

TECHNICAL REPORT



Guidelines for parameters measurement of HVDC transmission line

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IEC Secretariat
3, rue de Varembe
CH-1211 Geneva 20
Switzerland

Tel.: +41 22 919 02 11
info@iec.ch
www.iec.ch

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TECHNICAL REPORT



Guidelines for parameters measurement of HVDC transmission line

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

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**GUIDELINES FOR PARAMETERS MEASUREMENT OF
HVDC TRANSMISSION LINE**

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The text of this Technical Report is based on the following documents:

Draft	Report on voting
115/374/DTR	115/386/RVDTR

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this Technical Report is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/publications.

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INTRODUCTION

The development of global clean energy exacerbates uneven distributions of electrical energy, which intensifies the demand for HVDC transmission techniques as a high-efficiency long-distance transmission solution of the energy. Parameters of DC lines (e.g. overhead lines, cables, or their combination) are essential in modelling transmission lines in computations, of which the accuracy greatly affects the analysis results of the DC transmission system and the correctness of determining operating strategies. However, the parameters of DC lines are sensitive to the geological structures, weather characteristics along the transmission corridors, earthing modes and other uncertainties, which make the theoretical values of parameters invalid. Thus, on-site measurement is important.

The parameter testing of DC lines is generally carried out after the construction or renovation of DC projects. The measured parameters of DC transmission lines are important for several applications, mainly including DC transmission system steady-state calculation, transient calculation, fault analysis, electromagnetic environment calculation, construction quality assessment after newly launched HVDC project or renovation, etc. The test results of line parameters can be used to verify whether the actual parameters meet the requirements of engineering design. In steady-state calculation, DC resistance is generally used for power flow computation, voltage drop computation, and resistance loss computation under different operating modes. In transient calculation, the resistance, capacitance, inductance of the DC line in per-unit length and its frequency characteristics are essential in performing the over-voltage calculations under lightning strike, operation, fault, and other working conditions. In electromagnetic environment calculation, the capacitance analysis of the DC line is the prerequisite for the calculations of the surface electric field for the wire, the nominal electric field and ion flow electric field generated by the DC line in the surrounding space, which further give the important performance data of the DC line, including audible noise, radio interference, corona loss, etc.

Based on the accurate descriptions of DC line parameters, considering the actual needs of the above applications, the main DC line parameters described in this document are the DC resistance and frequency characteristics. Frequency characteristics refer to the response of line resistance per unit length, inductance, and capacitance as well as the necessary coupling capacitance and inductance under different frequencies.

This document introduces measurement specification, including measurement conditions, safety precautions, measurement instruments, measurement methods, etc., in order to measure the parameters of HVDC overhead transmission line and cable with a DC voltage level above 100 kV.

GUIDELINES FOR PARAMETERS MEASUREMENT OF HVDC TRANSMISSION LINE

1 Scope

This document gives information relevant to the on-site HVDC transmission line parameter measurement. HVDC transmission line can be overhead lines, land or submarine cables, or hybrid lines with overhead line section(s) and cable section(s) (or any combination of these).

This document is also relevant to line parameter measurement of earth electrode lines in HVDC power transmission systems.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

- IEC Electropedia: available at <https://www.electropedia.org/>
- ISO Online browsing platform: available at <https://www.iso.org/obp>

3.1

source terminal

terminal of a transmission line, at which a power source is applied for the parameter measurement

[SOURCE: IEC TR 63042-303:2021, 3.2]

3.2

ending terminal

terminal opposite to the source terminal of a transmission line

[SOURCE: IEC TR 63042-303:2021, 3.3]

3.3

parameter in unit length

resistance, inductance, and capacitance per unit length of HVDC transmission line. A length of 1 km is adopted as the unit length of a transmission line

3.4

frequency characteristics

parameters in unit length changing with different signal frequencies

**3.5
induced voltage**

voltage caused by electromagnetic or electrostatic effect of adjacent energized lines or equipment

[SOURCE: IEC TR 63042-303:2021, 3.7]

**3.6
induced current**

electric current resulting from the displacement of charge carriers due to an induced voltage

[SOURCE: IEC 60050-121:2008, 121-11-29]

**3.7
differential mode measurement**

applying two-phase signals with equal amplitude and opposite phase into bipolar line to measure the parameters of HVDC transmission line

**3.8
common mode measurement**

applying single-phase signal into bipolar line to measure the parameters of HVDC transmission line

**3.9
differential mode short-circuit impedance**

input complex impedance of the measured line with the ending terminal short-circuited in differential mode measurement

**3.10
differential mode open-circuit impedance**

input complex impedance of the measured line with ending terminal open-circuited in differential mode measurement

**3.11
common mode short-circuit impedance**

input complex impedance of the measured line with the ending terminal short-circuited in common mode measurement

**3.12
common mode open-circuit impedance**

input complex impedance of the measured line with the ending terminal open-circuited in common mode measurement

**3.13
signal connecting line**

test wire connecting the measured line with test equipment and earthing devices

4 General**4.1 Background**

The theoretical parameters of DC transmission lines can be invalidated by the varieties of soil resistivity and tower configurations caused by various terrains that DC transmission lines pass through, including mountains, rivers, plains, etc. Therefore, it is essential to obtain accurate parameters of DC lines through on-site measurement. To ensure the smooth progress of on-site measurement works and the accuracy of measurement results, this document has been prepared to clearly introduce the measuring items, measuring methods, measuring tools, measuring processes, and safety precautions.

4.2 Measurement items

- Induced voltage and induced current
- Insulation resistance
- Polarity verification
- DC resistance
- Frequency characteristics

4.3 Measurement conditions

- 1) Dismantle all temporary earthing wires along the line.
- 2) Nobody works on the line.
- 3) Isolate the line from the reactors, capacitors, voltage dividers and other equipment.
- 4) The parameters of overhead line and cable are measured separately in case of hybrid transmission line.
- 5) Earthing grid of the converter station is available to offer the earthing point for the measurement. The earthing device can be artificially set to provide a potential reference point for measurements when the test is done remotely.
- 6) Technically eliminate the effect of the resistance of the signal connecting line from the measured result when measuring the DC resistance.
- 7) Record the earthing status of adjacent transmission lines, as they can affect the result of the measurement.

