Fundamentals of Electric Drives

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Module No # 03

Lecture No # 13

Dual Converter-fed DC Motor, Multi-quadrant Operation Using Field Current Reversal

Hello and welcome to this lecture on the fundamentals of electric drives! In our previous session, we explored the multi-quadrant operation of DC drives fed by converters. We discussed how, through the use of mechanical switches, we can seamlessly transition from forward motoring to forward braking, and then on to reverse motoring. This was the core of our discussion last time, highlighting the versatility and control we have in managing DC motor operations.

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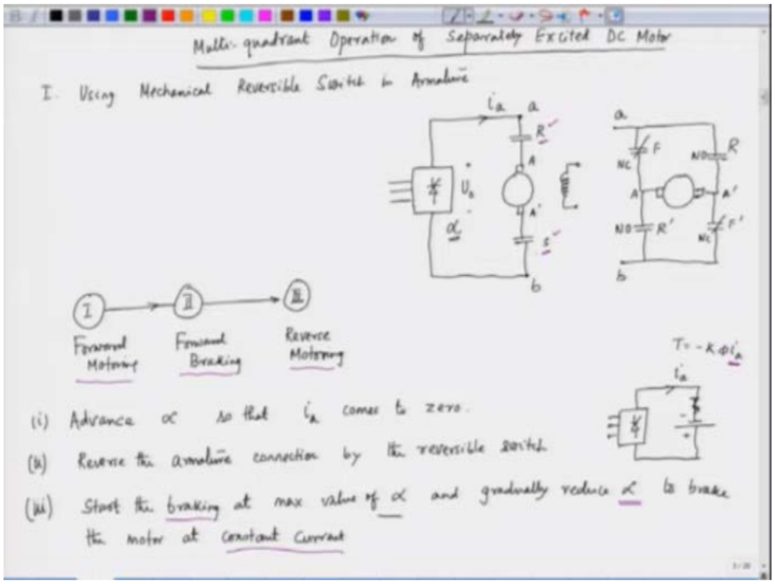

Multi-quadrant Operation of Separately Excited DC Motor

I. Using Mechanical Reversible Switch in Armature

① → Ⅱ → Ⅲ

Forward Motoring → Forward Braking → Reverse Motoring

(i) Advance α so that i_a comes to zero.

(ii) Reverse the armature connection by the reversible switch

(iii) Start the braking at max value of α and gradually reduce α to brake the motor at constant current

$T = -K\phi i_a$

In this setup, we have the armature connected to reversible switches, with a converter supplying power to the armature of the DC machine. This arrangement allows us to transition from the first quadrant, which is forward motoring, to forward braking by reversing the switches once the current drops to zero. After that, we can reverse the speed and move into reverse motoring.

However, using these mechanical contactors can sometimes be cumbersome, as they require maintenance and do not provide a very smooth transition between quadrants.

An alternative solution is to implement a dual converter, which we will be discussing in today's lecture. This method offers a more efficient and seamless way to manage the operation across multiple quadrants.

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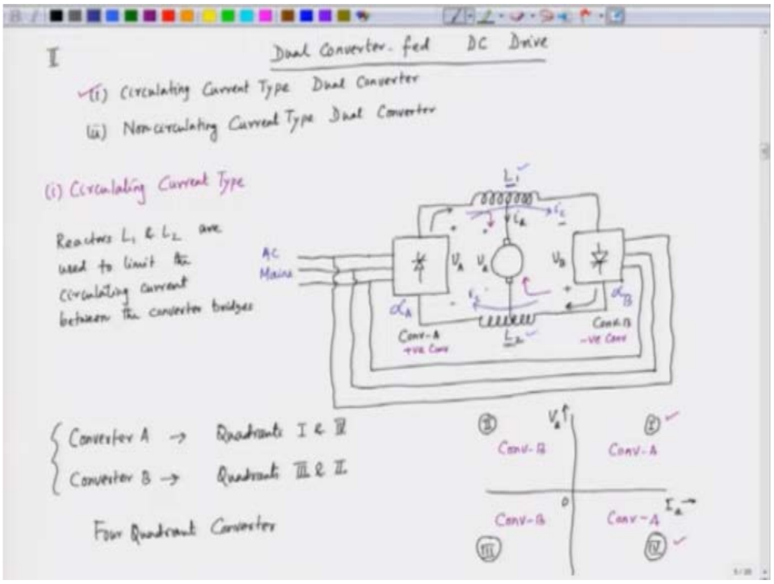

