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Internal Assesment Test - II

Sub:	**HVDC TRANSMISSION**							Code:	**10EE751**
Date:	03 / 11 / 2016	Duration:	90 mins	Max Marks:	50	Sem:	VII	Branch:	EEE

Answer Any FIVE FULL Questions

			Marks	OBE CO	OBE RBT
1	(a)	Draw the electrical equivalent circuit of HVDC transmission and explain the basic means of control for power reversal.	[6]	CO3	L2
	(b)	Summarize the desired features of HVDC converter control.	[4]	CO3	L2
2	(a)	With relevant figure, explain the combined characteristics of rectifier and inverter permitting reversal of power flow. Clearly explain the significance of positive and negative current margin.	[10]	CO3	L4
3	(a)	Draw the equivalent circuit for analyzing the stability of control of dc link. Derive the expression for damping coefficient for the same.	[10]	CO3, CO4	L4
4	(a)	Draw the schematic circuit of an analog computer for C.E.A control and explain with voltage waveform.	[5]	CO3	L2
	(b)	Write a short note on constant minimum ignition angle control.	[5]	CO3	L2
5	(a)	Explain the limitations of manual control.			L4
	(b)	Describe the constant current and constant voltage dc transmission systems. Compare them with respect to fault currents and energy loss.		CO5	L5
6		Write a short note on			
	(a)	Critical grid voltage	[5]	CO3	L2
	(b)	Grid bias and blocking	[5]	CO3	L2
7	(a)	Discus the ‘actual control characteristics’ of control scheme. In this context, explain the significance of ‘current margin’ and its range.	[10]	CO3	L4
8	(a)	Explain the individual characteristics of a rectifier and an inverter with neat sketches.	[5]	CO3	L2
	(b)	Draw the schematic circuit of analog computer for constant current control and explain.	[5]	CO3	L2

Course Outcomes		PO1	PO2	PO3	PO4	PO5	PO6	PO7	PO8	PO9	PO10	PO11	PO12
CO1:	Identify significance of DC over AC transmission system, types and application of HVDC links in practical power systems	3	3	1	2	0	1	0	0	0	0	0	1
CO2:	Analyze and compare different converters viz.3, 6 and 12 pulse converters.	3	3	2	2	1	1	0	0	0	0	0	2
CO3:	Analyze AC/DC system interactions and know the operation and control of DC systems.	3	3	2	2	2	0	0	0	0	0	0	0
CO4:	Apply protection for HVDC system against transient overvoltage and over currents	3	3	3	2	1	0	0	0	0	0	0	1
CO5:	Compare constant current and constant voltage transmission systems	1	2	1	2	0	1	0	0	0	0	0	1
CO6:	Analyse the DC transmission system with and without overlap angle	3	3	2	1	0	0	0	0	0	0	0	0

Cognitive level	KEYWORDS
L1	List, define, tell, describe, identify, show, label, collect, examine, tabulate, quote, name, who, when, where, etc.
L2	summarize, describe, interpret, contrast, predict, associate, distinguish, estimate, differentiate, discuss, extend
L3	Apply, demonstrate, calculate, complete, illustrate, show, solve, examine, modify, relate, change, classify, experiment, discover.
L4	Analyze, separate, order, explain, connect, classify, arrange, divide, compare, select, explain, infer.
L5	Assess, decide, rank, grade, test, measure, recommend, convince, select, judge, explain, discriminate, support, conclude, compare, summarize.

PO1 - *Engineering knowledge*; PO2 - *Problem analysis*; PO3 - *Design/development of solutions*; PO4 - *Conduct investigations of complex problems*; PO5 - *Modern tool usage*; PO6 - *The Engineer and society*; PO7- *Environment and sustainability*; PO8 – *Ethics*; PO9 - *Individual and team work*; PO10 - *Communication*; PO11 - *Project management and finance*; PO12 - *Life-long learning*

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		Marks	OBE	
			CO	RBT
1 (a)	Draw the electrical equivalent circuit of HVDC transmission and explain the basic means of control for power reversal.	[6]	CO3	L2

Ans

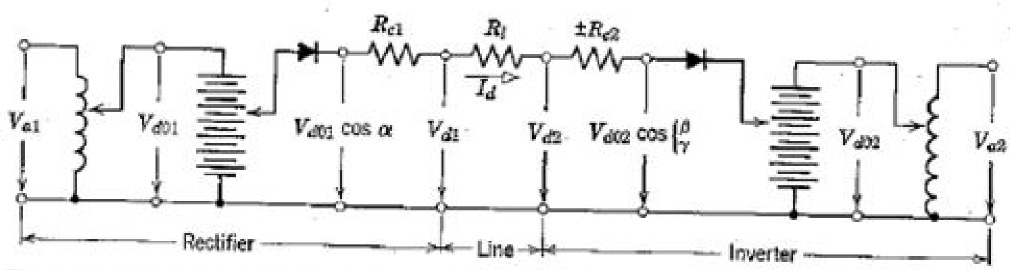


Fig. 4. Equivalent circuit of dc transmission valid for average currents and voltages in the steady state.

The current in a dc line operating in the steady state is given by Ohm's law as the difference in its terminal voltages divided by its resistance. By incorporating the equivalent circuits of the converters (given in Figures 13 and 18 in Chapter 3) with that of the line, Ohm's law may be extended to the internal voltages, embracing the commutation drops as shown in Figure 4. The current I_d in the line is then given by

$$I_d = \frac{V_{d01}\cos\alpha - V_{d02}\cos(\beta \text{ or } \gamma)}{R_{c1} + R_l \pm R_{c2}} \quad (1)$$

In this equation $\cos\beta$ is used in the numerator and $+R_{c2}$ in the denominator if the inverter is operated with constant ignition angle β; $\cos\gamma$ and $-R_{c2}$ are used if the extinction angle γ is constant. For present purposes, the former mode of operation is assumed, because it is the ignition angle β that can be directly controlled; the extinction angle γ is controlled indirectly through controlling β to values computed from the direct current I_d, the commutating voltage, and the desired extinction angle, as discussed in Section 5-10.

