When you have completed this exercise, you will understand how thyristor commutation is performed in thyristor three-phase bridges. You will be able to explain what a commutation failure is and how it affects the operation of an HVDC transmission system. You will learn what the commutation overlap in thyristor three-phase bridges is. You will learn the factors that increase the likelihood of commutation failures in thyristor three-phase bridges.

The Discussion of this exercise covers the following points:

- Thyristor commutation in thyristor three-phase bridges
- Commutation failure in thyristor three-phase bridges
- Conditions increasing the likelihood of commutation failures
- Commutation overlap in thyristor three-phase bridges
- Effect of the commutation overlap on the extinction angle ($\gamma$)
- Using $\gamma$ controllers to minimize the likelihood of commutation failures

A thyristor three-phase bridge consists of two groups of thyristors, as Figure 53 shows. The thyristors ($Q_1$, $Q_2$, and $Q_3$) in one group have their cathodes interconnected (common-cathode thyristor group), while the thyristors ($Q_6$, $Q_7$, and $Q_8$) in the other group have their anodes interconnected (common-anode thyristor group).

Figure 53. A thyristor three-phase bridge consists of two groups of thyristors: a common-cathode thyristor group ($Q_1$, $Q_2$, and $Q_3$) and a common-anode thyristor group ($Q_6$, $Q_7$, and $Q_8$).
Figure 54 shows waveforms of voltages and currents in a thyristor three-phase bridge when current flows continuously at the dc side of this bridge. For every cycle of the source voltage waveform, the six thyristors in the thyristor bridge are fired one after the other at regular intervals and in the following order: $Q_1$, $Q_5$, $Q_2$, $Q_4$, $Q_3$, and $Q_6$; thus, a different thyristor is fired at every 60° interval. When fired, each thyristor conducts current for an interval of 120°. The order in which the thyristors are fired causes the thyristors in the two groups (i.e., the common-cathode thyristor group and the common-anode thyristor group) to be fired alternately, (with a thyristor in each group fired every 120° interval). Consequently, at any given instant, one thyristor in the common-cathode thyristor group and one thyristor in the common-anode thyristor group are both conducting current, thereby allowing current to flow continuously through the bridge.
Figure 54. Waveforms of voltages and currents in a thyristor three-phase bridge when current flows continuously at the dc side of the bridge (firing angle $\alpha$ set to 30°).
A thyristor has a control terminal (gate) used to turn it on. Turning the thyristor on is achieved by applying a firing signal to this terminal while the thyristor is forward biased (i.e., while the voltage at the anode is higher than the voltage at the cathode). However, the thyristor has no control mechanism to turn it off. Consequently, once the thyristor has entered into conduction, it continues to conduct even if the firing signal used to turn it on is removed. The thyristor turns off only when the current flowing through it decreases to zero and the thyristor becomes reverse biased (i.e., the voltage at the anode becomes lower than the voltage at the cathode) for a certain time. In other words, the moment at which the thyristor turns off depends on the circuit conditions only.

In a thyristor three-phase bridge, the thyristor which is currently conducting current in a group turns off when the next thyristor in this group is fired. This is illustrated in Figure 55.

- Initially (Figure 55a), the current $I_{dc}$ flows through the thyristor bridge via thyristors $Q_1$ and $Q_5$.
- When thyristor $Q_1$ is fired (Figure 55b), it enters into conduction. This causes the current flowing through thyristor $Q_5$ to decrease to zero, and since this thyristor becomes reverse biased at this instant, it stops conducting. The current $I_{dc}$ now flows through thyristors $Q_1$ and $Q_6$.
- Sixty degrees later (Figure 55c), thyristor $Q_5$ is fired and enters into conduction. This causes the current flowing through thyristor $Q_6$ to decrease to zero, and since this thyristor becomes reverse biased at this instant, it stops conducting. The current $I_{dc}$ now flows through thyristors $Q_1$ and $Q_6$.
- This sequence of events repeats over and over as the thyristors are fired in the order stated earlier (i.e., $Q_1$, $Q_5$, $Q_2$, $Q_4$, $Q_3$, $Q_6$).
Figure 55. In a thyristor three-phase bridge, the thyristor which is currently conducting current in a group turns off when the next thyristor in this group is fired.
Commutation failure in thyristor three-phase bridges

Under certain circuit conditions (which will be studied later in this exercise), the thyristor that is currently conducting in a group (i.e., the outgoing thyristor) does not turn off when the next thyristor due to conduct in this group (i.e., the incoming thyristor) is fired. Consequently, the outgoing thyristor continues to conduct current $I_{dc}$, while the incoming thyristor remains off. This problem is referred to as a commutation failure because the current $I_{dc}$ fails to transfer from the outgoing thyristor to the incoming thyristor in the group.

When a commutation failure occurs in a thyristor three-phase bridge, the dc side of the bridge becomes short-circuited 60° later (i.e., when the next thyristor is fired). This is illustrated in Figure 56.

- Initially (Figure 56a), current $I_{dc}$ flows through the thyristor bridge via thyristors $Q_1$ and $Q_2$ (as in the previous example).
- When thyristor $Q_1$ is fired (Figure 56b), a commutation failure occurs, and thus current $I_{dc}$ continues to flow through the outgoing thyristor (i.e., thyristor $Q_2$) and thyristor $Q_3$.
- Sixty degrees later (Figure 56c), thyristor $Q_3$ is fired and enters into conduction. This causes thyristors $Q_2$ and $Q_3$ to be in conduction at the same time (a condition which never occurs during normal operation), thereby short-circuiting the dc side of the bridge. Consequently, current $I_{dc}$ increases rapidly and, when there is no current control circuit in the system, the overcurrent protection is very likely to trip.

Notice that commutation failures are likely to occur in thyristor bridges operating as inverters (i.e., bridges operating at firing angles higher than 90°), which will be explained later in the discussion.
Figure 56. When a commutation failure occurs in a thyristor three-phase bridge, the dc side of the bridge becomes short-circuited 60° later (i.e., when the next thyristor is fired).
When a commutation failure and the ensuing short-circuit at the dc side of the inverter bridge occur in an HVDC transmission system, the current $I_{dc}$ generally increases briefly until the current control loop at the rectifier bridge enters into action to bring current $I_{dc}$ back to the desired value (i.e., to the value of the current command of the system). However, the voltage $E_{dc}$ across the transmission line drops to zero, and thus the power $P_{dc}$ transferred through the system also drops to zero. This produces a large perturbation (i.e., a decrease to zero) in the active power at the ac side of both bridges, which can lead to severe instability in the two ac power networks linked by the system. These undesired effects of a commutation failure at the inverter bridge of an HVDC transmission system are illustrated in Figure 57. Notice that after a commutation failure and the ensuing short-circuit at the dc side of the inverter bridge, line currents continue to flow at the ac side of the rectifier bridge, but no line currents flow at the ac side of the inverter bridge.

