Fundamentals of Electric Drives

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Lecture-35

Low cost brushless DC motor (BLDCM), Trapezoidal permanent magnet AC motor

Hello and welcome to this lecture on the fundamentals of electric drives. In our last session, we explored the concept of self-controlled synchronous motor drives, focusing specifically on two examples of load-commutated synchronous motor drives. Now, let's delve deeper into the workings of the load-commutated synchronous motor drive.

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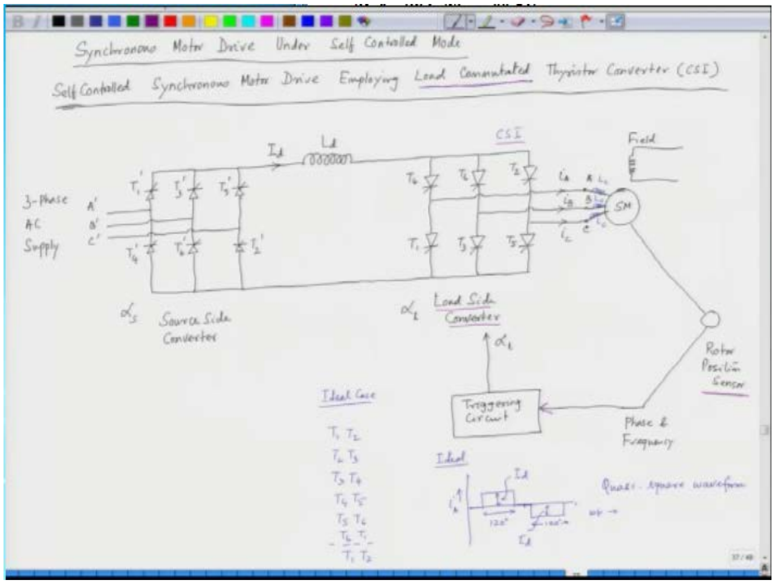

Synchronous Motor Drive Under Self Controlled Mode

Self Controlled Synchronous Motor Drive Employing Load Commutated Thyristor Converter (CSI)

What we observed is that the synchronous motor is connected to a load-side converter, specifically a Current Source Inverter (CSI). This synchronous motor operates using closed-loop rotor position feedback, which means we have a position sensor that provides essential feedback for controlling the load-side converter. Additionally, we derived the expression for the commutation overlap angle. This overlap angle, denoted as μ, can be evaluated from the derived expression and is crucial for the operation of the load-side converter.

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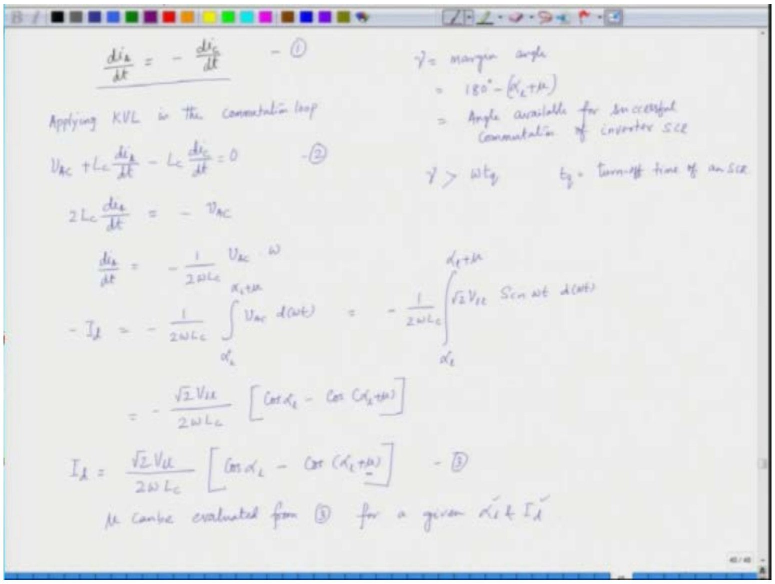