Direct current I_d, then, depends on the voltage drop—numerator of Eq. (1)—divided by the total resistance (denominator). Since in practice the resistances are fixed, the current is proportional to the difference of the two internal voltages and is controlled by controlling these voltages. The direct voltage at any designated point of the line, as well as the current, can be controlled by controlling the two internal voltages; for example, if the line is uniform and if the two commutating resistances are equal, the voltage at the midpoint of the line is the average of the internal voltages. The direct voltage at any other point of the line is a weighted average of the internal voltages. More generally, any two independent quantities, for example, power and voltage, could be controlled by the two internal voltages.

Each internal voltage can be controlled by either of two different methods: grid control or control of the alternating voltage. The internal voltage of the rectifier is written in Figure 4 and Eq. (1) as $V_{d01} \cos \alpha$. Grid control, delaying the ignition angle α (time α/ω), reduces the internal voltage from the ideal no-load voltage V_{d01} by the factor $\cos \alpha$. (It will be remembered that the voltage drop due to overlap is represented by the voltage across the commutating resistance R_{c1}.) The ideal no-load voltage V_{d01} is directly proportional to the alternating voltage—see Eq. (5) in Chapter 3. The alternating voltage in some exceptional cases could be controlled by generator excitation, but it is usually controlled by tap changing on the converter transformers.

Grid control is rapid (1 to 10 ms), but tap changing is slow (5 to 6 sec per step). Both these means of voltage control are applied cooperatively at each terminal. Grid control is used initially for rapid action and is followed by tap changing for restoring certain quantities (ignition angle in the rectifier or voltage in the inverter) to their normal values.

(b) Summarize the desired features of HVDC converter control.	[4]	CO3	L2

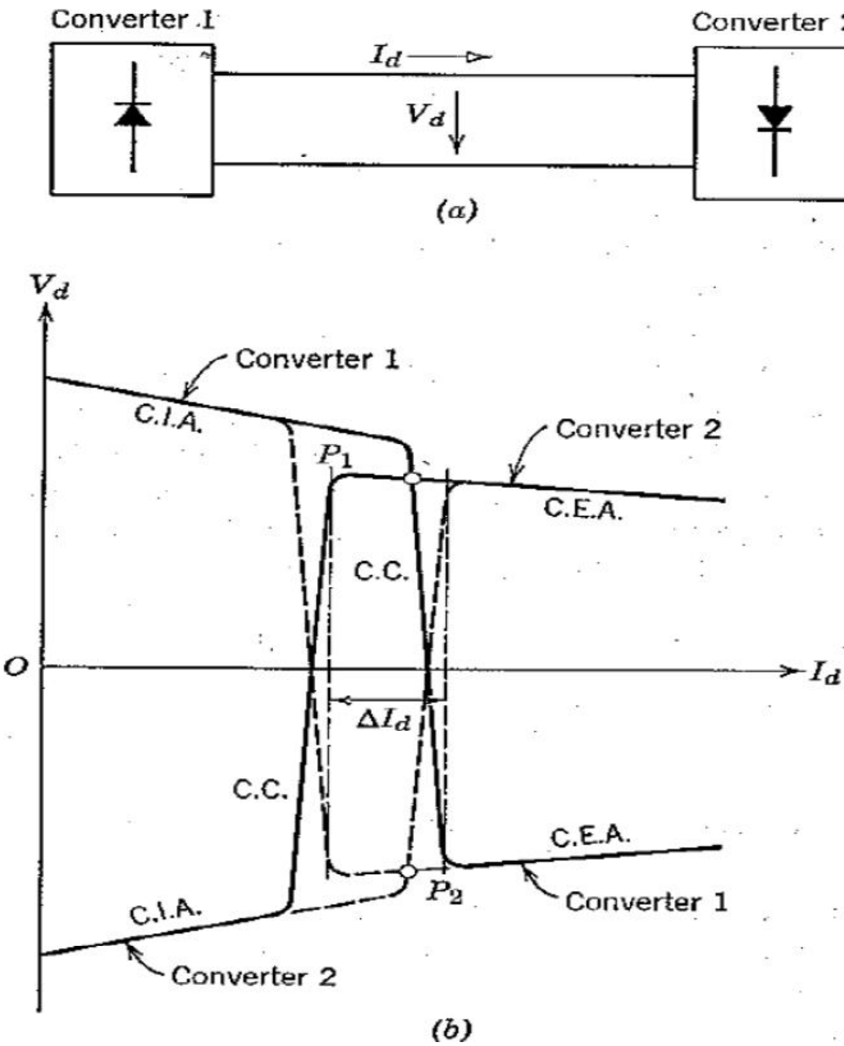
The following features are desirable:

1. Limitation of the maximum current so as to avoid damage to valves and other current-carrying devices
2. Limitation of the fluctuation of current due to the fluctuation of alternating voltage
3. Keeping the power factor as high as possible
4. Prevention of commutation failures of the inverter
5. Prevention of arcback of the rectifier valves
6. In multianode valves, providing a sufficient anode voltage before ignition occurs
7. Keeping the voltage at the sending end of the line constant at its rated value insofar as possible in order to minimize losses for a given power
8. Controlling the power delivered or, in some cases, the frequency at one end

2 (a) With relevant figure, explain the combined characteristics of rectifier and inverter permitting reversal of power flow. Clearly explain the significance of positive and negative current margin.	[10]	CO3	L4

Combined Characteristic of Rectifier and Inverter

In many dc transmission links each converter must function sometimes as a rectifier and at other times as an inverter. At times both converters are called on to work as inverters in order to deenergize the line rapidly. Therefore each converter is given a combined characteristic, as shown in Figure 8,



consisting of three linear portions: C.I.A., C.C., and C.E.A.

