Electricity and New Energy

HVDC Transmission Systems

Courseware Sample

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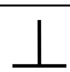
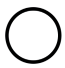
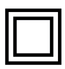
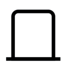
Safety and Common Symbols

The following safety and common symbols may be used in this manual and on the equipment:

Symbol	Description
⚠ DANGER	**DANGER** indicates a hazard with a high level of risk which, if not avoided, will result in death or serious injury.
⚠ WARNING	**WARNING** indicates a hazard with a medium level of risk which, if not avoided, could result in death or serious injury.
⚠ CAUTION	**CAUTION** indicates a hazard with a low level of risk which, if not avoided, could result in minor or moderate injury.
CAUTION	**CAUTION** used without the *Caution, risk of danger* sign ⚠, indicates a hazard with a potentially hazardous situation which, if not avoided, may result in property damage.
	Caution, risk of electric shock
	Caution, hot surface
	Caution, risk of danger
	Caution, lifting hazard
	Caution, hand entanglement hazard
	Notice, non-ionizing radiation
	Direct current
~	Alternating current
	Both direct and alternating current
3~	Three-phase alternating current
	Earth (ground) terminal

Safety and Common Symbols

Symbol	Description
	Protective conductor terminal
	Frame or chassis terminal
	Equipotentiality
	On (supply)
	Off (supply)
	Equipment protected throughout by double insulation or reinforced insulation
	In position of a bi-stable push control
	Out position of a bi-stable push control

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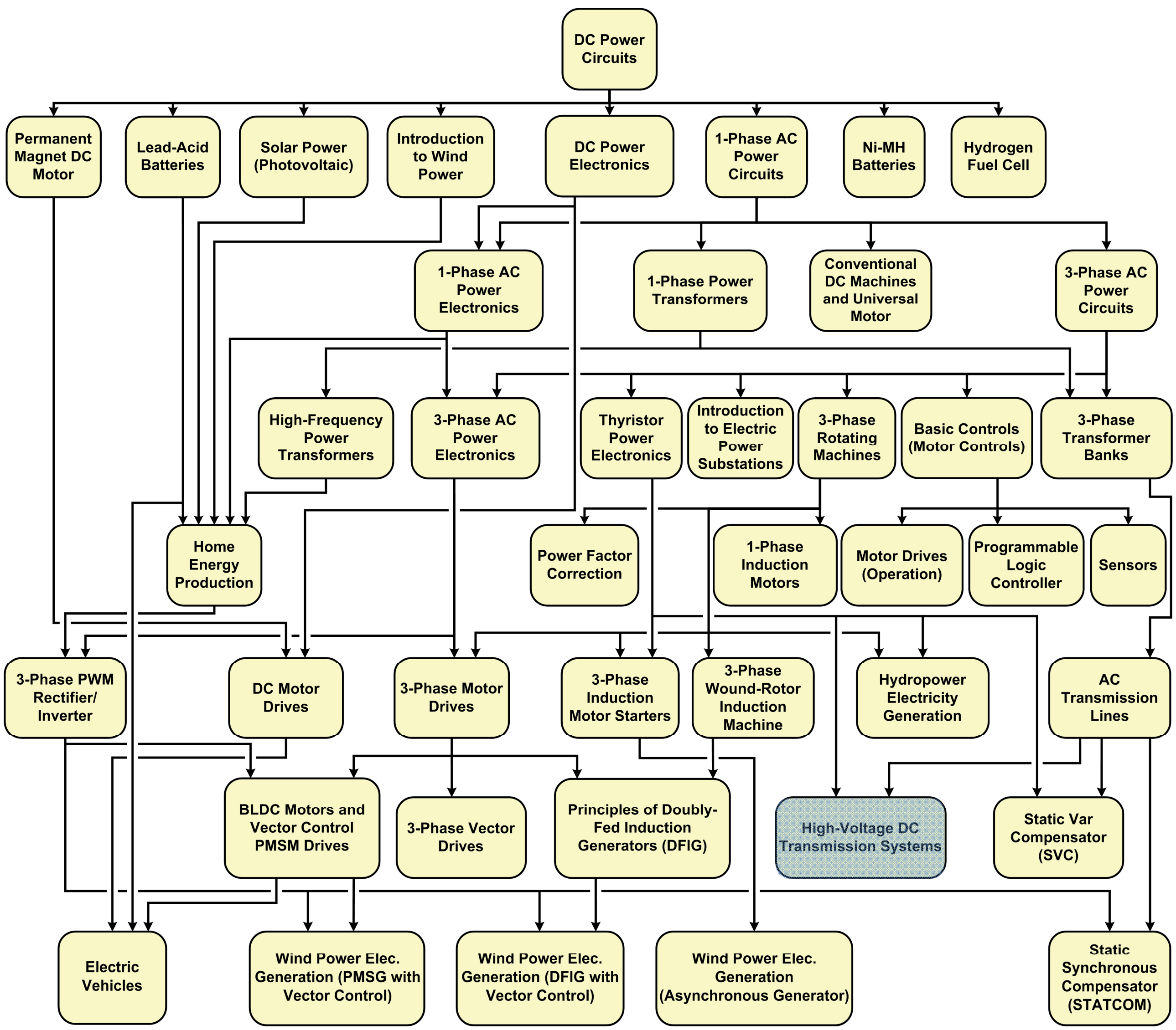
Preface

The production of energy using renewable natural resources such as wind, sunlight, rain, tides, geothermal heat, etc., has gained much importance in recent years as it is an effective means of reducing greenhouse gas (GHG) emissions. The need for innovative technologies to make the grid smarter has recently emerged as a major trend, as the increase in electrical power demand observed worldwide makes it harder for the actual grid in many countries to keep up with demand. Furthermore, electric vehicles (from bicycles to cars) are developed and marketed with more and more success in many countries all over the world.

To answer the increasingly diversified needs for training in the wide field of electrical energy, the Electric Power Technology Training Program was developed as a modular study program for technical institutes, colleges, and universities. The program is shown below as a flow chart, with each box in the flow chart representing a course.



The Electric Power Technology Training Program.

Preface

The program starts with a variety of courses providing in-depth coverage of basic topics related to the field of electrical energy such as ac and dc power circuits, power transformers, rotating machines, ac power transmission lines, and power electronics. The program then builds on the knowledge gained by the student through these basic courses to provide training in more advanced subjects such as home energy production from renewable resources (wind and sunlight), large-scale electricity production from hydropower, large-scale electricity production from wind power (doubly-fed induction generator [DFIG], synchronous generator, and asynchronous generator technologies), smart-grid technologies (SVC, STATCOM, HVDC transmission, etc.), storage of electrical energy in batteries, and drive systems for small electric vehicles and cars.

We invite readers of this manual to send us their tips, feedback, and suggestions for improving the book.

Please send these to did@de.festo.com.

The authors and Festo Didactic look forward to your comments.

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About This Manual

The development of HVDC (high-voltage, direct-current) transmission systems began in the early 1930's. In 1954, the first commercial HVDC transmission system was built in Sweden. This HVDC transmission system, called HVDC Gotland link, allowed transfer of dc power over a submarine cable linking the mainland of Sweden and the island of Gotland. At the time, HVDC transmission systems used mercury arc rectifiers to convert ac power into dc power for transmission over dc transmission lines. However, with the advent of semiconductors and the development of high-power electronic devices, mercury arc rectifiers were gradually replaced by thyristor bridges. Thus, since the end of the 1970s, new HVDC transmission systems most commonly use power converters made of thyristor three-phase bridges to convert electrical power from ac to dc, or from dc to ac.

Nowadays, HVDC transmission systems are used to transmit large amounts of electrical power over distances as long as 1000 km with very low transmission losses. HVDC transmission systems use overhead transmission lines made of only two conductors, compared to the three conductors in an ac transmission line. HVDC transmission systems can also use submarine cables made of only one conductor to efficiently transmit dc power under water over much longer distances compared to conventional ac power transmission systems.

The major advantage of HVDC transmission systems is that they permit the exchange of power between independent ac power systems operating at different frequencies. Furthermore, ac power systems linked by an HVDC transmission system do not need to operate in synchronism. Thus, each system can continue to operate with its own power controller and be developed independently.

HVDC transmission systems are an important element in the implementation of smart grids, as they allow fast and precise control of the amount of power transmitted between critical nodes of the grids. HVDC transmission systems also allow the direction of power flow to be reversed as required. HVDC transmission systems are often used together with flexible AC transmission systems (FACTS) to improve the control of the flow of electrical power in large interconnected grids. The use of HVDC transmission systems in conjunction with FACTS can help to stabilize ac power grids, increase the power-carrying capacity of existing transmission lines, limit the effects of disturbances in ac power systems and provide more accurate and faster frequency control compared to conventional frequency controllers.

About This Manual

HVDC converter station near Wellington, in New Zealand (photo courtesy of Marshelec).

Safety considerations

Safety symbols that may be used in this manual and on the equipment are listed in the Safety Symbols table at the beginning of the manual.

Safety procedures related to the tasks that you will be asked to perform are indicated in each exercise.

Make sure that you are wearing appropriate protective equipment when performing the tasks. You should never perform a task if you have any reason to think that a manipulation could be dangerous for you or your teammates.

Prerequisite

As a prerequisite to this course, you should have read the manuals titled *DC Power Circuits*, p.n. 86380, *Single-Phase AC Power Circuits*, p.n. 86358, *Single-Phase Power Transformers*, p.n. 86377, *Three-Phase AC Power Circuits*, p.n. 86360, *Thyristor Power Electronics*, p.n. 86363, *Three-Phase Transformer Banks*, p.n. 86379, and *AC Transmission Lines*, p.n. 86365.

Systems of units

Units are expressed using the International System of Units (SI) followed by the units expressed in the U.S. customary system of units (between parentheses).

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Sample Exercise

Extracted from

Student Manual

DC Current Regulation and Power Flow Control in HVDC Transmission Systems

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to explain how a current control loop operates. You will learn how to use current control loops at the rectifier and inverter stations of an HVDC transmission system to automatically control (regulate) the dc line current, and thus the amount of power transferred via the transmission line.

DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Operation with a current control loop at the rectifier bridge
  AC voltage fluctuations at the inverter bridge. AC voltage fluctuations at the rectifier bridge.
- Operation with current control loops at the rectifier and inverter bridges
- Setting the amount of power transferred through an HVDC transmission system
- Reversing the direction of power flow in an HVDC transmission system

DISCUSSION

Operation with a current control loop at the rectifier bridge

As you have previously learned, an HVDC transmission system allows dc power to be transferred via a transmission line in either direction. However, the dc line current, and thus the amount of power transferred via the line, is very sensitive to fluctuations of the ac voltage at either converter station.

This problem is generally solved by using a **current control loop** at the rectifier bridge, as Figure 36 shows. The current control loop uses a current sensor to measure the actual value of the dc line current I_{dc}. This loop compares the measured value of current I_{dc} to the value of the current command $I_{Ref.}$ (desired current value) and corrects for any difference (error) between the two by modifying the firing angle of the rectifier bridge until current I_{dc} is equal to the current command $I_{Ref.}$.

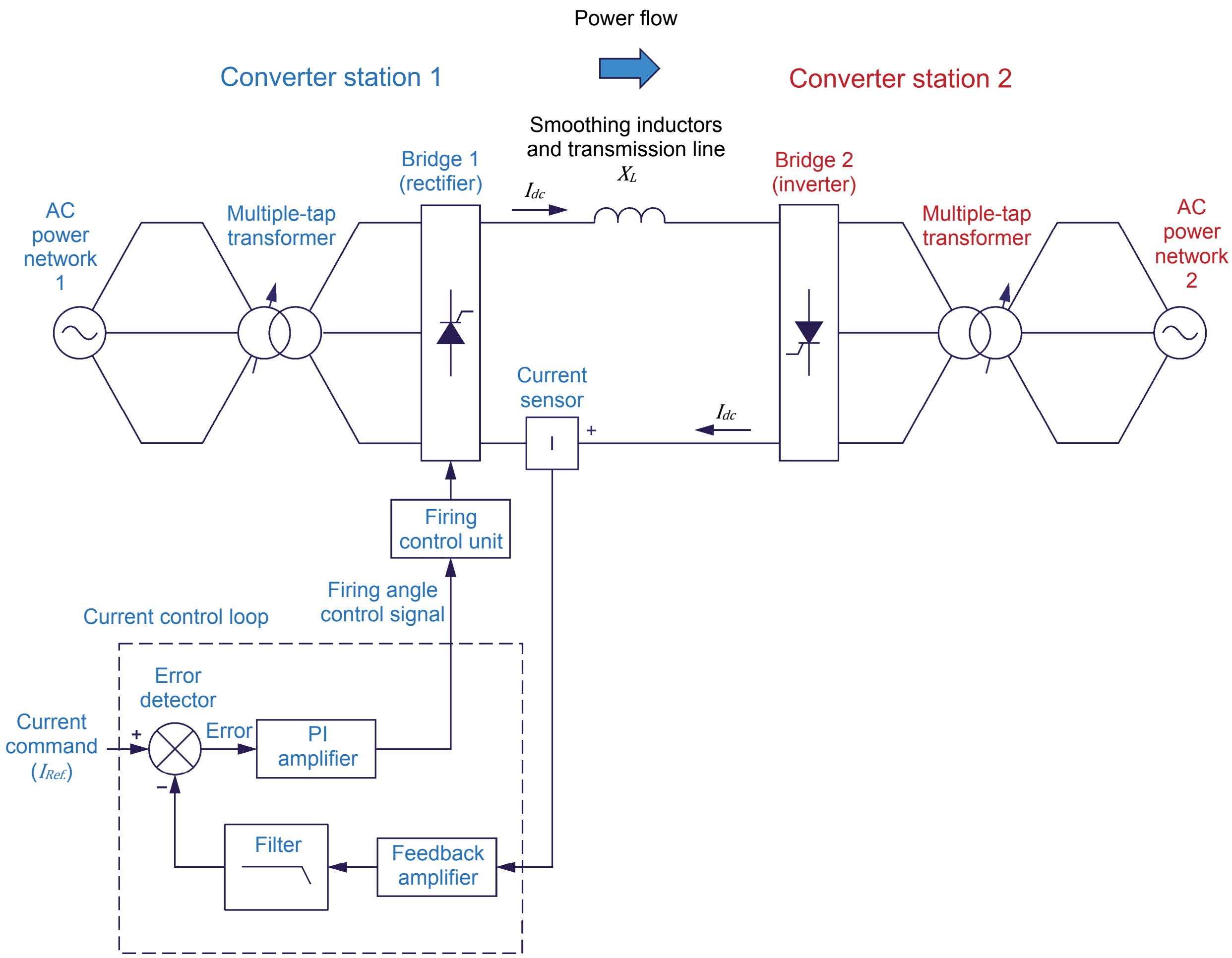

Figure 36. Current control loop used at the rectifier bridge of an HVDC transmission system.

The addition of a current control loop at the rectifier bridge of an HVDC transmission system modifies the voltage-versus-current relation of the rectifier bridge. Figure 37 shows the voltage-versus-current relation of a rectifier bridge whose firing angle is controlled by a current control loop. In this example, the current command $I_{Ref.}$ of the current control loop is set to 0.5 pu. The current control loop automatically adjusts the firing angle of the rectifier bridge to keep the dc current flowing through this bridge at a constant value, i.e., at the value of the current command $I_{Ref.}$ (0.5 pu).

To adjust the firing angle of the rectifier bridge, the current control loop produces a firing angle control signal (amplified error signal) which is applied to the firing control unit of the rectifier bridge. The firing angle control signal is proportional to the error (difference) between the measured current I_{dc} and the current command $I_{Ref.}$. Furthermore, the polarity of the firing angle control signal is the same as that of the error (difference) between the measured current I_{dc} and the current command $I_{Ref.}$.

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In the firing control unit, the firing angle control signal is multiplied by -1 to obtain the desired control action. Therefore, when the detected error is positive (i.e., when the measured current I_{dc} is lower than the current command $I_{Ref.}$), the firing angle control signal after multiplication is of negative polarity and decreases the firing angle of the rectifier bridge in order to increase the bridge dc voltage, and thus the dc current flowing through this bridge. Conversely, when the detected error is negative (i.e., when the measured current I_{dc} is higher than the current command $I_{Ref.}$), the firing angle control signal after multiplication is of positive polarity and increases the firing angle of the rectifier bridge in order to decrease the bridge dc voltage, and thus the dc current flowing through this bridge.

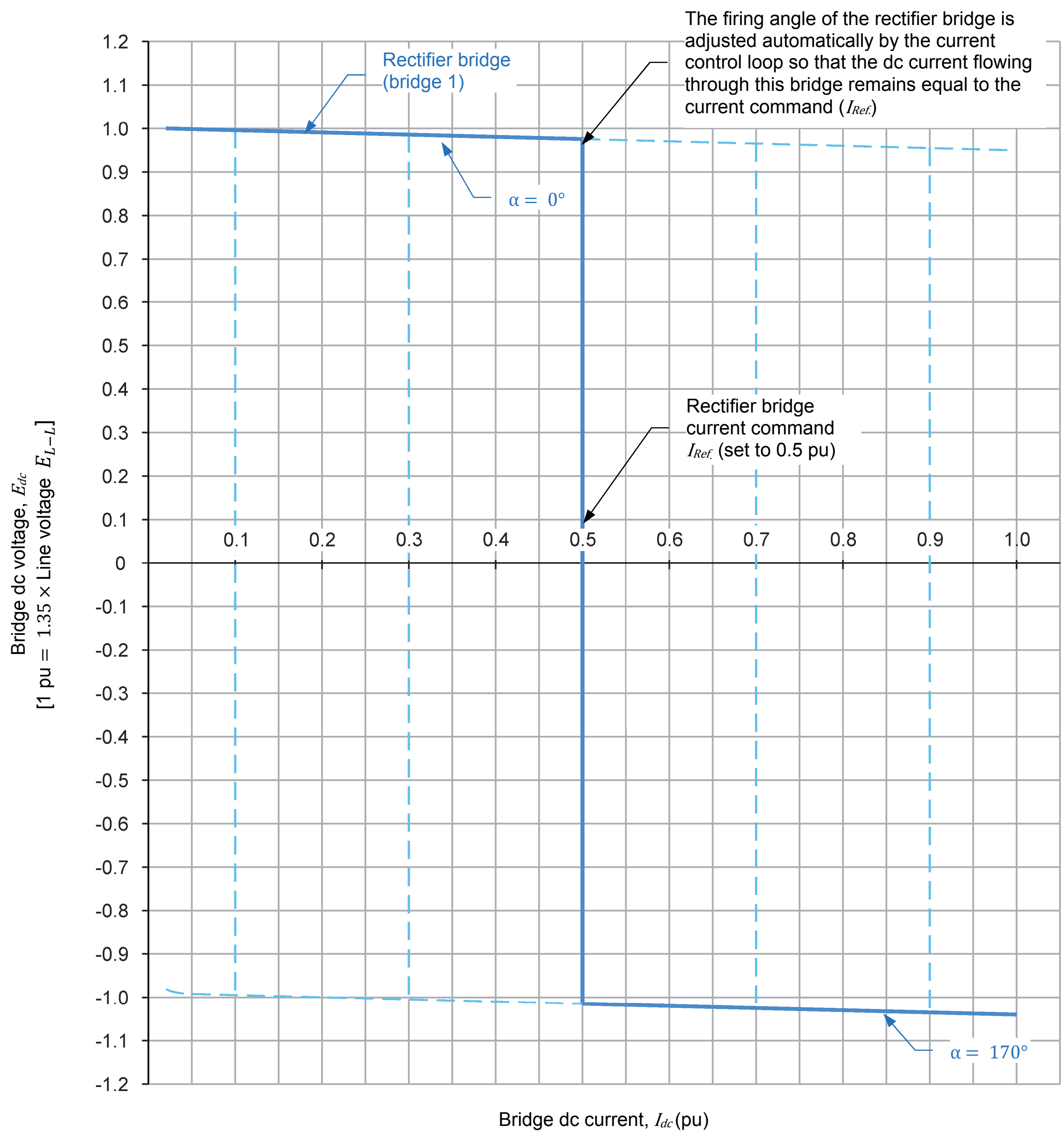

Figure 37. Voltage-versus-current relation at the dc side of the rectifier bridge.

Most firing control units can apply the arc cosine function to the firing angle control signal in order to linearize the relationship between this signal and the bridge dc voltage. The arc cosine function compensates for the non-linearity of the bridge dc voltage-versus-firing angle relation, which is cosinusoidal in nature. This improves the performance and stability of the current control loop. Note that when the arc cosine function is used in the firing control unit, the firing control signal does not have to be multiplied by -1 as this multiplication factor is already provided by the arc cosine function.

AC voltage fluctuations at the inverter bridge

Figure 38 shows how the current control loop of the rectifier bridge keeps the value of the dc line current I_{dc} constant, i.e., at the value of the current command $I_{Ref.}$, when ac voltage fluctuations occur at the inverter bridge. In this example, a firing angle of 18° is required at the rectifier bridge to set current I_{dc} to the value of the current command $I_{Ref.}$ (0.5 pu) when the ac voltage at the inverter bridge is at the nominal value. The ac voltage at the rectifier bridge is also considered to be at the nominal value. The voltage-versus-current relation of the inverter bridge at the nominal ac voltage is shown in bold red.