$$\frac{di_a}{dt} = -\frac{di_c}{dt} \quad -①$$

Applying KVL in the commutation loop

$$V_{ac} + L_c\frac{di_a}{dt} - L_c\frac{di_c}{dt} = 0 \quad -②$$

$$2L_c\frac{di_a}{dt} = -V_{ac}$$

$$\frac{di_a}{dt} = -\frac{1}{2\omega L_c}V_{ac} \quad \omega$$

$$-I_d = -\frac{1}{2\omega L_c}\int_{\alpha_\ell}^{\alpha_\ell+\mu} V_{ac}\, d(\omega t) = -\frac{1}{2\omega L_c}\int_{\alpha_\ell}^{\alpha_\ell+\mu}\sqrt{2}V_{\ell\ell}\sin\omega t\, d(\omega t)$$

$$= -\frac{\sqrt{2}V_{\ell\ell}}{2\omega L_c}\left[\cos\alpha_\ell - \cos(\alpha_\ell+\mu)\right]$$

$$I_d = \frac{\sqrt{2}V_{\ell\ell}}{2\omega L_c}\left[\cos\alpha_\ell - \cos(\alpha_\ell+\underline{\mu})\right] \quad -③$$

μ canbe evaluated from ③ for a given α_ℓ & I_d

γ = margin angle

$= 180° - (\alpha_\ell+\mu)$

= Angle available for successful commutation of inverter SCR

$\gamma > \omega t_q$ $\quad$ t_q = turn-off time of an SCR

And we also saw the closed loop speed control block diagram of this load commutated synchronous motor drive.

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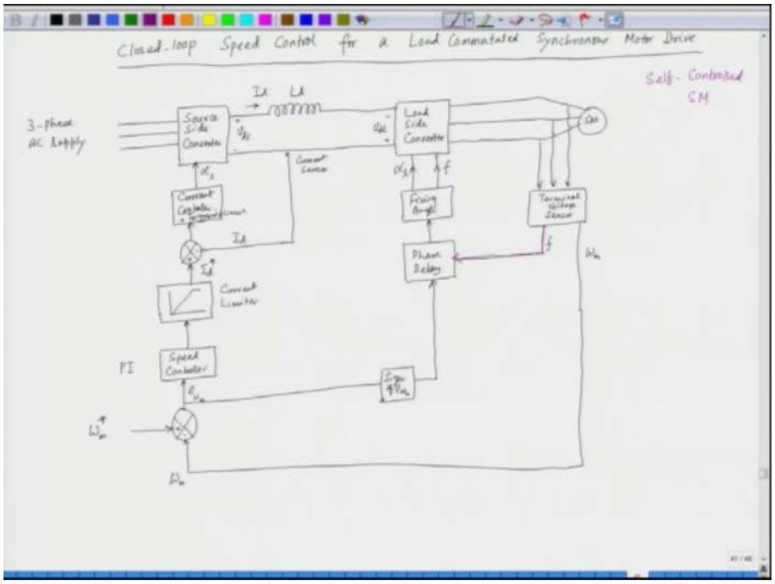

Closed-loop Speed Control for a Load Commutated Synchronous Motor Drive

It is essential to understand that this is a self-controlled synchronous motor. To achieve this, we require position feedback, specifically feedback regarding the phase of the rotor. This frequency feedback provides the necessary phase angle, allowing us to effectively control the load-side converter using this type of feedback. Without such feedback, we cannot operate the synchronous motor drive in self-control mode.

The synchronous motor must maintain synchronism with the rotor, meaning there needs to be a precise alignment between the stator and rotor across all frequencies. Now, let’s consider another type of motor known as brushless DC motors. Although they are also classified as synchronous motors, brushless DC motors inherently possess closed-loop position feedback. Let us delve into the details of brushless DC motors.