With the characteristics shown by solid lines, power is transmitted from converter 1 to converter 2. If the characteristics are changed to those shown by the broken lines, the direction of transmission is reversed by the reversal of direct voltage with no change in direct current. Both stations are given the same current command, but, at the station designated as inverter, a signal representing the current margin is subtracted from that current command, giving a smaller net current command. When it is desired to reverse the direction of power, the margin signal must be transferred to the station that becomes the inverter station.

During the reversal of power and voltage the shunt capacitance of the line must be first discharged and then recharged with the opposite polarity. This process implies a greater current at the end of the line initially the inverter than at the end initially the rectifier. The difference of terminal currents cannot exceed the current margin. Hence the shortest time of voltage reversal is

$$T = C\frac{\Delta V_d}{\Delta I_d}\text{ seconds} \tag{5}$$

where C is the line capacitance, ΔV_d the algebraic change of direct voltage, and ΔI_d the current margin.

The current margin signal corresponds to the horizontal separation ΔI_d of the constant-current characteristics of the two converters along the horizontal axis or between the corners P_1 and P_2 in Figure 8. Because of the slope of these C.C. characteristics, the actual separation between them varies with V_d, being least at the normal working point. The margin signal must be great enough to maintain a positive margin there in spite of errors in the current measurement and regulation. Operation at the intersection of the two steep C.C. characteristics, with both current regulators operating, would be erratic.

The necessity for the slope of the C.C. characteristics is explained in Section 5-11.

3 (a)	Draw the equivalent circuit for analyzing the stability of control of dc link. Derive the expression for damping coefficient for the same.	[10]	CO3, CO4	L4

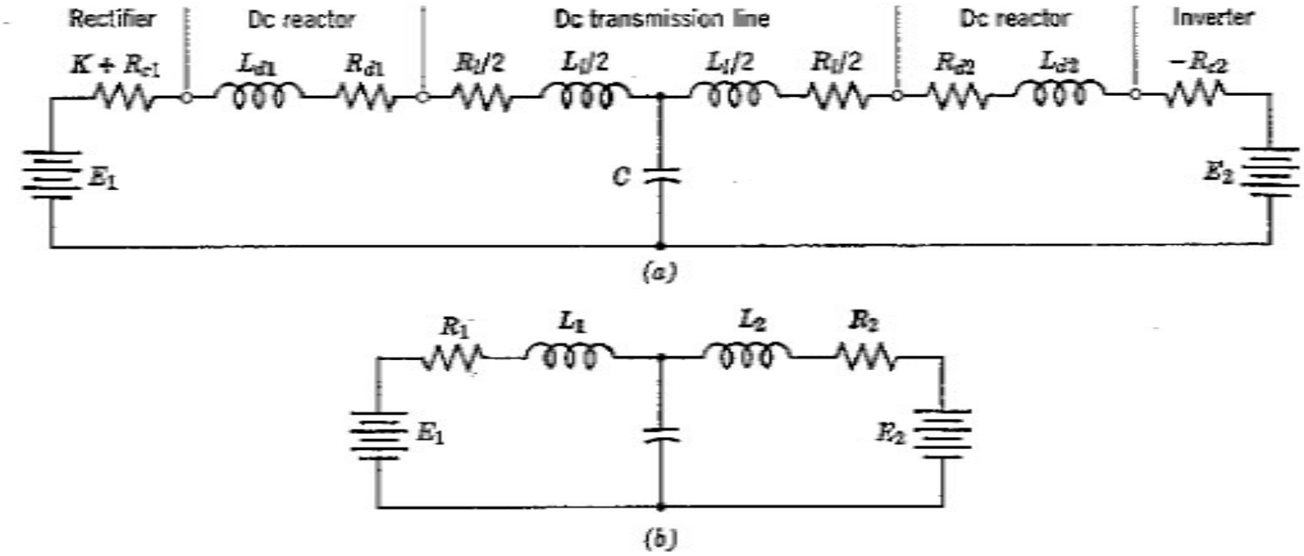


Fig. 19. Equivalent circuit of dc link for analysis of stability of control (*a*) before combination of line with terminal equipment; (*b*) after combination.

The equations of this circuit are

$$Z_1 I_1 - Z_m I_2 = E_1 \qquad (14a)$$

$$-Z_m I_1 + Z_2 I_2 = E_2 \qquad (14b)$$

where

$$Z_1 = R_1 + L_1 s + \frac{1}{Cs} \qquad (15a)$$

$$Z_2 = R_2 + L_2 s + \frac{1}{Cs} \qquad (15b)$$

$$Z_m = \frac{1}{Cs} \qquad (15c)$$

$$s = \sigma + j\omega = \text{complex frequency} \qquad (15d)$$

The characteristic equation of the circuit is found by setting the determinant of the impedances equal to zero:

$$\begin{vmatrix} Z_1 & -Z_m \\ -Z_m & Z_2 \end{vmatrix} = 0 \qquad (16)$$

or

$$Z_1 Z_2 - Z_m^2 = 0 \qquad (17)$$

Substitution of the values of the three impedances gives

$$\left(R_1 + L_1 s + \frac{1}{Cs}\right)\left(R_2 + L_2 s + \frac{1}{Cs}\right) - \left(\frac{1}{Cs}\right)^2 = 0 \qquad (18)$$

After performing the indicated multiplications, canceling the terms $\pm(1/Cs)^2$, and clearing of fractions, we have

$$L_1 L_2 C s^3 + (L_1 R_2 + L_2 R_1) C s^2 + (R_1 R_2 C + L_1 + L_2) s + (R_1 + R_2) = 0 \quad (19)$$

This is a cubic equation in s, and its roots are values of s that characterize the transient phenomena. A cubic equation with real coefficients has three roots, at least one of which is real. The other two may be real or a conjugate complex pair. From our knowledge of the nature of the circuit, we know that the latter alternative is more probable. The corresponding solution in the time domain, found from the inverse Laplace transform of Eq. (19), would have a damped direct current and a damped oscillatory current. If R_2 is negative, one or both of these terms may have negative damping; it is more likely that only the oscillatory term has it.