**Figure 57. Effects of a commutation failure at the inverter bridge of an HVDC transmission system.**

After a commutation failure and the ensuing short-circuit at the dc side of the inverter bridge, the firing angle of the inverter bridge must be decreased to return to normal commutation of the thyristors. This removes the short-circuit at the dc side of the inverter bridge and returns all parameters (voltage, current, power, etc.) in the HVDC transmission system to their normal values.

**Conditions increasing the likelihood of commutation failures**

Whenever a thyristor is fired in a three-phase bridge, the current $I_{dc}$ is commuted from the outgoing thyristor to the incoming thyristor in the group (i.e., the common-cathode or common-anode group of thyristors). For the commutation to be successful (i.e., to avoid a commutation failure), the following two conditions must be met (refer to Figure 58):

1. The current flowing through the outgoing thyristor must decrease to zero (meanwhile, the current in the incoming thyristor passes from zero to the value of $I_{dc}$).
2. The outgoing thyristor must remain reverse biased for a certain minimum time for this thyristor to recover its forward-voltage blocking capability and turn off completely. This minimum time is termed the **thyristor turn-off time** ($t_q$) and is an intrinsic characteristic of any thyristor. It is essential that the thyristor turn-off time $t_q$ be taken into consideration to ensure successful commutation of current $I_{dc}$.

![Figure 58. Turn-off time $t_q$ of a thyristor.](image)

In ac powered applications (like thyristor three-phase bridges), the turn-off time $t_q$ of a thyristor corresponds to an angular interval of the sine wave cycle. This angular interval is generally referred to as the **thyristor extinction angle** and is symbolized $\gamma_0$. The equation used to calculate $\gamma_0$ is:

$$\gamma_0 = 360 \times t_q \times f$$  \hspace{1cm} (4)

where:
- $\gamma_0$ is the thyristor extinction angle, expressed in degrees ($^\circ$).
- $t_q$ is the thyristor turn-off time, expressed in seconds (s).
- $f$ is the frequency of the ac power network, expressed in hertz (Hz).
For example, when the frequency of the ac power network is 50 Hz and the thyristor turn-off time $t_o$ is 100 $\mu$s, the thyristor extinction angle $\gamma_0$ is:

$$\gamma_0 = 360 \times 0.0001 \times 50 = 1.8^\circ$$

In most cases, the thyristor extinction angle $\gamma_0$ never exceeds a few degrees.

When a thyristor three-phase bridge operates as a rectifier (bridge firing angle lower than 90°), commutation failures are very unlikely to occur. This is because when the current $I_{dc}$ is commuted from the outgoing thyristor to the incoming thyristor, reverse bias is applied to the outgoing thyristor for a long time interval, so that the outgoing thyristor has significant time to recover its forward-voltage blocking capability and turn off completely.
For example, Figure 59 shows waveforms of voltages and currents in a thyristor three-phase bridge when the firing angle is 30°. The waveforms shown are the voltage ($E_{CK}$) at the common-cathode terminal of the bridge, the currents ($I_{Q1}$, $I_{Q2}$, and $I_{Q3}$) flowing through the thyristors in the common-cathode thyristor group ($Q_1$, $Q_2$, and $Q_3$), and the voltage ($E_{Qi}$) across thyristor $Q_i$ (i.e., the voltage across the anode and cathode of thyristor $Q_i$). As the figure shows, the voltage $E_{Qi}$ is virtually null when thyristor $Q_i$ is conducting. When thyristor $Q_i$ is fired, current $I_{c}$ transfers from thyristor $Q_i$ (outgoing thyristor) to thyristor $Q_j$ (incoming thyristor) and voltage $E_{Qi}$ becomes of negative polarity, thereby applying a reverse bias to thyristor $Q_i$. Voltage $E_{Qi}$ keeps a negative polarity, and thus thyristor $Q_i$ remains reverse biased for the next 210°. The angular interval during which thyristor $Q_i$ remains reverse biased is termed the extinction angle $\gamma$. Since the extinction angle $\gamma$ (210° in our example) is much higher than the extinction angle $\gamma_0$ (typical value of a few degrees) of thyristor $Q_i$, a commutation failure is very unlikely to occur. Figure 59 also illustrates why the firing angle in a thyristor three-phase bridge cannot exceed 180°. The green shaded area in this figure shows the window of opportunity for firing thyristor $Q_i$ and effectively transferring (commutating) current $I_{c}$ from thyristor $Q_i$ (outgoing thyristor) to thyristor $Q_j$ (incoming thyristor). This window, which extends over a span of 180°, corresponds to the angular interval during which voltage $E_{1,N}$ (i.e., voltage at the anode of thyristor $Q_i$) is higher than voltage $E_{CK,i}$ (i.e., voltage at the cathode of thyristor $Q_i$), which is equal to voltage $E_{3,N}$ since thyristor $Q_3$ is conducting current. Firing thyristor $Q_i$ beyond the above window of opportunity is useless (i.e., does not allow thyristor commutation) since thyristor $Q_i$ becomes reverse biased again due to voltage $E_{CK,N}$ (which is still equal to voltage $E_{3,N}$ since thyristor $Q_3$ is still conducting current $I_{c}$) becomes higher than voltage $E_{1,N}$. As a result, thyristor $Q_i$ stays into conduction and current $I_{c}$ does not transfer to thyristor $Q_j$.

The angular interval between the instant when a thyristor is fired (thyristor $Q_i$ in the example of Figure 59) and the maximum possible firing angle (180°) is referred to as the advance angle $\beta$. The advance angle $\beta$ is a measurement of how much thyristor firing is advanced with respect to the end of the window of opportunity (i.e., the end of the green shaded area in Figure 59), which ensures thyristor firing forces current $I_{c}$ to transfer from the outgoing thyristor to the incoming thyristor. The advance angle $\beta$ is equal to the angular interval (180°) of the window minus the firing angle $\alpha$ of the thyristor bridge. In equation form this is expresses as:

$$\beta = 180° - \alpha \tag{5}$$

where: $\beta$ is the advance angle, expressed in degrees (°).
$\alpha$ is the firing angle of the thyristor bridge, expressed in degrees (°).
Figure 59. When a thyristor three-phase bridge operates as a rectifier (bridge firing angle lower than 90°), commutation failures are very unlikely to occur because the extinction angle γ is much longer than the thyristor extinction angle γe.
When the firing angle $\alpha$ of the thyristor three-phase bridge increases, the extinction angle $\gamma$ and the advance angle $\beta$ both decrease. For example, Figure 60 shows what happens to the voltage and the current waveforms in the thyristor three-phase bridge of Figure 59 when the firing angle $\alpha$ of the bridge is increased to $120^\circ$. The extinction angle $\gamma$ and the advance angle $\beta$ both decrease to $60^\circ$.