When the ac voltage decreases at the inverter bridge, the current control loop increases the firing angle of the rectifier bridge to prevent current I_{dc} from increasing, thereby keeping current I_{dc} at the value of the current command $I_{Ref.}$. Conversely, when the ac voltage increases at the inverter bridge, the current control loop decreases the firing angle of the rectifier bridge to prevent current I_{dc} from decreasing, thereby keeping current I_{dc} at the value of the current command $I_{Ref.}$.

Notice that when the ac voltage increases too much at the inverter bridge, the current control loop decreases the firing angle of the rectifier bridge to the minimum value (0°). However, this is not sufficient to keep current I_{dc} at the value of the current command $I_{Ref.}$. As a result, current I_{dc}, and thus the amount of power transferred via the transmission line, starts decreasing significantly. A solution to this problem is discussed later in the discussion.

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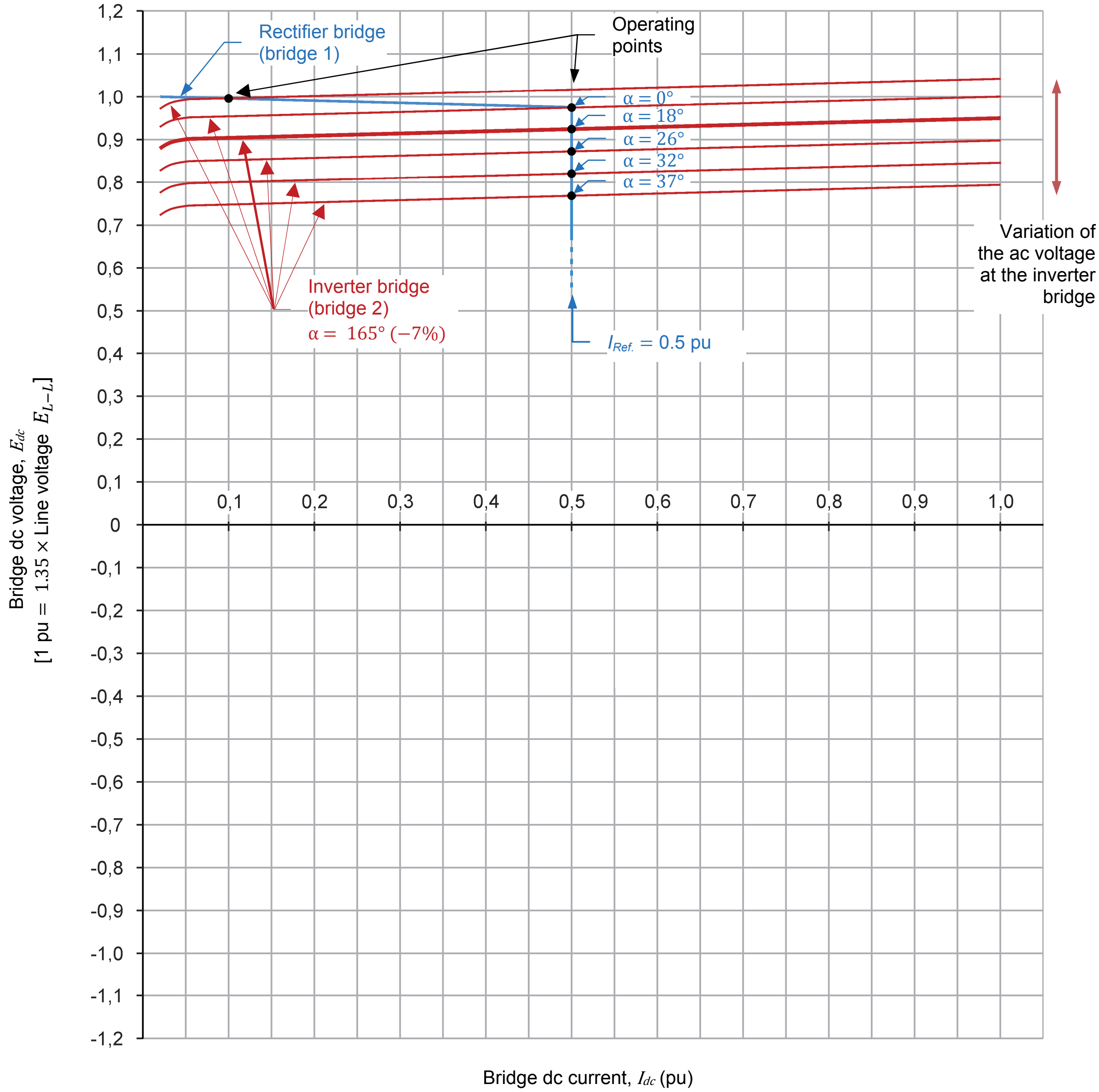

Figure 38. When ac voltage fluctuations occur at the inverter bridge, the current control loop at the rectifier bridge readjusts the firing angle of the rectifier bridge to keep the dc line current I_{dc} at the value of the current command $I_{Ref.}$ (0.5 pu).

AC voltage fluctuations at the rectifier bridge

The following five figures show how the current control loop at the rectifier bridge keeps the dc line current I_{dc} constant (i.e., at the value of the current command $I_{Ref.}$) when ac voltage fluctuations occur at the rectifier bridge. As Figure 39 shows, a firing angle of 18° is required at the rectifier bridge to set the dc line current I_{dc} to the value of the current command $I_{Ref.}$ (0.5 pu) when the ac voltage at the rectifier bridge is at the nominal value. The ac voltage at the inverter bridge is also considered to be at the nominal value.

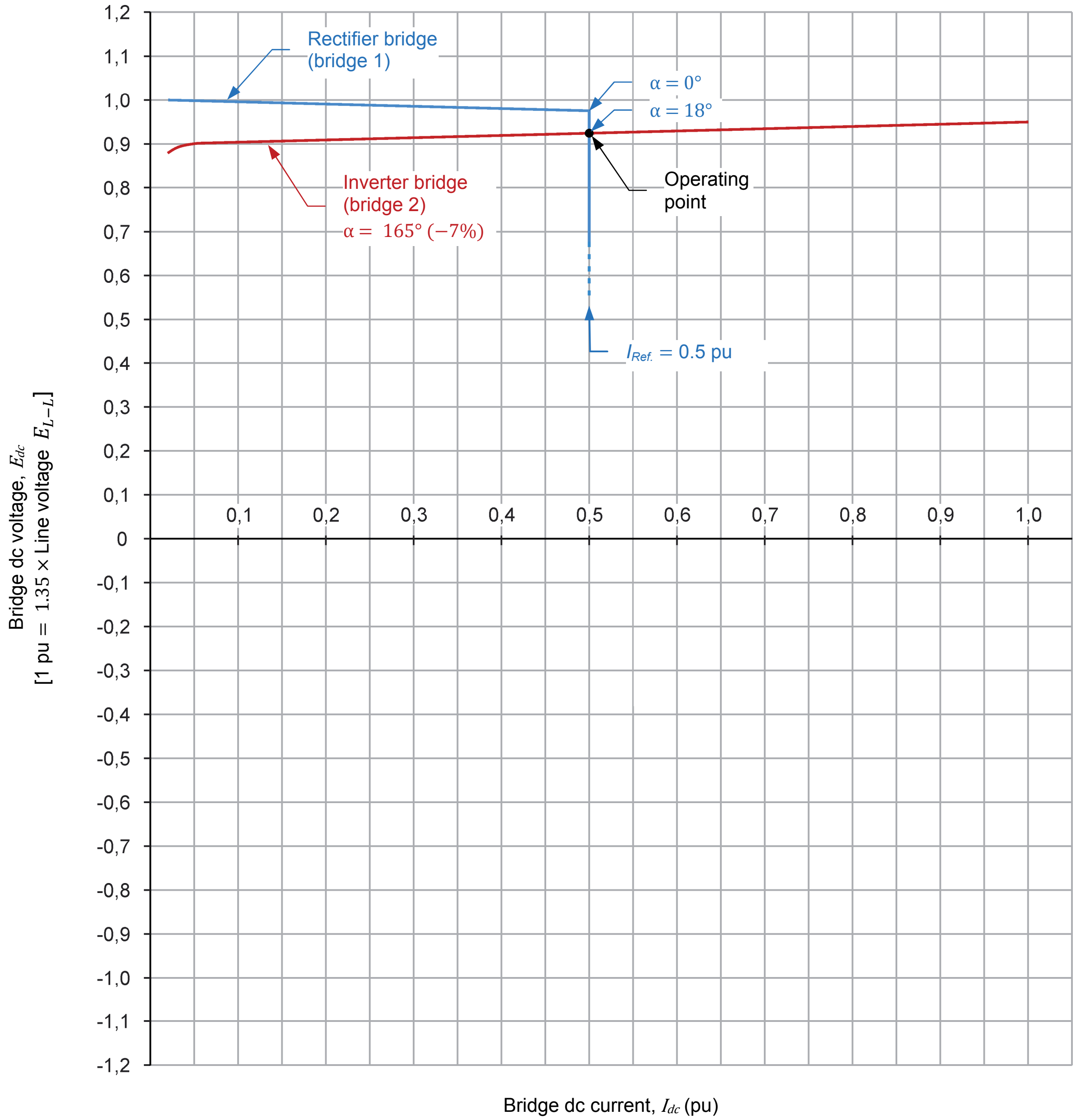

Figure 39. Voltage-versus-current relations of the rectifier and inverter bridges at the nominal ac voltage.

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When the ac voltage increases at the rectifier bridge (Figure 40 and Figure 41), the current control loop increases the firing angle of the rectifier bridge to prevent current I_{dc} from increasing, thereby keeping current I_{dc} at the value of the current command $I_{Ref.}$.

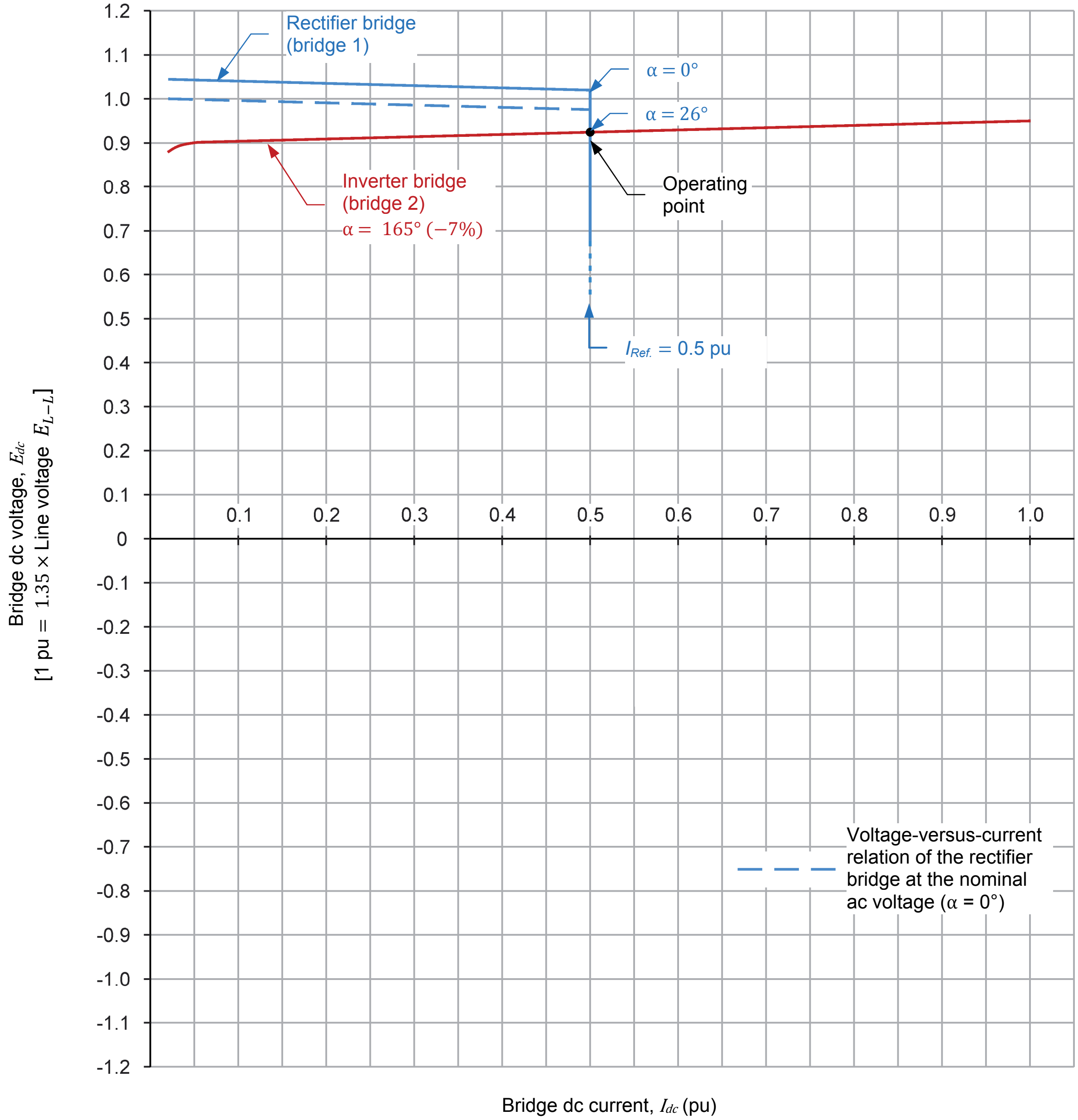

Figure 40. When the ac voltage increases at the rectifier bridge, the current control loop increases the firing angle of the rectifier bridge to keep the dc line current Idc at the value of the current command $I_{Ref.}$ (0.5 pu).

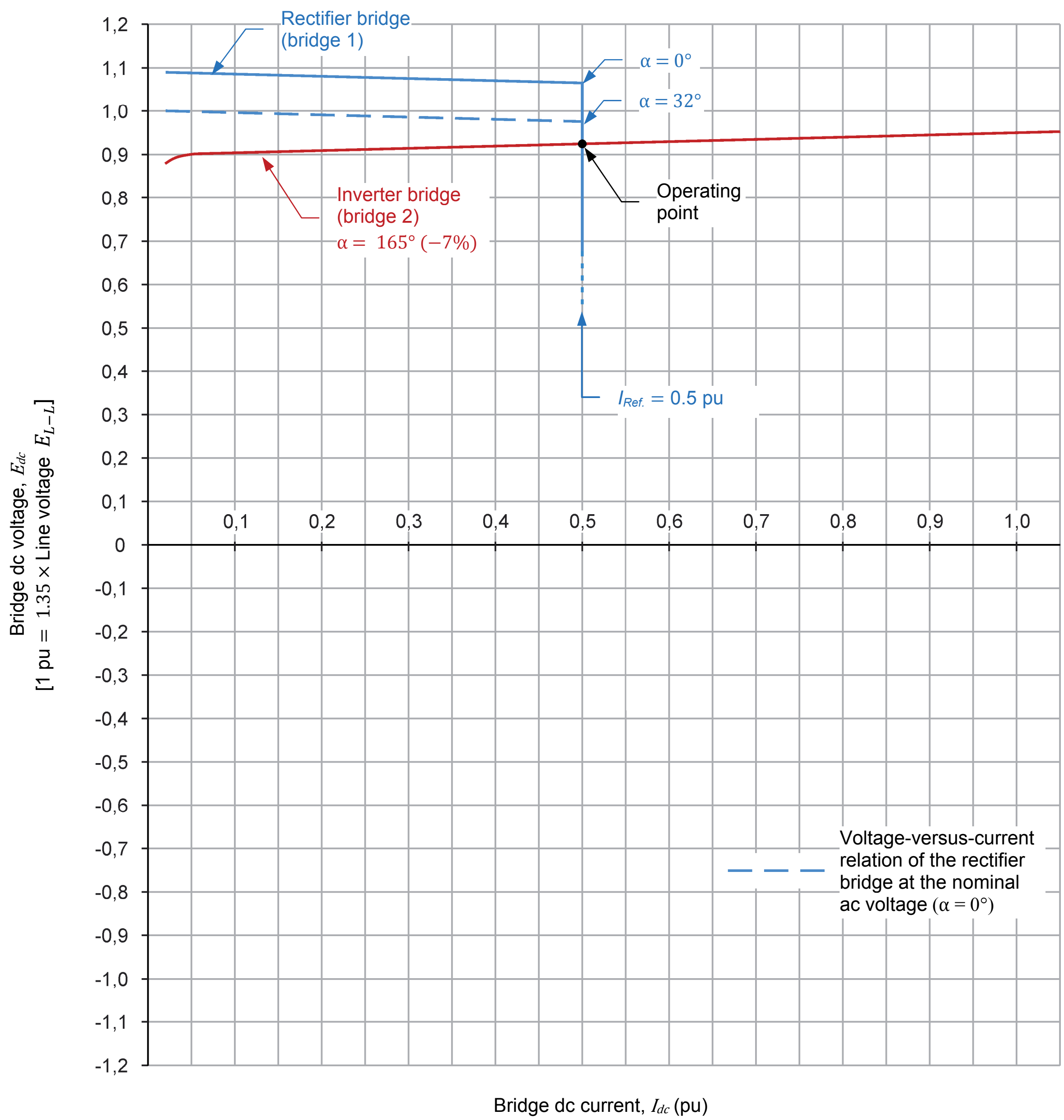

Figure 41. A further increase in the ac voltage at the rectifier bridge causes the current control loop to further increase the firing angle of the rectifier bridge to keep current I_{dc} at the value of the current command $I_{Ref.}$ (0.5 pu).

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Conversely, when the ac voltage decreases at the rectifier bridge (Figure 42), the current control loop decreases the firing angle of the rectifier bridge to prevent current I_{dc} from decreasing, thereby keeping current I_{dc} at the value of the current command $I_{Ref.}$.

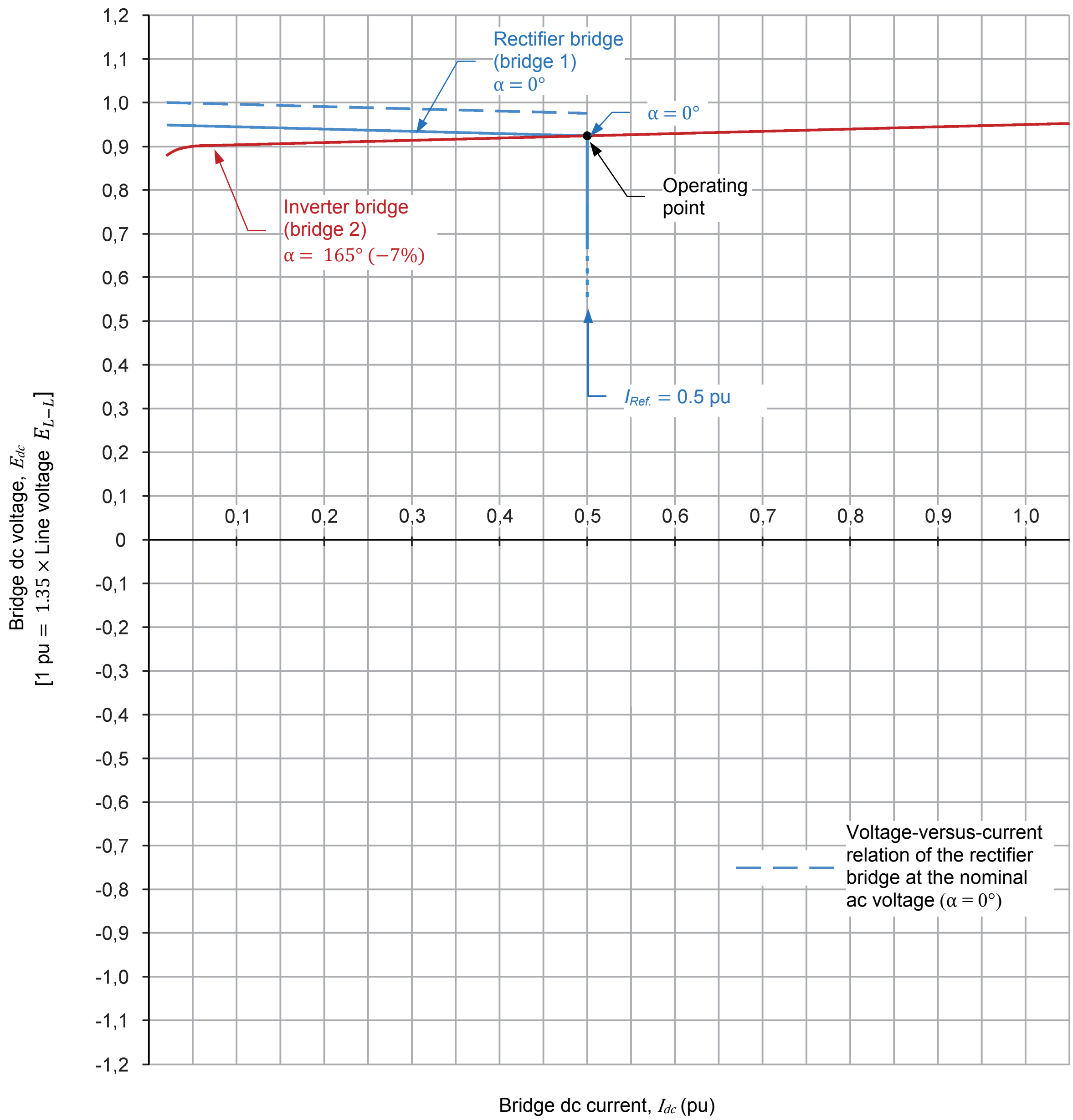

Figure 42. When the ac voltage decreases at the rectifier bridge, the current control loop decreases the firing angle of the rectifier bridge to keep current I_{dc} at the value of the current command $I_{Ref.}$ (0.5 pu).