If numerical values of the coefficients were given, the cubic polynomial could be factored into a linear one and a quadratic. Factoring of the algebraic cubic is very cumbersome. So let us make another simplifying assumption. Since we know that ordinarily $R_1 \gg L_1 s$, let us put $L_1 = 0$. Equation (19) then simplifies to the following quadratic:

$$L_2 R_1 C s^2 + (R_1 R_2 C + L_2)s + (R_1 + R_2) = 0$$

$$s^2 + \left(\frac{R_2}{L_2} + \frac{1}{R_1 C}\right) + \frac{R_1 + R_2}{L_2 R_1 C} = 0 \tag{20}$$

which corresponds to the simplified circuit in Figure 20. Since $R_1 \gg R_2$, we

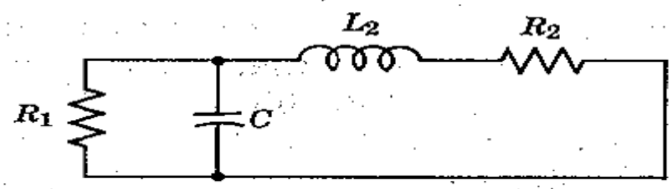


Fig. 20. Simplification of Figure 19*b* by putting $E_1 = E_2 = 0$ and $L_1 = 0$.

may further simplify Equation (20) by putting $R_2 = 0$ in the last term, which then becomes $1/L_2 C$. Equation (20) has the form

$$s^2 + 2\sigma s + (\omega^2 + \sigma^2) = 0 \tag{21}$$

or

$$s^2 + 2\zeta\omega_n s + \omega_n^2 = 0 \tag{22}$$

The undamped natural frequency is

$$\omega_n \cong \frac{1}{\sqrt{L_2 C}} \tag{23}$$

and the damping coefficient is

$$\sigma = \zeta\omega_n = \frac{1}{2}\left(\frac{R_2}{L_2} + \frac{1}{R_1 C}\right) \tag{24}$$

It is the average of two reciprocal time constants, the first of which, containing R_2, may be negative. For positive damping $\sigma > 0$; hence, if $R_2 < 0$,

$$R_1 < \frac{L_2}{(-R_2)C} \tag{25}$$

4 (a) Draw the schematic circuit of an analog computer for C.E.A control and explain with voltage waveform. [5] | CO3 | L2

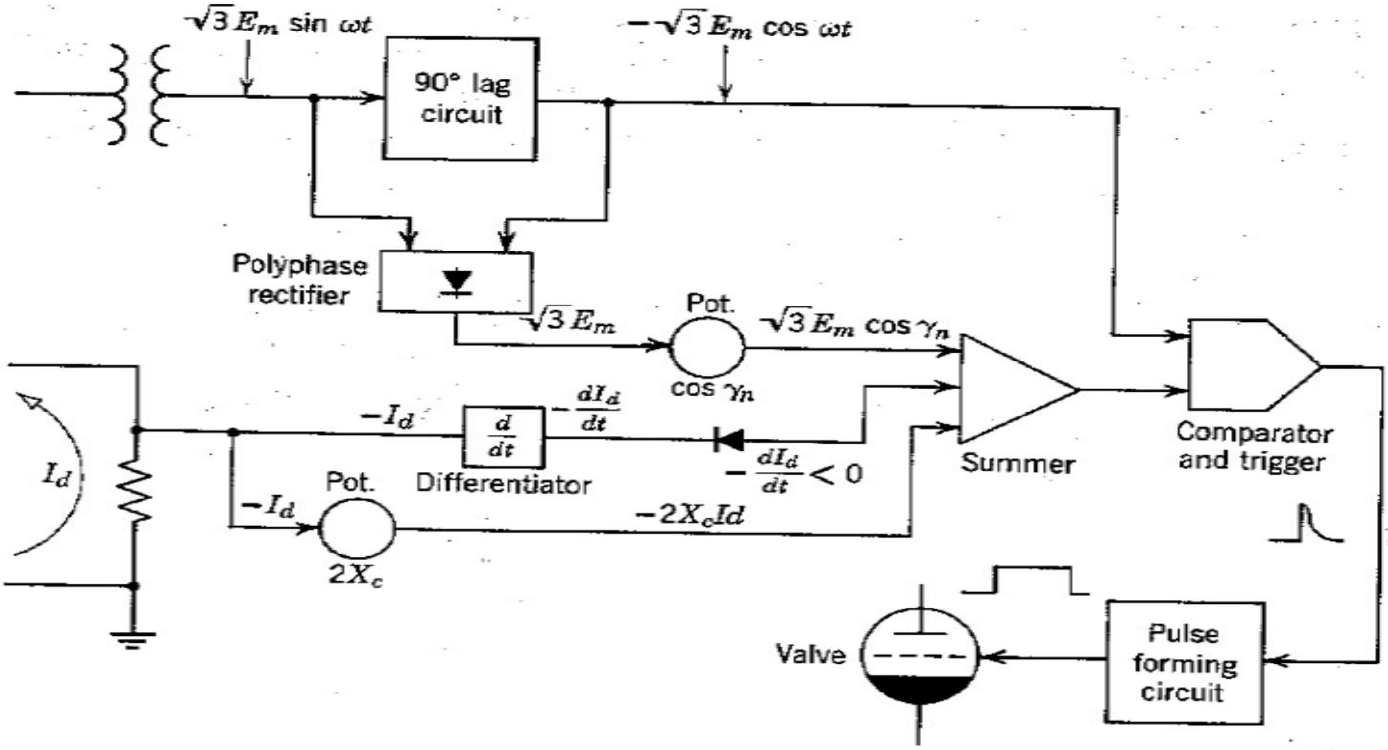


Fig. 11. Schematic circuit of analog computer for C.E.A. control. Pot., potentiometer. The signal dI_d/dt is explained in connection with Figure 15.