Dual Converter-fed DC Drive

(i) Circulating Current Type Dual Converter

(ii) Non-circulating Current Type Dual Converter

(i) Circulating Current Type

Reactors L_1 & L_2 are used to limit the circulating current between the converter bridges

Converter A → Quadrants I & IV

Converter B → Quadrants III & II

Four Quadrant Converter

Now, let's explore the second method known as the dual converter for DC drives. To begin with, we have two types of dual converters: the circulating current type and the non-circulating current type. For today's discussion, we will focus on the circulating current type dual converter and examine how it connects to the armature circuit.

In this configuration, we have two converters, which I will illustrate as boxes. Each of these converters is an SCR bridge, specifically a three-phase full control bridge converter. These two converter bridges are connected in an anti-parallel arrangement, but not directly. Instead, they are linked through inter-group reactance. This is how the two converters are connected in parallel or in an anti-parallel manner.

The armature is fed from the center tap of the converters. We denote this inductor or reactor as L1 and the other as L2. Both converters receive a supply from a three-phase source, which is connected to the mains. The second phase is also linked to the second converter, ensuring that all inputs come from the mains supply. We refer to these converters as Converter A and Converter B.

The voltage output from Converter A is designated as V_A, while the voltage output from Converter B is labeled as V_B. Since these converters are connected in an anti-parallel configuration, we position the positive side of one converter here and the negative side of the other here. The armature current, denoted as I_A, typically flows in this direction, and the back EMF voltage across the armature is represented as V_A.

These two converters can only carry current in one direction, as they utilize unidirectional switches. Therefore, the current from Converter A flows in this manner, while the current from Converter B flows in the opposite direction. Additionally, the inter-group reactors, L_1 and L_2, are integrated into the system to limit the circulating current between the converter bridges.

These reactors or inductors are essential for constraining the circulating current, denoted as I_c, that flows between the two bridges. Ideally, the voltages V_A and V_B should be the same; however, because they are converters, while the average voltage can be matched, the instantaneous voltages will not be identical. Consequently, some circulating current will occur between the two bridges, which needs to be minimized using the inter-group or inter-bridge reactors L_1 and L_2.

Now, let’s explore how many quadrants can be achieved with this setup. If we construct a voltage-current (V-I) plot, with voltage on the Y-axis and current on the X-axis, it will appear as follows:

This plot represents the armature voltage V_A and the armature current I_A. In this representation, we identify the first quadrant, the second quadrant, and the fourth quadrant. In the first quadrant, V_A is positive, and I_A is also positive. Conversely, in the second quadrant, V_A remains positive while I_A turns negative. This indicates that the current I_A must originate from one of the converters: either from Converter A or from Converter B.

If the current is positive, it must originate from Converter A. Conversely, if the current is negative, it has to be supplied by Converter B, as Converter B only provides current in that direction. This defines the flow: the current from Converter B is shown here, while the current from Converter A flows in the opposite direction. Therefore, we often refer to Converter A as the positive converter, capable of supplying positive current, or simply as the P converter. In contrast, Converter B is sometimes labeled as the negative converter, as it can only supply negative current.

In this context, the voltage from Converter A can indeed be negative; however, the current will always remain positive. This means that Converter A operates within quadrants 1 and 4 of the V-I plane. Specifically, the voltage can become negative when the triggering angle α_A exceeds 90 degrees, thanks to the full control bridge configuration. Nonetheless, regardless of the voltage, the current through Converter A must stay positive.

Now, let’s shift our focus to Converter B. Unlike Converter A, Converter B operates with reversible voltage but can only supply negative current. Consequently, Converter B functions within quadrants 2 and 3. Here, the voltage can be reversible, allowing it to operate in both quadrants 2 and 3.

This arrangement gives us four distinct quadrants of operation, which is why we refer to it as a four-quadrant converter. By utilizing a dual converter, we effectively create this four-quadrant capability, allowing operation across all possible quadrants.

