Fundamentals of Electric Drives

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Module No # 03

Lecture No # 15

Two- quadrant DC Chopper, Four-quadrant DC Chopper

Hello and welcome to our lecture on the fundamentals of electric drives! In our last session, we delved into the concepts of motoring and braking operations using chopper-fed control. Today, we will explore how to integrate both motoring and braking functions within a single chopper system.

Individually, a chopper can operate in either the first quadrant for motoring or the second quadrant for braking. However, we can cleverly combine these two operations within one chopper to achieve both motoring and braking capabilities.

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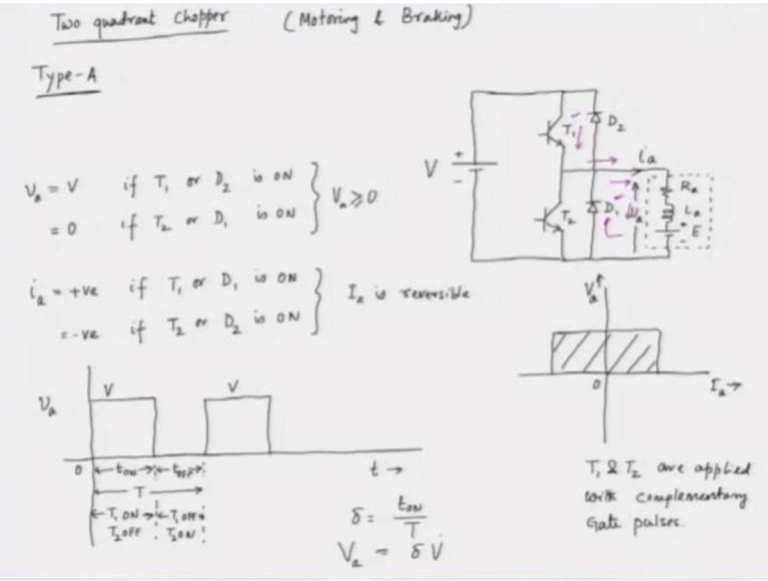

Two quadrant chopper (Motoring & Braking)

Type-A

$V_a = V$ if T_1 or D_2 is ON
$= 0$ if T_2 or D_1 is ON $\Big\}$ $V_a \geq 0$

$i_a = +ve$ if T_1 or D_1 is ON
$= -ve$ if T_2 or D_2 is ON $\Big\}$ I_a is reversible

$\delta = \frac{t_{ON}}{T}$

$V_a = \delta V$

T_1 & T_2 are applied with complementary Gate pulses.

In today’s lecture, we will focus on the two-quadrant chopper. Our objective is to achieve both motoring and braking functionalities using a single chopper system. We have two classifications, and we’ll start with Type A, which is the two-quadrant chopper.

A Type A two-quadrant chopper is designed to facilitate both motoring and braking operations. In this configuration, we combine the components necessary for each operation. The circuit includes feedback diodes, and the armature is represented by its resistance, inductance, and back EMF.

Let’s break down the components: on the input side, we have the supply voltage V. The components include transistor T_1, diode D_1, transistor T_2, and diode D_2. The armature resistance and inductance are also represented, along with the back EMF E, which corresponds to the armature of the DC machine, just as we discussed previously.

Now, the current flows into the armature, and the voltage across the armature is denoted as V_a. When we consider the supply voltage V, the armature voltage V_a equals V when either transistor T_1 or diode D_2 is turned on. This means that if either of these devices is conducting, the input voltage is equal to the output voltage, resulting in $V_a = V$.

Conversely, when either diode D_1 or transistor T_2 is activated, the armature voltage V_a drops to zero. In this scenario, the voltage V_i becomes short-circuited, leading to $V_a = 0$. It's important to note that V_a is always positive, indicating that $V_a \geq 0$.

Next, let’s consider the armature current I_a. The armature current can be either positive or negative. The current is positive if either transistor T_1 or diode D_1 is turned on. In this case, the current flows from the source, resulting in a positive value for I_a.

However, can the armature current be negative? Yes, it can be negative if either transistor T_2 or diode D_2 is activated. In this situation, I_a flows in the opposite direction, indicating that I_a is negative when T_2 or D_2 is conducting.

The voltage remains positive, which indicates that the current is reversible, meaning the armature current I_a can flow in either direction. Now, if we were to plot the operation of this Type A two-quadrant chopper, we could represent it in the V_i plane. Here, the armature voltage is on the Y-axis, while the armature current is on the X-axis, creating a standard XY coordinate system.