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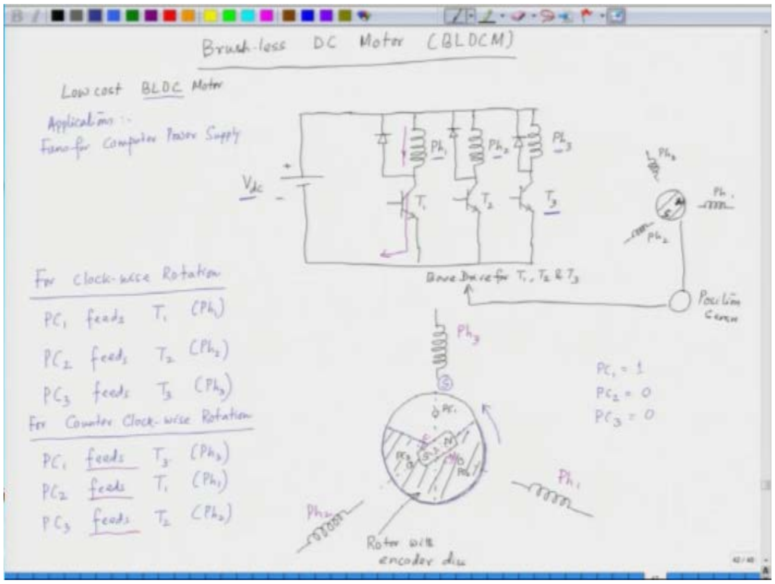

Brush-less DC Motor (BLDCM)

Low cost BLDC Motor

Applications :-
Fans for Computer Power Supply

For Clock-wise Rotation

PC_1 feeds T_1 (Ph_1)
PC_2 feeds T_2 (Ph_2)
PC_3 feeds T_3 (Ph_3)

For Counter Clock-wise Rotation

PC_1 feeds T_3 (Ph_3)
PC_2 feeds T_1 (Ph_1)
PC_3 feeds T_2 (Ph_2)

$PC_1 = 1$
$PC_2 = 0$
$PC_3 = 0$

We refer to this abbreviation as BLDCM, which stands for brushless DC motors. Today, we'll focus on a straightforward, low-cost BLDC motor. As previously mentioned, BLDC stands for brushless DC motors. In our discussion, we have a motor featuring three stator windings. Let’s say we have three stator windings, each energized by a power transistor. Thus, we have three power transistors, all supplied from a DC power source.

On the DC side, we have a supply voltage denoted as V_{dc}. We label these phases as Phase 1, Phase 2, and Phase 3. Each phase is connected to a freewheeling diode, which allows the current to flow when the transistor is switched off. Therefore, we have three transistors, T_1, T_2, and T_3, with V_{dc} on the DC side.

Now, if we visualize the construction of this type of brushless DC motor in a schematic manner, we observe the rotor along with the three stator windings: Phase A, Phase B (or Phase 2), and Phase C (or Phase 3). The rotor in this configuration is a permanent magnet rotor, featuring distinct North and South poles. Specifically, we have a North Pole and a South Pole on the rotor, creating a permanent magnetic field.

The stator is connected to the three power transistors in a specific configuration. Since this is a closed-loop drive system, we must include a position sensor. This sensor is connected to the rotor, allowing us to monitor the rotor's position and subsequently trigger the transistors T_1, T_2, and T_3. To illustrate this concept further, we'll consider a position sensor, such as an encoder, attached to the rotor. The rotor, having a permanent magnetic field, can be modeled with two poles: one North Pole and one South Pole. Let's examine the rotor structure of this brushless DC motor in more detail.

In the rotor, we have a structure that can be divided into sixty-degree segments. Within this setup, we find three phototransistors: P_{C1}, P_{C2}, and P_{C3}. Additionally, a magnet is positioned on the rotor, featuring a distinct North Pole and South Pole. So, we have the North Pole located here and the South Pole situated here. Essentially, the rotor consists of a magnet, which is integrated with an encoder disk.

It's important to note that a section of the encoder disk is opaque. This opaque region, marked clearly, plays a critical role in the operation of the phototransistors. Each phototransistor consists of a light-emitting diode (LED) on one side and a phototransistor on the other. When the light passes through the transparent region, the phototransistor receives the signal, resulting in an output of 1. Conversely, when the opaque region blocks the light, the output of the phototransistor drops to zero.

Now, let's look at how these phototransistors are aligned with the motor phases. Assume that this is Phase A (or Phase 1), aligned in one segment, followed by Phase 2, and then Phase 3 in subsequent segments. So, we have Phase 1 here, Phase 2 aligned at this position, and Phase 3 located here.

