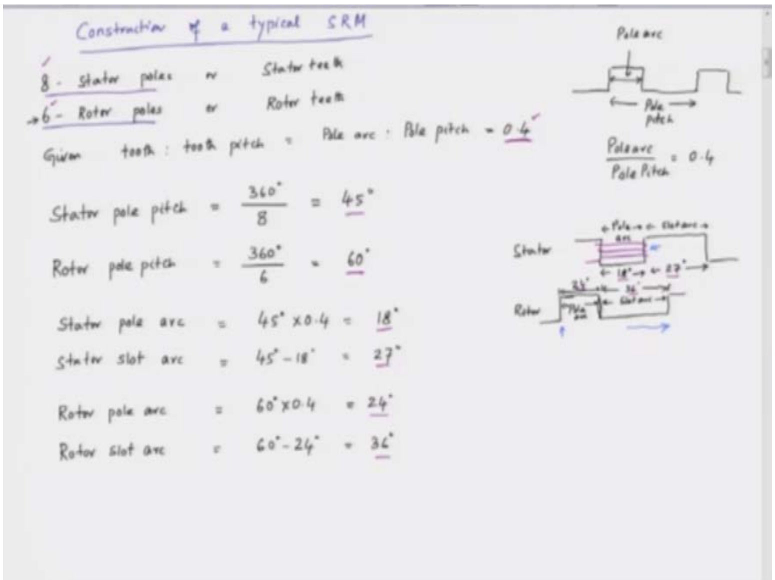

We have an 8-pole stator paired with a 6-pole rotor, and there are a few additional parameters we need to consider. In addition to these poles, we are given the tooth-to-tooth pitch, or more specifically, the ratio of pole arc to pole pitch, which is 0.4. This means that 40% of the pole pitch is occupied by the pole arc itself.

To calculate the stator pitch, we find that it measures 45 degrees, since we have 8 stator poles. For the rotor, with its 6 poles, the rotor pole pitch is calculated as $360^\circ / 6 = 60^\circ$. As we mentioned, the stator pole arc takes up 40% of the pole pitch, which results in a stator pole arc of $45^\circ \times 0.4 = 18^\circ$. Consequently, the stator slot arc is the remainder, giving us $45^\circ - 18^\circ = 27^\circ$.

For the rotor, the pole arc is calculated as $60^\circ \times 0.4 = 24^\circ$, while the rotor slot arc is $60^\circ - 24^\circ = 36^\circ$.

Now, let’s visualize this with a developed diagram. We can think of the motor as a cylindrical structure that we've "unwrapped" into a linear form. This development allows us to clearly distinguish the stator and rotor poles in a linear representation.

In this diagram, we see that the stator pole arc is 18° and the stator slot arc is 27°. Similarly, the rotor pole arc is 24° and the rotor slot arc is 36°.

As the rotor moves under the stator, it does so gradually and in a specific manner. The stator is equipped with windings, one of which is depicted here. As the rotor pole arc comes under the stator pole arc, the inductance of this winding will gradually increase due to the overlap. This overlap continues for 18° and then increases further until it reaches 24°, which corresponds to the rotor pole arc. After this point, the trailing edge of the rotor will align with the leading edge of the stator, marking a critical moment in the motor's operation.

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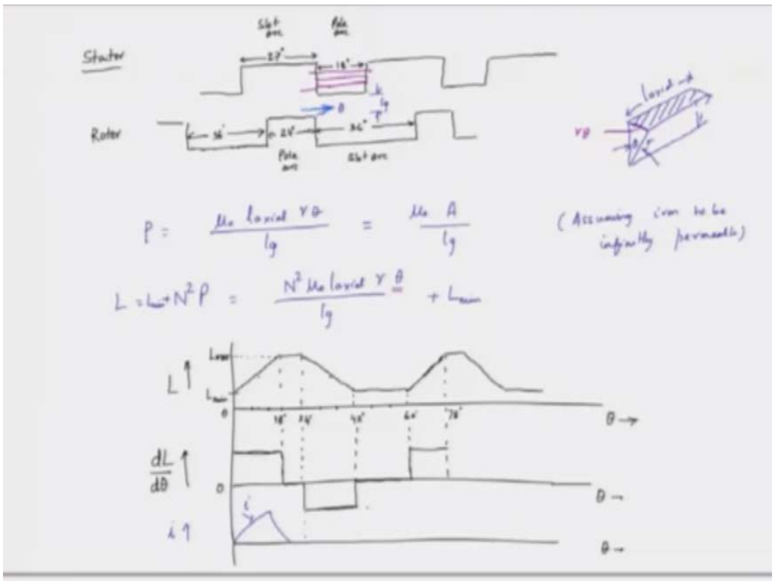