In this setup, the armature voltage is always positive; it can be zero, but it predominantly remains positive. Conversely, the current can indeed be negative. This configuration illustrates that our chopper operates within two quadrants, thereby designating it as a two-quadrant chopper.

Next, let’s examine the voltage and current waveforms. If we plot the armature voltage, it will either be V or 0. We can define time intervals for T_{ON}, T_{OFF}, and the total period T. During the T_{ON} interval, transistor T_1 is activated, while transistor T_2 is supplied with complementary pulses. This means that when T_1 is on, T_2 is off, and vice versa.

Thus, the output during these intervals reflects this relationship: for the duration when T_1 is on and T_2 is off, we label that segment as T_{ON}. During the subsequent interval, where T_1 is off and T_2 is on, we define that as T_{OFF}. As we analyze the armature voltage V_a, we see it alternates between V and 0.

Now, let’s discuss the duty cycle, represented by δ, which is defined as $\delta = \frac{T_{ON}}{T}$.

But what about the average armature voltage? From this voltage waveform, we can effortlessly calculate the average armature voltage through integration. By inspection, we can deduce that the average armature voltage equals $\delta \cdot V$, where δ represents the duty cycle.

Now, let’s proceed to plot the current waveform as well!

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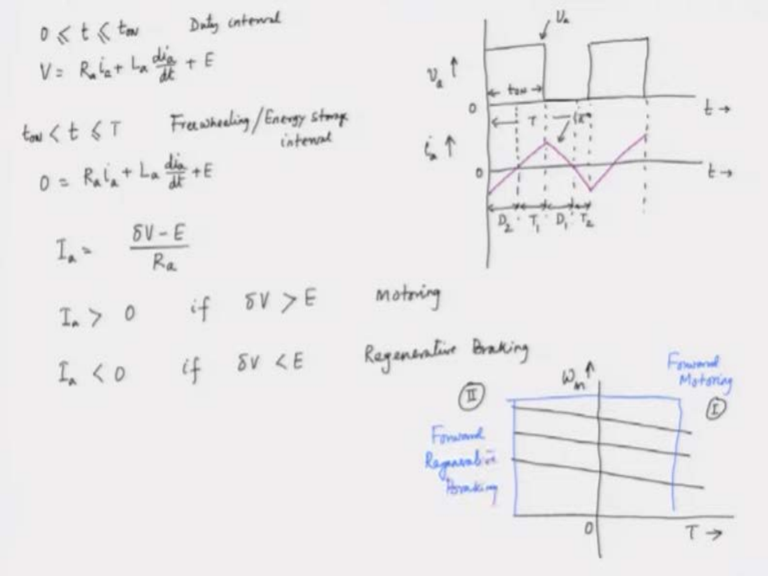

$0 \leqslant t \leqslant t_{ON}$ Duty interval

$V = R_a i_a + L_a \frac{di_a}{dt} + E$

$t_{ON} < t \leqslant T$ Freewheeling/Energy storage interval

$0 = R_a i_a + L_a \frac{di_a}{dt} + E$

$I_a = \frac{\delta V - E}{R_a}$

$I_a > 0$ if $\delta V > E$ motoring

$I_a < 0$ if $\delta V < E$ Regenerative Braking

Now, if we plot the current and voltage waveforms on the same graph, we can see that the voltage waveform presents a rectangular shape, characterized by time intervals T_{ON} and T_{OFF}. Alongside this, we will also plot the armature current waveforms. The time axis will be represented on the X-axis, with the armature voltage plotted above it and the armature current below.

Let's first consider how the current will behave. It's important to note that this is a first-order circuit. For the interval where $T > 0$ and $T < T_{ON}$, we can express the relationship using the equation:

$$V = R_a I_a + L_a \frac{dI_a}{dt} + E$$

Here, R_a I_a represents the armature resistance drop, $L_a \frac{dI_a}{dt}$ accounts for the inductive drop, and E is the back EMF.

During the duty interval, specifically for $T > T_{ON}$ and $T < T$, the current enters a free-wheeling state, and its value drops to zero. Therefore, the equation simplifies to:

$$0 = R_a I_a + L_a \frac{dI_a}{dt} + E$$

This phase is referred to as the free-wheeling interval or the energy storage interval. As we analyze the output current, we note that the armature current can exhibit various waveforms, allowing for both positive and negative values.