When a specific phase is energized, it generates a magnetic field, creating a South Pole that attracts the rotor’s North Pole. For example, when we energize Phase 1, the current flows through it and back to the power supply via the transistor. This flow of current generates a South Pole at the rotor. Consequently, the South Pole created will attract the rotor's North Pole, causing the rotor magnet to move. Since the encoder disk is fixed to the rotor, it also rotates with the rotor.

As the rotor rotates, the opaque region on the disk moves past the phototransistors. Initially, P_{C1} is receiving a signal of 1 because it is in the transparent region. However, as the rotor continues to move, this arrangement will change. When the rotor moves, the position of the opaque region will eventually block the light reaching P_{C1}, which will change its output signal accordingly.

To achieve clockwise rotation, we need to maintain the correct arrangement. Thus, when we energize Phase 1, the resulting motion of the rotor will indeed be clockwise as it aligns with the magnetic field dynamics created by the energized phases. This fascinating interaction between the rotor and the stator phases underpins the functionality of the brushless DC motor.

This region is transparent, while this adjacent region is opaque. When the region is opaque, the output of the phototransistor becomes zero. Currently, P_{C1} is in a transparent region, so its output is one, while P_{C2} and P_{C3} are both in opaque regions, resulting in their outputs being zero. Since P_{C1} is allowing light to pass through, it feeds the base of transistor T1.

For clockwise rotation, P_{C1} energizes T1, which is connected to Phase 1. As Phase 1 is energized, we observe that the North Pole of the rotor magnet will be attracted toward the South Pole created by the energized phase, causing the rotor to rotate in a clockwise direction. After some time, P_{C1} will become covered, and P_{C2} will be uncovered. At this point, the rotor magnet will align in such a way that its North Pole and South Pole will be positioned accordingly.

Under these conditions, P_{C2} must be energized, meaning it will feed transistor T2, which is connected to Phase 2. Subsequently, after some time, P_{C3} will activate, feeding T3, which is linked to Phase 3. This sequence ensures continuous rotation, as the encoder provides real-time feedback. At any given moment, one of the phototransistors will be in the "on" state, allowing the corresponding transistor to activate, resulting in seamless rotation.

Now, why is it referred to as a brushless DC motor? The answer lies in the absence of brushes; the motor achieves rotation using a direct current (DC) input without brushes. The motor operates as a brushless DC motor, with commutation performed electronically through the encoder and the three power transistors T1, T2, and T3. The windings, Phase 1, Phase 2, and Phase 3, are energized by these transistors, with a DC supply of V_{DC}. Thus, without any brushes in play, we maintain a continuous clockwise rotation, which we can refer to as a brushless DC motor or BLDC motor.

Now, what if we want to achieve counterclockwise rotation? In order to rotate the motor in the counterclockwise direction, we need to alter the connections accordingly. The new configuration will facilitate this counterclockwise rotation, allowing us to seamlessly transition from one rotational direction to the other.

Now, if we have the North Pole positioned here, it should be attracted to the South Pole, which we will place below Phase 3. Therefore, when we have a South Pole in that location, the North Pole will naturally be attracted toward it, causing the motor to rotate in a counterclockwise direction. In this scenario, P_{C3} or P_{C1} must energize Phase 3 by feeding the base of transistor T3. As a result, T3 will be activated, energizing Phase 3.

In a similar manner, P_{C2} should feed T1, which corresponds to Phase 1, while P_{C3} needs to feed T2 for Phase 2. To achieve counterclockwise rotation, we must rearrange the connections. Specifically, P_{C1} will be connected to the base of transistor T3, P_{C2} will connect to the base of transistor T1, and P_{C3} will feed the base of transistor T2.

This motor design is characterized as low-cost and efficient, primarily because it operates without brushes. The rotor consists of a permanent magnet, while the stator features concentric windings rather than distributed ones. These types of motors have gained immense popularity in applications like computer fans. For instance, in switched-mode power supplies, we utilize brushless DC motors for cooling fans. These fans are powered by DC electricity, allowing them to run for years without any damage. The absence of brushes eliminates the need for maintenance, making them exceptionally reliable. Similarly, the CPU fan is also a brushless DC motor, further demonstrating the practicality and efficiency of this design.

