Fundamentals of Electric Drives

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Lecture-34

Detailed analysis of commutation of load commutated thyrisor inverter, Derivation of overlap angle and margin angle, Closed-loop speed control scheme for load commutated inverter-fed synchronous motor drive

Hello and welcome to this lecture on the fundamentals of electric drives! In our previous discussion, we delved into the intricacies of commutation in converter-fed synchronous motor drives, specifically focusing on load commutation. During that session, we explored how the back EMF generated by the load is utilized for the commutation of the SCRs in the converter. This process is essential for ensuring the smooth operation of the drive.

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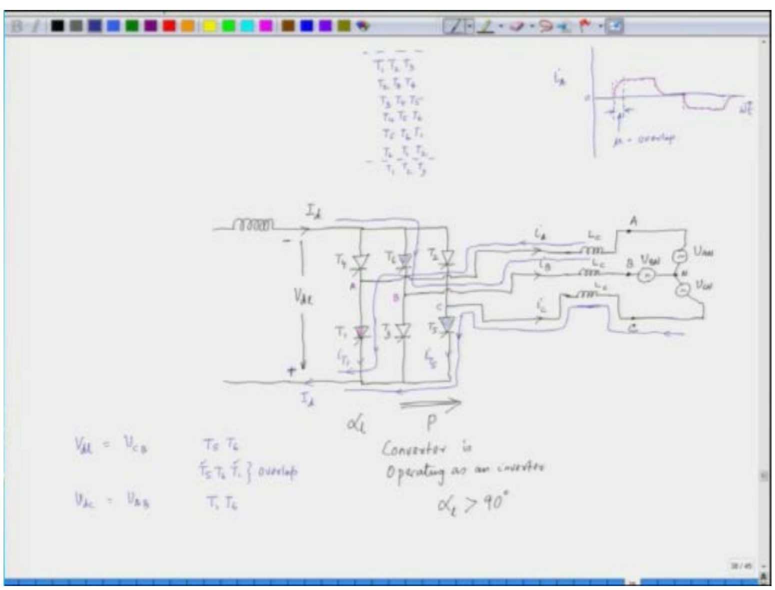

Let us assume, for the sake of discussion, that we have the conduction of SCR T_6 along with another SCR in conduction. When these two SCRs are conducting, we must consider the resulting voltage across them, known as the dieseling voltage. With SCRs in conduction, current flows in a particular direction, connecting these points in the circuit.

Specifically, the current is flowing as follows: it travels from the dieseling point and continues its path through the circuit. Now, let's define V_{dl}. The voltage V_{dl} is measured between these points, where one is positive and the other negative. Essentially, V_{dl} can be described as coming from point C through the commutation inductor. Therefore, we can state that V_{dl} is approximately equal to V_c, with point B serving as the reference point. For the moment, we can ignore any voltage drop across the inductor, leading us to conclude that $V_{dl} = V_{cB}$.

Next, when we trigger SCR T_1, we must ensure that this SCR is forward-biased, which necessitates that V_{ac} be positive. So, considering points A, B, and C, we find that V_{ac} must indeed be positive if we neglect the voltage drop across the components for now. As a result, SCR T_1 will become forward-biased, while SCR T_5 will gradually transition to a reverse-biased state. It's important to note that SCR T_5 was initially carrying current through it, sourced from the synchronous machine, and the current was flowing in this specific direction.

The current is indeed flowing from the synchronous machine. What we are aiming to achieve is to turn off SCR T_5 while simultaneously turning on SCR T_1. However, we must consider that the current is flowing through an inductor, and as such, the inductor current cannot be interrupted instantaneously. This means that the current will take some time to decrease, and it will actually present as a negative current due to its direction being opposite to the conventional current I_C.

When we trigger T_1, it will also start conducting, allowing current to flow through it, and this current will originate from phase A. Therefore, we have current entering from phase A, which contributes to the overall current I_d. The same current I_d will also flow because of T_5. Thus, we can express this relationship as i_{T5} and i_{T1}, which are ultimately the currents associated with the phases of the synchronous motor.

Now, as we transition to this new situation, we want V_{dl} to be equal to V_{AB}. This condition can be fully realized when both T_1 and T_6 are conducting for a brief period. During this time, we will have the conduction of T_5, T_6, and T_1 occurring simultaneously. The duration for which this transition takes place is referred to as the overlap time. In essence, the overlap time is the interval during which both T_5 and T_1 are conducting before the transition is complete. Now, let us delve deeper into this analysis.