Notice that when the ac voltage decreases too much at the rectifier bridge, the current control loop decreases the firing angle of the rectifier bridge to the minimum value (0°); this, however, is not sufficient to keep current I_{dc} at the value of the current command $I_{Ref.}$. As a result, current I_{dc} (and the amount of power transferred via the transmission line) starts decreasing significantly. In Figure 43, for example, the ac voltage at the rectifier bridge has decreased to such an extent that decreasing the firing angle of the rectifier bridge to 0° is insufficient to keep current I_{dc} (which is only 0.2 pu) at the value of the current command (0.5 pu). A solution to this problem is discussed in the next section.

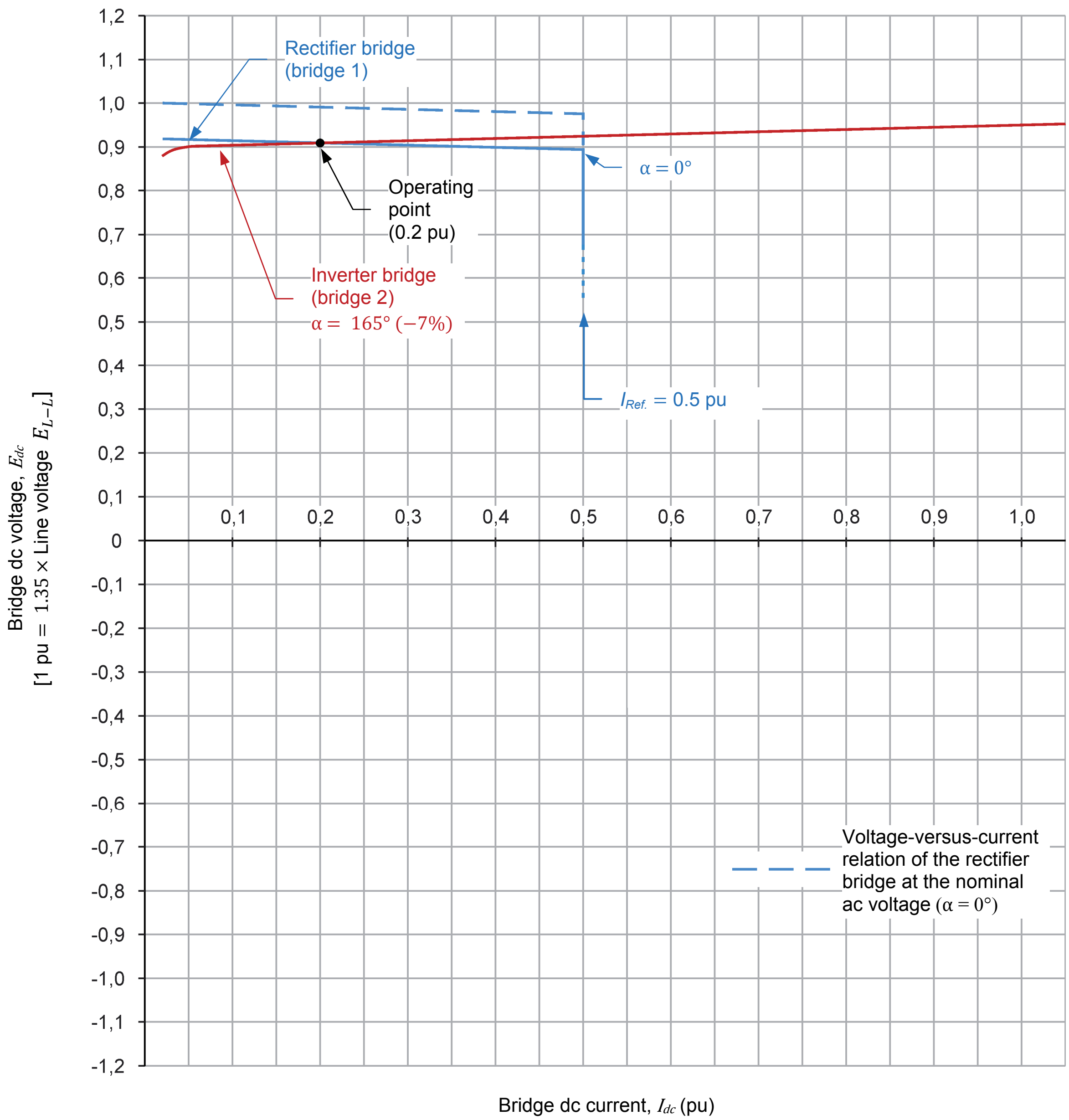

Figure 43. When the ac voltage decreases too much at the rectifier bridge, the current control loop decreases the firing angle of the rectifier bridge to the minimum value (0°); this is not sufficient to keep current I_{dc} at the value of the current command $I_{Ref.}$ (0.5 pu). As a result, current I_{dc} decreases and becomes lower (0.2 pu in this example) than the current command.

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Operation with current control loops at the rectifier and inverter bridges

Thus far, we have seen that the use of a current control loop at the rectifier bridge of an HVDC transmission system allows for automatic regulation in keeping the dc line current I_{dc} constant despite ac voltage fluctuations at either of the bridges, as long as the fluctuations are not too great. However, when the ac voltage increases too much at the inverter bridge or decreases too much at the rectifier bridge, the current control loop decreases the firing angle of the rectifier bridge to the minimum value (0°); this, however, is not sufficient to keep current I_{dc} constant (i.e., at the value of the current command). As a result, current I_{dc} (and the amount of power transferred via the transmission line), starts decreasing significantly.

This problem can be solved by adding a second current control loop at the inverter bridge of the HVDC transmission system. Figure 44 shows an HVDC transmission system with current control loops at both the rectifier and inverter bridges.

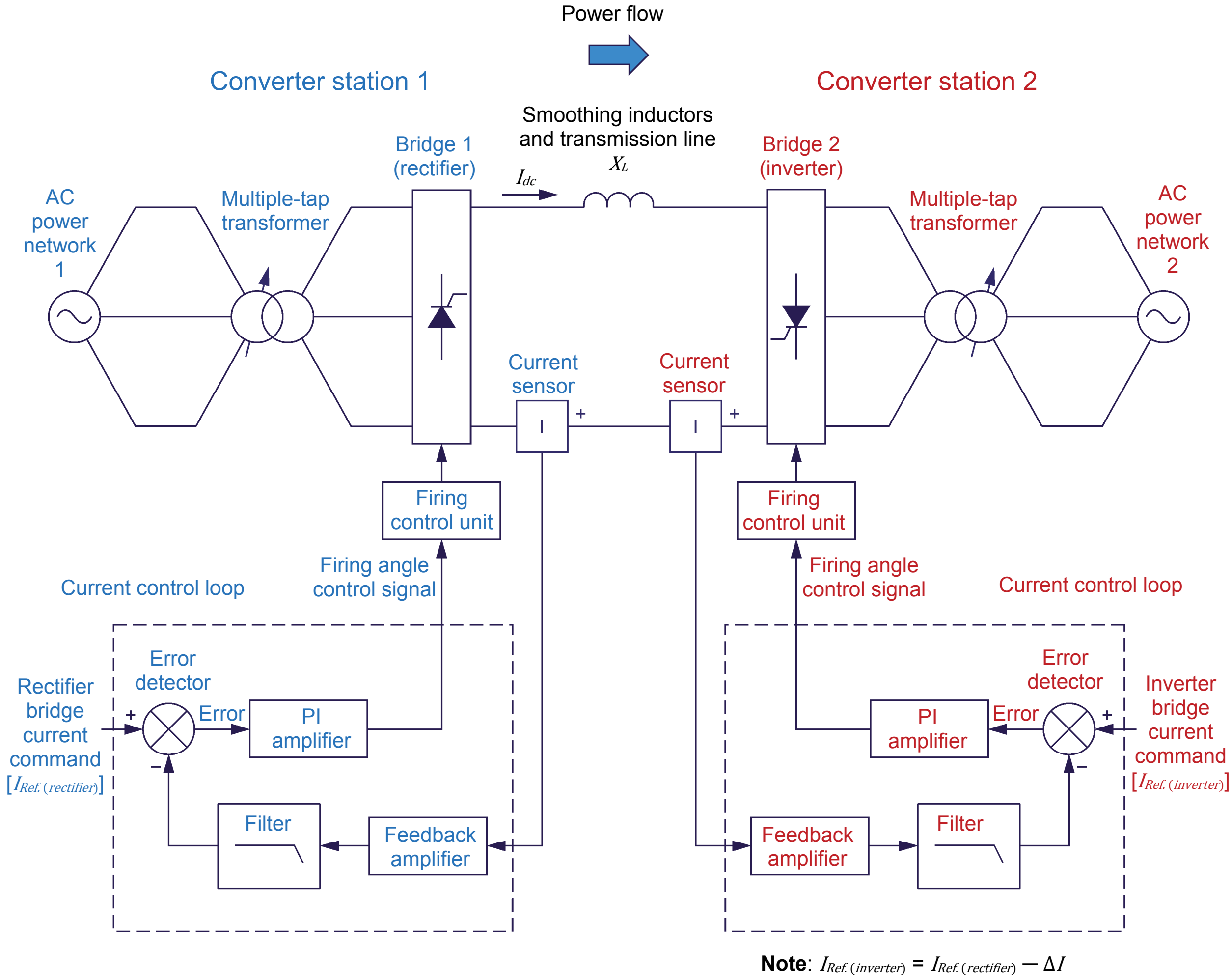

Figure 44. The addition of a second current control loop at the inverter bridge of an HVDC transmission system limits the effect of ac voltage fluctuations on the dc line current I_{dc} by keeping it within a predetermined current margin (ΔI).

The selected current margin depends on the magnitude of the harmonics (ripple) in the dc current. Thus the current margin must be wide enough to prevent any interaction between the loops due to harmonics in the dc current. A current margin of approximately 0.1 pu is common in HVDC transmission systems.

The current control loops at the rectifier and inverter bridges in Figure 44 are identical and they operate the same way. The only difference is that the current command $I_{Ref.\,(inverter)}$ of the current control loop at the inverter bridge has a value slightly lower than the current command $I_{Ref.\,(rectifier)}$ of the current control loop at the rectifier bridge to prevent any interaction between these loops. The difference between the values of these two current commands, $I_{Ref.\,(rectifier)} - I_{Ref.\,(inverter)}$, is known as the **current margin** (ΔI).

The combined action of the two current control loops limits the effect of ac voltage fluctuations on the dc line current I_{dc} (i.e., on the system's operating point) by keeping it within the current margin ΔI of the two thyristor bridges. Thus, these loops prevent current I_{dc} (and the amount of power transferred) from decreasing significantly when the ac voltage fluctuates to such an extent that the firing angle of the rectifier bridge reaches the minimum value (0°).

Figure 45 shows how the current control loops prevent the dc line current I_{dc}, and thus the amount of power transferred, from decreasing significantly when the ac voltage fluctuates to the extent that the firing angle of the rectifier bridge reaches the minimum value (0°). In this example, the current command $I_{Ref.\,(rectifier)}$ and the current margin ΔI are set to 0.5 pu and 0.05 pu, respectively, thereby resulting in a current command $I_{Ref.\,(inverter)}$ of 0.45 pu.

As long as the current control loop of the rectifier bridge is able to keep the current I_{dc} flowing through the bridges at the value of current command $I_{Ref.\,(rectifier)}$ (0.5 pu) by readjusting the firing angle of the rectifier bridge ($\alpha_{Rectifier}$), the current control loop of the inverter bridge keeps the firing angle of the inverter bridge ($\alpha_{Inverter}$) at the maximum value allowed (165° in our example). In that case, the current I_{dc} (0.5 pu) is higher than the current command $I_{Ref.\,(inverter)}$ (0.45 pu) of the current control loop at the inverter bridge. This control loop therefore attempts to decrease the current I_{dc} by increasing the dc voltage at the inverter bridge to the maximum possible value, i.e., by increasing the firing angle $\alpha_{Inverter}$ to the maximum value (165° in our example).

However, when the ac voltage decreases at the rectifier bridge or increases at the inverter bridge to the extent that the firing angle $\alpha_{Rectifier}$ reaches the minimum value (0°) and the current I_{dc} flowing through the bridges starts decreasing significantly [i.e., below the value of current command $I_{Ref.\,(inverter)}$ (0.45 pu)], the current control loop of the inverter bridge enters into action by decreasing the firing angle $\alpha_{Inverter}$. It does this in order to keep the current I_{dc} at the value of current command $I_{Ref.\,(inverter)}$, and thus prevent current I_{dc} from decreasing further. The current I_{dc} therefore passes from 0.5 pu to 0.45 pu when the current control loop of the inverter bridge enters into action, which prevents the amount of power transferred via the transmission line from decreasing significantly in spite of ac voltage fluctuations.

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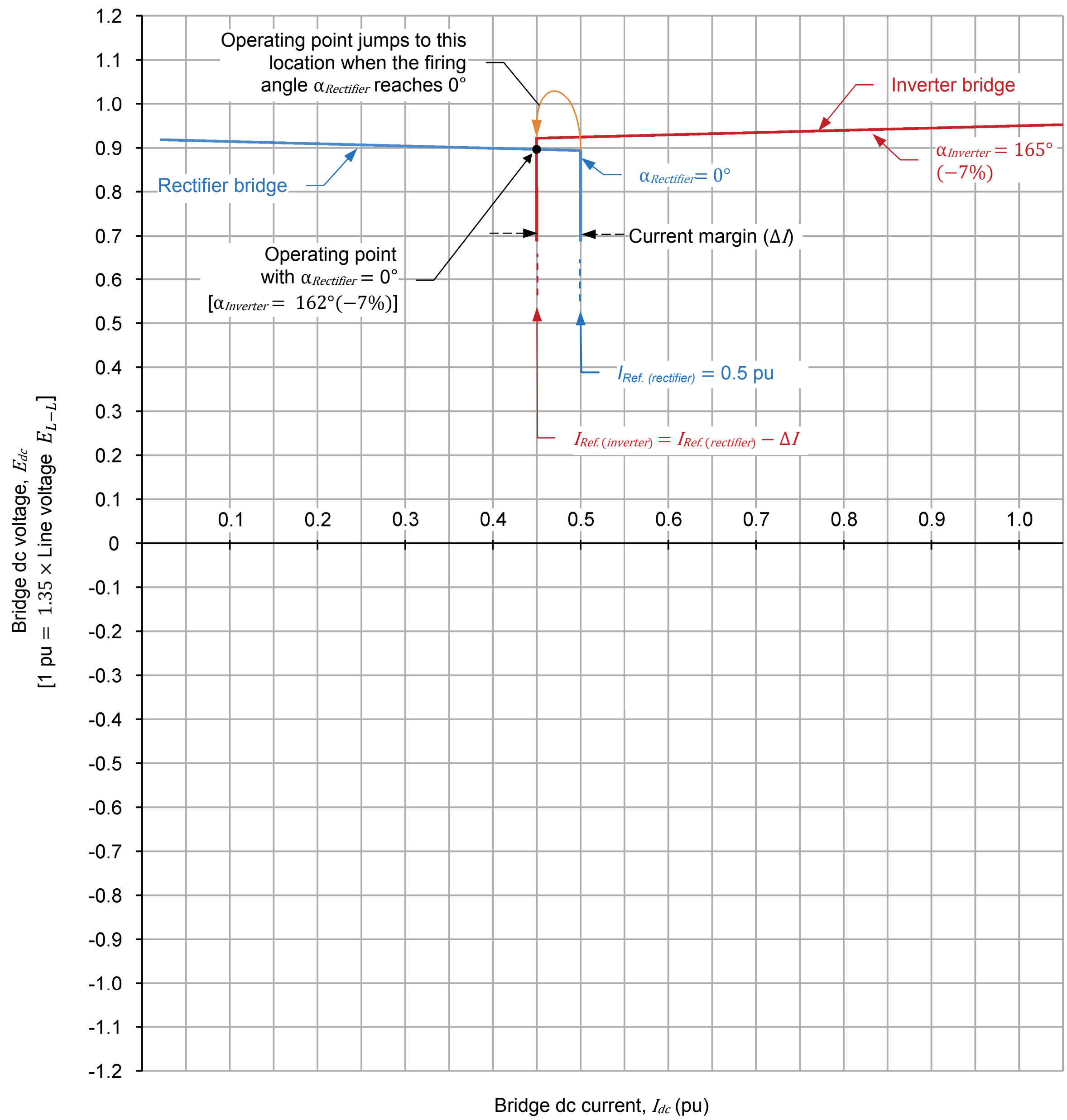

Figure 45. When the ac voltage decreases at the rectifier bridge or increases at the inverter bridge to the extent that the firing angle $\alpha_{Rectifier}$ reaches the minimum value (0°) and the current I_{dc} starts decreasing significantly, the current control loop of the inverter bridge enters into action to maintain current I_{dc} to $I_{Ref.\,(rectifier)} - \Delta I$ (i.e., 0.45 pu in the above example).

Figure 46 shows how the same two current control loops prevent the dc line current I_{dc}, and thus the amount of power transferred, from increasing significantly when the ac voltage fluctuates to the extent that the firing angle of the inverter bridge reaches the maximum value allowed (165° in our example).

As long as the current control loop of the inverter bridge is able to keep the current I_{dc} flowing through the bridges at the value of current command $I_{Ref.\,(inverter)}$ (0.45 pu) by readjusting the firing angle $\alpha_{Inverter}$, the current control loop of the rectifier bridge keeps the firing angle $\alpha_{Rectifier}$ at the minimum value (0°). In that case, the current I_{dc} (0.45 pu) is lower than the current command $I_{Ref.\,(rectifier)}$ of the current control loop at the rectifier bridge. This control loop therefore tries to increase the current I_{dc} by increasing dc voltage at the rectifier bridge to the maximum possible value, i.e., by decreasing the firing angle $\alpha_{Rectifier}$ to the minimum value (0°).

However, when the ac voltage increases at the rectifier bridge or decreases at the inverter bridge to the extent that the firing angle $\alpha_{Inverter}$ reaches the maximum value (165° in our example) and the current I_{dc} flowing through the bridges starts increasing significantly [i.e., above the value of current command $I_{Ref.\,(rectifier)}$ (0.5 pu)], the current control loop of the rectifier bridge enters into action by increasing the firing angle $\alpha_{Rectifier}$. It does this in order to keep the current I_{dc} flowing through the bridges at the value of current command $I_{Ref.\,(rectifier)}$, and thus prevent the current I_{dc} from increasing further. The current I_{dc} therefore passes from 0.45 pu to 0.5 pu (i.e., it returns to the initial value) when the current control loop of the rectifier bridge enters into action, which prevents current I_{dc} (and thus the amount of power transferred), from increasing significantly in spite of ac voltage fluctuations.

In short, as long as the ac voltage at both bridges remains close to the nominal value, the current control loop at the rectifier bridge keeps control of the system's operating point and maintains the current I_{dc} at $I_{Ref.\,(rectifier)}$. However, when the ac voltage at the rectifier bridge decreases too much or the ac voltage at the inverter bridge increases too much, the current control loop at the inverter bridge takes control of the system's operating point and maintains the current I_{dc} at a slightly lower value, i.e., at $I_{Ref.\,(rectifier)} - \Delta I$.