4.4 Safety precautions

- 1) It is important to take anti-interference measures to reduce the induced voltage or induced current, thus improving the safety of personnel or equipment. See Annex A for details.
- 2) Keep the line earthed when dismantling or assembling the test wires and use the earthing switch to short-circuit the ending terminal of the line.
- 3) Reliably connect the signal line, earthing wire and other wires. Keep the test wires sufficiently insulated to withstand test voltage and induced voltage.
- 4) Postpone the measurement if there are unfavourable weather conditions, such as thunderstorm, rain, snow, etc. Environmental data, such as temperature, humidity, and atmospheric pressure, also need to be recorded.
- 5) To protect the personnel and equipment from the lightning strike imposed on the measured line during the measurement, a safety spark gap is used between the signal line and earthing wire.
- 6) Use insulating gloves, insulating boots, insulating mat and other protective equipment to protect test personnel.

4.5 Measurement instruments

- 1) Before the measurement, the induced voltage and current can be estimated by the simulation calculation, in order to help select a suitable range of the voltmeters and ammeters.
- 2) The resistance-capacitance divider is used when testing the induced voltage.
- 3) A megohmmeter with a source voltage of higher than 5 kV is used in testing the insulation resistance.
- 4) The uncertainty of the DC resistance device is 0,5 % or lower, which can be determined based on the method of IEC Guide 115:2023.
- 5) The frequency range of the test power supply used for measuring the frequency characteristics covers the interval of 30 Hz to 2 500 Hz. In order to improve measurement accuracy, the measurement frequency points can avoid the inherent resonant frequency of the measured line. The voltage output of the test power supply is not less than 300 V and the current output is not less than 3 A.

- 6) The uncertainty of the Hall transducer (HT) is 1 % or lower, which can be determined based on the method of IEC Guide 115:2023. The frequency range of the current transformer (CT) covers the interval of 30 Hz to 2 500 Hz.
- 7) The uncertainty of the potential transformer (PT) is 0,5 % or lower, which can be determined based on the method of IEC Guide 115:2023. The frequency range of the PT covers the interval of 30 Hz to 2 500 Hz.

5 Induced voltage and induced current measurement

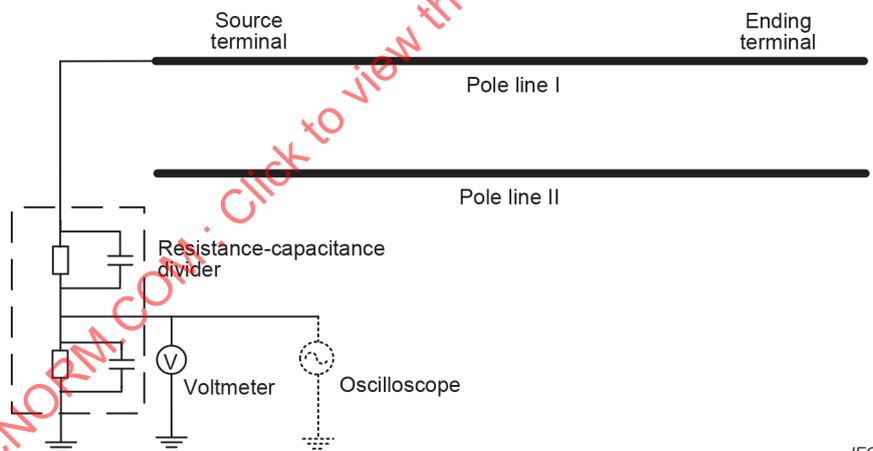
5.1 General

For the safety considerations, the induced voltage is first measured before line parameters measurements. The induced voltage and current are mainly caused by adjacent live AC/DC lines, of which the amplitude and frequency are comprehensively determined by the electrical geometric parameters of adjacent lines, weather conditions, geomagnetic storms, etc. Thus, it is difficult to accurately determine the induced voltage and current by theoretical calculations, which necessitates the on-site measurements. These measurements will form the basis for the succeeding works regarding anti-interference and safety.

Owing to the fact that the potential induced voltage might be beyond several tens of kV, the range of the measuring device would typically be in the range of 100 kV.

5.2 Induced voltage measurement

The induced voltage measurement is conducted at two pole lines separately. As shown in Figure 1, the measurement is performed at the source terminal by a resistance-capacitance divider and a voltmeter or an oscilloscope, with the ending terminal remaining open.



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Figure 1 – Induced voltage test with the ending terminal open-circuited

Afterwards, the measurement is performed at the source terminal with the ending terminals of two pole lines shorted and earthed, as shown in Figure 2. The induced voltage of pole line I and pole line II are measured and recorded in the same way as mentioned above.

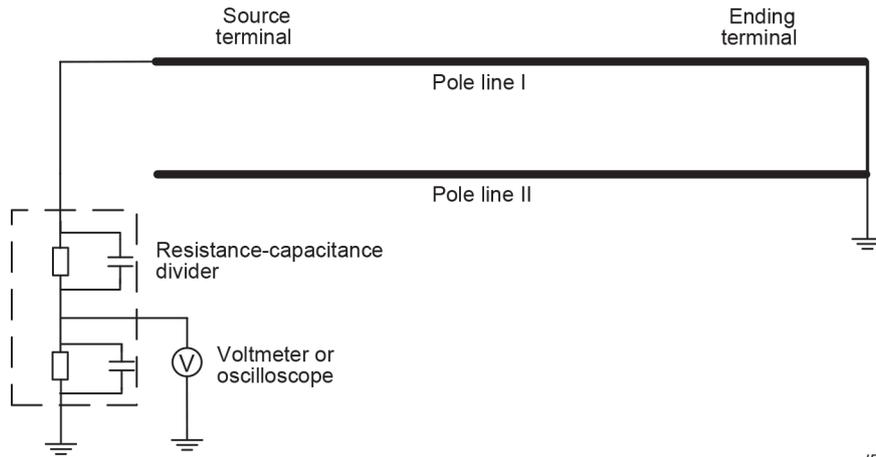


Figure 2 – Induced voltage test with the ending terminal short-circuited

5.3 Induced current measurement

The induced current is measured at the source terminal with ending terminal shorted and earthed as shown in Figure 3. The ammeter or the oscilloscope can be used to measure and record the induced current.