Figure 60. Increasing the firing angle $\alpha$ of the thyristor three-phase bridge to $120^\circ$ causes the extinction angle $\gamma$ and the advance angle $\beta$ to both decrease to $60^\circ$. 
Further increasing the firing angle $\alpha$ of the thyristor three-phase bridge to 165° causes the extinction angle $\gamma$ and the advance angle $\beta$ to further decrease to 15°, as Figure 61 shows.

![Diagram](image)

**Figure 61.** Further increasing the firing angle $\alpha$ of the thyristor three-phase bridge to 165° causes the extinction angle $\gamma$ and the advance angle $\beta$ to further decrease to 15°.
As long as the extinction angle $\gamma$ remains significantly higher than the thyristor extinction angle $\gamma_0$, thyristor commutation should occur without failure. However, as the firing angle $\alpha$ of the thyristor three-phase bridge approaches the maximum value ($180^\circ$), the extinction angle $\gamma$ becomes closer to the thyristor extinction angle $\gamma_0$, and commutation failures are more likely to occur; thus, commutation failures are more likely to occur in thyristor three-phase bridges that operate as inverters. Consequently, it is common practice to limit the maximum firing angle of thyristor three-phase bridges to less than $180^\circ$ (e.g., $165^\circ$) to ensure that the extinction angle $\gamma$ is large enough (i.e., significantly higher than the thyristor extinction angle $\gamma_0$) to ensure reliable thyristor commutation.

**Commuation overlap in thyristor three-phase bridges**

Thus far, it has been assumed that whenever a commutation occurs in a thyristor three-phase bridge, the current $I_d$ transfers instantaneously from the outgoing thyristor to the incoming thyristor (see waveforms of currents $I_{Q1}$, $I_{Q2}$, and $I_{Q3}$ in the previous figures). In actuality, current $I_d$ does not transfer instantaneously from the outgoing thyristor to the incoming thyristor because there is generally some inductive reactance at the ac side of the bridge that limits the maximum rate ($\Delta I/\Delta t$) at which the line currents can vary. Inductive reactance is present in HVDC transmission systems due mainly to the leakage inductance of the multiple-tap transformer used at the ac side of each thyristor three-phase bridge.

For example, Figure 62 shows the actual waveforms of the voltage at the common-cathode terminal ($E_{CK,N}$) of a thyristor three-phase bridge and the current flowing through the common-cathode group of thyristors ($Q_1$, $Q_2$, and $Q_3$) in this bridge when the firing angle $\alpha$ is $30^\circ$. Since current $I_d$ varies at a finite rate ($\Delta I/\Delta t$), determined mainly by the inductive reactance at the ac side of the bridge, it momentarily flows through two thyristors (i.e., through the outgoing and incoming thyristors) every commutation. This phenomenon is referred to as the **commutation overlap**. The angular interval corresponding to the duration of the commutation overlap is termed the **overlap angle**, and is symbolized $\mu$.

Due to the commutation overlap, two ac power lines are momentarily connected together, via the inductive reactance at the ac side of the bridge, every commutation. Consequently, the voltage $E_{CK,N}$ at the common-cathode terminal of the bridge settles to some value between the voltages present on the two ac power lines that are connected together during each commutation overlap interval (this produces small notches in the waveform of the common-cathode voltage $E_{CK,N}$ as shown in Figure 62).
Exercise 4 – Commutation Failure at the Inverter Bridge ● Discussion

Figure 62. Current $I_a$ in a thyristor three-phase bridge momentarily flows through the outgoing and incoming thyristors (i.e., commutation overlap occurs) every commutation due to the inductive reactance at the ac side of the bridge.

**Effect of the commutation overlap on the extinction angle ($\gamma$)**

The commutation overlap decreases the extinction angle $\gamma$ obtained for any given firing angle $\alpha$. This is because the commutation overlap delays the instant at which the current flowing through the outgoing thyristor decreases to zero, thereby reducing the time interval during which reverse bias is applied to this thyristor. Figure 63 shows an example in which the firing angle $\alpha$ of a thyristor three-phase bridge is set to 165°. The advance angle $\beta$ is, therefore, 15°. However, the extinction angle $\gamma$ is only 10° because the overlap angle $\mu$ due to the commutation overlap is 5°. The equation used to calculate the extinction angle $\gamma$ is represented as:

$$\gamma = \beta - \mu$$  \hspace{1cm} (6)

where:
- $\gamma$ is the extinction angle, expressed in degrees (°).
- $\beta$ is the advance angle, expressed in degrees (°).
- $\mu$ is the overlap angle, expressed in degrees (°).
The longer the commutation overlap (i.e., the larger the overlap angle $\mu$), the smaller the extinction angle $\gamma$, and thus the higher the likelihood of commutation failures in the thyristor three-phase bridge.

Figure 63. Commutation overlap in a thyristor three-phase bridge reduces the extinction angle $\gamma$ and thus increases the likelihood of commutation failures.
The duration of the commutation overlap is proportional to the value of the current \( I_{dc} \) flowing through the dc side of the thyristor three-phase bridge. For example, Figure 64 shows what happens to the voltage and current waveforms in the thyristor three-phase bridge of Figure 63 when the value of current \( I_{dc} \) doubles.

![Diagram showing voltage and current waveforms in a thyristor three-phase bridge](image)

**Figure 64.** Voltage and current waveforms in the thyristor three-phase bridge of Figure 63 when the value of current \( I_{dc} \) doubles.
As Figure 64 shows, the time taken by the current flowing through the outgoing thyristor (e.g., see current $I_{O1}$ in the figure) to decrease to zero doubles, and thus, the overlap angle $\mu$ also doubles (it passes from $5^\circ$ to $10^\circ$). This, in turn, causes the extinction angle $\gamma$ to decrease from $10^\circ$ to only $5^\circ$, making the thyristor three-phase bridge much more prone to commutation failures.

Similarly, a decrease in the voltage at the ac side of a thyristor three-phase bridge due to a fault in the ac power system connected to this bridge, significantly decreases the rate ($\Delta I/\Delta t$) at which the line currents can vary (this rate being limited by the inductive reactance at the ac side of the bridge, as mentioned earlier). Consequently, for any given value of current $I_{dc}$ flowing through the dc side of a thyristor three-phase bridge, the time taken by the current flowing through the outgoing thyristor to decrease to zero increases, and thus the overlap angle $\mu$ also increases.