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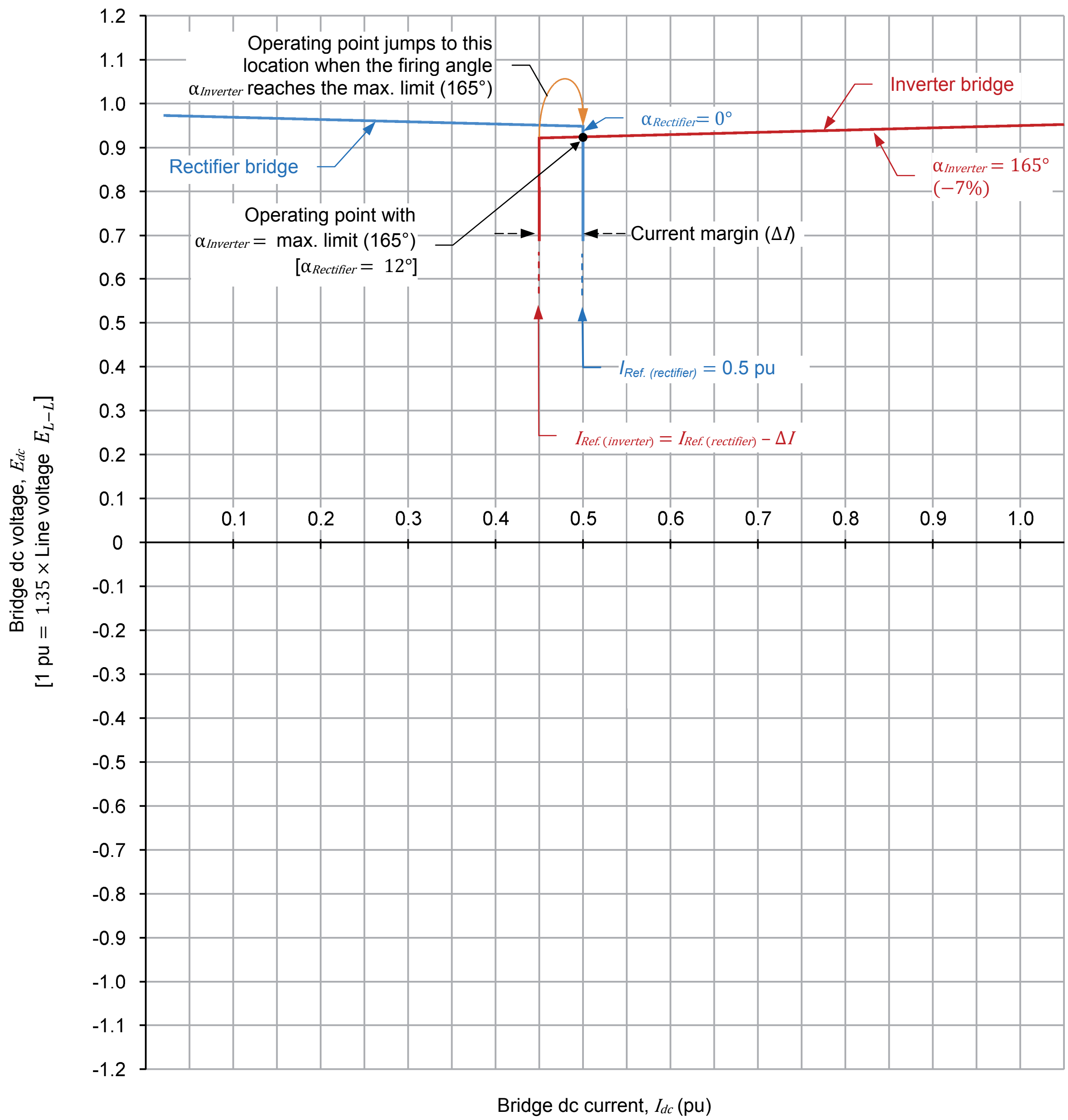

Figure 46. When the ac voltage increases at the rectifier bridge or decreases at the inverter bridge to the extent that the firing angle $\alpha_{Inverter}$ reaches the maximum value (165° in our example) and the current I_{dc} starts increasing significantly, the current control loop of the rectifier bridge enters into action to maintain current I_{dc} to $I_{Ref.\,(rectifier)}$ (i.e., 0.5 pu in the above example).

Setting the amount of power transferred through an HVDC transmission system

Since power is the product of voltage and current, the amount of dc power transferred through an HVDC transmission system can be adjusted by varying either the dc line voltage or the dc line current. However, the power losses (RI^2 losses) caused by heat dissipation in conductors increase with the square of current, while being virtually independent of the magnitude of voltage. Therefore, for any given amount of power transferred through an HVDC transmission system, it is best to operate at the highest dc voltage possible to keep the dc current as low as possible, and thus reduce the power losses to a minimum. The amount of power transferred can then be adjusted by varying the dc line current.

As an example, Figure 47 shows the voltage-versus-current relation of an HVDC transmission system in which the rectifier and inverter bridges are set to operate at the highest possible dc voltage. Initially, the current command of the HVDC transmission system (i.e., the current command $I_{Ref.\,(rectifier)}$) is set to 1.0 pu, while the current control loops set the firing angle of the rectifier bridge (bridge 1) to 0° and the firing angle of the inverter bridge (bridge 2) to the maximum (limit) value (165° in our example). Therefore, the maximum amount of power is transferred through the system. The amount of power transferred is adjusted (i.e., decreased) by varying the current command $I_{Ref.\,(rectifier)}$ over the range of values ensuring continuous current flow in the bridges (between 1.0 pu and 0.2 pu in this example). This causes the firing angle $\alpha_{Rectifier}$ to increase from 0° to 23°, while the firing angle $\alpha_{Inverter}$ remains at the maximum value (165°). The operating points on the voltage-versus-current relation of Figure 47 show that the dc voltage remains quite constant (i.e., close to the maximum value) over the dc current range ensuring continuous current flow (0.2 pu to 1.0 pu), with this voltage passing from 0.9 pu to 0.95 pu (a variation of only 0.05 pu) when the dc current passes from 0.2 pu to 1.0 pu.

Operating the rectifier and inverter bridges at the highest possible dc voltage over the dc current range ensuring continuous current flow not only keeps the power losses to a minimum, but also ensures that both bridges operate at a good DPF (above 0.9). This generally requires a variation of the firing angle between approximately 0° and 25° at the rectifier bridge, and the maximum firing angle at the inverter bridge (i.e., ≅ 165°). In Figure 47, for example, the DPF of the rectifier bridge passes from unity to 0.92 when the dc current passes from 1.0 pu to 0.2 pu because the firing angle $\alpha_{Rectifier}$ passes from 0° to 23°. The DPF of the inverter bridge is very good (≅ 0.95) since the firing angle $\alpha_{Inverter}$ is kept at the maximum value (165° in our example).

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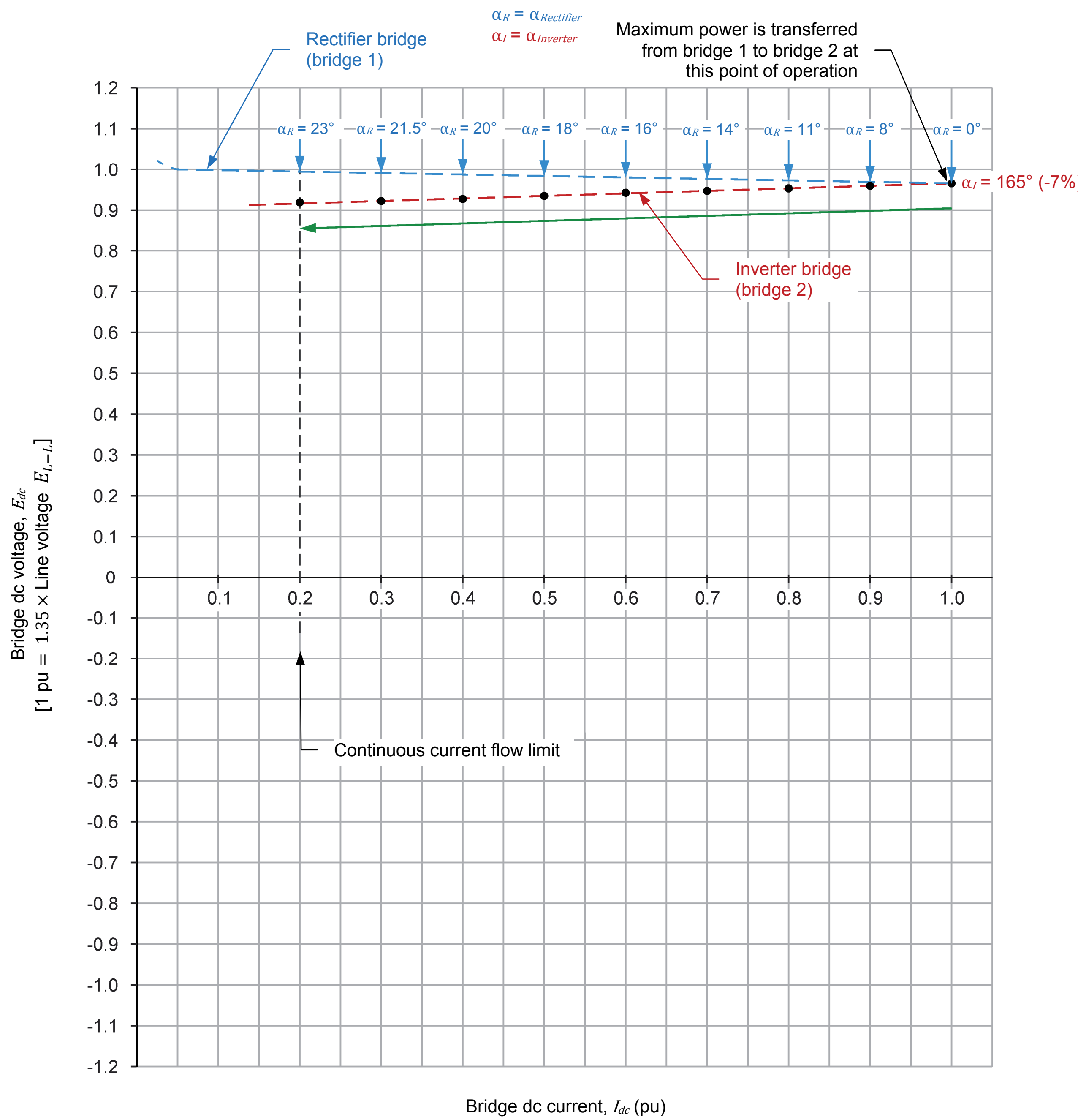

Figure 47. The amount of power transferred through an HVDC transmission system is set by adjusting the dc line current, i.e., the current command $I_{Ref.\ (rectifier)}$. To keep power losses (RI^2 losses) to a minimum and to ensure a good DPF at both thyristor bridges, the system is set to operate at the highest dc voltage possible.

To further decrease the amount of power transferred through the HVDC transmission system once the dc current has reached the minimum value (0.2 pu in our example) ensuring continuous current flow through the rectifier and inverter bridges, the dc voltage at which the system operates must be decreased. This is achieved by decreasing the maximum (limit) value of the inverter bridge firing angle ($\alpha_{Inverter}$) below 165°, as Figure 48 shows. Thus, the operating dc voltage can be decreased from maximum to zero by decreasing the limit value of the firing angle $\alpha_{Inverter}$ from 165° to 90°.

Operating an HVDC transmission system below the maximum dc voltage is an undesirable condition which should be allowed only temporarily (e.g., when it is necessary to decrease the power transferred to zero before reversing the direction of power flow). This is because operating the system below the maximum dc voltage reduces the power transfer efficiency since the RI^2 losses remain quite constant while the amount of power transferred decreases. Furthermore, this results in poor DPFs at both thyristor bridges. For example, consider the operating points obtained in Figure 48 when the current I_{dc} is set to the minimum value ensuring continuous current flow (0.2 pu) and the limit value of the firing angle $\alpha_{Inverter}$ is gradually decreased from 165° to 90° to reduce the operating dc voltage to zero.

- When the limit value of the firing angle $\alpha_{Inverter}$ is decreased from 165° to 150°, the firing angle $\alpha_{Rectifier}$ passes from 23° to 35°, as Figure 48 shows. Consequently, the DPF of the inverter bridge decreases from 0.95 to 0.87, while the DPF of the rectifier bridge decreases from 0.93 to 0.80. The DPFs at both bridges (0.87 and 0.80), therefore, are below 0.9 (the minimum DPF value that is generally considered acceptable).

- Further decreasing the limit value of the firing angle $\alpha_{Inverter}$ causes the firing angle $\alpha_{Rectifier}$ to further increase, as Figure 48 shows. Thus, when the limit value of the firing angle $\alpha_{Inverter}$ is decreased to 135°, 120°, 105°, and 90°, the firing angle $\alpha_{Rectifier}$ increases to 48°, 62°, 75°, and 90°, respectively. This causes the DPFs at both bridges to become worse and worse, decreasing to 0.71, 0.50, 0.24, to 0.00 at the inverter bridge, and to 0.65, 0.48, 0.25, and 0.00 at the rectifier bridge.

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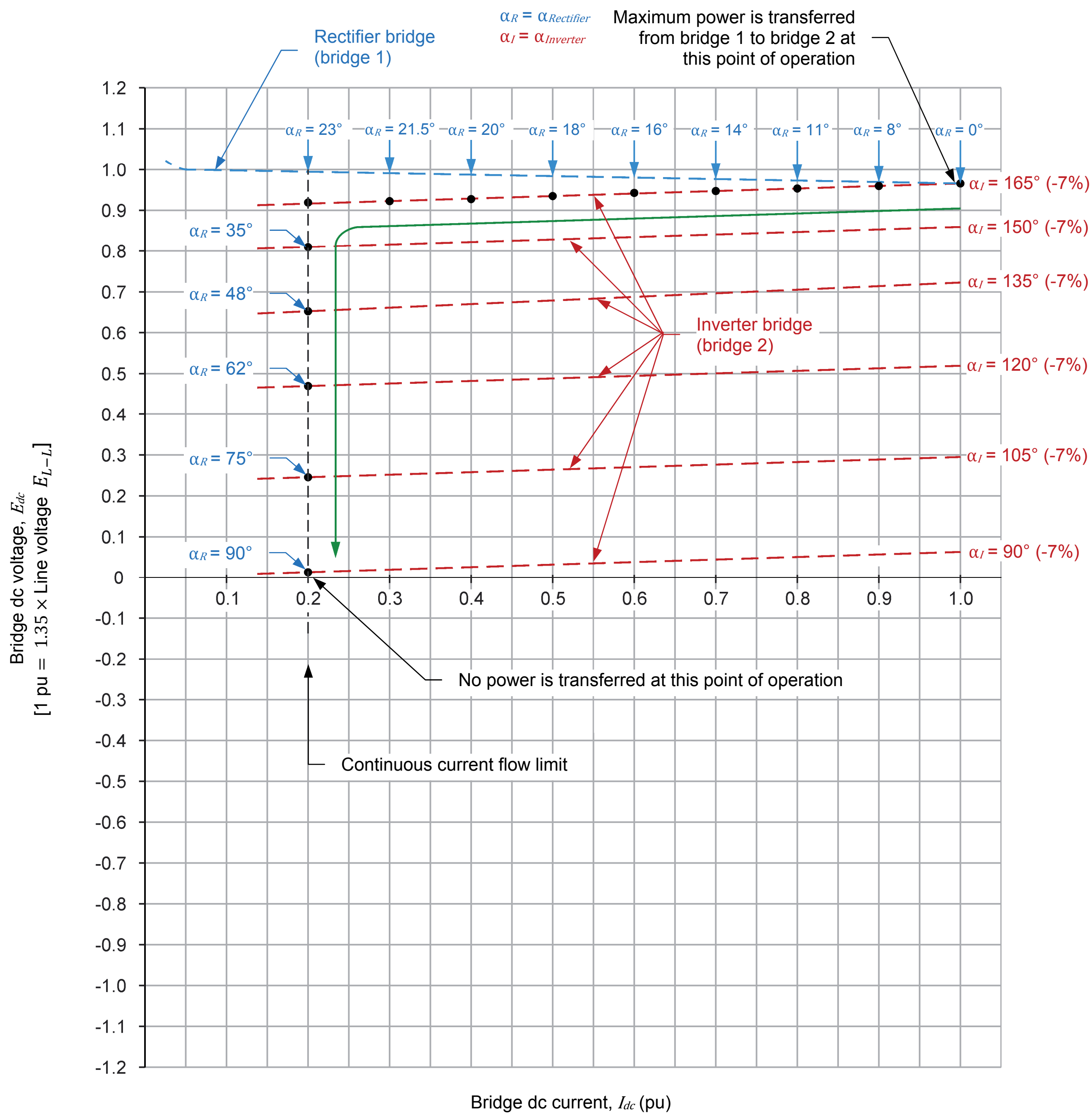

Figure 48. To decrease the amount of power transferred through an HVDC transmission system to zero, the dc voltage at which the system operates is reduced to zero. This, however, results in poor DPFs at both the rectifier and inverter bridges.

Reversing the direction of power flow in an HVDC transmission system

To reverse the direction of power flow in an HVDC transmission system, the power transferred from one bridge to the other must first be reduced to zero, then a procedure must be followed to make power flow in the opposite direction. For example, Figure 49 shows how to reverse the direction of power flow in an HVDC transmission system like the one shown in Figure 44. Initially, it is assumed that the maximum amount of power is transferred from bridge 1 to bridge 2 (i.e., the firing angle of bridge 1 is set to 0° and the firing angle of bridge 2 is set to 165°). The direction of power flow is reversed by performing the generic procedure below.

- Gradually decrease the amount of power flowing from bridge 1 to bridge 2 to zero. To do so, first decrease the dc current to the minimum value (0.2 pu in our example) ensuring continuous current flow in the bridges by decreasing the current command $I_{Ref.\,(rectifier)}$ of the bridge currently acting as a rectifier (i.e., bridge 1) to this minimum value. Then, decrease the voltage at which the system operates to zero by decreasing the maximum (limit) value of the firing angle $\alpha_{Inverter}$ of the bridge currently acting as an inverter (i.e., bridge 2) from 165° to 90°.

- Stop both bridges (i.e., stop thyristor firing in both bridges).

- Select the appropriate tap on the multiple-tap transformer of each converter station so that the bridge which will act as an inverter (i.e., bridge 1) operates at an ac voltage slightly lower than the bridge which will act as a rectifier (i.e., bridge 2).

- Set the current command $I_{Ref.\,(rectifier)}$ of the bridge which will act as a rectifier (i.e., bridge 2) to the minimum value (0.2 pu) ensuring continuous current flow in the bridges, then set the current command $I_{Ref.\,(inverter)}$ of the bridge which will act as an inverter (i.e., bridge 1) to $I_{Ref.\,(rectifier)} - \Delta I$.

- Set the maximum (limit) value of the firing angle $\alpha_{Inverter}$ of the bridge which will act as an inverter (i.e., bridge 1) to 90°.

- Start both bridges (the dc voltage at which the system operates should be approximately zero).

- Increase the dc voltage at which the system operates to maximum by gradually increasing the maximum (limit) value of the firing angle $\alpha_{Inverter}$ of the bridge now acting as an inverter (i.e., bridge 1) to the maximum value allowed (165° in our example).

- Set the current command $I_{Ref.\,(rectifier)}$ of the bridge now acting as a rectifier (i.e., bridge 2) to the value required to transfer the desired amount of power.

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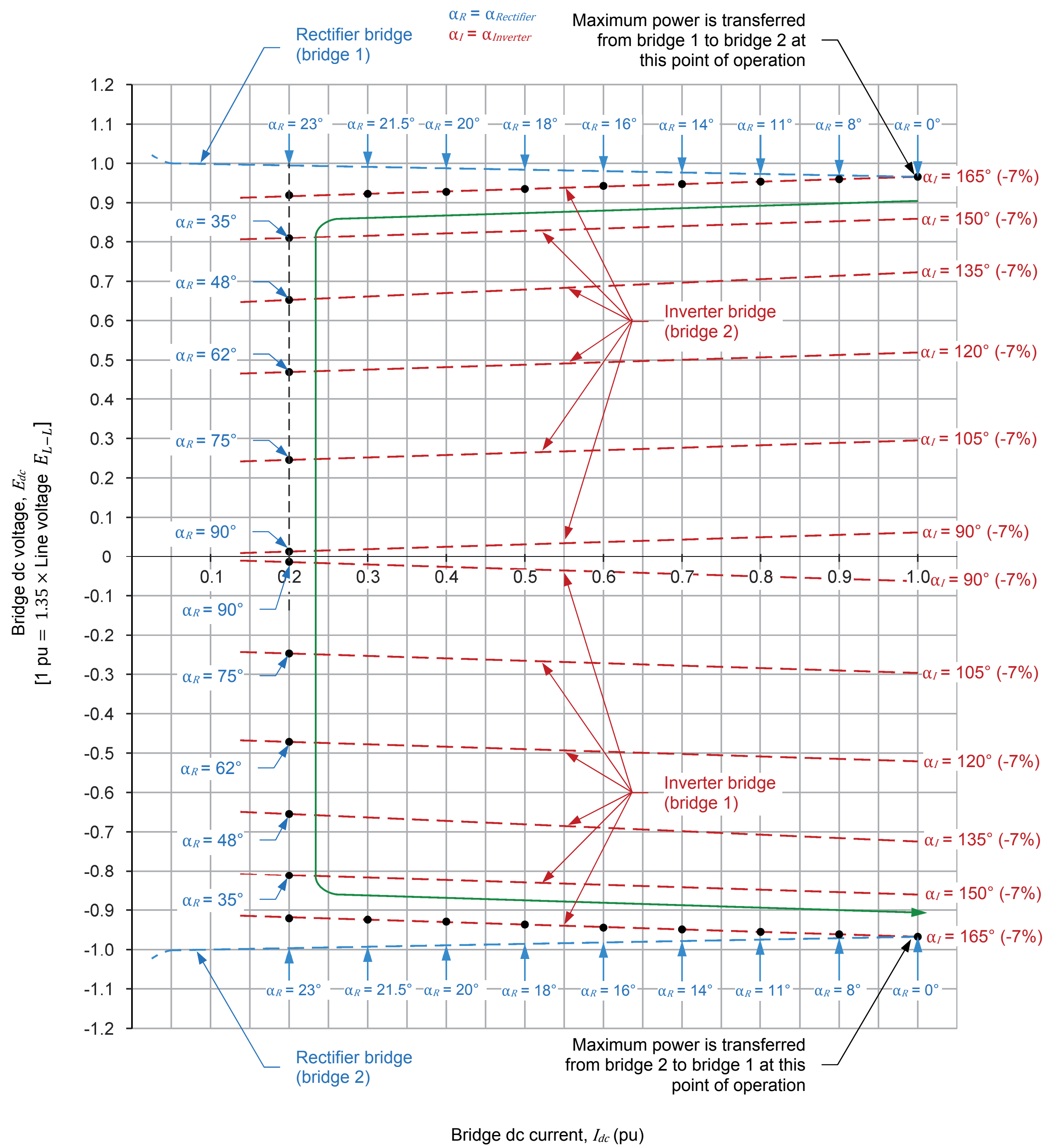

Figure 49. Diagram showing how the direction of power flow is reversed in an HVDC transmission system.

PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Set up and connections
- Operation of an HVDC transmission system with a current control loop at the rectifier bridge only
  Varying the current command of the rectifier bridge. AC voltage fluctuations at the inverter bridge. AC voltage fluctuations at the rectifier bridge.
- Operation of an HVDC transmission system with current control loops at the rectifier and inverter bridges
  Varying the current command at the rectifier bridge. AC voltage fluctuations at the inverter bridge. AC voltage fluctuations at the rectifier bridge.
- Varying the amount of power transferred via the HVDC transmission system
- Reversing the direction of power flow in the HVDC transmission system

PROCEDURE

Set up and connections

In this part of the exercise, you will set up a circuit representing an HVDC transmission system as well as 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 50, Figure 51, and Figure 52).

– 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 *Power Supply* 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.

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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 each Power Thyristors module, set switches S_1 and S_2 to the **I** (on) position. This interconnects thyristors Q_1 through Q_6 of each Power Thyristors module in a thyristor three-phase bridge.

   Connect the equipment as shown in Figure 50, Figure 51, and Figure 52. 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 X_L (inductance of the dc line and smoothing inductors). Note that terminals A1 and A2 in Figure 50 connect to the corresponding terminals in Figure 51, while terminals A3 and A4 in Figure 51 connect to the corresponding terminals in Figure 52.

   Inputs E1, E2, E3, I1, I2, and I3 of converter stations 1 and 2 (shown in Figure 50, Figure 51, and Figure 52) are all inputs of the DACI used in converter station 1. These inputs are used to measure parameters in the HVDC transmission system. Input E4 of the DACI used in converter station 1 provides synchronization of the firing signals for the Power Thyristors module in station 1. Input E4 of the DACI used in converter station 2 (represented by the red symbol E4 in Figure 52) provides synchronization of the firing signals for the Power Thyristors module in station 2. Input I4 of the DACI used in converter station 1 (represented by the blue symbol I4 in Figure 51) provides dc line current measurement for the current control loop of the thyristor bridge in station 1. Finally, input I4 of the DACI used in converter station 2 (represented by the red symbol I4 in Figure 51) provides dc line current measurement for the current control loop of the thyristor bridge in station 2.

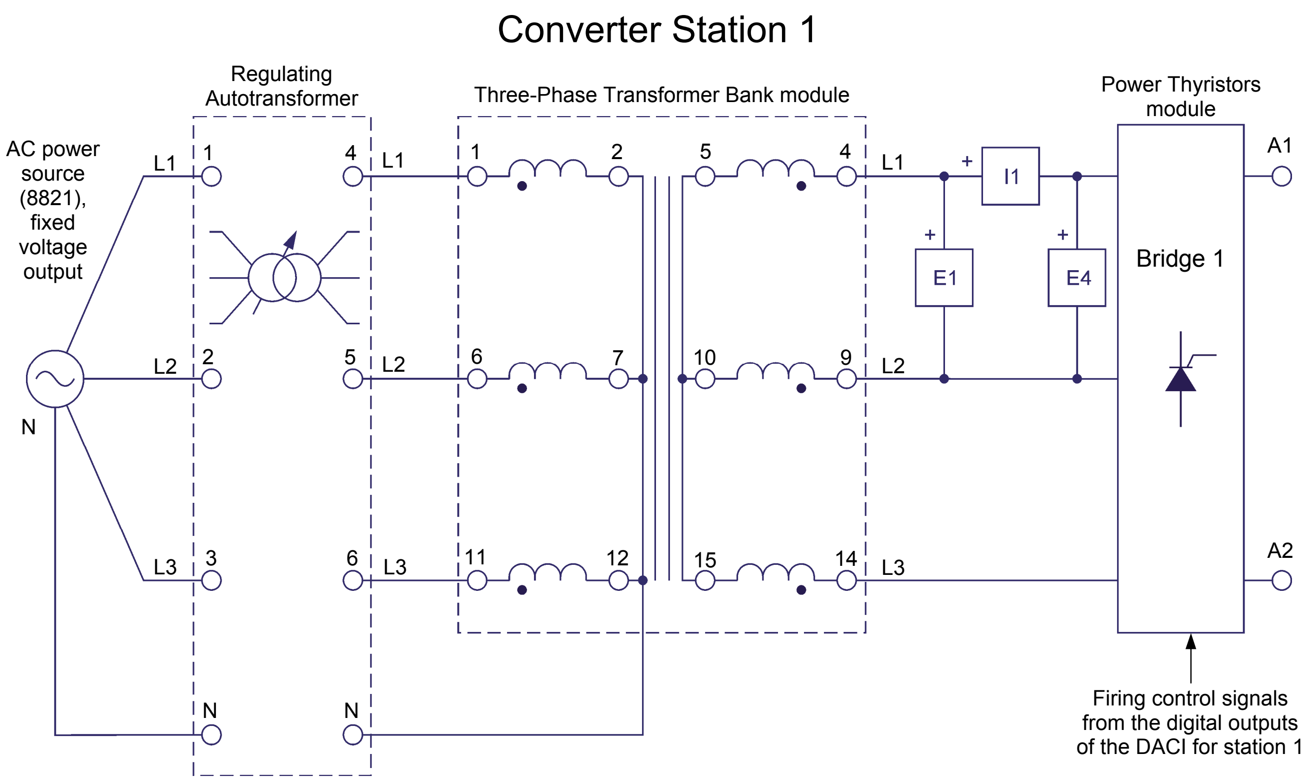
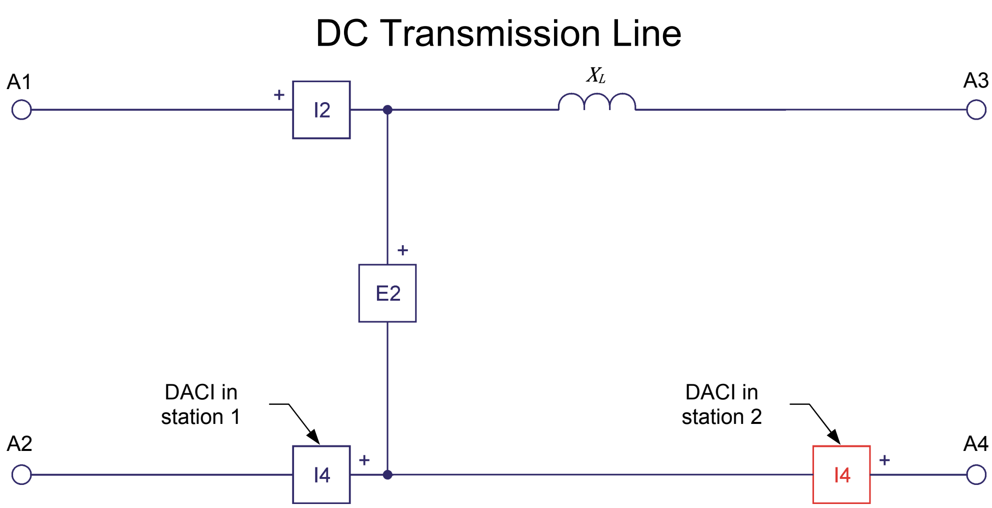


Figure 50. HVDC transmission system (part I).



Local ac power network		X_L (Ω)
Voltage (V)	**Frequency (Hz)**	
120	60	60
220	50	600
240	50	600
220	60	600

Figure 51. HVDC transmission system (part II).

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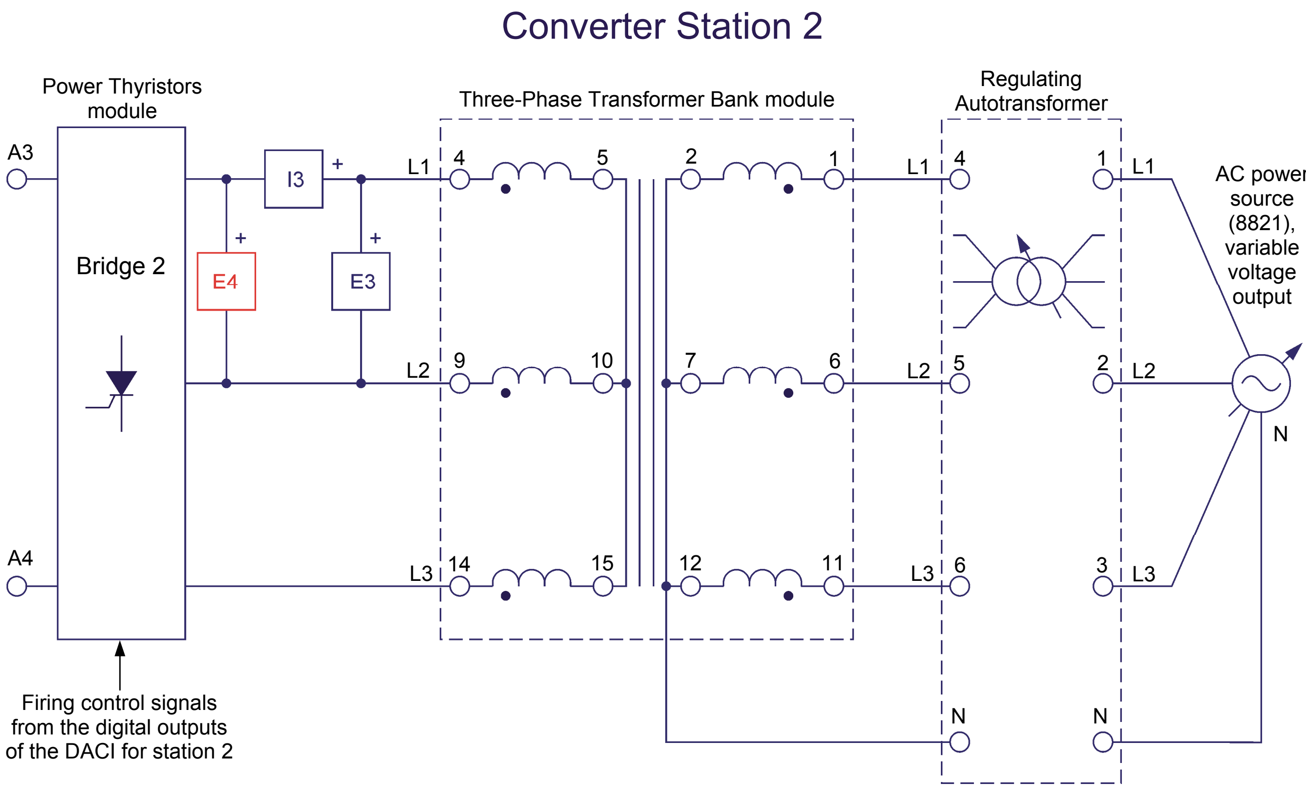

Figure 52. HVDC transmission system (part III).

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.

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*.

– Make sure that the *Control Type* parameter is set to *Independent*. This makes the current command of the current control loop at *Bridge 1* independent of the current command of the current control loop at *Bridge 2*.

– Set the *Current Command* parameter of *Bridge 1* to 0.2 pu by entering the adequate value in the field next to this parameter or by using the control knob in the lower left corner of the window. This sets the current command of the current control loop at *Bridge 1* to 0.2 pu.

The maximum value of the dc line current (I_{dc}) in the HVDC transmission system you set up (i.e., 1.0 A at an ac power network voltage of 120 V, or 0.5 A at ac power network voltages of 220 V and 240 V) corresponds to 1.0 pu. Therefore, set the Current Command *parameter of* Bridge 1 *to 0.2 A if your ac power network voltage is 120 V, or to 0.1 A if your local network power voltage is 220 V or 240 V.*

– Make sure that the *Inverter Limit* parameter of *Bridge 1* is set to 165°. This sets the maximum (limit) value of the firing angle at *Bridge 1* to 165°.

– Make sure that the *Arc-Cosine* parameter of *Bridge 1* is set to *On*. This enables the arc cosine corrector circuit of the current control loop at *Bridge 1*.

– Make sure that the *Controller Proportional Gain Kp* of *Bridge 1* is set to 0.2. Also, make sure that the *Controller Integral Gain Ki* of *Bridge 1* is set to 10.0.

– Make sure that the parameters Q_1 through Q_6 of *Bridge 1* are all set to *Active*. This makes the firing signals of these thyristors depend on the *Current Command* parameter of *Bridge 1*.

– Set the *Current Command* parameter of *Bridge 2* to 0.0 pu by entering 0.0 in the field next to this parameter or by using the control knob in the lower left corner of the window. This sets the current command of the current control loop at *Bridge 2* to 0.0 pu.

– Make sure that the *Inverter Limit* parameter of *Bridge 2* is set to 165°. This sets the maximum (limit) value of the firing angle at *Bridge 2* to 165°.

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– Make sure that the *Controller Proportional Gain Kp* of *Bridge 2* is set to 0.2. Also, make sure that the *Controller Integral Gain Ki* of *Bridge 2* is set to 0.0.

– Make sure that the parameters Q_1 through Q_6 of *Bridge 2* are all set to *Active*. This makes the firing signals of these thyristors depend on the *Current Command* parameter of *Bridge 2*.

– 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*.

With the above settings, the current control loop of bridge 1 (rectifier bridge) automatically adjusts the firing angle of this bridge to maintain the dc line current I_{dc} at the value of the current command $I_{Ref.}$ of the rectifier bridge. Meanwhile, the current control loop of bridge 2 (inverter bridge) maintains the firing angle of this bridge to the maximum (limit) value (i.e., 165°), thereby providing maximum opposition to current flow [this is because the current command of the current control loop at the inverter bridge has a value (0.0 pu) lower than that of bridge 1]. Therefore, the HVDC transmission system operates as if only one current control loop were present in the system (i.e., the current control loop at the rectifier bridge).

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, 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.

– Set three meters to measure the dc line current I_{dc} (*I2*) and voltage E_{dc} (*E2*), 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 $E_{1\text{-}2}$ (*E1*) and line current I_1 (*I1*) 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 $E_{1\text{-}2}$ (*E3*) and line current I_1 (*I3*) 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.

11. In LVDAC-EMS, open the Data Table window. Set the Data Table to record the firing angles of bridges 1 and 2, the current commands of bridges 1 and 2, the dc line current and voltage, the power transferred via the transmission line (i.e., the power transferred via the HVDC transmission system), as well as the line-to-line voltage $E_{1\text{-}2}$, active power, reactive power, and DPF at the ac side of the three-phase thyristor bridge in each converter station.

Operation of an HVDC transmission system with a current control loop at the rectifier bridge only

In this section, you will study the operation of an HVDC transmission system containing a current control loop at the rectifier bridge only. To do this, you will vary the current command of the current control loop at the rectifier bridge and measure the system parameters (dc line current and voltage, power transferred via the transmission line, as well as the firing angle, active power, reactive power, and DPF at the rectifier and inverter bridges). You will then simulate fluctuations of the ac voltage at the inverter and rectifier bridges and see how the current control loop of the rectifier bridge compensates for the effect of these fluctuations on the system operating point.

Varying the current command of the rectifier bridge

12. 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% by the Regulating Autotransformer in 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.

13. In the Metering window, observe the value of the dc line current I_{dc} (*I2*). Is current I_{dc} approximately equal to the value (0.2 pu) of the current command ($I_{Ref.}$) of the current control loop at bridge 1 (rectifier bridge)?

❑ Yes ❑ No

Is a small amount of power transferred from station 1 to station 2 via the transmission line? Explain.

____

____

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Note and record the firing angles of bridge 1 (rectifier bridge) and bridge 2 (inverter bridge) indicated by meters *Bridge-1* α and *Bridge-2* α, respectively, in the HVDC Transmission System Control window.

Firing angle of bridge 1 (rectifier bridge) = _______°

Firing angle of bridge 2 (inverter bridge) = _______°

Also, record the system parameters in the Data Table (i.e., the current commands and the firing angles of bridges 1 and 2, the dc line current and voltage, the power transferred via the transmission line, as well as the voltage $E_{1\text{-}2}$, active power, reactive power, and DPF at the ac side of bridges 1 and 2).

14. Set the current command $I_{Ref.}$ of the current control loop at bridge 1 (rectifier bridge) to each of the following values: 0.3 pu, 0.4 pu, 0.5 pu, 0.6 pu, 0.7 pu, 0.8 pu, 0.9 pu, and 1.0 pu. For each value of the current command $I_{Ref.}$, record the system parameters in the Data Table.

Examine the recorded data. Is the firing angle of bridge 1 (rectifier bridge) automatically adjusted to keep the dc line current I_{dc} (*I2*) equal to the current command $I_{Ref.}$ of the current control loop at bridge 1 (rectifier bridge)? Explain.

____

____

____

____

____

AC voltage fluctuations at the inverter bridge

15. Make sure that the current command $I_{Ref.}$ of the current control loop at bridge 1 (rectifier bridge) is set to the maximum value (1.0 pu). Record the system parameters in the Data Table.

What is the firing angle of bridge 1 (rectifier bridge)?

____

Are the DPFs at both bridges acceptable (i.e., > 0.9)? Explain.

____

Record the amount of power transferred via the transmission line when the dc line current I_{dc} is set to approximately 1.0 pu.

Power transferred via the transmission line (I_{dc} = 1.0 pu) = _______ W

16. While observing the value of the dc line current I_{dc} (*I2*) and the firing angle of bridge 1 (rectifier bridge), successively decrease the ac voltage at bridge 2 (inverter bridge) by approximately 5% and 10%, using the voltage control knob of the Power Supply. Record the system parameters in the Data Table for both settings of the ac voltage at bridge 2.

Does the dc line current I_{dc} remain constant, i.e., at the value (1.0 pu) of the current command $I_{Ref.}$ of the current control loop at bridge 1 (rectifier bridge) when the ac voltage at bridge 2 (inverter bridge) decreases by 5% and 10%? Explain.

____

____

What happens to the firing angle and DPF of bridge 1 (rectifier bridge) when the ac voltage at bridge 2 (inverter bridge) decreases by 5% and 10%?

____

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____

17. While observing the value of the dc line current I_{dc} (*I2*) and the firing angle of bridge 1 (rectifier bridge), return the ac voltage of bridge 2 (inverter bridge) to its initial value by setting the control knob of the Power Supply to 100%. This simulates another fluctuation (in this case, an increase) of the ac voltage at bridge 2 (inverter bridge).

Record the system parameters in the Data Table.

Does the dc line current I_{dc} remain equal to the value (1.0 pu) of the current command $I_{Ref.}$ of the current control loop at bridge 1 (rectifier bridge) when the ac voltage at bridge 2 (inverter bridge) increases and returns to its initial value? Why?

____

____

____

18. From your observations, does the current control loop of bridge 1 (rectifier bridge) make the dc line current I_{dc} insensitive to moderate fluctuations of the ac voltage at bridge 2 (inverter bridge)?

❑ Yes ❑ No

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Explain how the current control loop of bridge 1 (rectifier bridge) operates to keep the dc line current I_{dc} constant, i.e., at the value of the current command $I_{Ref.}$ despite ac voltage fluctuations at bridge 2 (inverter bridge).

____

____

____

19. Simulate a very large increase of the ac voltage at bridge 2 (inverter bridge) by setting the *Buck-Boost* selector on the Regulating Autotransformer module of station 2 (inverter station) to 0%. While doing this, observe what happens to the dc line current I_{dc} (*I2*) and the firing angle of bridge 1 (rectifier bridge). Does the value of current I_{dc}, and thus the amount of power P_{dc} transferred via the transmission line drop drastically? Why?

____

____

____

____

Record the system parameters in the Data Table.

20. On the Regulating Autotransformer module of station 2 (inverter station), set the *Buck-Boost* selector back to -15% to return the ac voltage at this station to its initial value.

21. In the HVDC Transmission System Control window, gradually decrease the current command $I_{Ref.}$ of the current control loop at bridge 1 (rectifier bridge) to 0.2 pu. Stop the *Monopolar HVDC Transmission System* function by clicking the *Start/Stop* button or by setting the *Status* parameter to *Stopped*.

AC voltage fluctuations at the rectifier bridge

22. 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.)

Modify the connections on the Power Supply in order for the variable, three-phase ac voltage output to become the ac power source for converter station 1 (rectifier station), and the fixed, three-phase ac voltage output to become the ac power source for converter station 2 (inverter station).

On the Power Supply, turn the three-phase ac power source on.

23. In the HVDC Transmission System Control window, start the Monopolar HVDC Transmission System.

Gradually increase the current command $I_{Ref.}$ of the current control loop at bridge 1 (rectifier bridge) to 0.6 pu. Record the system parameters in the Data Table.

24. While observing the value of the dc line current I_{dc} (*I2*) and the firing angle of bridge 1 (rectifier bridge), decrease the ac voltage at this bridge by approximately 5%, using the voltage control knob of the Power Supply. Record the system parameters in the Data Table.

Does the dc line current I_{dc} remain constant, i.e., at the value (0.6 pu) of the current command $I_{Ref.}$ of the current control loop at bridge 1 (rectifier bridge) when the ac voltage at this bridge decreases by 5%? Explain.