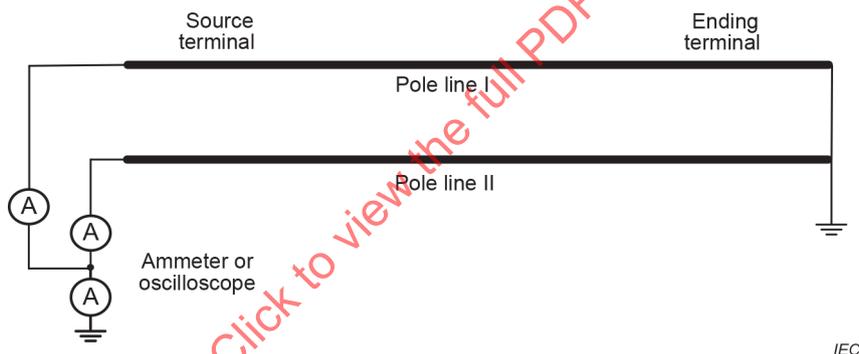


Figure 3 –Induced current test

6 Insulation resistance measurement

The insulation resistance measurement is conducted to verify the insulation condition of insulators along the line.

As shown in Figure 4, by keeping both terminals of pole line II earthed and the ending terminal of pole line I open-circuited, the open-circuited insulation resistance R_{10} of pole line I is measured by a megohmmeter at the source terminal of pole line I. The same method is performed for measuring the open-circuited insulation resistance of pole line II.

In practical measurements, the method of increasing the signal-to-noise of testing equipment is applied accordingly to reduce the effects of the interference. It is a general practice of using a megohmmeter greater than 5 000 V.

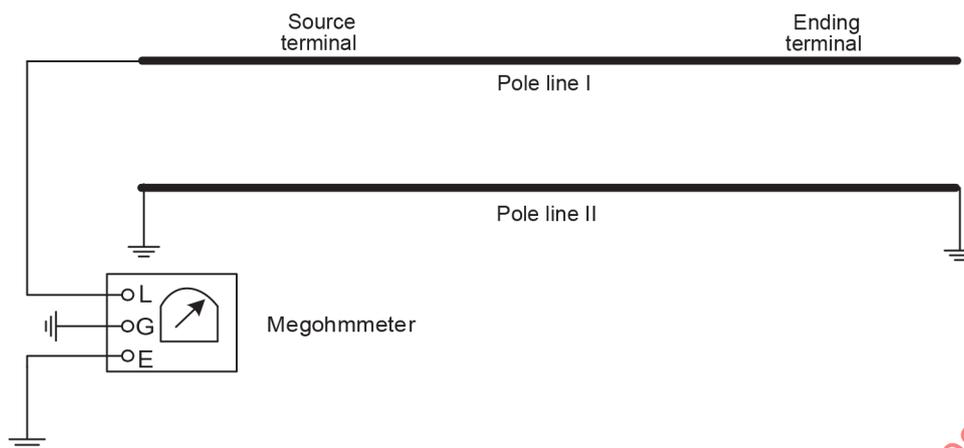


Figure 4 – Insulation resistance test of pole line I

7 Polarity verification

7.1 Polarity verification method using megohmmeter

Polarity verification is conducted to verify whether the polarity labels of positive and negative pole lines are matched at both terminals, which can be accomplished by the insulation resistance test.

By earthing both terminals of pole line II and the ending terminal of pole line I, the short-circuited insulation resistance R_{1s} of pole line I is measured with a megohmmeter at the source terminal of pole line I, as shown in Figure 5.

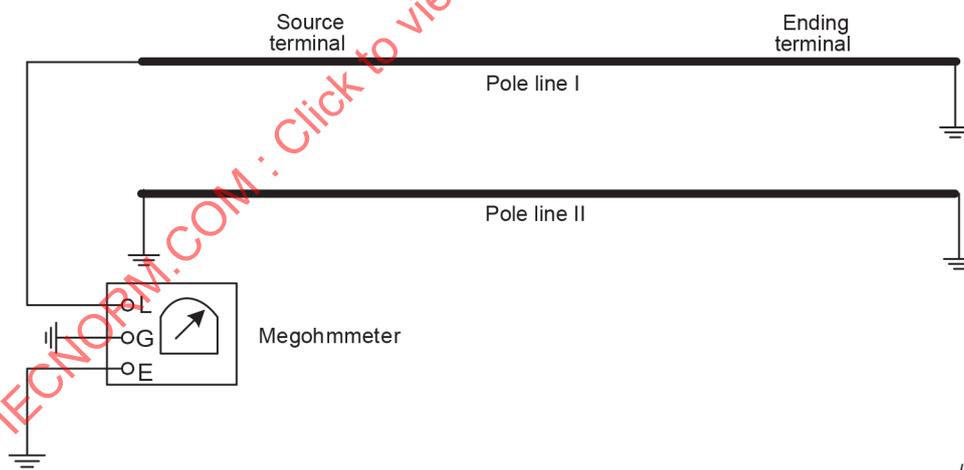


Figure 5 – Polarity verification of pole line I

- If R_{1o} gradually reaches a steady value, and R_{1s} reaches zero, the polarity of the pole line I is correct, and the insulation resistance value of pole line I is R_{1o} .
- If R_{1s} gradually reaches a constant value that is approximately equal to R_{1o} , the pole line I has a disconnection point.
- If $R_{1o} \approx R_{1s} \approx 0$, pole line I has an earthing point, and pole line I might be incorrectly identified in polarity or there might be a joint point between pole line I and pole line II.
- Repeat the test procedures specified above. The polarity of pole II is verified with the same method used for pole line I.

7.2 Polarity verification method using a battery

If the induced voltage is higher than the withstand voltage of the megohmmeter, using a battery is preferred for polarity verification.

As shown in Figure 6, by earthing both terminals of pole II and the ending terminal of pole I and installing a battery or batteries at the source terminal of pole line I, current I_1 is recorded. Afterwards, disconnect the ending terminal of pole I and record current I_2 .

The polarity of pole I is verified as follows:

- If $I_1 \neq 0$ and $I_2 \approx 0$, the polarity of pole I is correct;
- If $I_1 \approx I_2 \neq 0$, the polarity of pole I is incorrect. There can be one or more earthing points along pole line I. Otherwise, there can be one or more connection points between pole line I and pole line II;
- If $I_1 \approx I_2 \approx 0$, there can be one or more breaking points along pole I.

Repeat the test procedures specified above. The polarity of pole II can be verified with the same method used for pole line I.