To clarify this further, let's categorize the waveform into different time regions. For instance, in the first region, the voltage is positive while the current is negative. In examining the chopper circuit, we can infer that when the voltage is positive, either transistor T_1 is on or diode D_2 is conducting. However, since the current is negative, it confirms that D_2 must be the active device during this interval.

Now, moving to the second interval, we see that both the voltage and current are positive. In this scenario, it is evident that T_1 is the device carrying the current, confirming that T_1 is actively conducting during this time.

Now, let's examine the third interval, which corresponds to one complete time period T, where we again denote T_{ON}. In this third interval, the duration from T_{ON} to T is characterized by a voltage of zero, yet the current remains positive. The fact that the voltage is zero indicates that we are in a free-wheeling state, where energy is being stored. Since the current is positive during this phase, it confirms that free-wheeling is occurring through diode D_1, which is actively conducting the current.

Moving on to the fourth zone, we encounter a scenario where the voltage is still zero, but the current has turned negative. When the current is negative, it signifies that the transistor T_2 is on, indicating that energy is being stored in the inductor L_a for the purpose of braking operation. This interval represents the time during which T_2 is actively conducting. Thus, we can see how the cycle unfolds, with four distinct devices operating in various regions throughout the different time zones.

Now, let’s address the conditions under which we can determine whether the average current is positive or negative. It's essential to remember that if the current is reversible, the voltage will always remain positive or at least zero. The average current is influenced by the value of the applied voltage. Specifically, the relationship can be expressed as:

$$I_{avg} = \frac{\Delta V - E}{R_a}$$

In this equation, the average current will be positive if the average voltage exceeds the back EMF E. This condition indicates that we are in the motoring region. Therefore, we can conclude that the machine is in motoring mode when δ V is greater than E, signifying that the average current is positive.

In this scenario, the average current is negative if δ V is less than E, which indicates that we are in the regenerative braking mode. This system functions as a drive that can operate in two quadrants, allowing it to perform both motoring and braking. It’s crucial to note that the voltage is always positive, which in turn signifies that the speed is also positive.

Now, if we were to illustrate the operation on a speed-torque characteristic graph, we would see that this system operates in both of these quadrants. On this graph, speed is represented on the Y-axis, while torque is plotted on the X-axis. The operation of this converter spans both the first and second quadrants, which is why it is referred to as a two-quadrant converter.

The first quadrant corresponds to forward motoring, while the second quadrant is designated for forward regenerative braking. However, it’s important to highlight that, despite this converter’s ability to facilitate both motoring and braking, the speed can only move in one direction; it does not allow for speed reversal.

To address this limitation, we have another type of two-quadrant converter known as type B topology. This alternative topology also operates in two quadrants, but its design and functionality differ slightly from the type A topology we just discussed.

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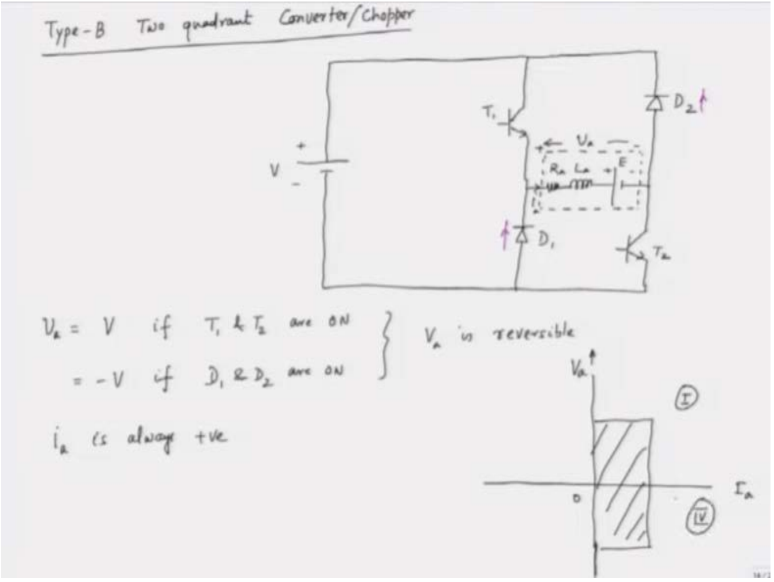

Let's take a closer look at the type B two-quadrant converter, or chopper. In this configuration, we have the transistors arranged in such a way that they are connected in series with the armature. The DC supply is represented by +B, and alongside, we have the diodes. This setup represents the armature of the DC machine, incorporating resistance, inductance, and back EMF. The armature current, denoted as I_a, flows into the circuit, while the voltage across the armature is V_a, with positive and negative polarities indicated.