What happens to the firing angle and DPF of bridge 1 (rectifier bridge) when the ac voltage at this bridge decreases by 5%?

Explain how the current control loop of bridge 1 (rectifier bridge) keeps the dc line current I_{dc} constant, i.e., at the value of the current command $I_{Ref.}$ when the ac voltage at this bridge decreases.

25. Further decrease the ac voltage at bridge 1 (rectifier bridge) until it is 10% lower than the initial value. While doing this, observe that when the ac voltage becomes lower than a certain level (i.e., when the firing angle of bridge 1 reaches 0°), the dc line current I_{dc}, and thus the amount of power P_{dc} transferred via the transmission line, start decreasing significantly. Is this accurate according to your observation?

❑ Yes ❑ No

Record the system parameters in the Data Table.

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Explain why the dc line current I_{dc}, and thus the amount of power P_{dc} transferred via the transmission line, decrease significantly when the ac voltage at bridge 1 (rectifier bridge) decreases too much.

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26. Slowly return the ac voltage at bridge 1 (rectifier bridge) to its initial value by setting the control knob of the Power Supply to 100%. While doing this, observe what happens to the dc line current I_{dc} (*I2*) and the firing angle of bridge 1. Record your observations and explain.

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Record the system parameters in the Data Table.

27. In the HVDC Transmission System Control window, gradually decrease the current command of bridge 1 to 0.2 pu. Stop the *Monopolar HVDC Transmission System* function by clicking the *Start/Stop* button or by setting the *Status* parameter to *Stopped*.

Operation of an HVDC transmission system with current control loops at the rectifier and inverter bridges

In this section, you will study the operation an HVDC transmission system containing current control loops at the rectifier and inverter bridges.

Varying the current command at the rectifier bridge

28. 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.)

Modify the connections on the Power Supply in order for the fixed, three-phase ac voltage output to become the ac power source for converter station 1 (rectifier station), and the variable, three-phase ac voltage output to become the ac power source for converter station 2 (inverter station).

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

– Make sure the *Function* parameter is set 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 $I_{Ref.\,(rectifier)}$ 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 $I_{Ref.\,(rectifier)}$ minus the current margin (ΔI) 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 $I_{Ref.\,(rectifier)}$ 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 ΔI* parameter to 0.05 pu. This sets the current margin ΔI 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.

30. On the Power Supply, turn the three-phase ac power source on.

In the HVDC Transmission System Control window, start the HVDC transmission system.

Wait a few seconds to let the system stabilize.

31. 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 $I_{Ref.\,(rectifier)}$ of the HVDC transmission system?

❑ Yes ❑ No

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

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

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

Also, record the system parameters in the Data Table (i.e., the firing angles of bridges 1 and 2, the current command $I_{Ref.\,(rectifier)}$, the current margin ΔI,

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the dc line current and voltage, the power transferred via the transmission line, as well as the voltage $E_{1\text{-}2}$, active power, reactive power, and DPF at the ac side of bridges 1 and 2).

32. Set the current command $I_{Ref.\,(rectifier)}$ 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 each of the following values: 0.3 pu, 0.4 pu, 0.5 pu, 0.6 pu, 0.7 pu, 0.8 pu, 0.9 pu, and 1.0 pu. After each new setting, wait a few seconds to let the system stabilize, then record the system parameters in the Data Table.

Examine the recorded data. Is the firing angle $\alpha_{Rectifier}$ of bridge 1 automatically adjusted to keep the current flowing through the bridges, and thus the dc line current I_{dc} at the value of current command $I_{Ref.\,(rectifier)}$? Explain.

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AC voltage fluctuations at the inverter bridge

33. Leave the current command $I_{Ref.\,(rectifier)}$ of the HVDC transmission system set to the maximum value (1.0 pu). While observing the value of the dc line current I_{dc} (*I2*) and the firing angles of bridges 1 and 2 (meters *Bridge-1* α and *Bridge-2* α), successively decrease the ac voltage at bridge 2 (inverter bridge) by approximately 5% and 10%, using the voltage control knob of the Power Supply. Record the system parameters in the Data Table for both settings of the ac voltage at bridge 2.

Does the dc line current I_{dc} remain constant, i.e., at the value (1.0 pu) of the current command $I_{Ref.\,(rectifier)}$ of the HVDC transmission system when the ac voltage at bridge 2 (inverter bridge) decreases by 5% and 10%? Explain.

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What happens to the firing angles of bridges 1 and 2 when the ac voltage at bridge 2 (inverter bridge) decreases by 5% and 10%?

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34. While observing the value of the dc line current I_{dc} and the firing angles of bridges 1 and 2, return the ac voltage at bridge 2 (inverter bridge) to its initial value by setting the control knob of the Power Supply to 100%. This simulates another fluctuation (in this case, an increase) of the ac voltage at bridge 2.

Record the system parameters in the Data Table.

Does the dc line current I_{dc} remain at the value (1.0 pu) of the current command $I_{Ref.(rectifier)}$ of the HVDC transmission system when the ac voltage at bridge 2 (inverter bridge) increases and returns to its initial value? Why?

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35. Do the observations made thus far demonstrate that the current control loop at bridge 2 (inverter bridge) does not interact with the current control loop at bridge 1 (rectifier bridge)? Explain.

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36. Simulate a very large increase of the ac voltage at bridge 2 (inverter bridge) by setting the *Buck-Boost* selector on the Regulating Autotransformer module of station 2 (inverter station) to 0%. While doing this, observe that the dc line current I_{dc} decreases only slightly (i.e., by approximately 0.05 pu) and not drastically. Record the system parameters in the Data Table.

Notice that the firing angle $\alpha_{Rectifier}$ of bridge 1 has decreased to the minimum possible value (0°). Is the firing angle $\alpha_{Inverter}$ of bridge 2 still at the maximum (limit) value (165°)? Explain.

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Is the dc line current I_{dc} approximately equal to the current command $I_{Ref.(rectifier)}$ minus the current margin ΔI (0.95 pu), indicating that the current control loop at bridge 2 (inverter bridge) has entered into action to prevent current I_{dc} from decreasing too much? Explain.

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37. On the Regulating Autotransformer module of station 2 (inverter station), set the *Buck-Boost* selector back to -15% to return the ac voltage at bridge 2 (inverter bridge) to its initial value. What happens to the dc line current I_{dc} and the firing angles of bridges 1 and 2? Why?

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Record the system parameters in the Data Table.

38. In the HVDC Transmission System Control window, set the *Current Margin ΔI* parameter (current margin ΔI of the HVDC transmission system) to the following values: 0.1 pu and 0.2 pu. For each current margin setting, perform the steps below:

– Simulate a very large increase of the ac voltage at bridge 2 (inverter bridge) by setting the *Buck-Boost* selector on the Regulating Autotransformer module of station 2 (inverter station) to 0%. Wait a few seconds to let the system stabilize, then record the system parameters in the Data Table.

– On the Regulating Autotransformer module of station 2 (inverter station), set the *Buck-Boost* selector back to -15% to return the ac voltage at bridge 2 (inverter bridge) to its initial value. Wait a few seconds to let the system stabilize, then record the system parameters in the Data Table.

Examine the data you recorded in the Data Table when the current margin ΔI of the HVDC transmission system is 0.1 pu and 0.2 pu. What happens to the dc line current I_{dc} when the ac voltage at bridge 2 (inverter bridge) increases to the extent that the firing angle $\alpha_{Rectifier}$ reaches the minimum value (0°) and the current control loop at bridge 2 (inverter bridge) enters into action? Explain.

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From your observations, does increasing the current margin ΔI of the HVDC transmission system cause the dc line current I_{dc}, and thus the amount of power P_{dc} transferred, to decrease by a greater extent (i.e., to a lower level) before the current control loop at bridge 2 (inverter bridge) enters into action to prevent current I_{dc} from decreasing further? Why?

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39. Gradually decrease the current command $I_{Ref.\,(rectifier)}$ of the HVDC transmission system to 0.2 pu. Stop the HVDC transmission system.

AC voltage fluctuations at the rectifier bridge

40. 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.)

Modify the connections on the Power Supply in order for the variable, three-phase ac voltage output to become the ac power source for converter station 1 (rectifier station), and the fixed, three-phase ac voltage output to become the ac power source for converter station 2 (inverter station).

On the Power Supply, turn the three-phase ac power source on.

41. Set the current margin ΔI of the HVDC transmission system to 0.1 pu, then start the HVDC transmission system.

Gradually increase the current command $I_{Ref.\,(rectifier)}$ of the HVDC transmission system to 0.6 pu. Wait a few seconds to let the system stabilize, then record the system parameters in the Data Table.

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42. While observing the value of the dc line current I_{dc} (*I2*) and the firing angles of bridges 1 and 2, slowly decrease the ac voltage at bridge 1 (rectifier bridge) using the voltage control knob of the Power Supply, and stop decreasing it as soon as the firing angle $\alpha_{Rectifier}$ of bridge 1 reaches 0°. While doing this, observe that the firing angle $\alpha_{Rectifier}$ of bridge 1 is automatically decreased to keep the dc line current I_{dc} at the value (0.6 pu) of the current command $I_{Ref.(rectifier)}$ of the HVDC transmission system. Record the system parameters in the Data Table.

43. Continue to very slowly decrease the ac voltage at bridge 1 (rectifier bridge) and observe that the dc line current I_{dc} starts decreasing below the value (0.6 pu) of the current command $I_{Ref.(rectifier)}$ of the HVDC transmission system. Explain why this occurs.

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Continue to very slowly decrease the ac voltage at bridge 1 (rectifier bridge) so that the dc line current I_{dc} is approximately equal to $I_{Ref.(rectifier)} - \frac{\Delta I}{2}$ (i.e., ≅ 0.55 pu) and record the system parameters in the Data Table. Are the firing angles of bridges 1 and 2 still 0° and 165°, respectively? Why?

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44. Continue to very slowly decrease the ac voltage at bridge 1 (rectifier bridge) until the dc line current I_{dc} is approximately equal to the current command of the current control loop at bridge 2 (inverter bridge), i.e., $I_{Ref(rectifier)}$ - ΔI (0.50 pu). Record the system parameters in the Data Table.

Further decrease the ac voltage at bridge 1 and observe that the dc line current I_{dc} stops decreasing (i.e., it remains at approximately 0.50 pu), while the firing angle $\alpha_{Inverter}$ of bridge 2 starts decreasing below 165°. Explain why this occurs.

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45. Slowly return the ac voltage at bridge 1 (rectifier bridge) to its initial value by setting the control knob of the Power Supply to 100%. While doing this, observe what happens to the dc line current I_{dc} and the firing angles of bridges 1 and 2. Record your observations and explain.

Record the system parameters in the Data Table.

Varying the amount of power transferred via the HVDC transmission system

In this section, you will learn how to vary the amount of power transferred via the HVDC transmission system.

46. Set the current margin ΔI of the HVDC transmission system to 0.05 pu.

Gradually increase the current command $I_{Ref(rectifier)}$ of the HVDC transmission system to the maximum value (1.0 pu).

47. Set the current command $I_{Ref.(rectifier)}$ of the HVDC transmission system to each of the following values: 1.0 pu, 0.9 pu, 0.8 pu, 0.7 pu, 0.6 pu, 0.5 pu, 0.4 pu, and 0.3 pu. After each new setting, wait a few seconds to let the system stabilize, then record the system parameters in the Data Table.

Examine the recorded data. Can the amount of power P_{dc} transferred via the HVDC transmission system be varied substantially by varying the value of the current command $I_{Ref.(rectifier)}$ over the usable range of dc line current I_{dc} (i.e., from approximately 0.3 pu to 1.0 pu)? Explain.

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Does the HVDC transmission system operate close to the maximum value of dc voltage E_{dc} when the value of the current command $I_{Ref.\,(rectifier)}$ is varied over the usable range of dc line current I_{dc}, thereby keeping the power losses (RI^2 losses) to a minimum? Explain.

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Do the DPFs at both bridges remain acceptable (i.e., > 0.9) when the value of the current command $I_{Ref.\,(rectifier)}$ is varied over the usable range of dc line current I_{dc}? Explain.

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Record the amount of power P_{dc} transferred via the HVDC transmission system when the current I_{dc} is 0.3 pu and the operating dc voltage E_{dc} is maximum (i.e., when $\alpha_{Inverter}$ = 165°). This value will be used to make a comparison later in the exercise.

Power transferred via the system (I_{dc} = 0.3 pu, $\alpha_{Inverter}$ = 165°) = _______ W

What must be done to further decrease the amount of power P_{dc} transferred via the transmission line once the current I_{dc} has reached the minimum usable value (0.3 pu)?

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48. Gradually reduce the operating dc voltage to zero, as indicated below.

- Make sure that the current command $I_{Ref.\,(rectifier)}$ of the HVDC transmission system is set to the minimum usable value (0.3 pu).

- Decrease the maximum (limit) value of bridge 2 (inverter bridge) from 165° to 90° in steps of 15°. To do this, successively set the *Inverter Limit* parameter of *Bridge 2* in the HVDC Transmission System Control window to each of the following values: 165°, 150°, 135°, 120°, 105°, and 90°. For each setting, wait a few seconds to let the system stabilize, then record the system parameters in the Data Table.

Examine the recorded data. What happens to the operating dc voltage E_{dc} and the amount of power P_{dc} transferred via the HVDC transmission system when the maximum (limit) value of the firing angle of bridge 2 (inverter bridge) is decreased from 165° to 90°? Explain.

Describe what happens to the DPFs at both bridges when the maximum (limit) value of the firing angle of bridge 2 (inverter bridge) is decreased from 165° to 90°. Does this show that operating an HVDC transmission system at low power levels for extended periods is highly undesirable?

Reversing the direction of power flow in the HVDC transmission system

In this section, you will use the method described in the Discussion to reverse the direction in which power flows through the HVDC transmission system.

49. Make sure that the amount of power P_{dc} transferred via the transmission line is zero [i.e., leave the current command $I_{Ref.\,(rectifier)}$ of the HVDC transmission system set to the minimum usable value (0.3 pu) and the maximum (limit) value of the firing angle of bridge 2 (inverter bridge) set to 90°].

50. Stop the HVDC transmission system.

51. On the Regulating Autotransformer of converter station 1 (left-hand station), set the *Buck-Boost* selector to -15%. This makes bridge 1 ready to operate as an inverter.

On the Regulating Autotransformer of converter station 2 (right-hand station), set the *Buck-Boost* selector to 0%. This makes bridge 2 ready to operate as a rectifier.

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

- Set the *Control Type* parameter to *Linked (Rectifier = Bridge 2)*. This makes bridge 2 operate as a rectifier and the current command of its current control loop equal to the current command $I_{Ref.\,(rectifier)}$ of the HVDC transmission system. This also makes bridge 1 operate as an inverter and the current command of its current control loop equal

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to $I_{Ref.\,(rectifier)}$ minus the current margin (ΔI) of the HVDC transmission system.

- Leave the *Rectifier Current Command* parameter set to 0.3 pu. This sets the current command $I_{Ref.\,(rectifier)}$ of the HVDC transmission system (i.e., the current command of the current control loop at bridge 2, which is set to operate as a rectifier) to 0.3 pu.

- Make sure that the *Current Margin ΔI* parameter is set to 0.05 pu. This sets the current margin ΔI of the HVDC transmission system to 0.05 pu. Therefore, this sets the current command of bridge 1 (inverter bridge) to 0.25 pu (0.3 pu – 0.05 pu = 0.25 pu).

- Set the *Inverter Limit* parameter of *Bridge 1* to 90°. This sets the maximum (limit) value of the firing angle at *Bridge 1* to 90°.

- Set the *Inverter Limit* parameter of *Bridge 2* to 165°. This sets the maximum (limit) value of the firing angle at *Bridge 2* to 165°.

53. Start the HVDC transmission system.

54. Gradually increase the maximum (limit) value of the firing angle of bridge 1 (i.e., the bridge now acting as an inverter) by setting the *Inverter Limit* parameter of *Bridge 1* in the HVDC Transmission System Control window to each of the following values: 90°, 105°, 120°, 135°, 150°, and 165°. After each new setting, wait a few seconds to let the system stabilize, then record the system parameters in the Data Table (i.e., the firing angles of bridges 1 and 2, the current command $I_{Ref.\,(rectifier)}$, the current margin ΔI, the dc line current and voltage, the power transferred via the transmission line, as well as the voltage $E_{1\text{-}2}$, active power, reactive power, and DPF at the ac side of bridges 1 and 2).

Examine the recorded data. What happens to the operating dc voltage E_{dc} and the amount of power P_{dc} transferred via the transmission line when the maximum (limit) value of the firing angle of bridge 1 (inverter bridge) is increased from 90° to 165°? Explain.

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Record the amount of power transferred via the HVDC transmission system when power flows from bridge 2 to bridge 1, for a dc current I_{dc} of 0.3 pu and a maximum operating dc voltage (i.e., $\alpha_{Inverter}$ = 165°).

Power transferred via the system (I_{dc} = 0.3 pu, $\alpha_{Inverter}$ = 165°) = _______ W

Compare the amount of power P_{dc} transferred via the transmission line when power flows from bridge 2 to bridge 1 (recorded above) to that transferred when power flows from bridge 1 to bridge 2 (recorded in step 47). Are they virtually the same? Explain.

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55. Set the current command $I_{Ref.\,(rectifier)}$ of the HVDC transmission system (i.e., the current command of the current control loop at bridge 2, which is set to operate as a rectifier) to each of the following values: 0.3 pu, 0.4 pu, 0.5 pu, 0.6 pu, 0.7 pu, 0.8 pu, 0.9 pu, and 1.0 pu. After each new setting, wait a few seconds to let the system stabilize, then record the system parameters in the Data Table.

Examine the recorded data. Can the amount of power transferred from station 2 to station 1 be varied the same way as when power flows in the opposite direction, i.e., by varying the value of the current command $I_{Ref.\,(rectifier)}$ of the HVDC transmission system over the usable range of dc line current I_{dc} (i.e., from 0.3 pu to 1.0 pu)? Explain.

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56. 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.

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CONCLUSION

In this exercise, you learned that when a current control loop is added at the rectifier bridge of an HVDC transmission system, the firing angle of the rectifier bridge is automatically adjusted to keep the dc line current I_{dc} constant despite ac voltage fluctuations at either of the bridges. However, when the ac voltage fluctuates too much, the current control loop cannot keep current I_{dc} constant (i.e., at the value of the current command). This problem can be solved by adding a second current control loop at the inverter bridge of the HVDC transmission system that is set to operate at a slightly lower current setpoint (i.e., at $I_{Ref.\ (rectifier)} - \Delta I$). You saw that the combined action of the two control loops limits the effect of ac voltage fluctuations on current I_{dc} (i.e., on the system operating point) by keeping it within the current margin ΔI of the system. This prevents current I_{dc}, and thus the amount of power transferred from decreasing or increasing significantly when the ac voltage fluctuates too much at either end of the HVDC transmission system. Finally, you learned that the amount of power transferred through an HVDC transmission system can be varied by varying the current command of the system over the usable range of current I_{dc}, while operating both bridges at the highest possible dc voltage. You learned that operating an HVDC transmission system below the maximum dc voltage is an undesirable condition which should be allowed only temporarily, due to the reduced power efficiency and poor DPFs at both thyristor bridges. Finally, you learned how to reverse the direction of power flow in an HVDC transmission system.

REVIEW QUESTIONS

1. When a current control loop is added at the rectifier bridge of an HVDC transmission system, how does it operate to keep the dc line current I_{dc} constant?

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2. When a current control loop is used at the rectifier bridge only, and the ac voltage increases too much at the inverter bridge or decreases too much at the rectifier bridge, what happens to the dc line current I_{dc}, and the power transferred via the transmission line? How can this problem be solved?

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3. Briefly explain the operation of an HVDC transmission system using current control loops at the rectifier and inverter bridges.

4. Explain why it is best to adjust the amount of power transferred through an HVDC transmission system by varying the dc line current, while keeping the operating voltage at the highest possible level.

5. Briefly describe the procedure used to reverse the direction of power flow in an HVDC transmission system.

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Sample

Extracted from

Instructor Guide

Exercise 3 DC Current Regulation and Power Flow Control in HVDC Transmission Systems

ANSWERS TO PROCEDURE STEP QUESTIONS

13. Yes

Yes. A small amount of power (approximately 28 W) is transferred from station 1 to station 2 via the transmission line.

Firing angle of bridge 1 (rectifier bridge) ≅ 31°

Firing angle of bridge 2 (inverter bridge) ≅ 165°

Parameters measured in the HVDC transmission system (current command $I_{Ref.}$ of the rectifier bridge set to 0.2 A).

AC side of station 1 (left-end station)						Transmission line			AC side of station 2 (right-end station)					
Bridge 1 (rectifier)		Line voltage $E_{1\text{-}2}$ (V)	Active power (W)	React. power (var)	DPF	DC current I_{dc} (A)	DC voltage E_{dc} (V)	DC power P_{dc} (W)	Bridge 2 (inverter)		Line voltage $E_{1\text{-}2}$ (V)	Active power (W)	React. power (var)	DPF
Current command $I_{Ref.}$ (A)	Firing angle (°)								Current command (A)	Firing angle (°)				
0.2	31	117	28	17	0.86	0.2	135	28	0.0	165	100	-27	10	0.94

14. The results are presented in the following table.

Parameters measured in the HVDC transmission system when the current command $I_{Ref.}$ of the current control loop at bridge 1 (rectifier bridge) is varied.