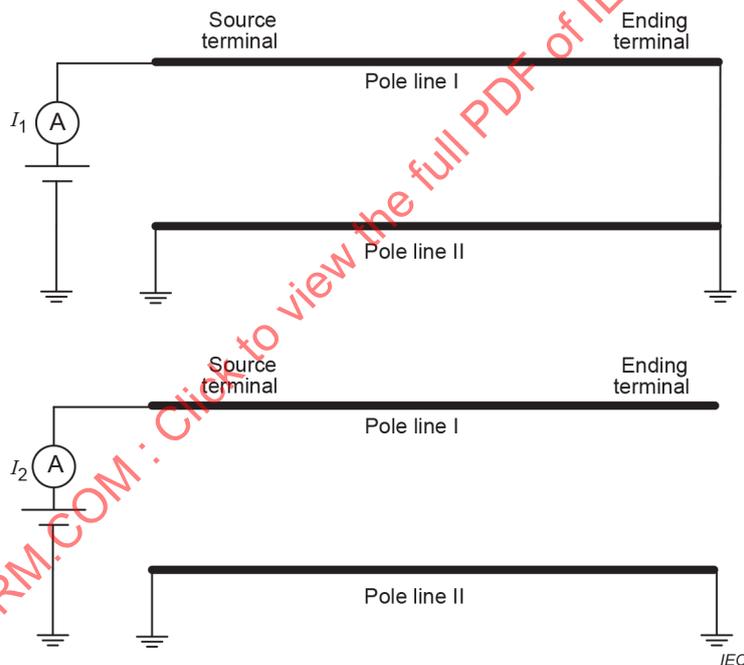


Figure 6 – Polarity verification for pole I using battery

If some faults, such as earthing faults and open-circuit faults, are found during the test process, measures are taken first to locate and remove the faults. The methods for locating faults are specified in Annex B.

8 Measurement of DC resistance

The DC resistance of the HVDC transmission line can be measured by the method in accordance with IEC 60468:1974. As shown in Figure 7, DC voltage U_{dc} and current I_{dc} are measured by earthing the ending terminal of pole line I and pole line II and installing a DC power source in series to pole line I and pole line II at source terminal.

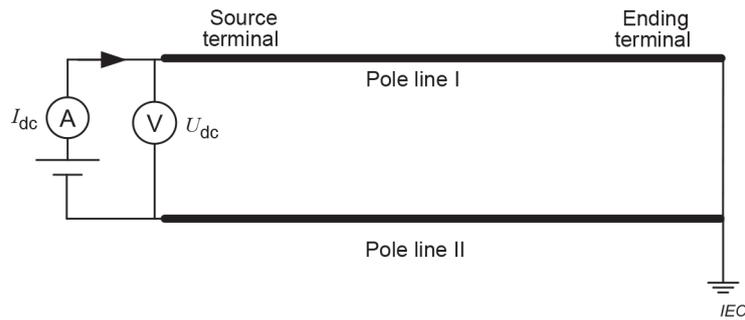


Figure 7 – Measurement of DC resistance

For the pole line I and pole II that are installed in parallel on the same tower, the DC resistance of two pole lines is approximately equal, where the value can be given by Formula (1).

$$R_l \approx R_{II} = \frac{U_{dc}}{2I_{dc}} \quad (1)$$

where

R_l is the DC resistance of pole line I;

R_{II} is the DC resistance of pole line II.

Taking the dedicated metallic return into account, the measurement of DC resistance is schematically illustrated in Figure 8. By shorting and earthing the ending terminals of pole line I, pole line II and the metallic return, and installing a DC power source between pole line I and the metallic return at source terminal, the DC voltage U_{1m} and the DC current I_{1m} between pole line I and the metallic return are measured.

The same measurement configuration is repeated to the other two ports at the source terminal (i.e. pole line II and metallic return line, pole line I and pole line II), measurements of the DC voltage U_{2m} , U_{12} and the DC current I_{2m} , I_{12} can be accomplished.

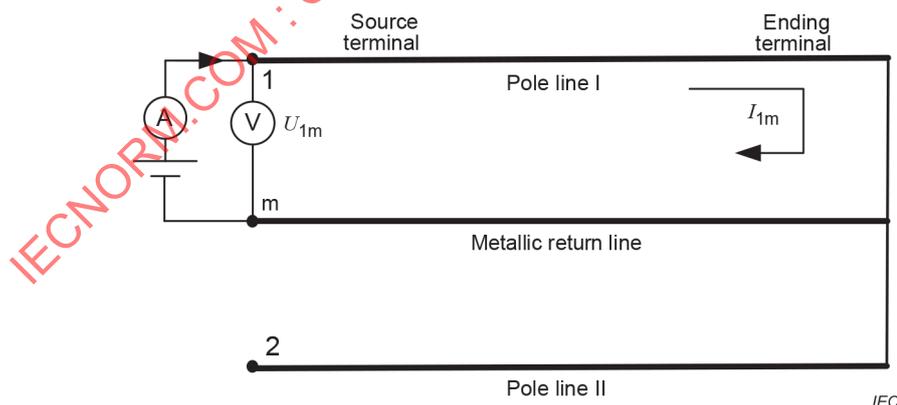


Figure 8 – Measurement of DC resistance with dedicated metallic return

The DC resistance of each line is then given by Formula (2), Formula (3), and Formula (4), respectively.

$$R_l = \left(\frac{U_{1m}}{I_{1m}} + \frac{U_{12}}{I_{12}} - \frac{U_{2m}}{I_{2m}} \right) / 2 \quad (2)$$

$$R_2 = \left(\frac{U_{12}}{I_{12}} + \frac{U_{2m}}{I_{2m}} - \frac{U_{1m}}{I_{1m}} \right) / 2 \quad (3)$$

$$R_m = \left(\frac{U_{1m}}{I_{1m}} + \frac{U_{2m}}{I_{2m}} - \frac{U_{12}}{I_{12}} \right) / 2 \quad (4)$$

where

R_1 is the DC resistance of pole line I;

R_2 is the DC resistance of pole line II;

R_m is the DC resistance of the metallic return.

An HVDC transmission line is generally hundreds or thousands of kilometres in length, and the temperature distribution along the line has an obvious impact on the measurement results. The standardized result is identified as the value converted to the temperature of 20 °C. The average temperature of the line can be determined by recording the temperature distribution, which enables the conversion to 20 °C by Formula (5).

$$R_{20} = \frac{R}{1 + (t - 20)\beta} \quad (5)$$

where

R_{20} is the DC resistance of measured line at 20 °C;

β is resistance temperature rise coefficient of the corresponding material of the measured line, with the unit of $1/^\circ\text{C}$; for example, for aluminium, $\beta = 0,004\ 3$ ($1/^\circ\text{C}$), and for copper, $\beta = 0,003\ 9$ ($1/^\circ\text{C}$);

t is the average temperature along the line, with the unit of °C;

R is the DC resistance of measured line at average temperature t .