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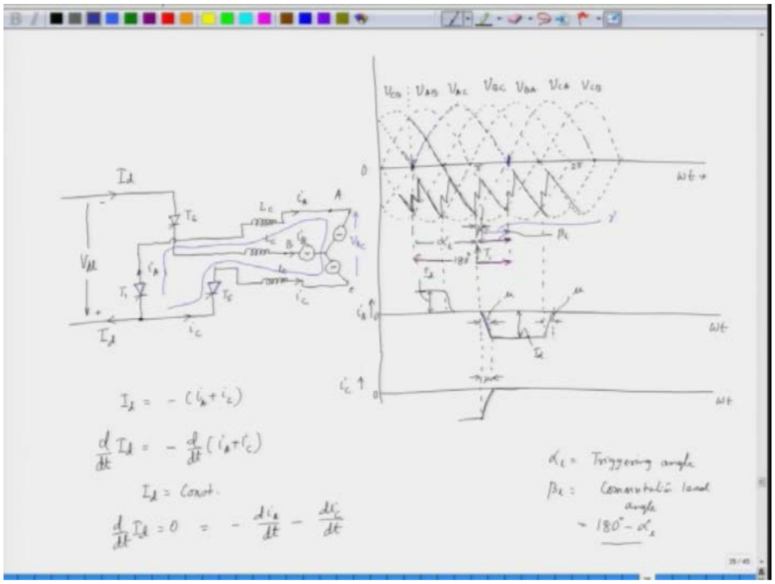

Now, let’s take a closer look at the equivalent circuit. In this scenario, we can illustrate the equivalent circuit here. Initially, T_6 was conducting, which means that phase B was active. Next, we have T_5, which was previously conducting and is connected to phase C. This setup represents our motor, and we can see the individual back electromotive forces (EMFs) represented here. So, we have phase B, phase A, and phase C connected accordingly.

Now, when we trigger thyristor T_1, this connects us to phase A. These components are our commutating inductors, and this is where the process begins. The dieseling voltage, denoted as V_{dl}, has its positive and negative terminals indicated, while the current flowing through this circuit is I_d, which is returning to this point. To fully comprehend this commutation process, we need to consider how the current was previously flowing through the circuit.

We have the individual currents: i_A, i_B, and i_C. Specifically, this current is i_C. According to Kirchhoff’s Current Law, we can express this relationship as:

$$I_d = -i_A + i_C$$

Here, it’s important to note that while i_A and i_C will flow in opposite directions, we can maintain this current direction for the sake of our analysis. Thus, we can rearrange this equation to show that:

$$I_d + i_A + i_C = 0 \quad \text{or} \quad I_d = -(i_A + i_C)$$

If we differentiate with respect to time, we obtain:

$$\frac{dI_d}{dt} = -\left(\frac{di_A}{dt} + \frac{di_C}{dt}\right)$$

Since I_d is a constant dieseling current, its rate of change is zero:

$$\frac{dI_d}{dt} = 0 \Longrightarrow 0 = -\frac{di_A}{dt} - \frac{di_C}{dt}$$

From this equation, we can deduce that:

$$\frac{di_A}{dt} = -\frac{di_C}{dt}$$

This derivation tells us that the rates of change of these currents are equal in magnitude but opposite in direction.

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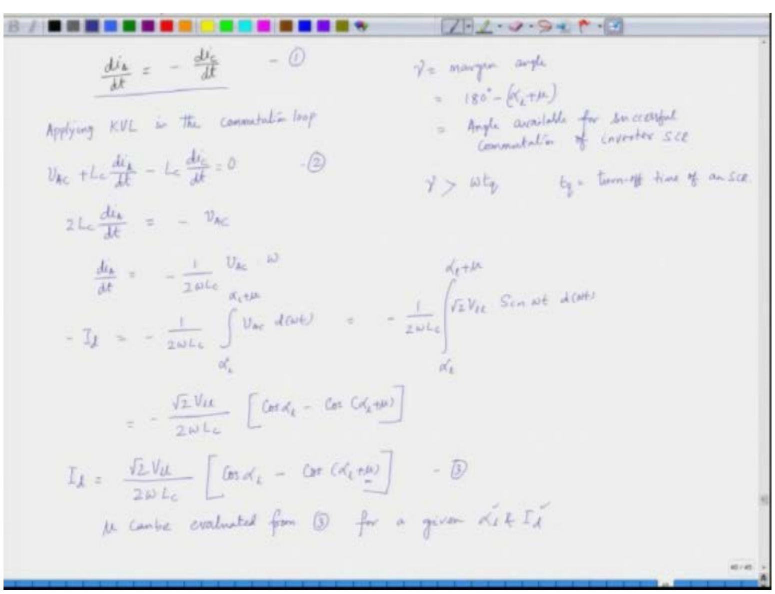

Now, if we plot the phase current, let's denote this as i_A. At the moment when we trigger T_1, which is indicated here, the current i_A will gradually rise from zero. Eventually, it will become negative. This transition occurs during the overlap time, represented as μ. The current will continue to flow until this point, corresponding to the voltage V_{AB}. Following this, we have V_{AC}, and at this juncture, the current will be taken over by V_{BC}.

