Fundamentals of Electric Drives

Prof. Shyama Prasad Das

Department of Electrical Engineering,

Indian Institute of Technology- Kanpur

Module No # 03

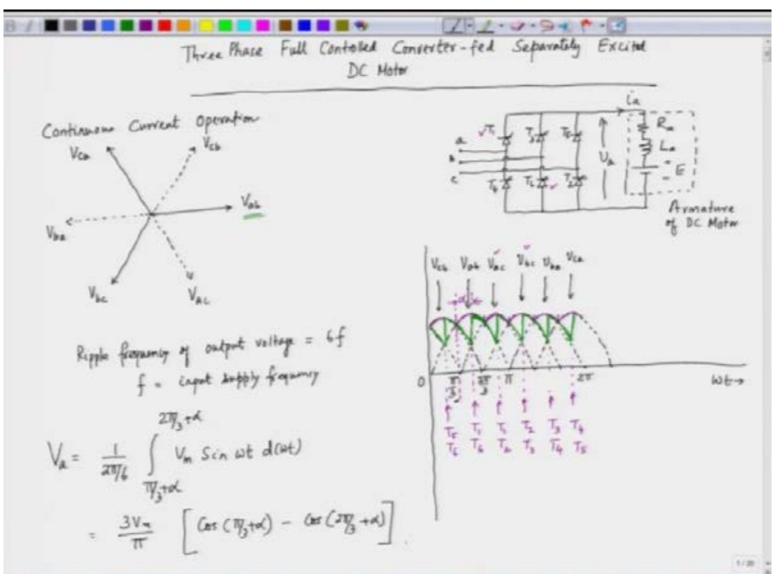
Lecture No # 12

Three Phase Full Controlled Converter-fed Separately Excited DC Motor, Multi-quadrant Operation of DC Motor

Hello and welcome to this lecture on the fundamentals of electric drives! In our last session, we discussed the half-controlled converter-fed separately excited DC motor. Today, we will delve into the fascinating world of the 3-phase fully controlled converter-fed separately excited DC motor.

When we refer to a 3-phase converter, it's essential to note that these systems are primarily used for higher power applications, typically those exceeding 10 kilowatts. The 3-phase AC supply plays a crucial role in providing the necessary power and efficiency for these applications. So, let's explore how these converters function and their significance in the realm of electric drives!

(Refer Slide Time: 00:53)



Today, we will explore the fascinating topic of the 3-phase fully controlled converter-fed separately excited DC motor. To begin, let’s examine the topology of the converter. This converter typically draws its supply from a 3-phase source, arranged in the form of a bridge configuration. Therefore, we can refer to it as a bridge converter.

Within this bridge, we have six silicon-controlled rectifiers (SCRs), labeled from T1 to T6. The input to the converter comes from the 3-phase AC supply, comprising Phase A, Phase B, and Phase C. The output of this configuration feeds the armature of the DC motor, which consists of resistance, inductance, and back EMF, denoted as E.

Now, focusing on the armature of the DC motor, we will define the output current as I_a and the output voltage across the armature as V_a. For our analysis, we will concentrate solely on continuous current operation. The phenomenon of discontinuous current only occurs within a very narrow range of operation, so our focus will be on continuous conduction.

Next, let's draw the output voltage waveform, V_a. We will represent this waveform with the angular frequency ω t plotted along the x-axis. To illustrate the output voltage, we will first plot the line voltages: V_{ab}, V_{bc}, and V_{ca}. Let’s go ahead and visualize these line voltages.

In this discussion, we focus on the voltage V_{ab}, which is the line voltage between phases A and B. This voltage is shifted by 120 degrees to produce V_{bc}, the line voltage between phases B and C. Similarly, V_{ca}, the line voltage between phases C and A, is also shifted by 120 degrees or $\frac{2\pi}{3}$ radians from V_{bc}.