9 Measurement of frequency characteristics of HVDC transmission line

9.1 General

Considering the existence of harmonics in an HVDC transmission system, parameter measurement of HVDC lines accordingly covers a frequency range up to the 50th harmonic even though there is a negligible magnitude of the harmonics above the 50th in an LCC-HVDC system. For the VSC-HVDC system, where harmonics above the 50th are possibly caused by resonance, parameter measurement of HVDC lines can be conducted at the frequencies subject to the availability of test power source.

The parameters at any selected frequency f are measured by following the procedures given in 9.2 to 9.4

9.2 Differential mode measurement

9.2.1 Measuring the differential mode short-circuit impedance

As shown in Figure 9, the ending terminal of pole line I and pole line II are shorted, and a two-phase symmetrical power source with the frequency of f and phase difference of 180° is installed between pole line I and pole line II at the source terminal, which enables the measurements of two-phase voltage $U_{s,f} = [\dot{U}_{I_{s,f}}, \dot{U}_{II_{s,f}}]$ and current $I_{s,f} = [\dot{I}_{I_{s,f}}, \dot{I}_{II_{s,f}}]$ at the source terminal.

9.2.2 Measuring the differential mode open-circuit impedance

As shown in Figure 10, under the same measurement configuration shown in Figure 9, after disconnecting the ending terminal of pole line I and pole line II, the voltage $U_{o,f} = [\dot{U}_{I_{o,f}}, \dot{U}_{II_{o,f}}]$ and current $I_{o,f} = [\dot{I}_{I_{o,f}}, \dot{I}_{II_{o,f}}]$ are measured.

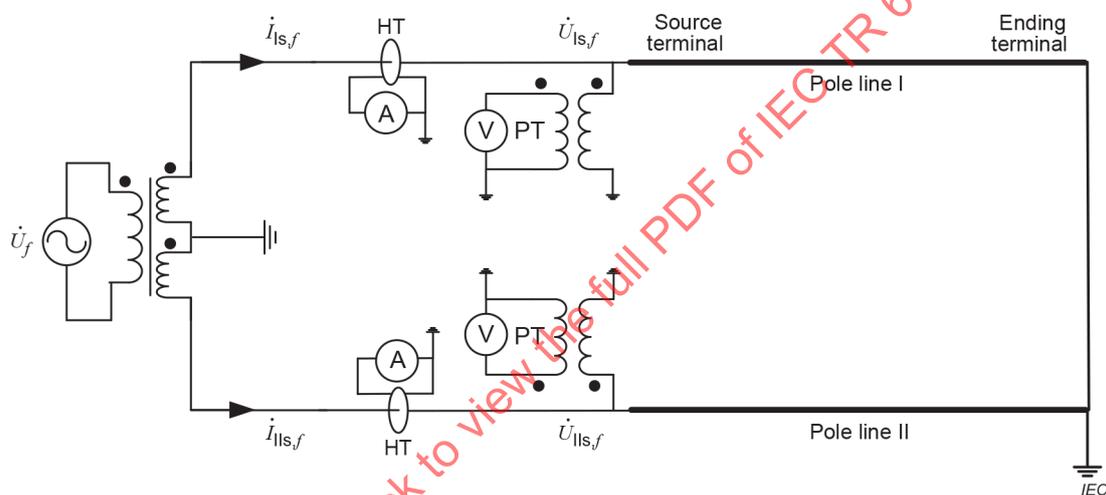


Figure 9 – Measurement of differential mode short-circuit impedance

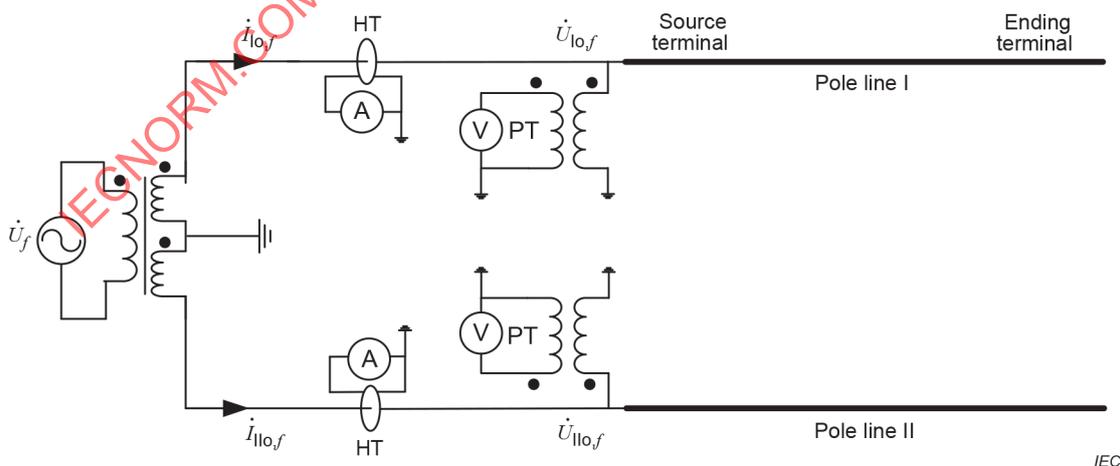


Figure 10 – Measurement of differential mode open-circuit impedance

9.2.3 Calculating the frequency characteristics of differential mode parameters

For selected frequency f , the resistance r_1 , inductance l_1 , capacitance c_1 in unit length of HVDC transmission line at differential mode are given by Formula (6) to Formula (12).

$$Z_{s1} = \frac{bU_{s,f}^T}{bI_{s,f}^T} \quad (6)$$

$$Z_{o1} = \frac{bU_{o,f}^T}{bI_{o,f}^T} \quad (7)$$

$$Z_{c1} = \sqrt{Z_{o1}Z_{s1}} \quad (8)$$

$$\gamma_1 = \frac{1}{L} \operatorname{arccoth}(Z_{s1}/Z_{c1}) \quad (9)$$

$$r_1 = \operatorname{Re}(\gamma_1 Z_{c1}) \quad (10)$$

$$l_1 = \frac{\operatorname{Im}(\gamma_1 Z_{c1})}{2\pi f} \quad (11)$$

$$c_1 = \frac{\operatorname{Im}(\gamma_1)}{2\pi f Z_{c1}} \quad (12)$$

where

b is the matrix of $\begin{bmatrix} 1 & 1 \\ 2 & -2 \end{bmatrix}$;

Z_{s1} is the short circuit impedance at differential mode;

Z_{o1} is the open circuit impedance at differential mode;

Z_{c1} is the characteristic impedance at differential mode;

γ_1 is the transmission constant at differential mode;

L is the length of measured line.