So, this fan serves as one application of brushless DC motors, particularly in computer power supplies. Now, it’s important to note that the torque produced in this context is inherently pulsating in nature. If we analyze the situation, we find that the torque is directly proportional to the angle between the two magnets involved: one being the permanent magnet of the rotor, which has distinct North and South Poles, and the other being the electromagnet created by the phase windings.

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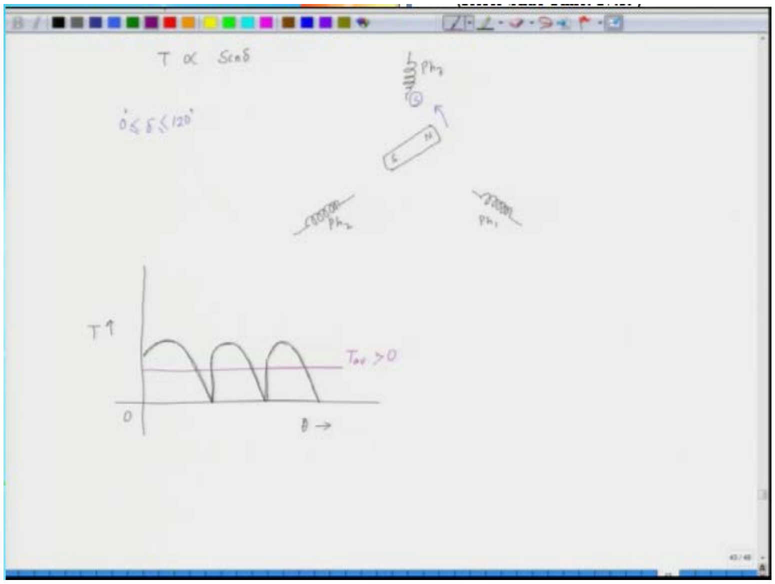

In our case, we have three phase windings, Phase 1, Phase 2, and Phase 3, arranged accordingly. The principle at play is straightforward: whenever we energize a winding, it generates a South Pole, which then attracts the North Pole of the rotor magnet. Consequently, this interaction enables the motor to rotate either clockwise or counterclockwise, depending on which winding is excited.

As we observe the interaction between the magnets, the angle between them changes between 0 to 120 degrees. The encoder indicates that this angle is 120 degrees when the photo coupler receives a high signal. Thus, the variation of Δ in this case occurs within that range. If we plot the torque waveform against the rotational angle θ, we can visualize how the torque behaves as the motor rotates.

As the motor turns, Δ starts at 120 degrees and moves toward 0 degrees. The resulting torque will oscillate in a sinusoidal fashion. Therefore, the torque versus θ graph reveals the output torque of the motor. Notably, since this torque is positive, the average value of the torque, denoted as T_{avg}, is also positive. This means the motor can rotate positively in either the clockwise or counterclockwise direction, albeit with a pulsating torque.

This torque pulsation is generally insignificant for fan applications because they are low-performance systems. While there may be some noise, it’s manageable. However, for drive applications requiring high performance, this torque pulsation can lead to vibrations and undesirable noise. Therefore, we will examine a more advanced brushless DC motor, where the low-cost design is replaced by a trapezoidal-excited permanent magnet DC motor. Let’s take a closer look at the trapezoidal-excited permanent magnet DC motor.

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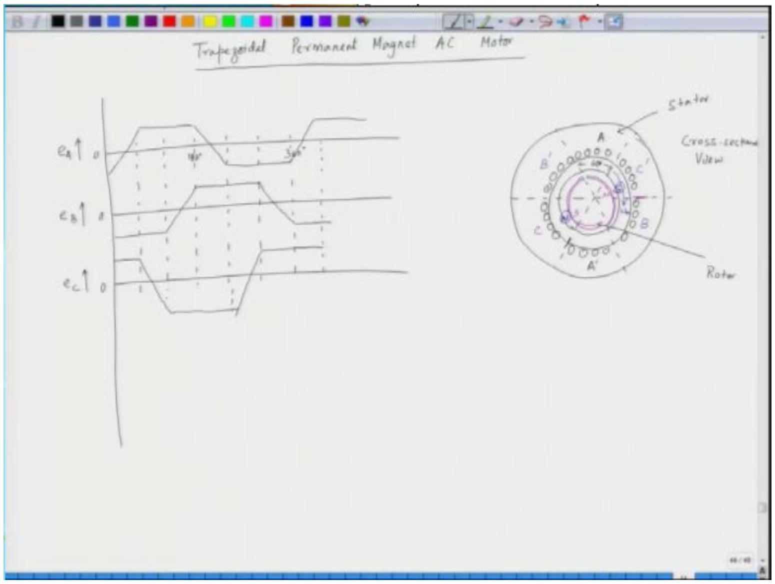