For example, Figure 65 shows what happens to the voltage and current waveforms in the thyristor three-phase bridge of Figure 63 when a decrease in voltage at the ac side of this bridge causes the rate ($\Delta I/\Delta t$) at which the line currents can vary to decrease by two. Figure 65 shows that the time taken by the current flowing through the outgoing thyristor (e.g., see current $I_{O1}$ in the figure) to decrease to zero doubles, and thus the overlap angle $\mu$ also doubles (it passes from $5^\circ$ to $10^\circ$). This, in turn, causes the extinction angle $\gamma$ to decrease from $10^\circ$ to only $5^\circ$, making the thyristor three-phase bridge much more prone to commutation failures.
Exercise 4 – Commutation Failure at the Inverter Bridge • Discussion

Figure 65. Voltage and current waveforms in the thyristor three-phase bridge of Figure 63 when a decrease in voltage at the ac side of the bridge causes the rate \(\Delta I/\Delta t\) at which the line currents can vary to decrease by two.
Using γ controllers to minimize the likelihood of commutation failures

In the previous section, we saw that an increase in the value of current $I_{dc}$ or a decrease in the rate ($\Delta I/\Delta t$) at which the line currents can vary both cause the overlap angle $\mu$ to increase, which causes the extinction angle $\gamma$ to decrease. If the extinction angle $\gamma$ becomes lower than the thyristor extinction angle $\gamma_{Yo}$, commutation failures occur. To prevent this undesired situation, a γ controller is often used in thyristor three-phase bridges operating as inverters. A γ controller continuously monitors the extinction angle $\gamma$ by measuring the time during which reverse bias is applied to each thyristor, and automatically adjusts the firing angle $\alpha$ of the thyristor bridge so that the extinction angle $\gamma$ remains higher than the thyristor extinction angle $\gamma_{Yo}$. Detailed description of the operation and use of γ controllers, however, is beyond the scope of this manual.

Figure 66. Converter transformers have inductance that limits the maximum rate ($\Delta I/\Delta t$) at which line currents can vary. The above figure shows an extra-high-voltage converter transformer used in an HVDC transmission system (© Siemens AG 2012, all rights reserved).
The Procedure is divided into the following sections:

- Set up and connections
- Extinction angle $\gamma$ versus the firing angle $\alpha$
- Commutation overlap
  Measuring the duration of the commutation overlap. Effect of the commutation overlap on the waveform of the dc voltage across the inverter bridge. Effect of the dc line current value on the duration of the commutation overlap. Effect of the ac voltage at the inverter bridge on the duration of the commutation overlap.
- Effect of a commutation failure at the inverter bridge of an HVDC transmission system
- Commutation failure resulting from a voltage decrease at the ac side of the inverter bridge of an HVDC transmission system

**Set up and connections**

*In this part of the exercise, you will set up a system representing an HVDC transmission system and the equipment required to measure the system parameters.*

1. Refer to the Equipment Utilization Chart in Appendix A to obtain the list of equipment required to perform the exercise.

   Install the equipment in the Workstation as indicated below to simplify the connections required to implement the HVDC transmission system (shown in Figure 67, Figure 68, Figure 69, and Figure 70).

   - Install the modules required to implement converter station 1 (i.e., a Regulating Autotransformer, a Three-Phase Transformer Bank, a Power Thyristors module, and a Data Acquisition and Control Interface) in the left-hand side openings of the Workstation.

   - Similarly, install the modules required to implement converter station 2 (i.e., a Regulating Autotransformer, a Three-Phase Transformer Bank, a Power Thyristors module, and a Data Acquisition and Control Interface) in the right-hand side openings of the Workstation.

   - Place the Three-Phase Transmission Line and Power Supply in the middle openings of the Workstation. (The two three-phase ac power sources in the Power Supply will be used as independent ac power sources for the two converter stations.)

2. On the Power Supply, make sure that the two ac power switches are set to the O (off) position, and that the voltage control knob is set to 0%. Connect the Power Supply to a three-phase ac power outlet.

3. Connect the Low Power Input of each Power Thyristors module to the 24 V ac power source of the Power Supply.
Connect the **Power Input** of each **Data Acquisition and Control Interface** to the 24 V ac power source of the **Power Supply**.

Turn the 24 V ac power source of the **Power Supply** on.

4. **Connect the USB port of each Data Acquisition and Control Interface to USB ports of the host computer.**

5. **Turn the host computer on, then start the LVDAC-EMS software.**

   In the LVDAC-EMS Start-Up window, make sure that both Data Acquisition and Control Interfaces (DACIs) are detected (the serial number of each DACI appears in the LVDAC-EMS Start-Up window). Select the network voltage and frequency that correspond to the voltage and frequency of your local ac power network, then click the **OK** button to close the LVDAC-EMS Start-Up window.

6. **On the Power Thyristors module in converter station 1, set switches $S_1$ and $S_2$ to the I (on) position. This interconnects thyristors $Q_1$ through $Q_6$ of this Power Thyristors module in a thyristor three-phase bridge for station 1.**

   On the Power Thyristors module in converter station 2, set switch $S_1$ to the I (on) position. Set switch $S_2$ to the O (off) position, which will allow you to connect meters in the thyristor three-phase bridge for station 2.

   Connect the equipment as shown in Figure 67, Figure 68, Figure 69, and Figure 70. Before you begin connecting the equipment, record in the space below the serial numbers of the DACI modules used to control the thyristor bridges in converter stations 1 and 2.

   Serial number of the DACI controlling the thyristor bridge (bridge 1) in station 1 (left-hand station) = ____________

   Serial number of the DACI controlling the thyristor bridge (bridge 2) in station 2 (right-hand station) = ____________

   Use the fixed, three-phase ac voltage output of the **Power Supply** as the ac power source for converter station 1 (left-end station). Use the variable, three-phase ac voltage output of the **Power Supply** as the ac power source for converter station 2 (right-end station). Use the Three-Phase Transmission Line module to implement inductance $L$ (inductance of the dc line and smoothing inductors). Note that terminals A1 and A2 in Figure 67 connect to the corresponding terminals in Figure 68, while terminals A3 and A4 in Figure 68 connect to the corresponding terminals in Figure 69. Figure 70 shows the detailed connection of the thyristor three-phase bridge in converter station 2 with the meters ($E_1$, $I_1$, $E_3$, and $I_3$) used to measure voltages and currents in this bridge (meter $E_3$ must first be connected to measure the voltage across thyristor $Q_3$ of this bridge, as Figure 70 shows).
Inputs $E_1$, $E_2$, $E_3$, $I_1$, $I_2$, and $I_3$ of converter stations 1 and 2 (shown in Figure 68 and Figure 70) are all inputs of the DACI used in converter station 1. These inputs are used to measure parameters in the HVDC transmission system. Input $E_4$ of the DACI used in converter station 1 provides synchronization of the firing signals for the Power Thyristors module in station 1. Input $E_4$ of the DACI used in converter station 2 (represented by the red symbol $E_4$ in Figure 69) provides synchronization of the firing signals for the Power Thyristors module in station 2. Input $I_4$ of the DACI used in converter station 1 (represented by the blue symbol $I_4$ in Figure 68) provides dc line current measurement for the current control loop of the thyristor bridge in station 1. Finally, input $I_4$ of the DACI used in converter station 2 (represented by the red symbol $I_4$ in Figure 68) provides dc line current measurement for the current control loop of the thyristor bridge in station 2.
Exercise 4 – Commutation Failure at the Inverter Bridge

**Procedure**

Figure 67. HVDC transmission system (part I).