The relation among the five quantities (α, γ_n, E_m, I_d, and L_c) was derived in Chapter 3. It depends on the fact that the time integral of the commutation voltage is equal to the change of magnetic flux linkages produced. The latter is $-2L_cI_d$. The former is

$$\int_{t_1}^{t_2} e_{ba}\,dt = \sqrt{3}\,E_m \int_{t_1}^{t_2} \sin\omega t\,dt = \sqrt{3}\,E_m \left.\frac{-\cos\omega t}{\omega}\right]_{t_1}^{t_2}$$

$$= \frac{\sqrt{3}\,E_m}{\omega}(\cos\omega t_2 - \cos\omega t_1) \qquad (10)$$

$$-\sqrt{3}\,E_m \cos\omega t_1 = \sqrt{3}\,E_m \cos\gamma_n - 2X_cI_d \quad \text{volts}$$

The required ignition time t_1 can be found by a real-time analog computer functioning in accordance with Eq. (12) and shown in Figure 11. Each term of the equation is represented on a greatly reduced scale. One input signal is a voltage proportional to the direct current I_d in the main converter circuit. This can be realized by using the voltage across a shunt through which I_d or a known fraction of I_d passes. Another input voltage $\sqrt{3}\,E_m \cos \gamma_n$ is a direct voltage that is proportional both to the desired $\cos \gamma_n$ (a constant) and to the crest value of the commutation voltage. This signal may be derived from a direct voltage obtained by full-wave rectification of the single-phase commutation voltage for the valve in question. These two inputs are summed algebraically, and the sum is compared with the instantaneous value of the third input, which is an alternating voltage with a crest value proportional to

that of the commutation voltage and a phase 90° behind that voltage. When the two quantities become equal, a pulse is generated that initiates the grid pulse to ignite the valve in question. The quantities involved in the analog comparison are shown in Figure 12.

(b) Write a short note on constant minimum ignition angle control. [5] | CO3 | L2

The next step in our study of the control of a converter is to examine in more detail how each of the three straight-line segments of the combined characteristic (Figure 8) can be obtained.

1. Constant minimum ignition angle
2. Constant current
3. Constant minimum extinction angle

If the constant minimum ignition delay angle α_0 is to be zero, no special provision need be made for it because zero is inherently the minimum possible delay.

If, however, the use of multianode valves requires a greater minimum delay—for example, $\alpha_0 = 5°$—control is required. The following method could be used. The voltage across each valve is measured, and if it is less than a

specified value—for example, $\sqrt{3}\,V_m \sin 5°$—the constant-current control is prevented from igniting the valve. Since the purpose of the delay is to ensure a certain voltage across the valve before igniting it, the method is logical, although it allows some variation in α to opposite changes in magnitude V_m of alternating voltage.

In practice, the voltages across the valves would not be used, but rather the secondary voltages of a control transformer. In order to meet the requirements of other control circuits, these voltages must be sinusoidal (free of notches caused by commutation). The primary windings of the control transformer must be connected to the network side of the main converter transformer in order to obtain sinusoidal control voltages, and both transformers must be similarly connected—for example, in YΔ—so that the control voltages are in phase with the commutating voltages.

5 (a) Explain the limitations of manual control. | | L4

The direct voltage at either end of a transmission line can vary in a sudden, unexpected, and undesired manner because of short circuits or other disturbances on the ac systems or because of faults in the converters. It is then the responsibility of the rapid grid control to maintain or restore the desired conditions on the dc line as far as possible with the available range of control. This use of rapid, automatic control is more important than the effecting of a rapid change of conditions on the dc line.

The need for rapid, automatic control will be shown by first supposing that each converter has only manual control of the ignition angle. Viewing the transmission line from its midpoint, draw a graph of the characteristic curve of voltage at this point versus current for the converter and half line on each side (Figure 5). Both characteristics are straight lines. For the left-hand (rectifier) side, the intercept on the vertical axis is the internal voltage of the rectifier, $V_{d01} \cos \alpha$, and the slope is $-(R_{c1} + R_l/2)$. For the right-hand (inverter) side, the intercept is the internal voltage of the inverter, $V_{d02} \cos \beta$, and the slope is $+(R_{c2} + R_l/2)$. Since, at a given place and time, there can be only one value of voltage and one value of current and since both these values must conform to the characteristics of both converters, they must be given by the coordinates of the intersection of the two characteristic lines. Let the intercepts of the two lines be adjusted so that their intersection lies at rated current and voltage (I_{dn}, V_{dn}) at point N. The slopes of the lines have been drawn on the assumption that at rated current the voltage drop due to

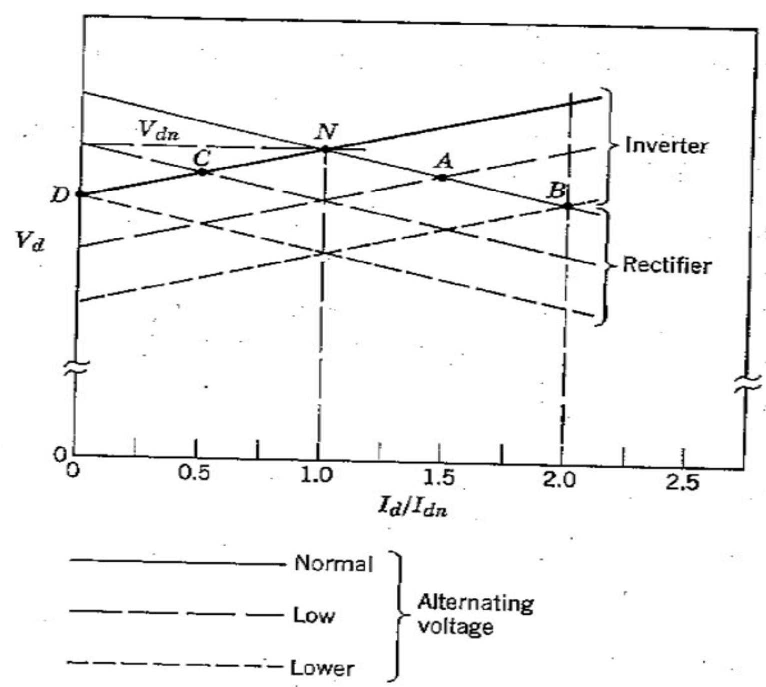


Fig. 5. Changes of direct current due to decreases of alternating voltage at either terminal of the dc line when both converters are operating at constant ignition angles.

commutation is 8% of rated voltage and the line drop is 9% of the same. $8 + 9/2 = 12.5\%$.