We will now delve into the topic of trapezoidal permanent magnet AC motors. Let’s take a closer look at the constructional features of this system. We have both a rotor and a stator. The stator is structured in such a way that it is divided into 60-degree intervals. In this diagram, we can clearly see the stator, and this component here represents the rotor.

The stator contains conductors that are distributed throughout its structure. For example, let’s designate one set of conductors as Phase A. When we refer to Phase A, it’s important to note that the opposite phase is designated as A'. Therefore, Phase A spans a 60-degree section here and another 60-degree section across from it. Adjacent to Phase A, we have Phase B, which is shifted by 120 degrees, represented here as B and B'. Lastly, we have Phase C, denoted as C and C'.

This image represents a cross-sectional view of the motor, where we can also observe the rotor equipped with permanent magnets. The rotor magnet is structured in a specific manner, with one set of permanent magnets placed on one side and another set on the opposite side. These magnets create distinct magnetic poles: one side generates a South Pole, while the opposite side produces a North Pole, giving us a two-pole structure.

As the rotor rotates, let's say, in the clockwise direction, it moves at an angular speed denoted as ω_M. To understand the electrical behavior of the motor, we can plot the induced electromotive force (EMF) in the stator windings for Phases A, B, and C.

In our plot, we will illustrate the induced EMF for each phase against the angle of rotation. The intervals we've established are 60 degrees, with corresponding marks for 180 degrees and 360 degrees. As the rotor rotates in the clockwise direction, the North Pole of the rotor enters beneath Phase A, while the South Pole follows closely behind. This dynamic interaction between the rotor and stator is critical for understanding the performance and operation of trapezoidal permanent magnet AC motors.

As we observe the rotor's movement, we can identify the beginning of the North Pole entering under Phase A. At this point, the induced electromotive force (EMF) in Phase A will gradually increase. We can assume that the South Pole will generate a negative induced EMF, while the North Pole, as it comes into alignment with the phase, will give rise to a positive induced EMF. Consequently, the induced EMF will transition from negative to positive over the 60-degree interval.

After the 60-degree mark, the North Pole will be completely aligned with Phase A, as the phase period is confined to this 60-degree angle. Therefore, once the North Pole occupies the entire 60 degrees of Phase A, it will remain there, and then, for the next 120 degrees, the North Pole stays constant. Afterward, it will decrease over another 60-degree span, remaining constant for yet another 120 degrees. The waveform produced during this process resembles a trapezoid, leading us to refer to this motor as a trapezoidally excited permanent magnet AC motor.

If we look at Phase B, we note that it is shifted from Phase A by 120 degrees. The beginning of Phase B occurs at this point, where it is shifted relative to Phase A. Consequently, the maximum value for Phase A will be reached just before Phase B begins. The waveform for Phase B will appear similarly to that of Phase A. Phase C, in turn, is shifted from Phase B by another 120 degrees. The positive portion of Phase C will initiate at this point, and if we plot this waveform, it will also take the trapezoidal shape, spanning a 120-degree interval.

Thus, we have the induced EMF waveforms for Phases A, B, and C. As the rotor continues to rotate within this three-phase stator system, it is essential to inject current into each phase to minimize torque ripple. The trapezoidal shape of the induced EMF signals indicates that the transitions occur over 60 degrees, with durations of 120 degrees for both positive and negative values.

In the upcoming lecture, we will delve into the currents injected into Phases A, B, and C, and the relevant calculations required to ensure that torque ripple is minimized effectively.