After that point, the inductance of the stator will gradually decrease. We can observe the variation of the inductance in the developed diagram here. The rotor is moving in this direction, and the inductance varies from a minimum value to a maximum value, which we can denote as L_{max}. The inductance increases linearly up to 18°, remains constant until 24°, and then decreases until it reaches 42°. Following this, it drops to a low minimum value up to 60°. Since this is a repetitive waveform, the same pattern will repeat after 60°.

Now, if we plot $\frac{dL}{d\theta}$, the rate of change of inductance with respect to the rotor angle θ, we can see that from 0° to 18°, the inductance remains constant. Between 18° and 24°, the $\frac{dL}{d\theta}$ is constant as well. This is because, during this interval, the inductance is increasing, leading to a derivative of zero.

Then, from 24° to 42°, the inductance begins to decrease, which results in a negative derivative during this range. We can identify the intervals here: 6° from 24° to 30°, another 6° from 30° to 36°, and continuing in 6° increments until we reach 60°.

The resulting graph of $\frac{dL}{d\theta}$ resembles a square wave with segments of zero value in between. Our objective here is clear: the currents should only flow during the positive $\frac{dL}{d\theta}$ intervals to maximize the torque. Thus, it's crucial to ensure that the switching occurs at the right times. This principle is fundamental to the operation of the switched reluctance motor.

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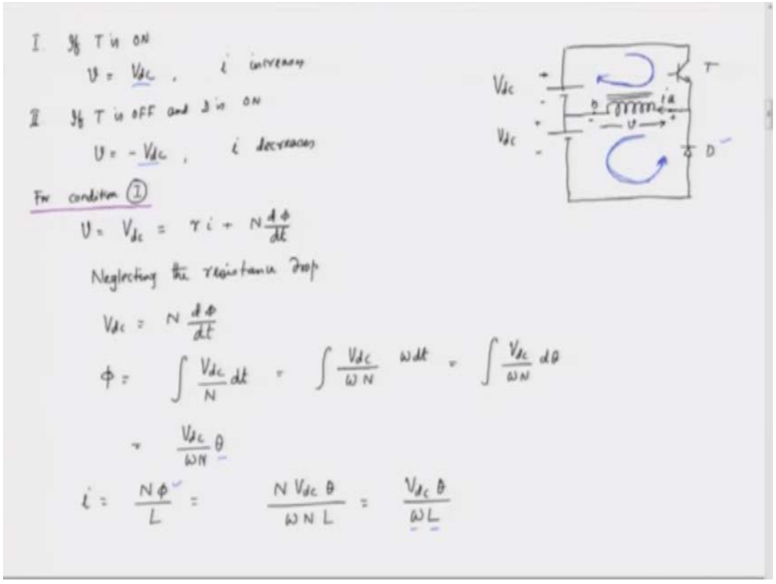

In our switching circuit, we can visualize the winding inductance as follows: our goal is for the current to be present only during the intervals of positive $\frac{dL}{d\theta}$. When switch T is turned on, current begins to flow through the circuit, resulting in a positive voltage across the winding, specifically, $V = +V_{dc}$. However, when switch T is turned off, the diode conducts, allowing the current to continue flowing in this direction.

As a result, on the other side of the circuit, the voltage becomes $V = -V_{dc}$. This setup illustrates the relationship between voltage and current effectively. If we integrate this voltage over time, we can derive the flux, which is dependent on the rotor angle, denoted as θ.

Now, let's consider the current. The current is related to the flux linkage through the inductance, represented as $N \cdot \phi$ divided by the inductance L. Therefore, the current is also a function of the rotor angle θ. As θ increases, the flux will correspondingly increase, and as we continue to increase θ, the current will rise as well.

However, it's essential to note that the current is inversely proportional to both the speed of the rotor and the inductance. This means that as the speed increases or as the inductance changes, we can expect variations in the current flowing through the system.