Now suppose that the alternating voltage at the inverter drops by 12.5% of V_{dn}. Then the inverter characteristic drops to that represented by the first parallel broken line below the solid line, and its intersection with the rectifier characteristic moves to point A, corresponding to $1.5I_{dn}$. A further 12.5% voltage drop increases the current to $2I_{dn}$ (point B). If the alternating voltage at the rectifier drops by 12.5% of V_{dn} while that of the inverter is normal, the rectifier characteristic drops to the first parallel broken line below the solid line, the intersection moves to point C, and the current drops to $0.5I_{dn}$. An additional 12.5% drop of alternating voltage lowers the characteristic to the second parallel broken line and moves the intersection to point D: the current becomes nil.

In this example, a dip in alternating voltage produces a percentage change in direct current of four times the percentage change of voltage. Such large fluctuations of current cannot be tolerated. The high overcurrents are especially undesirable, for they may lead to arcbacks of the rectifier (Section 6-3), commutation failures of the inverter (Section 6-5), and damage to the valves. The need for rapid control of current is indicated.

(b) Describe the constant current and constant voltage dc transmission systems. Compare them with respect to fault currents and energy loss. | CO5 | L5

5-5 CONSTANT CURRENT VERSUS CONSTANT VOLTAGE

Two obvious alternative ways of operating a dc transmission system while permitting control of transmitted power are the following:

1. Current held constant while voltage varies as the power does
2. Voltage held nearly constant while current varies as the power does

The same two methods could be used for ac transmission and distribution.

In the constant-current system, the various loads and one or more power sources are connected in series; a load or source is turned off by bypassing it after bringing its EMF to zero if it has one. This method has been widely used for street lighting circuits, and was used on several of the earlier dc transmission projects. In the constant-voltage system, the various loads and sources are connected in parallel; a load or source is taken out of service by opening the respective branch. This system is in general use in ac transmission and distribution systems and dc distribution systems.

In a HV dc transmission system having only two terminals (none to date have had more), the distinction between series and parallel connection of the two converters (rectifier and inverter) disappears. The choice between constant current and constant voltage must be made on other grounds. The chief differences concern the following:

1. The limitation of variation of current caused by variation of alternating voltage or by faults on the dc line or in the converters
2. The energy losses and efficiency

It is well known that short-circuit currents on a constant-voltage ac system can be very great although limited by system impedance, of which reactance is the major component. On a constant-voltage dc system, fault currents could conceivably be much greater, being limited only by circuit resistance. On a constant-current system, however, short-circuit currents are ideally limited to the value of the load current and in practice to about twice rated current. Accidental open circuits could give rise to high voltages, but in practice open-circuit faults are much rarer than short-circuit faults.

In a constant-voltage system the I^2R loss in the conductors is proportional to the square of the power transmitted; in a constant-current system, this loss always has its full-load value. If the system transmits less than rated power some of the time, as is true in nearly all transmission systems, the daily or annual energy loss is much less in a constant-voltage system than in a constant-current system. The opposite is true of those losses depending on voltage, such as corona loss and losses in insulation leakage. In practice, however, the voltage-dependent losses are always much less than the current-dependent losses.

Thus, consideration of losses favors the constant-voltage system, but limitation of current favors the constant-current system. In the past there was some uncertainty as to the choice, with the earlier dc projects using constant current. Now, however, it is possible by the use of automatic control to combine the best features of each.

6	Write a short note on			
(a)	Critical grid voltage	[5]	CO3	L2
(b)	Grid bias and blocking	[5]	CO3	L2

Critical Grid Voltage. The critical grid voltage is that which separates grid voltages which permit ignition from those which block ignition. The critical grid voltage varies oppositely from the anode voltage and is roughly proportional to it (Figure 1), but the exact value varies somewhat with temperature and vapor pressure in the valve. In addition, it depends on the geometry of the valve.

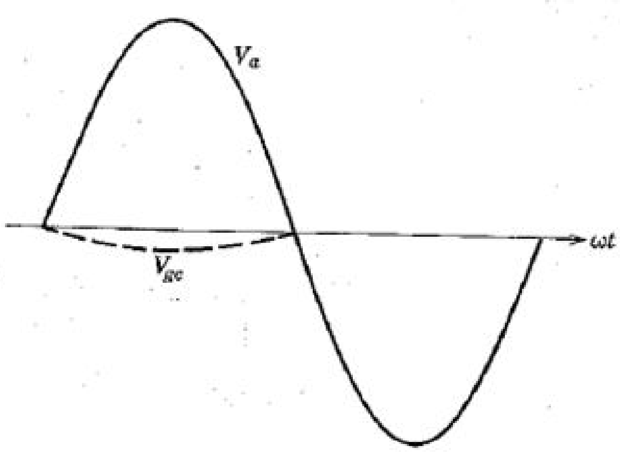


Fig. 1. Anode voltage V_a and corresponding critical grid voltage V_{gc} during a cycle.

Grid Bias and Blocking

A constant negative bias voltage of a few hundred volts is applied to the control grids of all valves continuously. When a valve is supposed to conduct, a positive pulse is added to this negative bias. The height of the grid pulses is more than enough to overcome the bias.

If, for clearing a fault in a converter bridge, it becomes necessary to block all the main valves of the bridge, the transmission of positive pulses to all their grids is interrupted, letting the negative bias remain on the grids.