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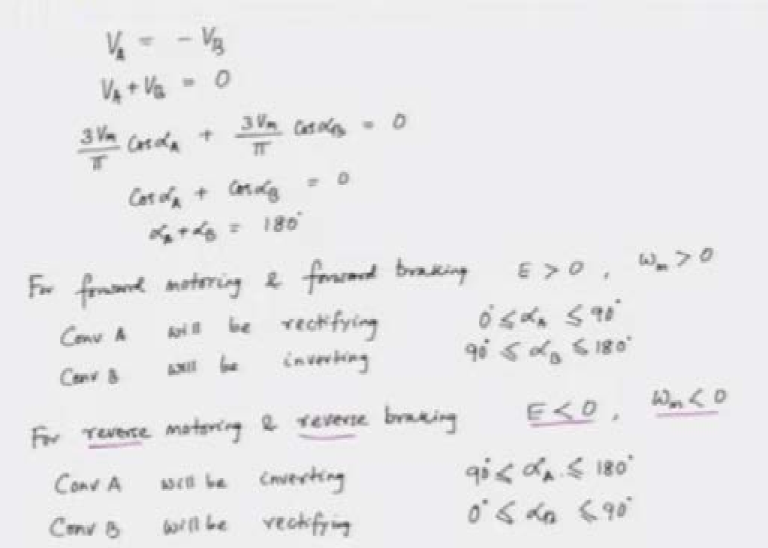

$$V_A = -V_B$$

$$V_A + V_B = 0$$

$$\frac{3V_m}{\pi} \cos\alpha_A + \frac{3V_m}{\pi} \cos\alpha_B = 0$$

$$\cos\alpha_A + \cos\alpha_B = 0$$

$$\alpha_A + \alpha_B = 180^\circ$$

For forward motoring & forward braking $E > 0$, $\omega_m > 0$

Conv A will be rectifying $0^\circ \leq \alpha_A \leq 90^\circ$

Conv B will be inverting $90^\circ \leq \alpha_B \leq 180^\circ$

For reverse motoring & reverse braking $E < 0$, $\omega_m < 0$

Conv A will be converting $90^\circ \leq \alpha_A \leq 180^\circ$

Conv B will be rectifying $0^\circ \leq \alpha_B \leq 90^\circ$

Now, let’s examine the relationship between the triggering angles α_A and α_B. Both converters are operated simultaneously, receiving appropriate triggering pulses to manage their outputs. It is crucial that the voltages from these two converters are equal; since inductors L_1 and L_2 ideally do not possess resistance, we must ensure that the voltages produced by the two converters remain balanced.

Let's establish the voltage equation: $V_A = -V_B$. This indicates that the voltage V_B must be the negative of V_A, which can also be expressed as $V_A + V_B = 0$. Consequently, the voltages of these two converters within this loop must sum to zero. In other words, the average voltage of Converter A added to the average voltage of Converter B should equal zero, since the inductors L_1 and L_2 do not introduce any average voltage drop.

When we express this as $V_A + V_B = 0$, we recognize that V_A is derived from a fully controlled bridge, represented by the equation:

$$V_a = \frac{3V_m}{\pi} \cos \alpha_A$$

Thus, we can rewrite our relationship as:

$$\frac{3V_m}{\pi} \cos \alpha_A + \frac{3V_m}{\pi} \cos \alpha_B = 0$$

From here, we can simplify to get:

$$\cos \alpha_A + \cos \alpha_B = 0$$

Further simplification yields the relationship:

$$\alpha_A + \alpha_B = 180^\circ$$

This means that the triggering angles of the two converters must add up to 180 degrees. For instance, if one converter operates at a triggering angle of 60°, the other must operate at $180^\circ - 60^\circ = 120^\circ$. This relationship allows us to determine one triggering angle if the other is known.

Now, when discussing forward motoring and braking, it is crucial to ensure that the drive operates effectively across all four quadrants. In the case of forward motoring and forward braking, the back electromotive force (EMF) is positive, meaning that E is greater than zero. When we refer to "forward," we imply that the speed is positive, indicating that the speed exceeds zero.

At the point where the speed reaches zero, Converter A will operate in rectifying mode, thus functioning as a rectifier.

Now, let’s clarify the operation of Converter B. When we say that Converter A is in rectifying mode, it indicates that the triggering angle α_A ranges from 0° to 90°. Conversely, when we state that Converter B is inverting, it operates at a negative output voltage, which means that α_B should fall between 90° and 180°.

It is crucial to emphasize that during forward motoring and forward braking, the voltage V_A remains positive. This positive voltage indicates that the motor is functioning in the forward direction, leading both V_A and V_B to be positive. Thus, for this scenario, α_A ranges from 0° to 90°, while α_B spans from 90° to 180°.