To fully represent the waveforms, we must also consider the negative voltages: V_{ba}, V_{cb}, and V_{ac}. For instance, the reverse of the voltage V_{ab} is V_{ba}, while the reverse of V_{bc} is V_{cb}, and the reverse of V_{ca} is V_{ac}. These negative voltages can be visualized clearly alongside their positive counterparts.

A phasor diagram provides a comprehensive understanding of these six voltages and their phase sequence: A, B, C. In this diagram, V_{ab} is represented, followed by V_{bc}, which lags V_{ab} by 120 degrees, and finally V_{ca}. Additionally, we can represent the negative voltages: the negative of V_{ab} is V_{ba}, the negative of V_{bc} is V_{cb}, and the negative of V_{ca} is V_{ac}.

Now, in the context of a fully controlled bridge, we intentionally delay the triggering angle from the point of crossover. For example, during a specific region when V_{ab} reaches its maximum value, SCRs T1 and T6 are most forward-biased. If these SCRs were replaced by diodes, the output voltage waveform would appear differently, resembling a natural output voltage of an uncontrolled rectifier. Thus, if we examine the region where V_{ac} is the most positive voltage, we would see a distinct output characteristic compared to when SCRs are utilized.

Continuing from our previous discussion, we observe that in the transition from one region to another, we analyze V_{bc} and its corresponding effects. These points mark the crossover between the two line voltages, where one voltage becomes the most positive, and consequently, the SCR pair connected to that voltage becomes most forward-biased.

At this specific instant, we establish a reference point and intentionally delay the triggering angle by a certain value, which we denote as α. This delay alters the output voltage. This concept is known as triggering delay, and the angle α represents this adjustment. As we delay the triggering angle, the output voltage waveform shifts accordingly. Rather than adhering to the original violet pattern, the output will now follow the modified green pattern. Thus, the voltage V_a will appear as illustrated in this new representation.

Similarly, we can apply the same principle to the other SCRs, allowing us to delay their triggering angles as well. This delay yields an output voltage that takes on a new form, with α varying from 0 to 180 degrees. This waveform depicts the output voltage of a three-phase fully controlled bridge converter.

If we examine the x-axis, we identify that this point represents 0, while one half-cycle is completed at π, culminating in a full cycle at 2π. Additionally, we can pinpoint specific angles such as $\frac{\pi}{3}$ and $\frac{2\pi}{3}$ along this axis, providing a clear reference for our analysis.

Next, we need to determine the average output voltage. This can be calculated by integrating over one-sixth of the cycle. Notably, during one complete cycle, we observe that the ripple frequency indicates that the SCRs are triggered six times. At a specific instant, we trigger SCRs T1 and T6, coinciding with the moment when V_{ac} reaches its maximum value. This process establishes a consistent framework for understanding the operation of the fully controlled three-phase bridge converter.

Let's break this down for clarity. We start with SCRs T_1 and T_2. At this instant, V_{bc} is the most positive voltage, which prompts us to trigger T_2 and T_3. As we proceed, we note that when V_{ba} reaches its maximum, we activate T_3 and T_4. Following that, when V_{ca} is at its peak, we trigger T_4 and T_5. This pattern continues until we reach the maximum voltage V_{cb}, where we trigger T_5 and T_6. This sequence illustrates how the SCRs are systematically triggered throughout the cycle.

Now, over one complete electrical cycle, we experience a ripple frequency of 6f. Therefore, the output ripple frequency of the output voltage corresponds to 6f, where f represents the frequency of the input supply.

Next, we turn our attention to calculating the average output voltage, denoted as V_a. To do this, we will integrate from $\frac{\pi}{3} + \alpha,$ assuming V_{ab} serves as our reference voltage. Here, the angle starts at 0, making this our reference point. The integration begins at $\frac{\pi}{3}$ since this angle corresponds to the line voltage. We apply a delay of angle α and continue the integration until we reach $\frac{2\pi}{3} + \alpha,$ acknowledging that each delay introduces an angle α.