We can label the transistors as T_1 and T_2, and the diodes as D_1 and D_2. Now, if both transistors T_1 and T_2 are turned on, we can express the armature voltage as $V_a = V$, meaning the voltage across the armature is the same as the source voltage V. Conversely, if both diodes D_1 and D_2 are conducting, the armature voltage becomes -V.

This indicates that the armature voltage is reversible; in other words, V_a can change its polarity. However, when it comes to the armature current, it is always positive. No matter the circumstances, the armature current I_a flows in only one direction, it cannot be reversed.

When we analyze the operation of this converter, we notice it differs from the type A converter. In a graphical representation, with voltage plotted on the Y-axis and current on the X-axis, we see that the current remains consistently positive while the voltage can be either positive or negative. Therefore, the type B converter operates within the first and fourth quadrants of the graph.

Although the type B converter can manage armature voltage control, it is not as widely adopted for that purpose. Instead, its primary application lies in the field circuit, where it can swiftly adjust the current. By controlling the triggering pulses, we can effectively manage the current more rapidly in the field circuit rather than in the armature circuit. This makes the type B chopper particularly advantageous for applications where quick current changes are necessary.

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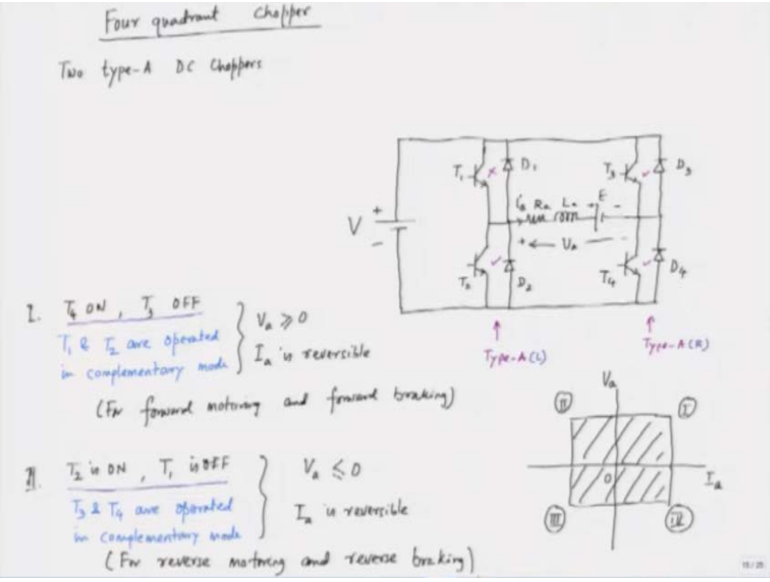
Four quadrant Chopper

Two type-A DC Choppers

I. T_4 ON, T_3 OFF
T_1 & T_2 are operated in complementary mode } $V_a \geqslant 0$, I_a is reversible
(For forward motoring and forward braking)

II. T_2 is ON, T_1 is OFF
T_3 & T_4 are operated in complementary mode } $V_a \leqslant 0$, I_a is reversible
(For reverse motoring and reverse braking)

Now, let’s explore the four-quadrant converter, also known as a four-quadrant chopper. This innovative design consists of two type A DC choppers working together. To illustrate, consider the armature circuit, which includes resistance, inductance, and back EMF. In this configuration, one type A chopper is connected at one terminal, equipped with a diode, while the second type A chopper is situated at the opposite terminal, also featuring two diodes, one on each side. This setup allows the four-quadrant chopper to operate across all four possible quadrants.

In our schematic, the input voltage V is represented, possibly by a battery, and we have the armature current I_a and armature voltage V_a labeled as well. We can designate the transistors and diodes as follows: T_1 and D_1 for the first type A chopper, T_2 and D_2 for the second type A chopper, T_3 and D_3 for the next, and finally T_4 and D_4 for the last.

Let's consider a scenario where T_4 is turned on, indicating that this switch is permanently in the ON position, while T_3 is switched off, remaining permanently off. In this state, T_1 and T_2 are operated in a complementary fashion, which means we apply the triggering pulses to both T_1 and T_2. This configuration essentially utilizes the first type A chopper.