The current i_A will take on a negative value, as illustrated here, and once again, we encounter the commutation overlap, which is represented by the angle μ. The characteristic of the current i_A will resemble a quasi-rectangular or quasi-square wave. Meanwhile, we have V_{CA} influencing this behavior. In this scenario, the current will exhibit a decreasing value, denoted as I_d, which is also represented as I_d again. Thus, the behavior of i_A can be depicted as follows.

Now, let's analyze the behavior of i_C at this instant during the commutation. Initially, i_C was negative, as it was responsible for carrying the current of phase C. When we trigger T_1, the current i_C will gradually decrease, and as i_A reaches its negative maximum, i_C will eventually approach zero. The loop formed by these currents reflects a decreasing loop for i_C and an increasing loop for i_A, and they are equal in magnitude but opposite in direction. Therefore, we can depict i_C as a decreasing current over time.

This entire process occurs during the commutation interval, denoted as μ, which is also highlighted here. Now, if we start from this point, we notice that V_{AC} becomes positive at this moment. This marks the instant of triggering, the beginning of the difference from which we can activate T_1.

This is our triggering angle, and the triggering can persist from this point until the next. The remaining angle here is referred to as β, which is the commutation lead angle. We define α as the triggering angle and β as the commutation lead angle, which can be expressed as:

$$\beta = 180^\circ - \alpha_l$$

This indicates that when we are triggering a thyristor in an inverter configuration, there exists an angle available for successful commutation. That angle is β_l, and we must also account for the overlap angle. Hence, β_l is defined as:

$$\beta_l = 180° - \alpha_l$$

This gives us a full understanding of the process from this point to the corresponding position in the waveform, where the entirety of 180° is reflected here. Thus, the remaining angle of 180° - α_l defines β_l, which is crucial in understanding the dynamics of commutation in this context.

Now, we will introduce an important angle known as the margin angle, denoted by γ. The margin angle is defined as:

$$\gamma = 180° - \alpha_l + \mu.$$

Essentially, the margin angle represents whatever is left over from 180° after accounting for α_l and μ. This margin angle plays a crucial role; it ensures the successful turn-off of the SCR.

Here, we can observe that the voltage V_{AC} provides the necessary forward bias to SCR T_1. At the same time, T_1 is also reverse-biasing SCR T_5. From the starting instant to the end instant we are considering, T_1 remains forward-biased. The remaining angle during this period is what we refer to as the margin angle. It is particularly significant because, during the overlap period represented by μ, both SCRs are conducting. This overlap period provides the time available for the successful commutation of the inverter's SCR. Importantly, this margin angle γ must exceed:

$$\gamma > T \cdot \omega \cdot t_q.$$

where t_q is the turn-off time of the SCR.

Let’s return to our analysis of the commutation process. We previously established that the rate of change of current is equal and opposite. If we examine the loop in this scenario, we find that it forms a closed loop, allowing us to apply Kirchhoff’s Voltage Law (KVL).

By applying KVL to this closed loop, we have:

$$V_{AC} + L_c \frac{di_A}{dt} - L_c \frac{di_C}{dt} = 0$$

This indicates that there is a potential drop across the inductor L_c, associated with the changing currents i_A and i_C. If we continue from this point, we can observe an increase in potential, and then, as we progress further along the loop, we will notice a corresponding decrease in potential. This dynamic illustrates the intricate balance of voltages and currents during the commutation process, highlighting the critical role of the margin angle in ensuring effective operation.

Let's delve into the equation we have established. We can apply our initial equation, let's label it as Equation (1), and proceed by substituting for $\frac{di_A}{dt}$ in order to simplify it. This gives us:

$$2L_c \frac{di_A}{dt} = -V_{AC}$$

From this, we can deduce that:

$$\frac{di_A}{dt} = -\frac{1}{2\omega L_c} V_{AC}$$

Now, if we examine this further, we can substitute I_A with the value of I_d. This substitution takes place during a specific time interval, and V_{AC} is represented by a sine wave starting from a given point.