Thus, we are essentially integrating over this interval. Our voltage expression can be defined as $V_m \sin(\omega t)$, and we will integrate this with respect to d(ω t). The average voltage can be calculated as $\frac{1}{2\pi} \cdot \frac{1}{6}$, reflecting that we are working with one-sixth of the cycle, equivalent to $\frac{2\pi}{6}$.

Simplifying this, we arrive at $\frac{3V_m}{\pi}$. However, we must remember to factor in the cosine terms from our integration, leading us to the expression $-\left(\cos\left(\frac{\pi}{3} + \alpha\right) - \cos\left(\frac{2\pi}{3} + \alpha\right)\right)$. Upon further simplification, we ultimately derive the voltage value as follows.

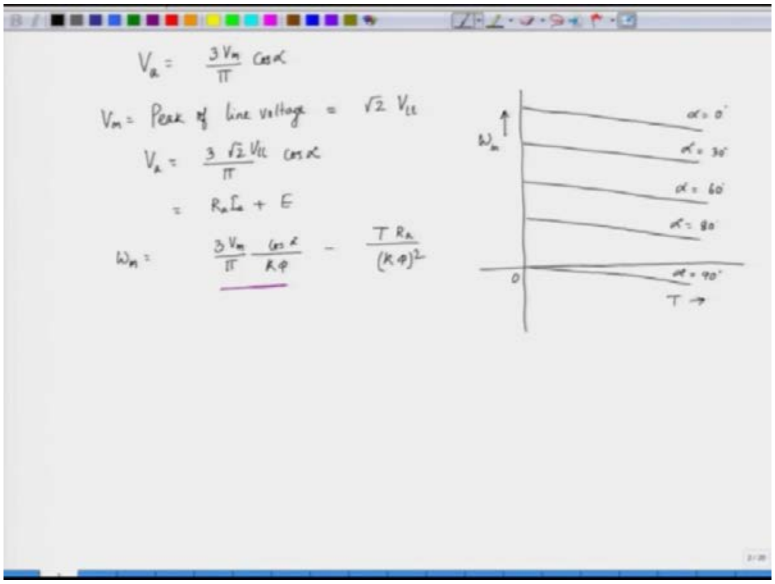
The average output voltage V_a is expressed as:

$$V_a = \frac{3V_m}{\pi} \cos \alpha.$$

Upon simplification, we find that the output is indeed $\frac{3V_m}{\pi} \cos \alpha$. Here, V_m represents the peak of the line voltage, and since our input is alternating current (AC), the line voltage is equivalent to $\sqrt{2}$ times the line-to-line voltage (V_{ll}). Therefore, we can also represent V_a as:

$$V_a = \frac{3\sqrt{2}V_{ll}}{\pi}\cos\alpha.$$

(Refer Slide Time: 15:34)



In this analysis, we are assuming continuous current operation. Given the ripple frequency of 6f, the likelihood of the current dropping to zero is quite remote; such a scenario only occurs within a very narrow operational range. Consequently, we will not delve into discontinuous current operation for the purposes of this course.

Now, if we wish to plot the speed-torque characteristics, we need to equate this voltage to the armature drop and the back electromotive force (EMF). This relationship is defined as:

$$V_a = I_a R_a + E.$$

From this equation, we can derive the speed-torque characteristics. The expression for angular speed ω_m is:

$$\omega_m = \frac{3V_m}{\pi}\cos\alpha \cdot \frac{1}{K\phi} - \frac{TR_a}{K\phi^2}$$

When we plot these speed-torque characteristics, the no-load speed (also known as the "Knoller speed") is determined by this equation. Notably, the angle α can vary from 0 to 180 degrees, which introduces the possibility of the torque becoming negative.