In this mode, with T_4 ON and T_3 OFF, we are primarily engaging the left-hand chopper. Thus, we can denote this as the left side (L) and the right side (R) for reference. When the left type A chopper is active, the armature voltage V_a remains positive, while the armature current I_a is reversible. This means that while V_a is consistently positive (it can also be zero), the armature current I_a can take on both positive and negative values.

This configuration allows us to operate in forward motoring and forward braking, given that the voltage remains positive during this operation.

Now, let's consider a second situation. In this case, T_1 is ON and T_2 is also ON, while T_1 remains OFF. Consequently, T_3 and T_4 are now operated in complementary mode. This setup enables us to harness the full potential of the four-quadrant converter, facilitating both motoring and braking operations effectively across all quadrants.

What we are aiming to achieve here is a shift in our operational mode. Currently, T_2 is in the ON state while T_1 is OFF. In this configuration, T_3 and T_4 are operated in complementary mode. As a result, the armature voltage V_a becomes negative, which leads us to a scenario where V_a is negative and I_a is reversible. This specific condition allows us to operate in reverse motoring and reverse braking.

To visualize this, let’s plot the operation of this four-quadrant chopper in the V_a - I_a plane, where the armature voltage V_a is on the vertical axis and the average armature current I_a is on the horizontal axis. In our first condition, V_a is positive while I_a remains reversible. This operation falls within the first and fourth quadrants.

Now, for the second condition, we find ourselves in a scenario with negative voltage and reversible current. Here, V_a is negative, which means we are operating in the third and fourth quadrants.

To summarize the quadrant operations, we can delineate them as follows:

- In the first quadrant, both voltage and current are positive.
- In the second quadrant, we have positive voltage but negative current, which represents forward braking.
- In the third quadrant, both voltage and current are negative, indicating that the motor is in reverse motoring mode.
- Lastly, in the fourth quadrant, we encounter negative voltage paired with positive current, signifying reverse braking.

Through the use of this four-quadrant chopper, we can effectively navigate through all these operational scenarios, facilitating a comprehensive range of motor functions.

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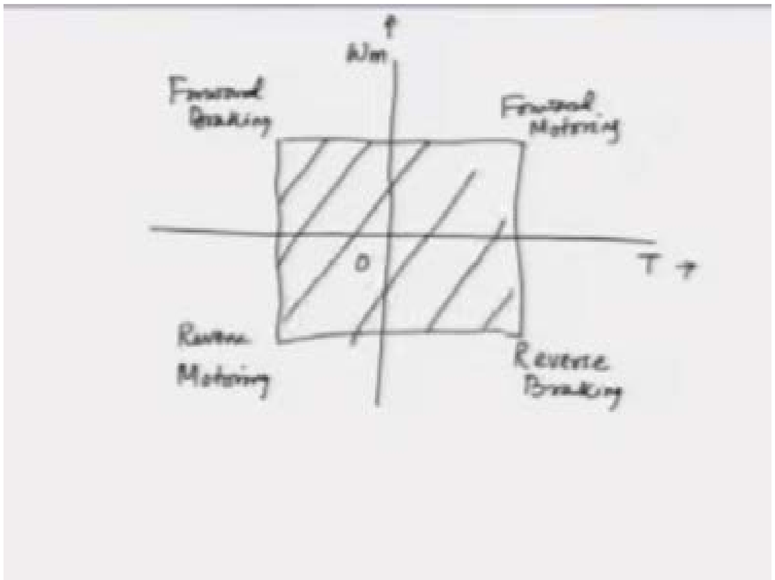

In examining the speed-torque characteristics, it's evident that this type of converter enables a drive to operate seamlessly across all possible quadrants. Here in the speed-torque plane, we can see the four operational modes: forward motoring, forward braking, reverse motoring, and reverse braking. By utilizing a four-quadrant chopper, we can effectively navigate through all these quadrants.

To illustrate this further, consider the application of a four-quadrant chopper-fed DC motor in an electric vehicle. This configuration allows the vehicle not only to move forward and brake in the forward direction but also to reverse direction, performing reverse motoring, and subsequently brake while moving backward.

This capability is essential for any industrial drive that requires reversible operation, highlighting the importance of incorporating a four-quadrant chopper into such systems.

With that, we conclude our discussion on chopper-fed DC motors, focusing on their motoring and braking conditions. We will delve deeper into this topic in our next lecture.