Now, let's examine the case of reverse motoring. To facilitate reverse motoring, we need to change the polarity of the supply voltage. This action results in a negative back EMF, which in turn implies that the supply voltage must also be negative. Therefore, for reverse motoring and reverse braking, we find that the back EMF is negative, and the speed is also negative. When we refer to reverse motoring, we understand that the speed is negative, which means the back EMF follows suit and is likewise negative.

In this scenario of reverse motoring and reverse braking, what happens to Converter A? The output voltage of Converter A must be negative, which means that Converter A will be operating in inverting mode. Consequently, the triggering angle α_A must range from 90° to 180°.

On the other hand, Converter B will be in rectifying mode, meaning that α_B will fall between 0° and 90°. Thus, in the context of reverse motoring, we observe that Converter A operates in inverting mode while Converter B functions in rectifying mode.

Now, we also have another type of dual converter known as the non-circulating current type dual converter. We will briefly touch on that topic as well.

Now, let's explore the second type of dual converter: the non-circulating current type dual converter. In this configuration, we again have two bridges connected to the same three-phase supply, which is designated as abc. However, unlike the circulating current type, these two converters are directly connected in anti-parallel.

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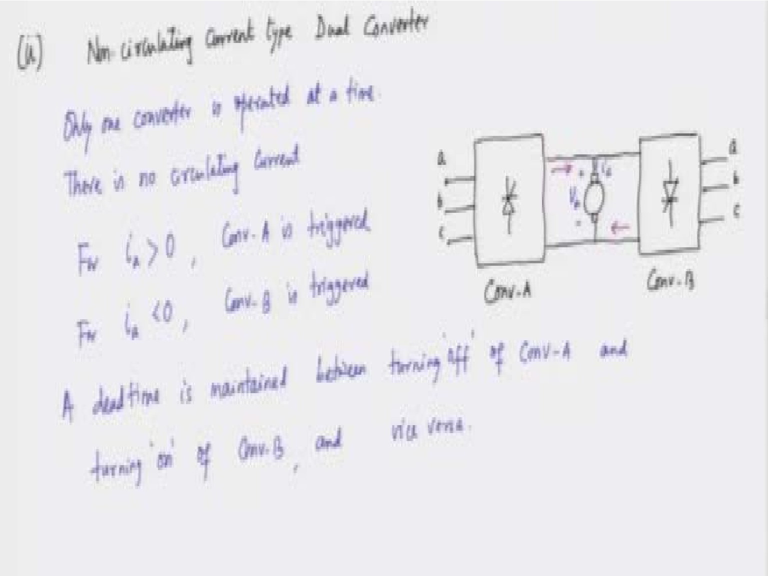

(ii) Non-circulating Current type Dual Converter

Only one converter is operated at a time.

There is no circulating current

For $i_A > 0$, Conv-A is triggered

For $i_A < 0$, Conv-B is triggered

A deadtime is maintained between turning 'off' of Conv-A and turning 'on' of Conv-B, and vica versa.

Here, we have Converter A and Converter B, both of which are supplied by the same three-phase supply. The armature is connected to a common point, which serves as the armature connection. It’s important to note that Converter A and Converter B do not operate simultaneously; rather, only one converter operates at a time. When we require forward motoring or forward braking, we utilize Converter A. Conversely, for reverse motoring and reverse braking, we engage Converter B.

This means that Converter A is solely responsible for supplying positive current, while Converter B exclusively provides negative current. Since only one converter operates at any given time, there is no circulating current in this setup.

The output current I_A is monitored, along with the output voltage V_A. To achieve a positive output current, we trigger Converter A, and when we need a negative output current, we trigger Converter B. This operational method allows for clear control of the current direction based on the selected converter.

To achieve a positive output current I_A, we trigger Converter A, while to obtain a negative output current, Converter B must be activated. However, it's crucial to introduce a dead time when switching from triggering Converter A to triggering Converter B. This pause ensures that one bridge is completely turned off before the next bridge is engaged. If we neglect this precaution, there is a risk of short-circuiting the AC supply. Therefore, we maintain a dead time between the deactivation of Converter A and the activation of Converter B, and vice versa.