9.3 Common mode measurement

9.3.1 Measuring the common mode short-circuit impedance

As shown in Figure 11, by shorting both terminals of two pole lines and earthing the ending terminals, single-phase voltage source with the frequency of f is applied at the source terminal and voltage $\dot{U}_{s,f}$ as well as current $\dot{I}_{s,f}$ at the frequency f at the source terminal are measured.

9.3.2 Measuring the common mode open-circuit impedance

As shown in Figure 12, under the same measurement configuration shown in Figure 11 except for the open circuit at the ending terminal, the voltage $\dot{U}_{o,f}$ and current $\dot{I}_{o,f}$ at the source terminal are measured.

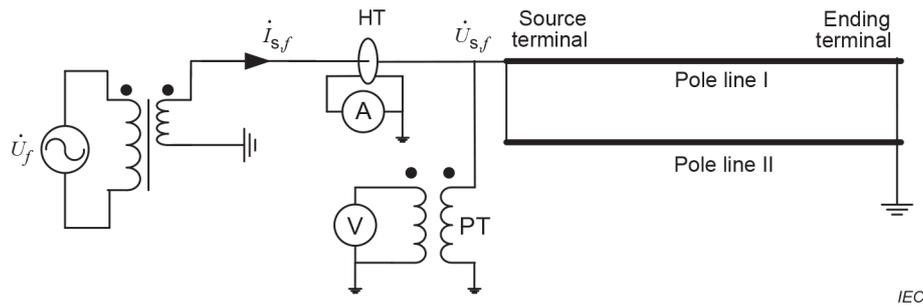


Figure 11 – Measurement of common mode short-circuit impedance

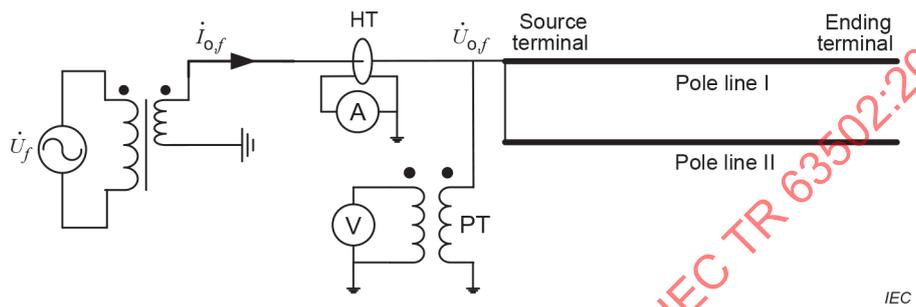


Figure 12 – Measurement of common mode open-circuit impedance

9.3.3 Calculating the frequency characteristics at common mode parameters

For the selected frequency f , the resistance r_0 , inductance l_0 and capacitance c_0 in unit length of HVDC transmission line at common mode are given by Formula (13) to Formula (19).

$$Z_{s0} = \frac{\dot{U}_{s,f}}{\dot{I}_{s,f}} \quad (13)$$

$$Z_{o0} = \frac{\dot{U}_{o,f}}{\dot{I}_{o,f}} \quad (14)$$

$$Z_{c0} = \sqrt{Z_{o0}Z_{s0}} \quad (15)$$

$$\gamma_0 = \frac{1}{L} \operatorname{arccoth}(Z_{s0}/Z_{c0}) \quad (16)$$

$$r_0 = \operatorname{Re}(\gamma_0 Z_{c0}) \quad (17)$$

$$l_0 = \frac{\operatorname{Im}(\gamma_0 Z_{c0})}{2\pi f} \quad (18)$$

$$c_0 = \operatorname{Im}\left(\frac{\gamma_0}{2\pi f Z_{c0}}\right) \quad (19)$$

where

Z_{s0} is the short circuit impedance at common mode;

- Z_{00} is the open circuit impedance at common mode;
- Z_{c0} is the characteristic impedance at common mode;
- γ_0 is the transmission constant at common mode;
- L is the length of measured line.

9.4 Calculating the coupling parameters of pole line I and pole line II

After obtaining inductance l_1 , capacitance c_1 , inductance l_0 , and capacitance c_0 in per unit length at the specified frequency f , coupling parameters between two pole lines are given by Formula (20) and Formula (21).

$$m_{I-II} = \frac{l_0 - l_1}{2} \quad (20)$$

$$c_{I-II} = \frac{c_1 - c_0}{2} \quad (21)$$

where

m_{I-II} is the mutual inductance of pole line I and pole line II;

c_{I-II} is the mutual capacitance of pole line I and pole line II.

It is noted that the calculation of the above parameters is based on the telegraph equations of the transmission line. See Annex C for details.

After determining parameters at all selected frequencies, the frequency characteristics of HVDC transmission line can be given accordingly. See Annex D for details.

10 Measurement of coupling parameters of two bipolar HVDC transmission lines

10.1 Measuring frequency characteristics at differential mode measurement

As shown in Figure 13, two bipolar transmission lines are noted as A and B, respectively. Either circuit A or circuit B can be regarded as a single-pole transmission line. By keeping the ending terminals of circuit A and B shorted and earthed, a two-phase power source with the frequency of f and phase angle difference of 180° is installed between A and B, which enables the measurements of the voltage $U_{s,f} = [\dot{U}_{As,f}, \dot{U}_{Bs,f}]$ as well as the current $I_{s,f} = [\dot{I}_{As,f}, \dot{I}_{Bs,f}]$ at the source terminal. Afterwards, by keeping the same measurement configurations except for the open circuit at the ending terminal, the voltage $U_{o,f} = [\dot{U}_{Ao,f}, \dot{U}_{Bo,f}]$ as well as current $I_{o,f} = [\dot{I}_{Ao,f}, \dot{I}_{Bo,f}]$ are measured as shown in Figure 14.

For selected frequency f , the inductance l_{1d} and capacitance c_{1d} in unit length of two bipolar HVDC transmission lines at differential mode are given by Formula (6) to Formula (12).