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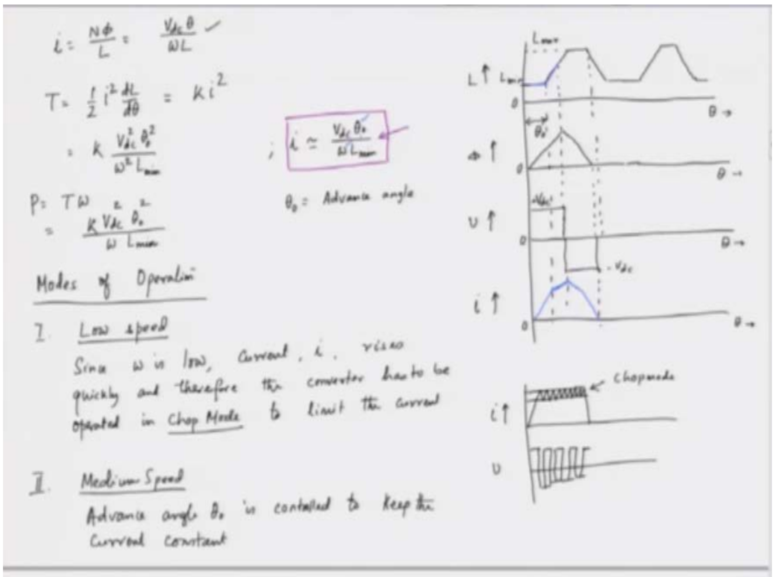

Let's examine how we switch the various voltages in our system. When we plot the variation of inductance against the rotor angle θ, we find that the graph resembles a trapezoidal signal. This inductance starts at zero, and our objective is to ensure that the current only exists during the rising phase of this inductance.

Now, let's consider the flux. If we plot the flux, we observe that it increases linearly. This linear increase is due to the applied voltage, which is initially constant and then begins to decrease. The behavior of the current is closely related to this flux. The nature of the flux is such that, when we apply a positive voltage V (specifically, $+V_{dc}$), by closing the transistor switch, the situation changes when we open the switch, leading to a negative voltage of $-V_{dc}$.

It is crucial to ensure that the current drops to zero before the trailing edge of the inductance occurs. Now, if we plot the current in this scenario, we see that the current behaves in a specific manner: it rises alongside the inductance. This rise occurs when the inductance is at its minimum, represented as L_{min}, and peaks at L_{max}.

This relationship arises because the current is inversely proportional to the inductance. We can express this relationship mathematically as $I = \frac{N\Phi}{L}$. If we simplify this further, we find that I can be expressed as $\frac{V_{dc}\theta}{\omega L}$. Thus, we see that when the inductance is very low, the applied voltage causes the current to rise to its maximum possible value. This illustrates how the dynamics of the inductance directly influence the current in the system.

As the inductance begins to increase, we notice that the rise of the current, despite having a positive voltage applied, is somewhat restricted. This interplay involves various variables: the inductance, the flux, the applied voltage in the winding, and the current itself. The current's rise is impeded because the inductance is gradually increasing on this rising side.

To manage this increase in inductance, we need to quench the current. We do this by applying a negative voltage, specifically -V_{dc}. As a result, the current will gradually decrease, ensuring that it drops to zero just before the onset of -$\frac{dL}{d\theta}$. This strategic switching allows us to maintain the current only during the positive $\frac{dL}{d\theta}$.

This process repeats in every cycle, allowing us to maximize the current during the positive $\frac{dL}{d\theta}$, which in turn maximizes the torque. Now, if we look at the expression for torque, it can be represented as:

$$\text{Torque} = \frac{1}{2} I^2 \frac{dL}{d\theta}.$$

Since $\frac{dL}{d\theta}$ remains constant during the rising edge of the inductance, we can express it as $K \cdot I^2$. Therefore, we can derive that:

$$I = K \frac{V_{dc}^2 \theta^2}{\omega^2}.$$

Given that the current predominantly rises when the inductance is at its minimum, it approaches its peak just before the positive $\frac{dL}{d\theta}$ begins. This leads us to express the inductance as $L = L_{\min}$, indicating that we are indeed considering the situation at or near L_{min}.

Furthermore, in this scenario, we can describe the current as:

$$I = \frac{V_{dc}\theta_0}{\omega L_{\min}}.$$

Here, θ_0 represents the advanced angle, which signifies that we are applying the voltage θ_0 in advance of the commencement of the positive $\frac{dL}{d\theta}$. This technique is essential for optimizing the performance of the system.

Before the inductance begins to rise, we apply the voltage V_{dc} prior to reaching the advanced angle, θ_0. Now, let's take a closer look at the expression for torque. At low speeds, we notice that the current rises very rapidly. In such cases, we need to impose limits on the current to avoid excessive levels, which is why the converter operates in chop mode.