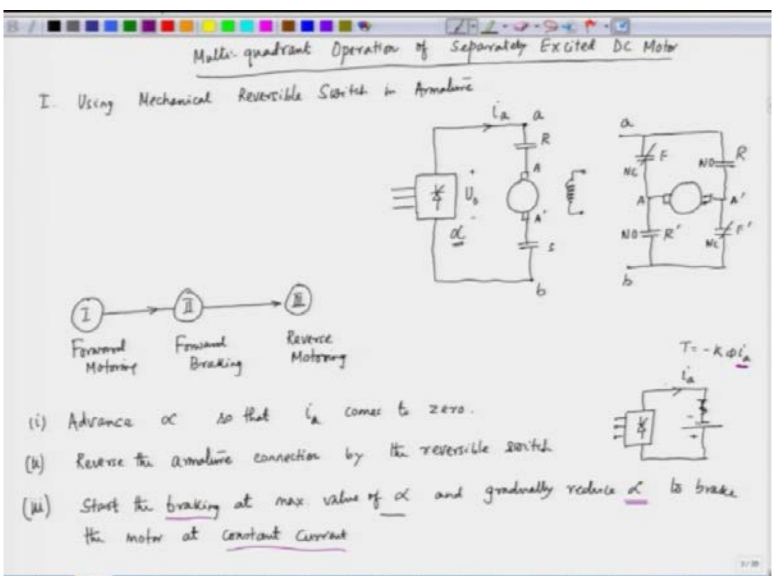
Let's examine specific values of α: for instance, when $\alpha = 0$, $\alpha = 30^\circ$, $\alpha = 60^\circ$, and perhaps $\alpha = 80^\circ$. However, at $\alpha = 90^\circ$, we reach a critical point where the no-load speed becomes zero, indicating that continuous current conduction is maintained.

In our plot, we will depict angular speed ω_m on the y-axis and torque on the x-axis. This results in the torque-speed characteristics for a three-phase, full-controlled converter-fed DC motor drive, which is particularly suited for higher power applications.

When dealing with significant power levels, we typically prefer three-phase converters over single-phase converters.

Now, let's transition to discussing the multi-quadrant operation of DC drives. It is essential to understand that whenever we operate a drive, it may employ a single converter, either a fully controlled single-phase converter or a fully controlled three-phase converter. However, our objective is to ensure that the drive can operate in multiple quadrants. So, what are the necessary steps to facilitate this multi-quadrant operation?

(Refer Slide Time: 19:28)



Today, we will be discussing the multi-quadrant operation of separately excited DC motors. To illustrate this, let's start with the first method: using a mechanical reversible switch in the armature circuit.

In this setup, we have a converter that supplies power to the armature of a separately excited DC motor. Specifically, we utilize a three-phase fully controlled converter for this purpose. Alongside this, we incorporate a reversible switch, denoted as R_s, which facilitates the directional control of the current.

Now, the current flows in a specific direction through the armature, and there is a corresponding voltage applied. The operation of this reversible switch can be understood as follows: it consists of four switches. One pair of switches is designated as the forward switch, while the other pair connects the armature in the opposite direction.

Let’s label two points in our circuit: point A and point B. Here, point A refers to one terminal, while point B refers to another. We can identify two pairs of switches: F and F' as well as R and R'. Notably, the switches F and F' are normally closed (NC) switches, which means they typically allow current to flow. Therefore, with the forward voltage applied, point A is connected to the output of the converter, leading to a positive voltage and a unidirectional current flow.

When we decide to change the direction of the current, we open the normally closed switch F. This action enables the ON switches R and R' to close, effectively reversing the current through the armature. For example, if point A is connected to A' and A to B, activating R and R' would alter the current flow accordingly.

Now, let’s outline the operational steps involved in this multi-quadrant process. The first step, known as forward motoring, allows the motor to run in the desired direction. To transition to the second step, which is fast forward braking, we must engage the braking process. Finally, we arrive at the third step, which is termed reverse motoring.

It's important to note that shifting from step one (forward motoring) to step two (fast forward braking) and then to step three (reverse motoring) cannot occur automatically with a single converter. Instead, careful control and switching are required to facilitate these transitions smoothly and effectively.

To successfully execute the braking process, we must follow several essential steps. First and foremost, we initiate what is known as forward braking. How do we accomplish this? We start by increasing the triggering angle, denoted as α. Initially, the bridge operates at a specific triggering angle α. By advancing this angle, we aim to bring the armature current I_a down to zero; this marks our first step.