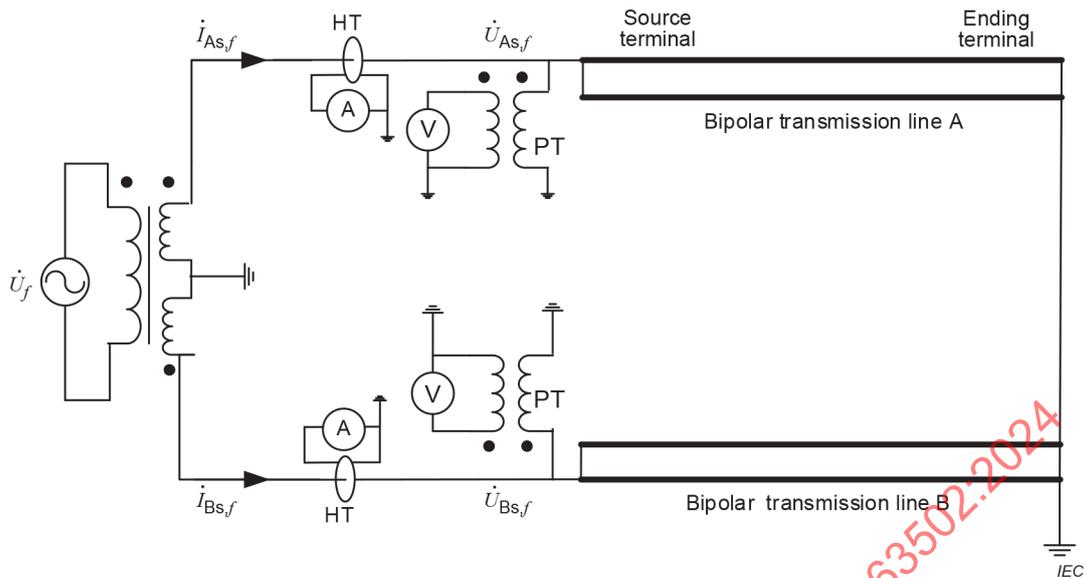


Figure 13 – Measurement of differential mode short circuit impedance for two bipolar transmission lines

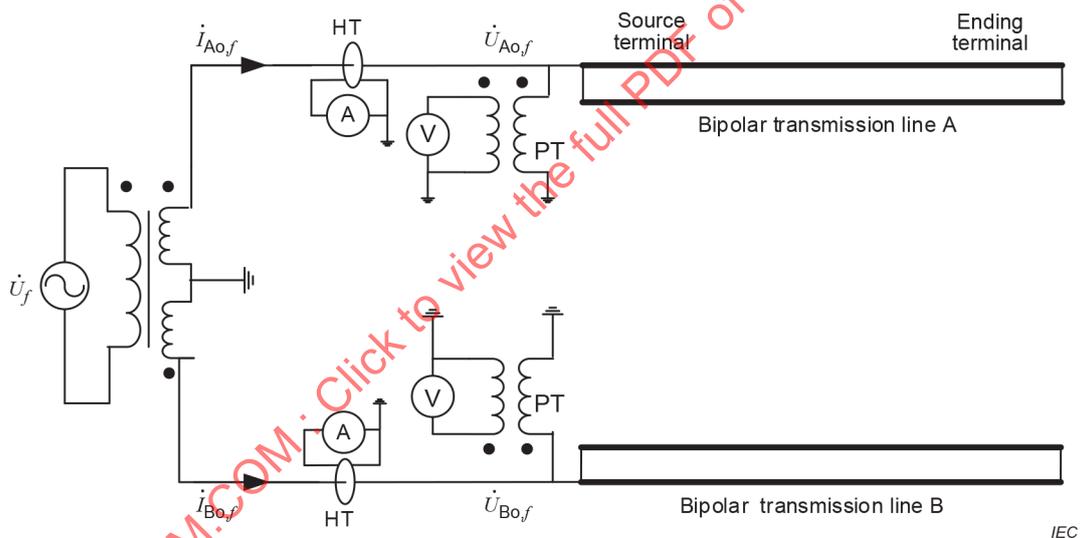


Figure 14 – Measurement of differential mode open circuit impedance for two bipolar transmission lines

10.2 Measuring frequency characteristics at common mode measurement

As shown in Figure 15, the measurement is configured by shorting the source terminals of circuit A and B and keeping the ending terminals of both circuits shorted and earthed. A single-phase source with the frequency of f is installed at the source terminal, which enables the measurements of the voltage $\dot{U}_{s,f}$ and current $\dot{I}_{s,f}$ at the source terminal. Afterwards, by applying the same measurement configuration except for insulating the ending terminals of circuit A and B from earth, $\dot{U}_{o,f}$ and current $\dot{I}_{o,f}$ at the source terminal are measured, as shown in Figure 16. For selected frequency f , the inductance l_{0d} and capacitance c_{0d} in unit length of two bipolar HVDC transmission line at common mode are given from Formula (13) to Formula (19).

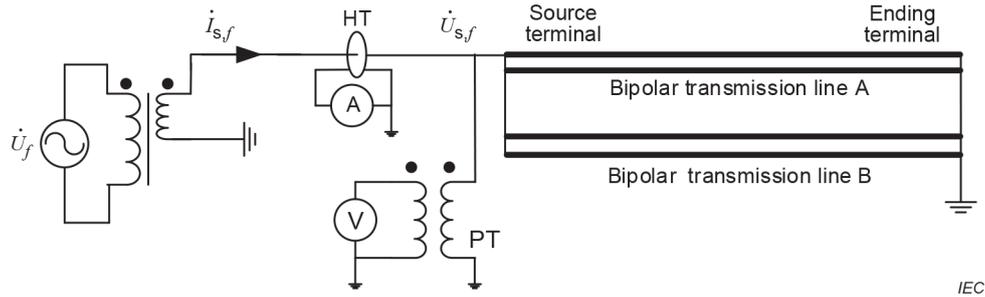


Figure 15 – Measurement of common mode short circuit impedance for two bipolar transmission line