So, we have different modes of operation. During low-speed conditions, since ω is low, the current I can rise quickly. Therefore, to manage this rapid increase, the converter must be operated in chop mode to effectively limit the current. In this chop mode, the current rises swiftly but is contained within a specific band. This means that we repeatedly apply and remove the voltage, allowing the current to operate within this constrained range.

Now, as the speed increases, the dynamics change. Observing the equation, we can see that the current does not continue to rise as quickly because the speed is increasing. To maintain a constant current as the speed escalates, we must increase the advanced angle θ_0.

At medium speeds, for instance, the advanced angle θ_0 is carefully controlled to ensure that the current remains constant. This adjustment is vital, as keeping the current steady means that θ_0 must increase in tandem with ω. So, as the speed goes up, θ_0 is also incrementally increased to maintain that constant current.

However, it's important to note that the power will also remain approximately constant in this scenario. To clarify, the power can be expressed as:

$$\text{Power} = T \cdot \omega \approx K \cdot V_d^2 \cdot \frac{\theta_0^2}{\omega \cdot L_{\min}}.$$

Thus, we conclude that the power stays approximately constant because we keep the current stable by appropriately increasing θ_0. This careful coordination is essential for optimizing the performance of our system.

We will be dividing our operating zone into several distinct regions, and these zones can be illustrated on a torque versus speed graph. In this representation, we designate a base speed, referred to as ω_{base}. During this phase, we maintain a constant current through chop mode. The graph includes not only the torque but also the current and the advanced angle θ_0.

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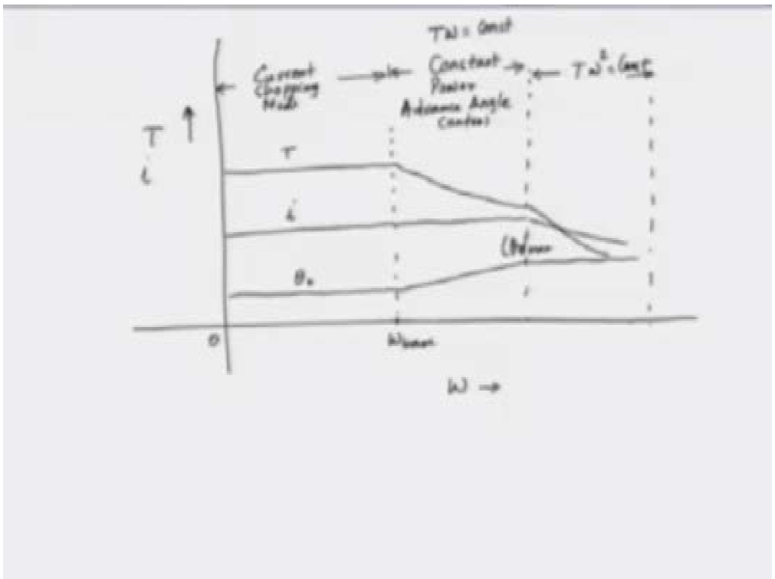

Initially, θ_0 is kept constant while we operate in chop mode, which is specifically known as current chopping mode. As we progress, we gradually increase θ_0 to maintain that constant current. What we observe here is that the current I remains steady, which in turn allows the product $T \cdot \omega$ to also stay constant. The power can be expressed as proportional to θ_0^2.

In this scenario, we essentially maintain constant power, which is also referred to as constant torque-speed operation. This phase is characterized by advanced angle control, where the advanced angle θ_0 increases. However, it's important to note that while the advanced angle is rising, the torque itself decreases.

Once the advanced angle reaches its maximum permissible value, we then keep θ_0 constant. Beyond this point, any further increase in the advanced angle will lead to a decline in both current and torque. This particular region is defined by the relationship $T \cdot \omega^2 =$ constant.

So, the modes of operation of a switched reluctance motor reveal that initially, below the base speed, we maintain constant torque by operating in chop mode. As we subsequently increase the advanced angle, the torque decreases, yet the power remains constant. This behavior continues until we reach a certain threshold for θ_0, at which point we must carefully manage the system to maintain optimal performance.

We have reached the maximum possible advanced angle, denoted as $\theta_0^{\max}$. Beyond this point, we cannot increase the advanced angle any further. If we maintain this constant advanced angle while simultaneously increasing the speed, we will observe a decrease in current. Since the current is decreasing, the power will also inevitably decline. Therefore, as we increase the speed, the power output decreases.