When transitioning between the operations of Converter A and Converter B, it is essential to ensure that one converter is entirely off before the other is triggered. This requirement is particularly important because, in this configuration, there are no intergroup reactors to limit the current flow. Hence, we allow for a dead time between the two converters to prevent any issues.

Now, moving on from the non-circulating current type dual converters, we will explore another method for achieving multi-quadrant operation: reversing the field current. In our system, we have both the armature and the field windings. While we've previously discussed armature control, we will now delve into the concept of field control and how it allows us to reverse the back electromotive force (back EMF). Let's explore field control in detail.

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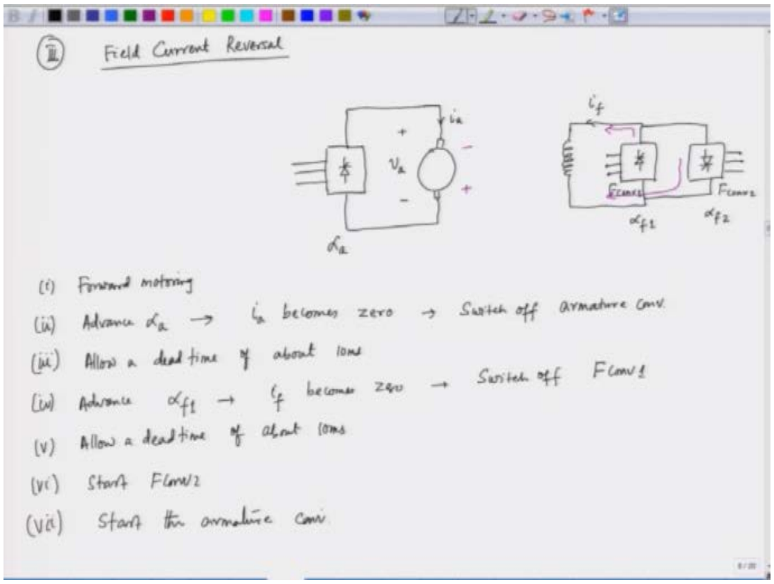

(III) Field Current Reversal

(i) Forward motoring

(ii) Advance α_a → i_a becomes zero → Switch off armature conv.

(iii) Allow a dead time of about 10ms

(iv) Advance α_{f1} → i_f becomes zero → Switch off Fconv1

(v) Allow a dead time of about 10ms

(vi) Start Fconv2

(vii) Start the armature conv

The third method for achieving multi-quadrant operation is through field current reversal. In this configuration, the armature is supplied by a fully controlled bridge, typically a three-phase bridge, just as usual. However, the field winding is supplied by a separate set of bridges. We essentially have a dual converter-type setup, consisting of two anti-parallel bridges that provide power to the field winding.

In our system, we can visualize it as follows: we have two bridges supplying the field winding, which we refer to as Field Converter 1 and Field Converter 2. Both bridges are connected to a three-phase supply. The field current is denoted as I_f, and the triggering angle for the first bridge is labeled as α_{F1}, while the triggering angle for the second bridge is denoted as α_{F2}.

On the armature side, we have the armature current I_A and the armature voltage V_A, with the triggering angle of the armature bridge referred to as α_A.

Now, let's discuss how we reverse the back electromotive force (back EMF). When we are operating in the forward motoring mode, the first step we take is to advance the triggering angle α.

This describes the first operation in reversing the back EMF. If we want to reverse the field current, we begin by advancing α_A. When we advance α_A, what occurs is that V_A becomes negative, and consequently, the armature current I_A decreases to zero. At this point, when I_A reaches zero, there is no armature current flowing, so we need to introduce a dead time.

During this dead time, we switch off the armature converter, allowing for a brief period, approximately 10 milliseconds, before proceeding. After this, we advance α_{F1}. For instance, let’s say α_{F1} was initially positive, resulting in a positive field current. When we advance α_{F1}, the field current I_f becomes negative and eventually reaches zero.

Once I_f is at zero, we switch off Field Converter 1 and allow another dead time of about 10 milliseconds before starting Field Converter 2. When we activate Field Converter 2, the current reverses direction; earlier, the current flowed in one direction, but now it flows in the opposite direction.

This is how we achieve the reversal of the back EMF. Once the back EMF has reversed, we can then start the armature converter. Thus, we effectively transition from forward motoring to forward braking and then to reverse motoring. As a result of the reversed field current, the torque becomes negative. This concludes today’s lecture, and we will continue our discussion in the next class.