![HVDC transmission system (part I)](image1)

- **AC power source** (8821), fixed voltage output
- **Regulating Autotransformer**
- **Three-Phase Transformer Bank module**
- **Converter Station 1**
- **Power Thyristors module**
- **Bridge 1**
- **Firing control signals from the digital outputs of the DACI for station 1**

Figure 68. HVDC transmission system (part II).

![HVDC transmission system (part II)](image2)

- **DC Transmission Line**
- **Local ac power network**

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<th>Voltage (V)</th>
<th>Frequency (Hz)</th>
<th>$X_L$ (Ω)</th>
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<td>60</td>
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<td>600</td>
</tr>
</tbody>
</table>

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Exercise 4 – Commutation Failure at the Inverter Bridge

**Procedure**

Figure 69. HVDC transmission system (part III).

**Converter Station 2**

See detailed bridge connections with meters in the figure below.

Firing control signals from the digital outputs of the DACI for station 2.

AC power source (8821), variable voltage output.

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7. **Connect the Digital Outputs of each Data Acquisition and Control Interface to the Firing Control Inputs of the associated Power Thyristors module, using the provided cable with DB9 connectors.**

Also, perform the following connections to be able to observe the firing control signals (AI-1 and AI-3) applied to thyristors $Q_1$ and $Q_3$ of the thyristor bridge in station 2 (inverter bridge): connect Firing Control Inputs 1 and 3 of the Power Thyristors module in station 2 to Analog Inputs 1 and 3, respectively, of the DACI in station 1, using 2 mm leads. Connect the common (white) terminal of the Firing Control Inputs on the Power Thyristors module in station 2 to one of the two analog common (white) terminals of the DACI in station 1, using a 2 mm lead.

8. **On the Regulating Autotransformer in converter station 1, set the Buck-Boost selector to 0% and the Phase Shift selector to 0°.**

On the Regulating Autotransformer in converter station 2, set the Buck-Boost selector to -15% and the Phase Shift selector to 0°.

Since the HVDC transmission system will be used to transfer power from converter station 1 to converter station 2, the above settings will make the thyristor bridge in station 2 (inverter bridge) operate at an ac voltage lower than the ac voltage at which the thyristor bridge in station 1 (rectifier bridge) operates.
9. In LVDAC-EMS, open the HVDC Transmission System Control window. A dialog box appears. Select the serial number of the DACI that is used to control thyristor bridge 1 (i.e., the serial number of the thyristor bridge in converter station 1, recorded in step 6), then click the OK button to close the dialog box and open the HVDC Transmission System Control window.

In the HVDC Transmission System Control window, make the following settings:

- Set the Function parameter to Monopolar HVDC Transmission System.
- Set the Control Type parameter to Linked (Rectifier = Bridge 1). This makes bridge 1 operate as a rectifier and the current command of its current control loop equal to the current command $I_{\text{ref (rectifier)}}$ of the HVDC transmission system. This also makes bridge 2 operate as an inverter and the current command of its current control loop equal to $I_{\text{ref (inverter)}}$ minus the current margin ($\Delta I$) of the HVDC transmission system.
- Set the Rectifier Current Command parameter to 0.3 pu by entering the adequate value in the field next to this parameter or by using the Rectifier Current Command knob in the lower left corner of the window. This sets the current command $I_{\text{ref (rectifier)}}$ of the HVDC transmission system (i.e., the current command of the current control loop at bridge 1, which is set to operate as a rectifier) to 0.3 pu.
- Set the Current Margin $\Delta I$ parameter to 0.05 pu. This sets the current margin $\Delta I$ of the HVDC transmission system to 0.05 pu. Therefore, the current command of the current control loop at bridge 2 (inverter bridge) is set to 0.25 pu (0.3 pu – 0.05 pu = 0.25 pu).
- Leave the other parameters set to their default values.
- Start the Monopolar HVDC Transmission System function by clicking the Start/Stop button or by setting the Status parameter to Started.

10. In LVDAC-EMS, open the Metering window. A dialog box appears. Select the serial number of the DACI that is used to perform parameter measurements in the HVDC transmission system [i.e., the same DACI that is used to control the thyristor bridge (bridge 1) in converter station 1], then click the OK button to close the dialog box and open the Metering window.

In the Metering window, set three meters to measure the dc line current $I_{\text{dc (i2)}}$ and voltage $E_{\text{dc (e2)}}$, and the power transferred $P_{\text{dc}} [PQS2(E2,i2)]$ via the transmission line.
Extinction angle $\gamma$ versus the firing angle $\alpha$

In this section, you will observe the effect which the value of the firing angle $\alpha_{\text{inverter}}$ of the inverter bridge has on the extinction angle $\gamma$, and the likelihood of commutation failures in this bridge.

11. On the Power Supply, set the voltage control knob to 100%. Turn the three-phase ac power source on by setting the main power switch to I (on).
   - The voltage at the fixed, three-phase ac voltage output of the Power Supply feeds the thyristor bridge (rectifier bridge) in converter station 1.
   - The voltage at the variable, three-phase ac voltage output of the Power Supply feeds the thyristor bridge (inverter bridge) in converter station 2. This voltage is maximum (i.e., equal to the voltage at the fixed, three-phase ac voltage output of the Power Supply) since the voltage control knob is set to 100%. It is reduced by 15% in the Regulating Autotransformer of station 2.

For the remainder of this exercise, the thyristor bridge in station 1 (left-end station) will be referred to as bridge 1, while the thyristor bridge in station 2 (right-hand station) will be referred to as bridge 2.

12. In the Metering window, observe the value of the dc line current $I_{dc}$ (I2). Is current $I_{dc}$ approximately equal to the value (0.3 pu) of the current command $I_{\text{ref.(rectifier)}}$ of the HVDC transmission system?

   □ Yes □ No

Record the firing angle $\alpha_{\text{rectifier}}$ of bridge 1 (rectifier bridge) and the firing angle $\alpha_{\text{inverter}}$ of bridge 2 (inverter bridge), indicated by meters Bridge-1 $\alpha$ and Bridge-2 $\alpha$, respectively, in the HVDC Transmission System Control window.

Firing angle $\alpha_{\text{Rectifier}}$ of bridge 1 = ________°

Firing angle $\alpha_{\text{Inverter}}$ of bridge 2 = ________°

Does this confirm that the HVDC transmission system operates normally?