AC side of station 1 (left-end station)						Transmission line			AC side of station 2 (right-end station)					
Bridge 1 (rectifier)		Line voltage $E_{1\text{-}2}$ (V)	Active power (W)	React. power (var)	DPF	DC current I_{dc} (A)	DC voltage E_{dc} (V)	DC power P_{dc} (W)	Bridge 2 (inverter)		Line voltage $E_{1\text{-}2}$ (V)	Active power (W)	React. power (var)	DPF
Current command $I_{Ref.}$ (A)	Firing angle (°)								Current command (A)	Firing angle (°)				
0.3	29.2	116	43	24	0.87	0.3	136	42	0.0	165	101	-40	14	0.95
0.4	27.8	116	57	30	0.88	0.4	138	56	0.0	165	101	-54	17	0.95
0.5	26.1	116	72	36	0.90	0.5	139	70	0.0	165	102	-67	21	0.96
0.6	24.5	115	87	40	0.91	0.6	140	85	0.0	165	102	-81	24	0.96
0.7	22.3	115	102	43	0.92	0.7	142	100	0.0	165	103	-95	27	0.96
0.8	20.3	115	118	44	0.94	0.8	143	115	0.0	165	103	-108	30	0.96
0.9	17.8	114	133	44	0.95	0.9	144	130	0.0	165	103	-121	34	0.96
1.0	14.2	114	149	43	0.96	1.0	145	146	0.0	165	104	-136	39	0.96

Yes. The results in the table show that when the current command $I_{Ref.}$ of the current control loop at bridge 1 (rectifier bridge) is increased from 0.3 pu to 1.0 pu (i.e., from 0.3 A to 1.0 A), the firing angle of bridge 1 is decreased to increase the current flowing through this bridge so that the dc line current I_{dc} equals the value of the current command $I_{Ref.}$.

15. The firing angle of bridge 1 (rectifier bridge) is 14° approximately.

Yes. The DPF is 0.96 at both the rectifier and inverter bridges, which is very good.

Power transferred via the transmission line [I_{dc} = 1.0 pu (1.0 A)] = 146 W

16. The results are presented in the following table.

Parameters measured in the HVDC transmission system.

AC side of station 1 (left-end station)						Transmission line			AC side of station 2 (right-end station)					
Bridge 1 (rectifier)		Line voltage E_{1-2} (V)	Active power (W)	React. power (var)	DPF	DC current I_{dc} (A)	DC voltage E_{dc} (V)	DC power P_{dc} (W)	Bridge 2 (inverter)		Line voltage E_{1-2} (V)	Active power (W)	React. power (var)	DPF
Current command $I_{Ref.}$ (A)	Firing angle (°)								Current command (A)	Firing angle (°)				
1.0	22.4	113	144	60	0.92	1.0	139	140	0.0	165	99	-129	37	0.96
1.0	28.5	113	137	75	0.88	1.0	132	133	0.0	165	94	-122	36	0.96

Yes. The table above shows that the dc line current I_{dc} remains equal to the value (1.0 pu or 1.0 A) of the current command $I_{Ref.}$ of the current control loop at bridge 1 (rectifier bridge) when the ac voltage at bridge 2 (inverter bridge) decreases by 5% and 10%.

When the ac voltage at bridge 2 (inverter bridge) decreases by 5%, the firing angle of bridge 1 (rectifier bridge) increases from the initial value (14°) to approximately 22°, causing the DPF of this bridge to decrease from approximately 0.96 to 0.92. When the ac voltage at bridge 2 (inverter bridge) decreases by 10%, the firing angle of bridge 1 (rectifier bridge) further increases to approximately 29°, causing the DPF of this bridge to further decrease to 0.88.

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17. The results are presented in the following table.

Parameters measured in the HVDC transmission system.

AC side of station 1 (left-end station)						Transmission line			AC side of station 2 (right-end station)					
Bridge 1 (rectifier)		Line voltage E_{1-2} (V)	Active power (W)	React. power (var)	DPF	DC current I_{dc} (A)	DC voltage E_{dc} (V)	DC power P_{dc} (W)	Bridge 2 (inverter)		Line voltage E_{1-2} (V)	Active power (W)	React. power (var)	DPF
Current command $I_{Ref.}$ (A)	Firing angle (°)								Current command (A)	Firing angle (°)				
1.0	13.8	113	150	38	0.97	1.0	146	146	0.0	165	104	-136	37	0.97

Yes. This is because when the ac voltage at bridge 2 (inverter bridge) increases and returns to its initial value, the firing angle of bridge 1 (rectifier bridge) returns (decreases) to the initial value (approximately 14°) to maintain the dc line current I_{dc} at the value (1.0 pu or 1.0 A) of the current command $I_{Ref.}$ of the current control loop at bridge 1 (rectifier bridge).

18. Yes

To keep the dc line current I_{dc} constant, i.e., at the value of the current command $I_{Ref.}$ despite ac voltage fluctuations at bridge 2 (inverter bridge), the current control loop of bridge 1 (rectifier bridge) operates as described below.

- When the ac voltage decreases at bridge 2 (inverter bridge), the current control loop of bridge 1 (rectifier bridge) increases the firing angle of this bridge to prevent the current flowing through the bridges from increasing, thereby keeping the dc line current I_{dc} at the desired value.

- Conversely, when the ac voltage increases at bridge 2 (inverter bridge), the current control loop of bridge 1 (rectifier bridge) decreases the firing angle of this bridge to prevent the current flowing through the bridges from decreasing, thereby keeping the dc line current I_{dc} at the desired value.

19. Yes, the value of the dc line current I_{dc} drops drastically, passing from 1.0 pu to 0.17 pu (i.e., from 1.0 A to 0.17 A). The amount of power P_{dc} transferred via the transmission line also drops drastically, passing from approximately 146 W to 27 W. This is because the ac voltage at bridge 2 (inverter bridge) increased so much that the current control loop of bridge 1 (rectifier bridge) decreased the firing angle of this bridge to the minimum possible value (0°); this, however, is not sufficient to prevent the dc current flowing through the bridges from decreasing below the value of the current command $I_{Ref.}$.

The results are presented in the following table.

Parameters measured in the HVDC transmission system.

AC side of station 1 (left-end station)						Transmission line			AC side of station 2 (right-end station)					
Bridge 1 (rectifier)		Line voltage E_{1-2} (V)	Active power (W)	React. power (var)	DPF	DC current I_{dc} (A)	DC voltage E_{dc} (V)	DC power P_{dc} (W)	Bridge 2 (inverter)		Line voltage E_{1-2} (V)	Active power (W)	React. power (var)	DPF
Current command I_{Ref} (A)	Firing angle (°)								Current command (A)	Firing angle (°)				
1.0	0.0	117	27	0	1.0	0.17	157	27	0.0	165	117	-26	8	0.95

23. The results are presented in the following table.

Parameters measured in the HVDC transmission system.

AC side of station 1 (left-end station)						Transmission line			AC side of station 2 (right-end station)					
Bridge 1 (rectifier)		Line voltage E_{1-2} (V)	Active power (W)	React. power (var)	DPF	DC current I_{dc} (A)	DC voltage E_{dc} (V)	DC power P_{dc} (W)	Bridge 2 (inverter)		Line voltage E_{1-2} (V)	Active power (W)	React. power (var)	DPF
Current command I_{Ref} (A)	Firing angle (°)								Current command (A)	Firing angle (°)				
0.6	22.4	115	88	37	0.92	0.6	142	86	0.0	165	103	-82	24	0.96

24. The results are presented in the following table.

Parameters measured in the HVDC transmission system.

AC side of station 1 (left-end station)						Transmission line			AC side of station 2 (right-end station)					
Bridge 1 (rectifier)		Line voltage E_{1-2} (V)	Active power (W)	React. power (var)	DPF	DC current I_{dc} (A)	DC voltage E_{dc} (V)	DC power P_{dc} (W)	Bridge 2 (inverter)		Line voltage E_{1-2} (V)	Active power (W)	React. power (var)	DPF
Current command I_{Ref} (A)	Firing angle (°)								Current command (A)	Firing angle (°)				
0.6	10.3	109	89	18	0.98	0.6	143	87	0.0	165	104	-83	23	0.97

Yes. The table above shows that the dc line current I_{dc} remains constant, i.e., at the value (0.6 pu or 0.6 A) of the current command I_{Ref} of the current control loop at bridge 1 (rectifier bridge) when the ac voltage at this bridge decreases by 5%.

When the ac voltage at bridge 1 (rectifier bridge) decreases by 5%, the firing angle of this bridge decreases from approximately 22° to approximately 10°, causing the DPF to increase from 0.93 to 0.98.

When the ac voltage decreases at bridge 1 (rectifier bridge), the current control loop of this bridge decreases the firing angle of the bridge to prevent the current flowing through the bridges from decreasing, and thus keep the dc line current I_{dc} constant, i.e., at the value (0.6 pu or 0.6 A) of the current command I_{Ref} of the current control loop at bridge 1 (rectifier bridge).

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25. Yes

The results are presented in the following table.

Parameters measured in the HVDC transmission system.

AC side of station 1 (left-end station)						Transmission line			AC side of station 2 (right-end station)					
Bridge 1 (rectifier)		Line voltage E_{1-2} (V)	Active power (W)	React. power (var)	DPF	DC current I_{dc} (A)	DC voltage E_{dc} (V)	DC power P_{dc} (W)	Bridge 2 (inverter)		Line voltage E_{1-2} (V)	Active power (W)	React. power (var)	DPF
Current command $I_{Ref.}$ (A)	Firing angle (°)								Current command (A)	Firing angle (°)				
0.6	0.0	103	42	1	1.0	0.3	139	41	0.0	165	103	-40	12	0.96

When the ac voltage decreases too much at bridge 1 (rectifier bridge), the current control loop of this bridge decreases the firing angle of the bridge to the minimum possible value (0°); this, however, is not sufficient to prevent the current flowing through the bridges from decreasing below the rectifier-bridge current command $I_{Ref.}$. As a result, the dc line current I_{dc}, and thus the amount of power P_{dc} transferred via the transmission, line start decreasing significantly.

26. The dc line current I_{dc} remains below the current command $I_{Ref.}$ (0.6 pu of 0.6 A) of the current control loop at bridge 1 (rectifier bridge) and the firing angle of this bridge remains at 0° as long as the ac voltage at bridge 1 has not increased back to a certain level. Past this level, the firing angle of bridge 1 starts increasing and current I_{dc} remains constant at the value of the current command $I_{Ref.}$ (0.6 pu or 0.6 A).

The results are presented in the following table.

Parameters measured in the HVDC transmission system.

AC side of station 1 (left-end station)						Transmission line			AC side of station 2 (right-end station)					
Bridge 1 (rectifier)		Line voltage E_{1-2} (V)	Active power (W)	React. power (var)	DPF	DC current I_{dc} (A)	DC voltage E_{dc} (V)	DC power P_{dc} (W)	Bridge 2 (inverter)		Line voltage E_{1-2} (V)	Active power (W)	React. power (var)	DPF
Current command $I_{Ref.}$ (A)	Firing angle (°)								Current command (A)	Firing angle (°)				
0.6	22.4	114	88	36	0.93	0.6	142	86	0.0	165	104	-83	25	0.96

31. Yes

Firing angle $\alpha_{Rectifier}$ of bridge 1 (rectifier bridge) ≅ 29°

Firing angle $\alpha_{Inverter}$ of bridge 2 (inverter bridge) = 165°

The results are presented in the following table.

Parameters measured in the HVDC transmission system.

HVDC transmission system		AC side of station 1 (left-end station)					Transmission line			AC side of station 2 (right-end station)				
Current command $I_{Ref.\,(rectifier)}$ (A)	Current margin ΔI (A)	Bridge-1 (rectifier) firing angle $\alpha_{Rectifier}$ (°)	Line voltage $E_{1\text{-}2}$ (V)	Active power (W)	React. power (var)	DPF	DC current I_{dc} (A)	DC voltage E_{dc} (V)	DC power P_{dc} (W)	Bridge-2 (inverter) firing angle $\alpha_{Inverter}$ (°)	Line voltage $E_{1\text{-}2}$ (V)	Active power (W)	React. power (var)	DPF
0.3	0.05	29.4	116	42	24	0.87	0.3	135	41	165	100	-40	13	0.95

32. The results are presented in the following table.

Parameters measured in the HVDC transmission system when the value of the current command $I_{Ref.\,(rectifier)}$ of the HVDC transmission system is varied.

HVDC transmission system		AC side of station 1 (left-end station)					Transmission line			AC side of station 2 (right-end station)				
Current command $I_{Ref.\,(rectifier)}$ (A)	Current margin ΔI (A)	Bridge-1 (rectifier) firing angle $\alpha_{Rectifier}$ (°)	Line voltage $E_{1\text{-}2}$ (V)	Active power (W)	React. power (var)	DPF	DC current I_{dc} (A)	DC voltage E_{dc} (V)	DC power P_{dc} (W)	Bridge-2 (inverter) firing angle $\alpha_{Inverter}$ (°)	Line voltage $E_{1\text{-}2}$ (V)	Active power (W)	React. power (var)	DPF
0.3	0.05	29.4	116	42	24	0.87	0.3	135	41	165	100	-40	13	0.95
0.4	0.05	27.9	116	59	31	0.88	0.4	137	55	165	101	-53	17	0.95
0.5	0.05	26.6	115	71	36	0.89	0.5	138	69	165	101	-67	21	0.95
0.6	0.05	24.9	115	87	40	0.91	0.6	140	84	165	102	-80	23	0.96
0.7	0.05	22.9	114	101	43	0.92	0.7	141	99	165	102	-94	27	0.96
0.8	0.05	21.1	114	117	44	0.93	0.8	142	114	165	103	-107	30	0.96
0.9	0.05	18.8	114	133	45	0.95	0.9	143	129	165	103	-121	34	0.96
1.0	0.05	14.5	114	149	43	0.96	1.0	145	145	165	104	-134	37	0.97

Yes. When the value of current command $I_{Ref.\,(rectifier)}$ is increased from 0.3 pu to 1.0 pu (i.e., from 0.3 A to 1.0 A), the firing angle $\alpha_{Rectifier}$ of bridge 1 is decreased in order to increase the current flowing through the bridges so that the dc line current I_{dc} equals the value of the current command $I_{Ref.\,(rectifier)}$.

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33. The results are presented in the following table.

Parameters measured in the HVDC transmission system.

HVDC transmission system		AC side of station 1 (left-end station)					Transmission line			AC side of station 2 (right-end station)				
Current command $I_{Ref.(rectifier)}$ (A)	Current margin ΔI (A)	Bridge-1 (rectifier) firing angle $\alpha_{Rectifier}$ (°)	Line voltage $E_{1\text{-}2}$ (V)	Active power (W)	React. power (var)	DPF	DC current I_{dc} (A)	DC voltage E_{dc} (V)	DC power P_{dc} (W)	Bridge-2 (inverter) firing angle $\alpha_{Inverter}$ (°)	Line voltage $E_{1\text{-}2}$ (V)	Active power (W)	React. power (var)	DPF
1.0	0.05	23.5	114	143	63	0.92	1.0	138	140	165	99	-130	38	0.96
1.0	0.05	29.4	114	137	77	0.87	1.0	131	133	165	94	-123	36	0.96

Yes. The table above shows that the dc line current I_{dc} remains constant at the value (1.0 pu or 1.0 A) of the current command $I_{Ref.(rectifier)}$ when the ac voltage at bridge 2 (inverter bridge) decreases by 5% and 10%.

When the ac voltage at bridge 2 (inverter bridge) decreases by 5% and 10%, the firing angle $\alpha_{Rectifier}$ of bridge 1 increases from an initial value of approximately 15° to approximately 24° and 30°, respectively, while the firing angle $\alpha_{Inverter}$ of bridge 2 remains at 165°.

34. The results are presented in the following table.

Parameters measured in the HVDC transmission system.

HVDC transmission system		AC side of station 1 (left-end station)					Transmission line			AC side of station 2 (right-end station)				
Current command $I_{Ref.(rectifier)}$ (A)	Current margin ΔI (A)	Bridge-1 (rectifier) firing angle $\alpha_{Rectifier}$ (°)	Line voltage $E_{1\text{-}2}$ (V)	Active power (W)	React. power (var)	DPF	DC current I_{dc} (A)	DC voltage E_{dc} (V)	DC power P_{dc} (W)	Bridge-2 (inverter) firing angle $\alpha_{Inverter}$ (°)	Line voltage $E_{1\text{-}2}$ (V)	Active power (W)	React. power (var)	DPF
1.0	0.05	14.8	113	149	42	0.96	1.0	145	145	165	104	-136	38	0.96

Yes. This is because when the ac voltage at bridge 2 (inverter bridge) increases and returns to its initial value, the firing angle $\alpha_{Rectifier}$ of bridge 1 is decreased to approximately 15° in order to keep the dc line current I_{dc} at the value (1.0 pu or 1.0 A) of the current command $I_{Ref.(rectifier)}$ of the HVDC transmission system.

35. Yes, since the observations made thus far show that the dc line current I_{dc} is maintained at the value (1.0 pu or 1.0 A) of the current command $I_{Ref.(rectifier)}$ of the HVDC transmission system. Thus, it is as if a single current control loop were present in the HVDC transmission system [i.e., a current control loop at bridge 1 (rectifier bridge) only]. This is because the current command $I_{Ref.(inverter)}$ of the current control loop at bridge 2 has a value (0.95 pu) lower than that (1.0 pu) of the current command $I_{Ref.(rectifier)}$ at bridge 1, due to the current margin ΔI (0.05 pu) of the HVDC transmission system. Consequently, the current control loop at bridge 2 (inverter bridge) attempts to decrease the dc line current I_{dc} by keeping the firing angle $\alpha_{Inverter}$ of bridge 2 at the maximum (limit) value (i.e., 165°), which prevents any interaction between the two control loops.

36. The results are presented in the following table.

Parameters measured in the HVDC transmission system.

HVDC transmission system		AC side of station 1 (left-end station)					Transmission line			AC side of station 2 (right-end station)				
Current command $I_{Ref.(rectifier)}$ (A)	**Current margin ΔI (A)**	**Bridge-1 (rectifier) firing angle $\alpha_{Rectifier}$ (°)**	**Line voltage $E_{1\text{-}2}$ (V)**	**Active power (W)**	**React. power (var)**	**DPF**	**DC current I_{dc} (A)**	**DC voltage E_{dc} (V)**	**DC power P_{dc} (W)**	**Bridge-2 (inverter) firing angle $\alpha_{Inverter}$ (°)**	**Line voltage $E_{1\text{-}2}$ (V)**	**Active power (W)**	**React. power (var)**	**DPF**
1.0	0.05	0.0	114	146	10	0.99	0.95	151	143	150	121	-136	7	0.87

No, the firing angle $\alpha_{Inverter}$ of bridge 2 is no longer at the maximum (limit) value (165°). This firing angle has decreased to approximately 150°.

Yes, the dc line current I_{dc} is approximately equal to the current command $I_{Ref.(rectifier)}$ minus the current margin ΔI (0.95 pu):

$$I_{dc} = I_{Ref.(rectifier)} - \Delta I = 1.0 \text{ pu} - 0.05 \text{ pu} = 0.95 \text{ pu}$$

This indicates that the current control loop at bridge 2 (inverter bridge) has entered into action by decreasing the firing angle $\alpha_{Inverter}$ in order to keep the current flowing through the bridges, and thus the current I_{dc}, at the value above (0.95 pu) to prevent current I_{dc} from decreasing further.

37. The dc line current I_{dc} returns to the initial value (1.0 pu or 1.0 A), i.e., to the value of the current command $I_{Ref.(rectifier)}$ of the HVDC transmission system. The firing angle $\alpha_{Rectifier}$ of bridge 1 increases to approximately 15°, while the firing angle $\alpha_{Inverter}$ of bridge 2 returns to its maximum (limit) value (165°). This is because the decrease of the ac voltage at bridge 2 (inverter bridge) results in an increase of the dc line current I_{dc} which causes the current control loop of bridge 1 (rectifier bridge) to re-enter into action by increasing the firing angle $\alpha_{Rectifier}$ of this bridge. It does this in order to keep the current I_{dc} flowing through the bridges at the value (1.0 pu or 1.0 A) of the current command $I_{Ref.(rectifier)}$ of the HVDC transmission system, and thus prevent current I_{dc} from increasing further.

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The results are presented in the following table.

Parameters measured in the HVDC transmission system.

HVDC transmission system		AC side of station 1 (left-end station)					Transmission line			AC side of station 2 (right-end station)				
Current command $I_{Ref.\,(rectifier)}$ (A)	Current margin ΔI (A)	Bridge-1 (rectifier) firing angle $\alpha_{Rectifier}$ (°)	Line voltage $E_{1\text{-}2}$ (V)	Active power (W)	React. power (var)	DPF	DC current I_{dc} (A)	DC voltage E_{dc} (V)	DC power P_{dc} (W)	Bridge-2 (inverter) firing angle $\alpha_{Inverter}$ (°)	Line voltage $E_{1\text{-}2}$ (V)	Active power (W)	React. power (var)	DPF
1.0	0.05	14.7	113	150	40	0.97	1.0	145	146	165	104	-136	38	0.96

38. The results are presented in the following table.

Parameters measured in the HVDC transmission system.