To find out the integration, we can express $-I_d$ as follows:

$$-I_d = -\frac{1}{2\omega L_c} \int V_{AC} \ d\omega t$$

The integration limits will span from α to α_l and ultimately to $\alpha_l + \mu$. Here, V_{AC} is the line voltage. Thus, we can write:

$$-I_d = -\frac{1}{2\omega L_c} \int_{\alpha_L}^{\alpha_L+\mu} V_{AC} \ d\omega t$$

If we wish to obtain the peak value, we can multiply the RMS value by $\sqrt{2}$. This leads us to:

$$-I_d = -\frac{1}{2\omega L_c} \cdot \sqrt{2} V_{\text{line-to-line}} \cdot \sin(\omega t)$$

Upon integrating from α_l to $\alpha_l + \mu$, we find:

$$-I_d = -\frac{\sqrt{2}V_{\text{line-to-line}}}{2\omega L_c}[-\cos(\omega t)]_{\alpha_L}^{\alpha_L+\mu}$$

This results in:

$$-I_d = -\frac{\sqrt{2}V_{\text{line-to-line}}}{2\omega L_c}[\cos(\alpha_L) - \cos(\alpha_L + \mu)]$$

By removing the negative sign from both sides, we arrive at:

$$I_d = \frac{\sqrt{2}V_{\text{line-to-line}}}{2\omega L_c}[\cos(\alpha_L) - \cos(\alpha_L + \mu)]$$

This equation is pivotal as it provides a variant expression that yields the value of μ for a given α_l. Thus, if we know I_d and α_l, we can evaluate μ.

As we analyze the commutation process, we observe the delay of the current and the phase lag. Next, we will transition from AC to DC using another converter, or inversely, from AC to a synchronous machine. Let’s take a closer look at the block diagram illustrating the control of the synchronous machine.

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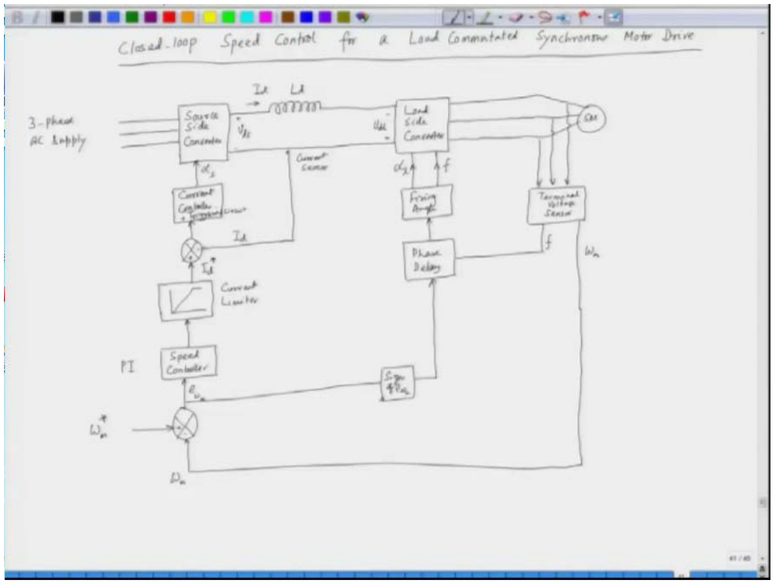

Let's take a closer look at the block diagram representing the speed control loops. We have two converters in this system: one on the source side and the other on the load side. The load-side converter feeds the synchronous motor, converting the AC voltage from a three-phase or AC supply into DC voltage. Here, we denote V_{ds} for the source voltage and V_{dl} for the load voltage.

In this setup, we incorporate a terminal voltage sensor. This sensor monitors the terminal voltage of the synchronous motor to ensure proper synchronization of the frequency. The key here is to align the frequency of the terminal voltage with that of the rotor. While we may not have a dedicated position sensor, the motor's position can often be inferred from the terminal voltage readings.

To control the system effectively, we provide a reference speed, denoted as ω and compare it with the actual speed obtained from the terminal voltage sensor. This comparison yields a differential speed value. The difference, or speed error, is processed by a speed controller.

Next, we have a current limiter, which ensures that the output current is maintained within a safe value. The reference current, I_d^*, is compared with the actual value of I_d sensed from the current sensor. The current error is fed into the current controller, which governs the triggering of the current. This controller helps to adjust the firing angle α_s for the load-side converter.

Furthermore, we set the load-side firing angle α_l based on this feedback. The system also accounts for frequency adjustments; this is accomplished through a phase delay block that receives input from the voltage sensor, which processes the sine of the error. Importantly, this block introduces a phase shift of 180 degrees.

Overall, we can observe that this is a closed-loop speed control system. The feedback mechanism makes this drive self-controlled, enhancing its stability and performance, especially in high-power applications.

With that, we'll conclude today's lecture. We will continue our discussion in the next session.