As we advance the angle α, the output voltage V_o becomes negative. Consequently, the current I_a will not be sustained by the input voltage, leading to a gradual decrease in I_a until it reaches zero. At this point, it is crucial to remember that the field is separately excited, and we do not alter the field connections during this process.

Once I_a approaches zero, we proceed to the next step: reversing the armature connections using the reversible switch. This action is followed by a third step, where we start braking at the maximum value of α and gradually reduce α. Essentially, we begin with α at its maximum possible value, ensuring the motor brakes at a constant current.

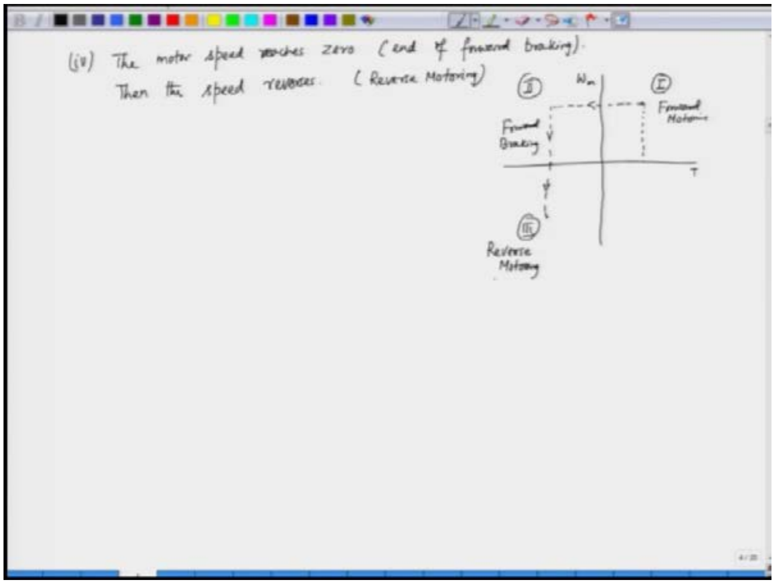
Now, with the armature connection reversed, the back electromotive force (back EMF) also reverses. Thus, we need to advance the triggering angle α further. It’s important to note that, while we start with an advanced α, the current remains positive throughout this process. However, the torque experiences a reversal due to the armature connection change. The torque can be expressed as:

$$T = -K\phi I_a$$

Here, the reversal of the armature connection leads to a negative torque. When the torque turns negative, braking occurs effectively. Therefore, our braking strategy relies on controlling α to ensure we can brake at a constant current. In this scenario, with the torque being negative, we enter the braking mode where I_a is managed to achieve the maximum possible torque during braking.

As we progress, the motor's speed gradually reverses until it ultimately reaches zero. This marks the conclusion of the forward braking phase. Once the armature connection is reversed, the torque turns negative, causing the speed to reverse as well. When this happens, the motor continues to accelerate in the negative direction, entering what we refer to as reverse motoring.

(Refer Slide Time: 28:29)



In this context, we transition from one quadrant of operation to another. Specifically, we move from quadrant one, which represents forward motoring, into quadrant four, where braking occurs. The fourth quadrant is characterized by negative torque. From there, we transition into the second quadrant, and eventually into the third quadrant.

To illustrate this progression: we start in the first quadrant, then move to the second quadrant, apply braking at the maximum possible torque, and finally operate under reverse motoring conditions. Although the motor speed eventually drops to zero, the torque remains negative due to the reversal of the armature connection. This indicates that we are now functioning in reverse motoring.

This process demonstrates how we can transition between quadrants for a separately excited, fully controlled converter-fed DC motor. It’s worth noting that, traditionally, mechanical contractors are employed to change the armature connections, which can sometimes be cumbersome. However, we can achieve the same effect electronically by utilizing a dual converter. This dual converter consists of two converters connected in an anti-parallel configuration, enabling a seamless transition between forward motoring, forward braking, and reverse motoring. We will delve deeper into this topic in the next lecture.