In this scenario, we recognize that while $T \cdot \omega^2$ remains constant, this principle is central to the operation of the switched reluctance motor. The converter plays a crucial role here, ensuring that the appropriate voltage is applied to the stator windings. By effectively controlling the converter, we can operate the motor in various modes, thereby allowing us to manage the torque of the switched reluctance motor with precision.

As previously mentioned, this motor is particularly advantageous for space applications due to its rotor design, which does not incorporate any windings. Now, let us transition to an important category of drives that are utilized for traction applications. So, what do we mean by traction drives? Let's delve into the concept of traction drives and explore their significance.

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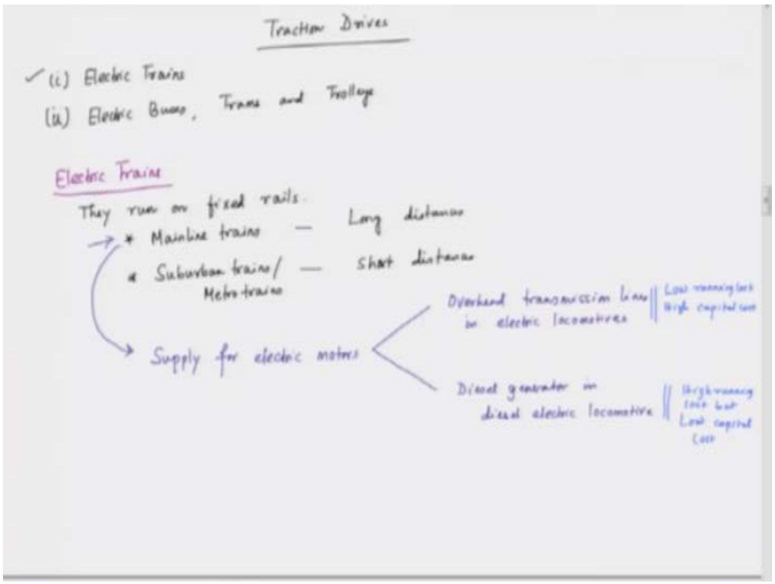

Our next discussion will focus on traction drives. When we refer to traction drives, we primarily mean electric trains, which represent one significant category. Additionally, we include electric buses, trams, and trolleys in this classification. Electric trains are designed for higher power applications, typically operating in the megawatt range, with a typical rating of around 6,000 horsepower or even more.

In contrast, electric buses, trams, and trolleys cater to medium and low power applications. However, all these vehicles utilize traction motors, and their torque-speed characteristics exhibit similar patterns. Now, let's delve into the drive features used in electric trains.

Electric trains operate on fixed rails, and there are primarily two types of trains: mainline trains and suburban trains, which we often refer to as metro trains. Mainline trains are designed for long-distance travel, while suburban trains or metro trains are intended for shorter distances.

Typically, long-distance trains do not experience frequent starts and stops; the number of stops is limited. Conversely, suburban or local trains, including metro trains, have multiple starts and stops along their routes. Consequently, we need to accelerate and decelerate suburban trains more frequently than we do with mainline trains.

Let's begin our discussion with mainline trains. In the case of mainline trains, we should examine the supply systems that power the electric motors.

In electric locomotives, we can utilize overhead transmission lines to supply power, particularly for mainline trains. There are primarily two types of power sources for mainline trains: one is the overhead transmission line, and the other is a diesel generator found in diesel-electric locomotives.

The diesel generator operates on an internal combustion engine and generates electricity to power the electric motors. Ultimately, in all these locomotives, the driving force behind the wheels comes from electric motors. But why do we prefer electric motors? The answer lies in their ability to accelerate smoothly and provide seamless speed control. Unlike traditional mechanical systems, there are no gears to change, making operation much more straightforward. Electric motors also facilitate easy reversal of direction and allow for effective braking without any hassle.

Now, when we compare the overhead transmission lines to diesel generators, it's important to note the operational costs. Diesel generators typically have a high running cost due to fuel consumption, which means that this class of locomotive can be more expensive to operate over time. However, they often come with a lower capital cost since the initial investment in infrastructure is less. On the other hand, electric locomotives powered by overhead transmission lines generally have a lower running cost, although they require a higher initial capital investment due to the need to erect the transmission lines.

Therefore, when deciding between electric locomotives and diesel-electric locomotives, we must weigh these factors carefully to determine which option best suits our needs.