7 (a) Discus the 'actual control characteristics' of control scheme. In this context, explain the significance of 'current margin' and its range. [10] | CO3 | L4

5-7 ACTUAL CONTROL CHARACTERISTICS

Individual Characteristics of Rectifier and Inverter

These are plotted in rectangular coordinates of direct current I_d and direct voltage V_d at some common point, say, at the sending end of the dc line. Let the rectifier be equipped with a constant-current regulator. If this regulator functions ideally, the rectifier characteristic is a vertical line (*AB* in Figure 6). In practice it is not quite vertical but does have a high negative slope. Let the inverter be equipped with a C.E.A. regulator. Then the inverter characteristic is a line given by

$$V_d = V_{d02} \cos \gamma + (R_l - R_{c2})I_d \tag{4}$$

On the assumption that the commutation resistance R_{c2} is somewhat greater than the line resistance R_l, this line (*CD* in Figure 6) has a small negative slope.

Since at the common point there can be only one voltage and one current, their values must be given by the coordinates of the intersection of the rectifier and inverter characteristics (*E*).

Both characteristic lines can be shifted. The rectifier characteristic can be shifted horizontally by adjusting the *current command* (*order* or *setting*), which is one of the inputs to the current regulator, the other being the measured current. If the measured current is less than the current command, the regulator advances the firing time (decreases the delay angle α), thus raising the rectifier internal voltage in proportion to $\cos \alpha$ and thus raising I_d—see Eq. (1). If the opposite is true, it increases α, thus decreasing $\cos \alpha$ and I_d. The inverter characteristic can be raised or lowered by means of the tap changer on the transformer at the inverter station, which varies the alternating voltage on the valve side. As soon as the tap changer is moved each step, the C.E.A. regulator very quickly restores the desired value of γ. The internal direct voltage at the inverter is changed in proportion to the alternating voltage, since $\cos \gamma$ is constant, and this tends to change the direct current, which, however, is quickly restored to the set value by the current regulator at the

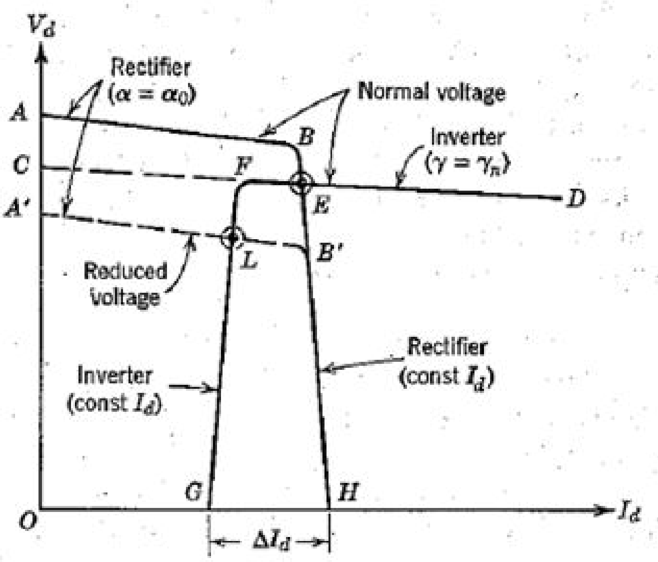


Fig. 7. Actual characteristics of control scheme.

8 (a) Explain the individual characteristics of a rectifier and an inverter with neat sketches. [5] | CO3 | L2

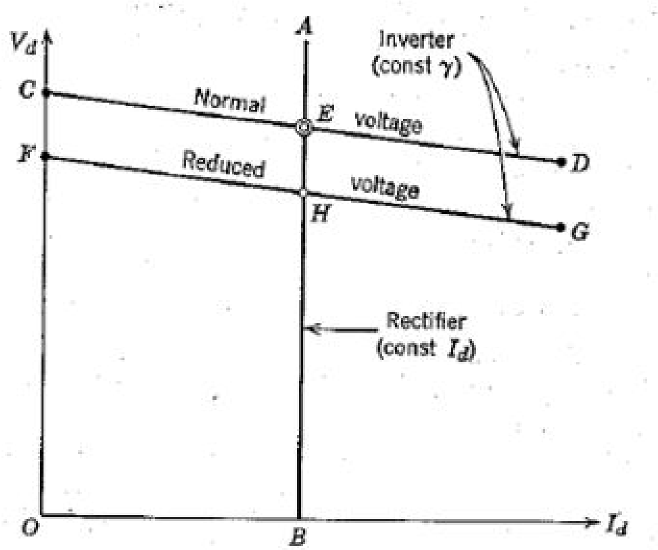


Fig. 6. Characteristics of control scheme—first step of explanation.

Individual Characteristics of Rectifier and Inverter

These are plotted in rectangular coordinates of direct current I_d and direct voltage V_d at some common point, say, at the sending end of the dc line. Let the rectifier be equipped with a constant-current regulator. If this regulator functions ideally, the rectifier characteristic is a vertical line (*AB* in Figure 6). In practice it is not quite vertical but does have a high negative slope. Let the inverter be equipped with a C.E.A. regulator. Then the inverter characteristic is a line given by

$$V_d = V_{d02} \cos \gamma + (R_l - R_{c2})I_d \quad (4)$$

On the assumption that the commutation resistance R_{c2} is somewhat greater than the line resistance R_l, this line (*CD* in Figure 6) has a small negative slope.

Since at the common point there can be only one voltage and one current, their values must be given by the coordinates of the intersection of the rectifier and inverter characteristics (*E*).