□ Yes □ No

13. Start the Oscilloscope and display the firing signals of thyristors $Q_1$ and $Q_3$ ($AI-1$ and $AI-3$) of bridge 2 (inverter bridge), the waveforms of the currents ($I_1$ and $I_3$) flowing through thyristors $Q_1$ and $Q_3$ of bridge 2, and the waveforms of the voltages ($E_1$ and $E_3$) across thyristors $Q_1$ and $Q_3$ of bridge 2 ($E_1$ and $E_3$).

   Set the Oscilloscope to the continuous refresh mode. Make sure the Trigger type is set to Software. Select the firing signal of thyristor $Q_1$ ($AI-1$) of bridge 2 as the trigger source and set the trigger level and slope to 1 V and Rising, respectively. Set the time base to display one or two cycles of the thyristor firing signals.
14. Decrease the maximum (limit) value of the firing angle $\alpha_{\text{inverter}}$ of bridge 2 (inverter bridge) to 135°. To do this, set the Inverter Limit parameter of Bridge 2 in the HVDC Transmission System Control window to 135. Observe that this causes the firing angle $\alpha_{\text{inverter}}$ (meter Bridge-2 $\alpha$) to pass from 165° to 135°.

Observe the firing signals and the voltage and current waveforms displayed on the Oscilloscope. Describe what happens when thyristor $Q_1$ in bridge 2 (inverter bridge) is fired. Explain briefly.

On the Oscilloscope, observe the waveforms of the voltages across thyristors $Q_1$ and $Q_t$ of bridge 2. Notice that when either of these two thyristors turns off, the voltage across the thyristor passes from zero to a negative value, thereby applying a reverse bias to the thyristor for a significant part of the ac power cycle.

Using the Oscilloscope, determine the extinction angle $\gamma$ (i.e., the angular interval during which a reverse bias is applied to the outgoing thyristor). Record the value below.

Extinction angle $\gamma (\alpha_{\text{inverter}} = 135^\circ) = \text{______}^\circ$.

Are commutation failures likely to occur in a three-phase thyristor bridge operating under the current conditions? Explain.

15. Increase the maximum (limit) value of the firing angle $\alpha_{\text{inverter}}$ of bridge 2 (inverter bridge) to 170° while observing the waveforms displayed on the
Oscilloscope. Notice that this causes the firing angle $\alpha_{\text{inverter}}$ to pass from $135^\circ$ to $170^\circ$. What happens to the voltages across thyristors $Q_1$ and $Q_3$ and to the extinction angle $\gamma$?

Using the Oscilloscope, determine the extinction angle $\gamma$. Record the value below.

Extinction angle $\gamma$ ($\alpha_{\text{inverter}} = 170^\circ$) = _____ °

From your observations, what effect does increasing the maximum (limit) value of the firing angle $\alpha_{\text{inverter}}$ of bridge 2 (inverter bridge) have on the likelihood of commutation failures in this bridge? Explain.
Commutation overlap

In this section, you will measure the duration of the commutation overlap for a given value of the dc line current $I_{dc}$. You will observe the effect of the commutation overlap on the waveform of the dc voltage across the inverter bridge. You will then observe the effect that increasing the dc current $I_{dc}$ or reducing the ac voltage at the inverter bridge has on the duration of the commutation overlap.

Measuring the duration of the commutation overlap

16. In the HVDC Transmission System Control window, set the maximum (limit) value of the firing angle $\alpha_{inverter}$ of bridge 2 (inverter bridge) to 165°. Notice that this causes the firing angle $\alpha_{inverter}$ to pass from 170° to 165°.

Set the Oscilloscope to display the firing signal (AI-1) of thyristor $Q_1$ in bridge 2 (inverter bridge), the waveforms of the currents ($I_1$ and $I_3$) flowing through thyristors $Q_1$ and $Q_3$ in bridge 2, and the waveform of the voltage ($E_3$) across thyristor $Q_3$ in bridge 2. (Turn the other Oscilloscope channels off.) Set the Oscilloscope time base to 0.2 ms/div.

Place the Oscilloscope in the single refresh mode. Set the Trigger type to Hardware. Select the firing signal (AI-1) of thyristor $Q_1$ as the trigger source and set the trigger level and slope to 1 V and Rising, respectively.

17. On the Oscilloscope, click the Single Refresh button to start a single-acquisition cycle. The Oscilloscope display should be refreshed with the waveforms of the currents through thyristors $Q_1$ and $Q_3$, as well as the voltage across thyristor $Q_3$, at the instant when thyristor $Q_1$ is fired.

Observe that when thyristor $Q_1$ is fired, the current flowing through bridge 2 does not transfer instantaneously from thyristor $Q_3$ (outgoing thyristor) to thyristor $Q_1$ (incoming thyristor). Instead, the current briefly flows through both thyristors $Q_1$ and $Q_3$ (i.e., commutation overlap occurs), then thyristor $Q_3$ turns off completely and the current flowing through $Q_3$ becomes null (zero). Notice that a brief downward spike appears in the waveform of the current flowing through thyristor $Q_3$ just before this current becomes null (i.e., the current flowing through thyristor $Q_3$ momentarily reverses direction before thyristor $Q_3$ turns off completely).

Measure the duration of the commutation overlap (i.e., the time interval between the instant at which current starts flowing through thyristor $Q_3$ and the instant at which the negative spike in the current flowing through thyristor $Q_3$ reaches the maximum value).

Commutation overlap duration ($I_{dc} = 0.3 \text{ pu}$, $E_{ac \text{ inverter}} = 100\%$) = _____ ms

Determine the overlap angle $\mu$.

Overlap angle $\mu = _____^\circ$
Effect of the commutation overlap on the waveform of the dc voltage across the inverter bridge

18. Stop the Monopolar HVDC Transmission System function by clicking the Start/Stop button or by setting the Status parameter to Stopped.

On the Power Supply, turn the three-phase ac power source off by setting the main power switch to the O (off) position. (Leave the 24 V ac power source of the Power Supply turned on.)

(Refer to Figure 70.) Disconnect input E3 of the DACI used in converter station 1 from thyristor Q3 of bridge 2 (inverter bridge). Reconnect input E3 across bridge 2 as indicated by the dotted lines in Figure 70 in order to measure the voltage $E_{dc}$ across bridge 2.


20. On the Oscilloscope, click the Single Refresh button to start a single-acquisition cycle, and observe the waveforms of the currents through thyristors Q1 and Q3, as well as the voltage $E_{dc}$ across bridge 2 (inverter bridge) when thyristor Q3 is fired. Notice that a small notch is present in voltage $E_{dc}$ during the commutation overlap. Explain why.

Effect of the dc line current value on the duration of the commutation overlap

21. Stop the Monopolar HVDC Transmission System function by clicking the Start/Stop button or by setting the Status parameter to Stopped.

On the Power Supply, turn the three-phase ac power source off by setting the main power switch to the O (off) position. (Leave the 24 V ac power source of the Power Supply turned on.)