HVDC transmission system		AC side of station 1 (left-end station)					Transmission line			AC side of station 2 (right-end station)				
Current command $I_{Ref.\,(rectifier)}$ (A)	Current margin ΔI (A)	Bridge-1 (rectifier) firing angle $\alpha_{Rectifier}$ (°)	Line voltage $E_{1\text{-}2}$ (V)	Active power (W)	React. power (var)	DPF	DC current I_{dc} (A)	DC voltage E_{dc} (V)	DC power P_{dc} (W)	Bridge-2 (inverter) firing angle $\alpha_{Inverter}$ (°)	Line voltage $E_{1\text{-}2}$ (V)	Active power (W)	React. power (var)	DPF
1.0	0.1	0.0	114	139	9	0.99	0.9	151	135	151	121	-128	73	0.87
1.0	0.1	14.5	113	149	40	0.97	1.0	145	145	165	104	-135	38	0.96
1.0	0.2	0.0	114	124	8	0.99	0.8	151	121	152	120	-115	62	0.88
1.0	0.2	14.6	113	150	40	0.97	1.0	145	145	165	104	-136	38	0.96

When the current margin ΔI of the HVDC transmission system is set to 0.1 pu (i.e., 0.1 A), the dc line current I_{dc} decreases from 1.0 pu to 0.9 pu (i.e., from 1.0 A to 0.9 A). When the current margin ΔI is set to 0.2 pu (i.e., 0.2 A), the current I_{dc} decreases from 1.0 pu to 0.8 pu (i.e., from 1.0 A to 0.8 A).

Yes. This is because when the current margin ΔI of the HVDC transmission system is increased, the value of the current command of the current control loop at bridge 2 (inverter bridge), which is equal to $I_{Ref.\,(rectifier)} - \Delta I$, decreases, so that this control loop enters into action at a lower value of current I_{dc}. For example, the table above shows that when the current margin ΔI is set to 0.1 pu, the amount of power P_{dc} transferred decreases from 145 W (maximum level) to 135 W. When the current margin ΔI is increased to 0.2 pu, the amount of power P_{dc} transferred decreases from 145 W to 121 W.

41. The results are presented in the following table.

Parameters measured in the HVDC transmission system.

HVDC transmission system		AC side of station 1 (left-end station)					Transmission line			AC side of station 2 (right-end station)				
Current command $I_{Ref.\,(rectifier)}$ (A)	Current margin ΔI (A)	Bridge-1 (rectifier) firing angle $\alpha_{Rectifier}$ (°)	Line voltage $E_{1\text{-}2}$ (V)	Active power (W)	React. power (var)	DPF	DC current I_{dc} (A)	DC voltage E_{dc} (V)	DC power P_{dc} (W)	Bridge-2 (inverter) firing angle $\alpha_{Inverter}$ (°)	Line voltage $E_{1\text{-}2}$ (V)	Active power (W)	React. power (var)	DPF
0.6	0.1	22.4	114	87	36	0.92	0.6	140	84	165	102	-81	24	0.96

42. The results are presented in the following table.

Parameters measured in the HVDC transmission system.

HVDC transmission system		AC side of station 1 (left-end station)					Transmission line			AC side of station 2 (right-end station)				
Current command $I_{Ref.\,(rectifier)}$ (A)	Current margin ΔI (A)	Bridge-1 (rectifier) firing angle $\alpha_{Rectifier}$ (°)	Line voltage $E_{1\text{-}2}$ (V)	Active power (W)	React. power (var)	DPF	DC current I_{dc} (A)	DC voltage E_{dc} (V)	DC power P_{dc} (W)	Bridge-2 (inverter) firing angle $\alpha_{Inverter}$ (°)	Line voltage $E_{1\text{-}2}$ (V)	Active power (W)	React. power (var)	DPF
0.6	0.1	0.0	106	86	4	0.99	0.6	141	85	165	103	-81	22	0.97

43. This occurs because the firing angle $\alpha_{Rectifier}$ of bridge 1 has reached the minimum value (0°). Consequently, the current control loop at bridge 1 (rectifier bridge) is unable to further decrease the firing angle $\alpha_{Rectifier}$ of this bridge to keep the dc line current I_{dc} at the value (0.60 pu or 0.60 A) of the current command $I_{Ref.\,(rectifier)}$.

The results are presented in the following table.

Parameters measured in the HVDC transmission system.

HVDC transmission system		AC side of station 1 (left-end station)					Transmission line			AC side of station 2 (right-end station)				
Current command $I_{Ref.\,(rectifier)}$ (A)	Current margin ΔI (A)	Bridge-1 (rectifier) firing angle $\alpha_{Rectifier}$ (°)	Line voltage $E_{1\text{-}2}$ (V)	Active power (W)	React. power (var)	DPF	DC current I_{dc} (A)	DC voltage E_{dc} (V)	DC power P_{dc} (W)	Bridge-2 (inverter) firing angle $\alpha_{Inverter}$ (°)	Line voltage $E_{1\text{-}2}$ (V)	Active power (W)	React. power (var)	DPF
0.6	0.1	0.0	105	79	3	0.99	0.55	140	77	165	103	-74	20	0.96

Yes. This is because the current control loop at bridge 2 (inverter bridge) has not entered into action yet [i.e., the dc line current I_{dc} has not decreased enough to reach the value (0.50 pu or 0.50 A) of the current command of the current control loop at bridge 2].

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44. The results are presented in the following table.

Parameters measured in the HVDC transmission system.

HVDC transmission system		AC side of station 1 (left-end station)					Transmission line			AC side of station 2 (right-end station)					
Current command $I_{Ref.(rectifier)}$ (A)	Current margin ΔI (A)	Bridge-1 (rectifier) firing angle $\alpha_{Rectifier}$ (°)	Line voltage $E_{1\text{-}2}$ (V)	Active power (W)	React. power (var)	DPF	DC current I_{dc} (A)	DC voltage E_{dc} (V)	DC power P_{dc} (W)	Bridge-2 (inverter) firing angle $\alpha_{Inverter}$ (°)	Line voltage $E_{1\text{-}2}$ (V)	Active power (W)	React. power (var)	DPF
0.6	0.1	0.0	105	71	3	0.99	0.5	139	70	165	102	-67	19	0.96
0.6	0.1	0.0	102	70	4	0.99	0.5	135	68	160	102	-66	25	0.94

This occurs because when the dc line current I_{dc} reaches the value (0.50 pu or 0.50 A) of the current command of the current control loop at bridge 2 (i.e., $I_{Ref(rectifier)} - \Delta I$), this current control loop enters into action and starts decreasing the firing angle $\alpha_{Inverter}$ of bridge 2 in order to prevent the current I_{dc} from decreasing further. For example, the table above shows that when the ac voltage at bridge 1 (rectifier bridge) decreases from 105 V to 102 V, the firing angle $\alpha_{Inverter}$ of bridge 2 decreases from 165° to 160°, which keeps current I_{dc} at the value (0.50 pu or 0.50 A) of the current command of the current control loop at bridge 2, and thus prevents current I_{dc} from decreasing further.

45. When the ac voltage at bridge 1 (rectifier bridge) returns to its initial value, the dc line current I_{dc} remains at the value (0.50 pu or 0.50 A) of the current command of the current control loop at bridge 2 (inverter bridge) as long as the firing angle $\alpha_{Inverter}$ required at bridge 2 is below the limit value (165°). When the firing angle $\alpha_{Inverter}$ required at bridge 2 reaches the limit value, the current I_{dc} starts increasing, passing from the value (0.50 pu or 0.50 A) of the current command of the current control loop at bridge 2 to the value (0.60 pu or 0.60 A) of the current command $I_{Ref.(rectifier)}$ of the HVDC transmission system. Meanwhile, the firing angles $\alpha_{Rectifier}$ and $\alpha_{Inverter}$ remain at 0° and 165°, respectively. When current I_{dc} reaches 0.60 pu, the current control loop of bridge 1 re-enters into action (i.e., it starts increasing the firing angle $\alpha_{Rectifier}$ of bridge 1) to keep current I_{dc} at the value (0.60 pu or 0.60 A) of the current command $I_{Ref.(rectifier)}$, and thus prevent current I_{dc} from increasing further.

The results are presented in the following table.

Parameters measured in the HVDC transmission system.

HVDC transmission system		AC side of station 1 (left-end station)					Transmission line			AC side of station 2 (right-end station)				
Current command $I_{Ref.(rectifier)}$ (A)	Current margin ΔI (A)	Bridge-1 (rectifier) firing angle $\alpha_{Rectifier}$ (°)	Line voltage $E_{1\text{-}2}$ (V)	Active power (W)	React. power (var)	DPF	DC current I_{dc} (A)	DC voltage E_{dc} (V)	DC power P_{dc} (W)	Bridge-2 (inverter) firing angle $\alpha_{Inverter}$ (°)	Line voltage $E_{1\text{-}2}$ (V)	Active power (W)	React. power (var)	DPF
0.6	0.1	22.6	114	87	40	0.92	0.6	140	85	165	103	-81	24	0.96

47. The results are presented in the following table.

Parameters measured in the HVDC transmission system.

HVDC transmission system		AC side of station 1 (left-end station)					Transmission line			AC side of station 2 (right-end station)				
Current command $I_{Ref.(rectifier)}$ (A)	Current margin ΔI (A)	Bridge-1 (rectifier) firing angle $\alpha_{Rectifier}$ (°)	Line voltage $E_{1\text{-}2}$ (V)	Active power (W)	React. power (var)	DPF	DC current I_{dc} (A)	DC voltage E_{dc} (V)	DC power P_{dc} (W)	Bridge-2 (inverter) firing angle $\alpha_{Inverter}$ (°)	Line voltage $E_{1\text{-}2}$ (V)	Active power (W)	React. power (var)	DPF
1.0	0.05	10.0	113	153	30	0.98	1.0	148	149	165	107	-140	38	0.96
0.9	0.05	13.8	113	134	34	0.97	0.9	145	131	165	105	-123	33	0.96
0.8	0.05	17.5	113	118	38	0.95	0.8	143	115	165	104	-109	30	0.96
0.7	0.05	20.4	114	102	37	0.94	0.7	142	99	165	103	-95	27	0.96
0.6	0.05	21.8	114	87	36	0.92	0.6	141	85	165	103	-82	24	0.96
0.5	0.05	23.9	114	71	33	0.91	0.5	140	70	165	102	-67	20	0.96
0.4	0.05	25.8	115	57	28	0.90	0.4	139	56	165	102	-54	17	0.95
0.3	0.05	27.7	116	43	23	0.88	0.3	137	41	165	102	-41	13	0.95

Yes. The table above shows that when the value of the current command $I_{Ref.(rectifier)}$ of the HVDC transmission system is decreased from 1.0 pu to 0.3 pu (i.e., from 1.0 A to 0.3 A), the amount of power P_{dc} transferred via the system passes from 149 W (maximum value) to 41 W (i.e., it decreases by more than three times the initial value). This provides a substantial variation in the amount of power transferred via the HVDC transmission system.

Yes. The results in the table above indicate that the dc voltage E_{dc} at which the system operates remains close to the maximum value, i.e., it decreases by less than 10% of the maximum value (148 V) when the value of the current command $I_{Ref.(rectifier)}$ is decreased from 1.0 pu to 0.3 pu.

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The results in the table show that the DPF at bridge 1 (rectifier bridge) remains acceptable (i.e., it passes from 0.98 to 0.91) when current I_{dc} passes from 1.0 pu to 0.5 pu (i.e., from 1.0 A to 0.5 A), whereas the DPF is a bit low (at or slightly below 0.9) when current I_{dc} is lower than 0.5 pu. On the other hand, the DPF at bridge 2 (inverter bridge) remains very good (approximately 0.96) over the usable range of current I_{dc}.

Power transferred via the system (I_{dc} = 0.3 pu, $\alpha_{Inverter}$ = 165°) = 41 W

The dc voltage E_{dc} at which the system operates must be decreased by decreasing the maximum (limit) value of the firing angle of bridge 2 (inverter bridge).

48. The results are presented in the following table.

Parameters measured in the HVDC transmission system.

HVDC transmission system		AC side of station 1 (left-end station)					Transmission line			AC side of station 2 (right-end station)				
Current command $I_{Ref.\,(rectifier)}$ (A)	Current margin ΔI (A)	Bridge-1 (rectifier) firing angle $\alpha_{Rectifier}$ (°)	Line voltage $E_{1\text{-}2}$ (V)	Active power (W)	React. power (var)	DPF	DC current I_{dc} (A)	DC voltage E_{dc} (V)	DC power P_{dc} (W)	Bridge-2 (inverter) firing angle $\alpha_{Inverter}$ (°)	Line voltage $E_{1\text{-}2}$ (V)	Active power (W)	React. power (var)	DPF
0.3	0.05	27.8	116	43	23	0.88	0.3	137	42	165	102	-40	14	0.94
0.3	0.05	37.4	116	40	27	0.83	0.3	123	39	150	102	-38	21	0.88
0.3	0.05	48.7	116	31	36	0.65	0.3	102	30	135	102	-30	31	0.69
0.3	0.05	62.9	116	24	43	0.48	0.3	73	24	120	101	-23	38	0.51
0.3	0.05	74.7	117	12	45	0.26	0.3	40	12	105	101	-12	39	0.29
0.3	0.05	92.5	118	0	51	0.0	0.3	3	1	90	101	0	44	0.0

The table above shows that when the maximum (limit) value of the firing angle of bridge 2 (inverter bridge) is decreased from 165° to 90°, the operating dc voltage E_{dc} passes from a value close to the maximum (137 V) to virtually zero, and the amount of power P_{dc} transferred decreases from 42 W to approximately zero (1 W).

The DPFs at both bridges become worse and worse. The table above shows that when the maximum (limit) value of the firing angle of bridge 2 (inverter bridge) is decreased from 165° to 90°, the DPF of bridge 1 (rectifier bridge) passes from 0.88 to 0, while the DPF of bridge 2 (inverter bridge) passes from 0.94 to 0. This shows that operating an HVDC transmission system at low power levels for extended periods is highly undesirable as this results in a poor DPF at each bridge.

54. The results are presented in the following table.

Parameters measured in the HVDC transmission system.

HVDC transmission system		AC side of station 1 (left-end station)					Transmission line			AC side of station 2 (right-end station)				
Current command $I_{Ref.(rectifier)}$ (A)	Current margin ΔI (A)	Bridge-1 (inverter) firing angle $\alpha_{Inverter}$ (°)	Line voltage E_{1-2} (V)	Active power (W)	React. power (var)	DPF	DC current I_{dc} (A)	DC voltage E_{dc} (V)	DC power P_{dc} (W)	Bridge-2 (rectifier) firing angle $\alpha_{Rectifier}$ (°)	Line voltage E_{1-2} (V)	Active power (W)	React. power (var)	DPF
0.3	0.05	90	99	0	43	0.0	0.3	9	0.4	92.2	118	1	51	0.0
0.3	0.05	105	100	-12	40	0.29	0.3	-37	-11	74.5	117	10	45	0.21
0.3	0.05	120	100	-22	38	0.51	0.3	-69	-23	62.7	117	23	43	0.47
0.3	0.05	135	101	-29	31	0.68	0.3	-100	-29	49.1	117	29	37	0.63
0.3	0.05	150	101	-38	21	0.87	0.3	-122	-38	37.8	116	39	27	0.83
0.3	0.05	165	101	-40	14	0.94	0.3	-136	-40	28.7	116	42	24	0.87

The table above shows that when the maximum (limit) value of the firing angle of bridge 1 (inverter bridge) is increased from 90° to 165°, the operating dc voltage E_{dc} passes from a value close to zero (≅ 9 V) to a value close to the maximum (-136 V), and the amount of power transferred increases from virtually zero (0.4 W) to -136 W.

Power transferred via the system (I_{dc} = 0.3 pu, $\alpha_{Inverter}$ = 165°) = -40 W

Yes. When operating at a dc line current I_{dc} of 0.3 pu and the maximum dc voltage ($\alpha_{Inverter}$ = 165°), the amount of power P_{dc} transferred via the HVDC transmission system when power flows from bridge 2 to bridge 1 (-40 W) is virtually the same as when power flows from bridge 1 to bridge 2 (41 W). However, the polarity of power P_{dc} is negative (because E_{dc} is negative) when power flows from bridge 2 to bridge 1, while the polarity of power P_{dc} is positive (because voltage E_{dc} is positive) when power flows from bridge 1 to bridge 2.

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55. The results are presented in the following table.

Parameters measured in the HVDC transmission system.

HVDC transmission system		AC side of station 1 (left-end station)					Transmission line			AC side of station 2 (right-end station)				
Current command $I_{Ref.\,(rectifier)}$ (A)	Current margin ΔI (A)	Bridge-1 (inverter) firing angle $\alpha_{Inverter}$ (°)	Line voltage $E_{1\text{-}2}$ (V)	Active power (W)	React. power (var)	DPF	DC current I_{dc} (A)	DC voltage E_{dc} (V)	DC power P_{dc} (W)	Bridge-2 (rectifier) firing angle $\alpha_{Rectifier}$ (°)	Line voltage $E_{1\text{-}2}$ (V)	Active power (W)	React. power (var)	DPF
0.3	0.05	165	102	-41	14	0.94	0.3	-136	-41	29.5	117	43	24	0.87
0.4	0.05	165	102	-54	18	0.95	0.4	-137	-55	27.4	117	58	31	0.88
0.5	0.05	165	103	-67	21	0.96	0.5	-138	-68	26.2	116	71	36	0.90
0.6	0.05	165	103	-81	25	0.96	0.6	-139	-83	24.1	116	87	40	0.91
0.7	0.05	165	104	-95	28	0.96	0.7	-140	-97	22.9	116	102	43	0.92
0.8	0.05	165	104	-109	32	0.96	0.8	-140	-112	20.8	115	118	45	0.93
0.9	0.05	165	105	-123	36	0.96	0.9	-141	-127	18.5	115	134	45	0.95
1.0	0.05	165	105	-137	40	0.96	1.0	-142	-141	15.3	114	149	44	0.96

Yes. The table above shows that when the value of the current command $I_{Ref.\,(rectifier)}$ of the HVDC transmission system is increased from 0.3 pu to 1.0 pu (i.e., from 0.3 A to 1.0 A), the amount of power P_{dc} transferred via the system passes from -41 W to -141 W (i.e., it increases by more than three times the initial value). This provides a substantial variation in the amount of power transferred via the HVDC transmission system, just as when power flows in the opposite direction.

Answers to Review Questions

1. The current control loop uses a current sensor to measure the actual value of the dc line current I_{dc}. This loop compares the measured value of current I_{dc} to the value of the current command $I_{Ref.}$ (desired current value) and corrects for any difference (error) between the two by modifying the firing angle of the rectifier bridge until current I_{dc} is equal to the current command $I_{Ref.}$.

2. The dc line current I_{dc}, and thus the amount of power transferred through the line, starts decreasing significantly. This is because the current control loop decreases the firing angle of the rectifier bridge to the minimum value (0°); this is not sufficient to keep current I_{dc} at the value of the current command $I_{Ref.}$. This problem can be resolved by adding a second current control loop at the inverter bridge of the HVDC transmission system that is set to operate at a slightly lower current setpoint (i.e., at $I_{Ref.\,(rectifier)} - \Delta I$).

3. As long as the ac voltage at both bridges remains close to the nominal value, the current control loop at the rectifier bridge keeps control of the system's operating point and maintains the current I_{dc} at $I_{Ref.\,(rectifier)}$. However, when the ac voltage at the rectifier bridge decreases too much or the ac voltage at the inverter bridge increases too much, the current control loop at the inverter bridge takes control of the system's operating point and maintains the current I_{dc} at a slightly lower value, i.e., at $I_{Ref.\,(rectifier)} - \Delta I$.

4. This is because the power losses (RI^2 losses) caused by heat dissipation in conductors increase with the square of current, while being virtually independent of the magnitude of voltage. Therefore, for any given amount of power transferred through an HVDC transmission system, it is best to operate at the highest dc voltage possible to keep the dc current as low as possible, and thus reduce the power losses to a minimum.

5. Gradually decrease the amount of power flowing through the transmission line to zero: first decrease the dc line current I_{dc} to the minimum value ensuring continuous current flow in the bridges, then decrease the voltage at which the system operates to zero by decreasing the maximum (limit) value of the firing angle of the bridge currently acting as an inverter to 90°.

- Stop both bridges (i.e., stop thyristor firing in both bridges).

- Select the appropriate tap on the multiple-tap transformer of each converter station so that the bridge which will act as an inverter operates at an ac voltage slightly lower than the bridge which will act as a rectifier.

- Set the current command $I_{Ref.\,(rectifier)}$ of the bridge which will act as a rectifier to the minimum value ensuring continuous current flow in the bridges, then set the current command $I_{Ref.(inverter)}$ of the bridge which will act as an inverter to $I_{Ref.\,(rectifier)}$ - ΔI.

- Set the maximum (limit) value of the firing angle of the bridge which will act as an inverter to 90°.

- Start both bridges.

- Increase the dc voltage at which the system operates to maximum by gradually increasing the maximum (limit) value of the firing angle of the bridge now acting as an inverter to the maximum value allowed.

- Set the current command $I_{Ref.\,(rectifier)}$ of the bridge now acting as a rectifier to the value required to transfer the desired amount of power.

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