Both characteristic lines can be shifted. The rectifier characteristic can be shifted horizontally by adjusting the *current command* (*order* or *setting*), which is one of the inputs to the current regulator, the other being the measured current. If the measured current is less than the current command, the regulator advances the firing time (decreases the delay angle α), thus raising the rectifier internal voltage in proportion to $\cos \alpha$ and thus raising I_d—see Eq. (1). If the opposite is true, it increases α, thus decreasing $\cos \alpha$ and I_d. The inverter characteristic can be raised or lowered by means of the tap changer on the transformer at the inverter station, which varies the alternating voltage on the valve side. As soon as the tap changer is moved each step, the C.E.A. regulator very quickly restores the desired value of γ. The internal direct voltage at the inverter is changed in proportion to the alternating voltage, since $\cos \gamma$ is constant, and this tends to change the direct current, which, however, is quickly restored to the set value by the current regulator at the

(b) Draw the schematic circuit of analog computer for constant current control and explain. [5] | CO3 | L2 |

If the measured current in a rectifier is less than the set current, α must be decreased in order to increase $\cos \alpha$ and thus raise the internal voltage of the rectifier $V_{d0} \cos \alpha$. The difference between the internal voltages of the rectifier and the inverter is thereby increased, and the direct current is increased proportionally—see Eq. (1). If the measured current exceeds the set current, α must be increased instead of decreased, and all the quantities mentioned above are changed in the opposite sense.

In the inverter, if the measured current is too low, the internal voltage must be decreased instead of being increased as in the rectifier in order to increase the difference of internal voltages. This refers, however, to the absolute value of the inverter voltage. If we consider the inverter voltage to be negative, which is usual if the same converter sometimes rectifies and at other times inverts, the algebraic value of inverter voltage must be increased, as in a rectifier; and to accomplish this, α must be decreased, as in a rectifier. The curve of cos α versus α in the range from 0 to π is monotonic (Figure 9); anywhere in this range, a decrease of α increases the algebraic internal voltage V_{d0} cos α. This means that the same constant-current controller can be used on a given converter without change of connections during both rectification and inversion. (In practice, however, the same current setting is transmitted to both terminals of a dc line, and the current margin is subtracted from the current setting of the inverter; that is, the error signal for the inverter's current regulator is $\varepsilon = I_{ds} - \Delta I_d - I_d$.) This prevents the current regulators at both terminals from functioning simultaneously.

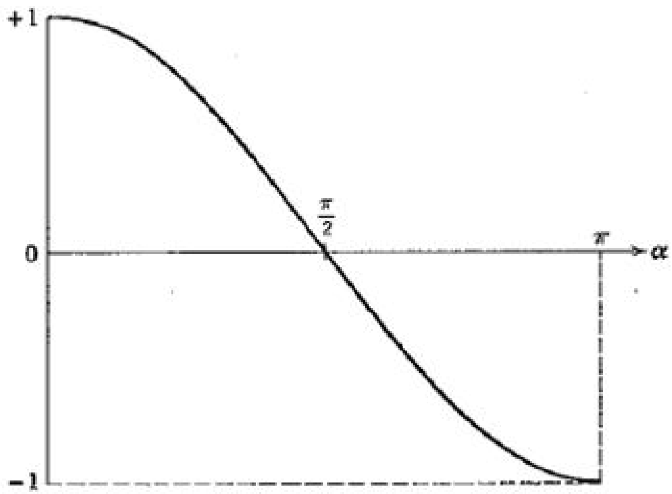


Fig. 9. Curve of cos α versus α.

The current regulator (Figure 10) is a simple kind of feedback amplifier characterized by a gain and a time constant. Its differential equation is

$$v + T\frac{dv}{dt} = K\varepsilon \tag{6}$$

where v = instantaneous value of V_{d0} cos α
$T = R_2C$ = time constant
K = gain of amplifier and phase-shift circuit
ε = error signal

The corresponding transfer function is

$$\frac{v}{\varepsilon} = \frac{K}{Ts + 1} \tag{7}$$

where s is the variable of the Laplace transform. In practice, the transfer function may be more complicated than that of Eq. (7).

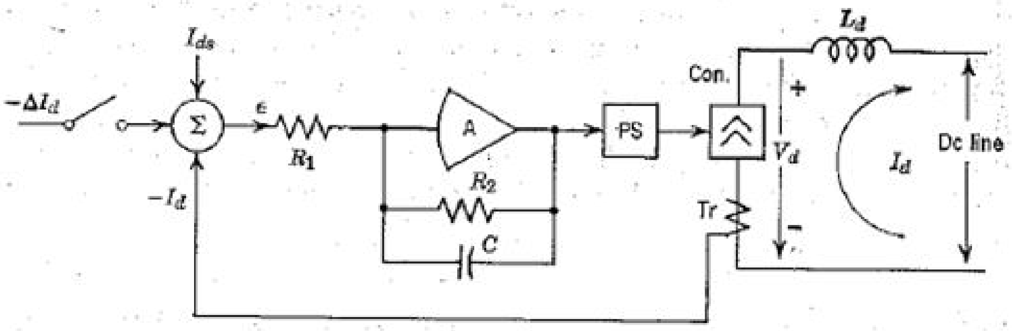


Fig. 10. Schematic diagram of constant-current regulator: I_{ds}, current command signal; ΔI_d, current margin signal; I_d, line current and signal; R_1, input resistor; R_2, feedback resistor; C, feedback capacitor; A, high-gain amplifier; PS, phase-shift circuit; Con., converter; V_d, direct voltage of converter; L_d, dc reactor; Tr, dc current transformer; Σ, summer; ε, error signal.

The slope of the "constant-current" segment in the V_d, I_d plane in the steady state may be found by putting into Eq. (7) $s = 0$, $v = V_d + R_c I_d$, and $\varepsilon = I_{ds} - I_d$ and then taking the derivative

$$\frac{dV_d}{dI_d} = -(K + R_c) \tag{8}$$

Usually $K \gg R_c$. In order to obtain a true constant-current characteristic, represented by a vertical line, the gain K of this kind of regulator would have to be infinite. As shown in Section 5-11, however, the gain cannot be made too great without producing instability.

Only one current regulator per pole per terminal is required: it can control all the valves in the several bridges. In bipolar schemes, the current regulators of the two poles are normally given equal settings, so that the neutral current is small if both poles are in operation. Where ground-return current is objectionable, the neutral current can put an additional signal into the regulators in the proper sense to better equalize the currents of the two poles.