(Refer to Figure 70.) Reconnect input E3 of the DACI used in converter station 1 to measure the voltage across thyristor Q3 in bridge 2 (inverter bridge).

22. Start the HVDC transmission system. On the Power Supply, turn the three-phase ac power source on.
23. Place the Oscilloscope in the continuous refresh mode.

While observing the waveforms on the Oscilloscope screen, gradually increase the current command $I_{\text{ref (rectifier)}}$ of the HVDC transmission system to 1.0 pu.

What happens to the duration of the commutation overlap, and therefore to the overlap angle $\mu$, when the dc line current $I_{\text{dc}}$ increases? Why?

24. Place the Oscilloscope in the single refresh mode. Measure the duration of the commutation overlap when the current $I_{\text{dc}}$ is 1.0 pu.

Commutation overlap duration ($I_{\text{dc}} = 1.0 \text{ pu}, E_{\text{ac inverter}} = 100\%) = \text{_____ ms}$

Determine the overlap angle $\mu$.

Overlap angle $\mu = \text{_______}^\circ$

Compare the value of the overlap angle $\mu$ obtained with a current $I_{\text{dc}}$ of 1.0 pu (recorded above) to that obtained with a current $I_{\text{dc}}$ of 0.3 pu (recorded in step 17).
25. From your observations, what is the effect of increasing the current $I_d$ on the overlap angle $\mu$, the extinction angle $\gamma$, and the likelihood of commutation failures in bridge 2 (inverter bridge)? Explain.
Effect of the ac voltage at the inverter bridge on the duration of the commutation overlap

26. Place the Oscilloscope in the continuous refresh mode.

27. While observing the waveforms on the Oscilloscope screen, slowly reduce the ac voltage at bridge 2 (inverter bridge) down to 60% of its original value by setting the control knob of the Power Supply to approximately 60%.

What happens to the duration of the commutation overlap, and therefore to the overlap angle $\mu$, when the ac voltage at bridge 2 decreases? Why?

28. Place the Oscilloscope in the single refresh mode. Measure the duration of the commutation overlap when the ac voltage at bridge 2 (inverter bridge) is decreased to approximately 60%.

Commutation overlap duration ($I_{dc} = 1.0 \text{ pu, } E_{ac\text{ inverter}} = 60\%) = \text{_______ ms}$

Determine the overlap angle $\mu$.

Overlap angle $\mu = \text{_______ }^\circ$

Compare the value of the overlap angle $\mu$ obtained with an ac voltage of 60% at bridge 2 (recorded above) to that obtained with an ac voltage of 100% at bridge 2 (recorded in step 24).
29. From your observations, what is the effect of decreasing the ac voltage at bridge 2 (inverter bridge) on the overlap angle $\mu$, the extinction angle $\gamma$, and the likelihood of commutation failures in bridge 2 (inverter bridge)? Explain.

30. In the HVDC Transmission System Control window, gradually decrease the current command $I_{\text{ref (rectifier)}}$ to 0.3 pu. Stop the Monopolar HVDC Transmission System function by clicking the Start/Stop button or by setting the Status parameter to Stopped.

Effect of a commutation failure at the inverter bridge of an HVDC transmission system

In this section, you will produce a commutation failure at the inverter bridge of an HVDC transmission system and observe what happens to the system parameters.

31. On the Power Supply, turn the three-phase ac power source off by setting the main power switch to the O (off) position. (Leave the 24 V ac power source of the Power Supply turned on.)

Refer to Figure 71, Figure 72, and Figure 73. Modify the meter connections in order to be able to measure the line-to-line voltage and line current at the ac side of both thyristor three-phase bridges in the HVDC transmission system.
Exercise 4 – Commutation Failure at the Inverter Bridge

Procedure

1. **Local ac power network**

<table>
<thead>
<tr>
<th>Voltage (V)</th>
<th>Frequency (Hz)</th>
<th>$X_L$ (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>220</td>
<td>50</td>
<td>600</td>
</tr>
<tr>
<td>240</td>
<td>50</td>
<td>600</td>
</tr>
<tr>
<td>220</td>
<td>60</td>
<td>600</td>
</tr>
</tbody>
</table>

2. **Converter Station 1**

   - AC power source (8821), fixed voltage output
   - Regulating Autotransformer
   - Three-Phase Transformer Bank module
   - Power Thyristors module
   - Firing control signals from the digital outputs of the DACI for station 1

3. **DC Transmission Line**

   - DACI in station 1
   - DACI in station 2

Figure 71. HVDC transmission system (part I).

Figure 72. HVDC transmission system (part II).
32. In the Metering window of LVDAC-EMS, open the Acquisition Settings dialog box, set the Sampling Window to 8 cycles, then click the OK button to close the dialog box. Set the meters as indicated below.

- Keep the three meters that are set to measure the dc line current $I_{dc}$ ($I_2$) and voltage $E_{dc}$ ($E_2$), and the power transferred $P_{dc}$ [$PQS2 (E2,I2)$] via the transmission line.

- Set two meters to measure the rms values of line-to-line voltage $E_{L1,2}$ ($E_1$) and line current $I_1$ ($I_1$) at the ac side of the three-phase thyristor bridge (bridge 1) in converter station 1. Set three meters to measure the active power [$PQS1 (E1,I1)$ 3~], reactive power [$PQS1 (E1,I1)$ 3~], and displacement power factor [$PF (E1, I1)$ 3~] at the ac side of the three-phase thyristor bridge (bridge 1) in converter station 1.

- Set two meters to measure the rms values of line-to-line voltage $E_{L1,2}$ ($E_3$) and line current $I_3$ ($I_3$) at the ac side of the three-phase thyristor bridge (bridge 2) in converter station 2. Set three meters to measure the active power [$PQS3 (E3,I3)$ 3~], reactive power [$PQS3 (E3,I3)$ 3~], and displacement power factor [$PF (E3, I3)$ 3~] at the ac side of the three-phase thyristor bridge (bridge 2) in converter station 2.
33. In LVDAC-EMS, open the Data Table. Set the Data Table to record the following system parameters: the firing angles of bridges 1 and 2, the current command $I_{\text{Ref}}(\text{rectifier})$, the current margin $\Delta I$, the dc line current and voltage, the power transferred via the dc transmission line, as well as the line voltage $E_{L2}$, line current, active power, reactive power, and DPF at the ac side of bridges 1 and 2.

34. In the HVDC Transmission System Control window, make sure that the current command $I_{\text{Ref}}(\text{rectifier})$ and current margin ($\Delta I$) of the HVDC transmission system are set to 0.3 pu and 0.05 pu, respectively. Also, make sure that the maximum (limit) value of the firing angle $\alpha_{\text{inverter}}$ of bridge 2 (inverter bridge) is set to 165°.

35. On the Power Supply, set the voltage control knob to 100%. Turn the three-phase ac power source on.

In the HVDC Transmission System Control window, start the Monopolar HVDC Transmission System function by clicking the Start/Stop button or by setting the Status parameter to Started.

Wait a few seconds to let the system stabilize.

36. In the HVDC Transmission System Control window, gradually increase the current command $I_{\text{Ref}}(\text{rectifier})$ of the system to 0.8 pu.

In the Metering window, notice that the value of the dc line current $I_{dc}$ ($I_2$) is approximately equal to the value (0.8 pu) of the current command $I_{\text{Ref}}(\text{rectifier})$ of the system.

Record the system parameters in the Data Table.

37. On the Oscilloscope, make the necessary settings to display the following waveforms: the line current ($I_1$) and active power ($P_1$) at the ac side of bridge 1 (rectifier bridge), the dc line current ($I_2$) and voltage ($E_2$), the power ($P_2$) transferred via the dc transmission line, as well as the line current ($I_3$), line-to-line voltage ($E_3$) and active power ($P_3$) at the ac side of bridge 2 (inverter bridge). Set the Oscilloscope to the continuous refresh mode and verify that the waveforms are properly displayed.

38. Set the Oscilloscope time base to 20 ms/div. Select the dc current ($I_2$) as the Trigger source. Set the Trigger level to 2.0 pu. Make sure that the Trigger slope is set to Rising.

On the Oscilloscope, click the Single Refresh button to start a single-acquisition cycle. (No waveforms are displayed on the Oscilloscope and the Metering window is not refreshed until the triggering event occurs.)

39. In the HVDC Transmission System Control window, increase the maximum (limit) value of the firing angle $\alpha_{\text{inverter}}$ of bridge 2 (inverter bridge) in 1° steps.
until a commutation failure occurs (i.e., until the Oscilloscope display is refreshed due to the occurrence of the triggering event). This should occur when the maximum (limit) value of the firing angle $\alpha_{\text{inverter}}$ of bridge 2 is approximately 173°.

Record the maximum (limit) value of the firing angle $\alpha_{\text{inverter}}$ at which the commutation failure occurs

Maximum (limit) firing angle at bridge 2 = ______ °

40. Observe the waveforms displayed on the Oscilloscope. Explain what happens when a commutation failure occurs at bridge 2 (inverter bridge) and how the HVDC transmission system reacts.

41. Make sure the Metering window is in the continuous refresh mode. Record the system parameters in the Data Table.

Examine the recorded data to understand the effect of a commutation failure and the ensuing short-circuit at bridge 2 (inverter bridge) of the HVDC transmission system.

Does the dc line current $I_{\text{dc}}$ remain at its original value (0.8 pu) (with an exception being made for the initial transient spike)?

☐ Yes    ☐ No

Is the dc line voltage $E_{\text{dc}}$ nearly zero, and thus the dc power transferred via the transmission line virtually null? Explain.
Does current still flow at the ac side of bridge 1 (rectifier bridge)? Why?


Does current still flow at the ac side of bridge 2 (inverter bridge)? Why?


42. In the Metering window, observe that the displayed values are virtually constant, indicating that once a commutation failure occurs at bridge 2 (inverter bridge), the ensuing short-circuit is permanent.

Decrease the maximum (limit) value of the firing angle $\alpha_{inverter}$ of bridge 2 to 165° (inverter bridge) in 1° steps. Notice that when the maximum (limit) firing angle at bridge 2 has decreased to a certain value, the short-circuit at the dc side of bridge 2 ceases (i.e., the dc line current and voltage, and the power transferred via the transmission line return to their initial values, recorded in step 36).

Did the other system parameters (line current, voltage, power, and DFP) at the ac side of each bridge return back to their original values?

☐ Yes  ☐ No

Commutation failure resulting from a voltage decrease at the ac side of the inverter bridge of an HVDC transmission system

43. Set the maximum (limit) value of the firing angle $\alpha_{inverter}$ of bridge 2 to 2° or 3° less than the value which created a commutation failure in the previous section (recorded in step 39). This will provide the system with a minimal safety margin against commutation failure.

44. On the Oscilloscope, click the Single Refresh button to start a single-acquisition cycle. (No waveforms are displayed on the Oscilloscope and the Metering window is not refreshed until a triggering event occurs.)

45. On the Power Supply, momentarily reduce the ac voltage at bridge 2 (inverter bridge) by quickly setting the voltage control knob to the 50% position and returning it to the 100% position. Observe that a
commutation failure occurs (i.e., the Oscilloscope display is refreshed due to the occurrence of the triggering event).

Observe the waveforms displayed on the Oscilloscope. Explain why a commutation failure occurred at bridge 2.

46. On the Power Supply, turn the three-phase ac power source off by setting the main power switch to the O (off) position. Turn the 24 V ac power source of the Power Supply off. Close the LVDAC-EMS software. Disconnect all leads and return them to their storage location.

**Conclusion**

In this exercise, you learned how thyristor commutation is performed in thyristor three-phase bridges. You learned that the six thyristors in a thyristor three-phase bridge are fired in such a way that at any given instant, one thyristor in the common-anode thyristor group and one thyristor in the common-anode thyristor group are both conducting current, thereby allowing current to flow continuously through the bridge. You learned that when a commutation failure occurs in a thyristor three-phase bridge, the dc side of the bridge becomes short-circuited 60° later (i.e., when the next thyristor is fired). This causes the dc voltage across the transmission line to drop to zero, and thus the power transferred through the system to drop to zero. You learned that commutation failures are more likely to occur in thyristor three-phase bridges that operate as inverters because as the firing angle \( \alpha \) approaches 180°, the extinction angle \( \gamma \) becomes closer to the thyristor extinction angle \( \gamma_0 \). You also learned that commutation overlap in thyristor three-phase bridges reduces the extinction angle \( \gamma \) and thus increases the likelihood of commutation failures.

**Review Questions**

1. Explain how the six thyristors in a thyristor three-phase bridge are fired to allow current to flow continuously through the bridge.
2. What is meant by “commutation failure”? Describe the effect a commutation failure has on the dc current $I_{dc}$ and voltage $E_{dc}$, and on the dc power transferred via the transmission line, and explain this effect.

________________________________________

________________________________________

________________________________________

________________________________________

3. State the two conditions required for commutation to be successful (i.e., to avoid a commutation failure) and explain these conditions.

________________________________________

________________________________________

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________________________________________

4. What is meant by “commutation overlap”? Explain the effect that commutation overlap has on the extinction angle $\gamma$.

________________________________________

________________________________________

________________________________________

________________________________________
5. What happens to the overlap angle $\mu$, the extinction angle $\gamma$, and the likelihood of commutation failures when the current $I_{dc}$ flowing through the dc side of a thyristor three-phase bridge increases? What happens when the voltage at the ac side of the bridge decreases due to a fault in the ac power system connected to this bridge? Explain.