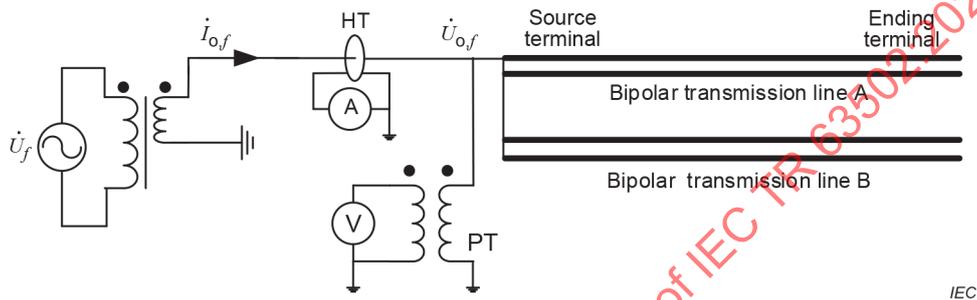


Figure 16 – Measurement of common mode open circuit impedance for two bipolar transmission line

10.3 Calculating the mutual coupling parameters

After determining the parameters l_{1d} , c_{1d} , l_{0d} and c_{0d} , the mutual coupling parameters between circuit A and B are given by Formula (22) and Formula (23).

$$m_{A-B} = \frac{l_{0d} - l_{1d}}{2} \quad (22)$$

$$c_{A-B} = \frac{c_{1d} - c_{0d}}{2} \quad (23)$$

where

m_{A-B} is the mutual inductance of circuit A and B;

c_{A-B} is the mutual capacitance of circuit A and B.

11 Measurement of frequency characteristics of HVDC transmission line with dedicated metallic return line

Owing to the concerns of environment protection, some HVDC transmission projects are configured with a metallic return line to eliminate the unfavourable effects caused by large DC current flowing into earth. The parameter measurement principle of HVDC transmission line with a separate metallic return line is consistent with Clause 9, the measurement configurations are shown in Figure 17, Figure 18, Figure 19 and Figure 20.

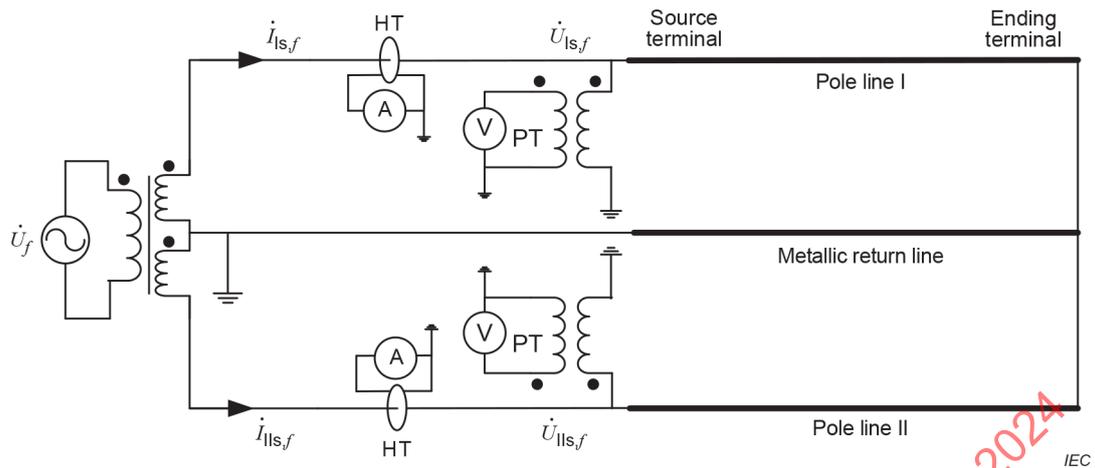


Figure 17 – Measurement of differential mode short-circuit impedance with metallic return line

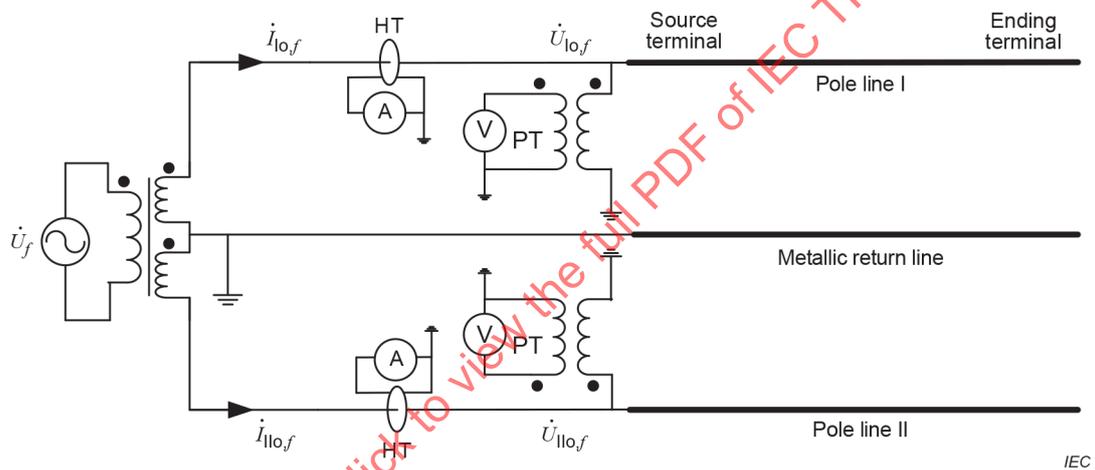


Figure 18 – Measurement of differential mode open-circuit impedance with metallic return line

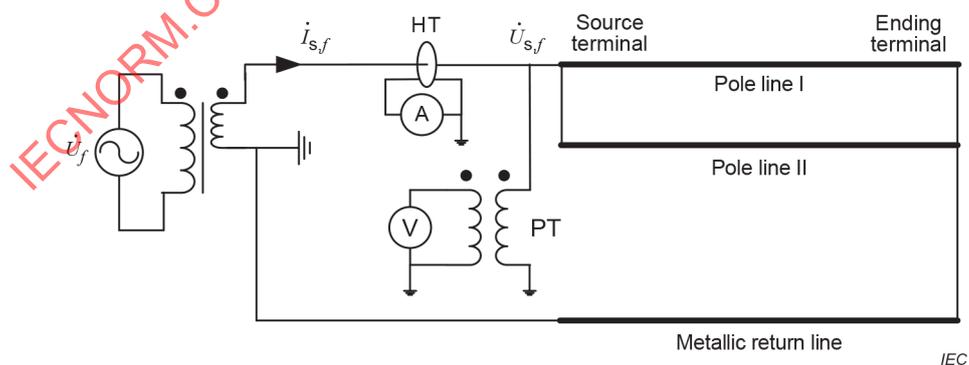


Figure 19 – Measurement of common mode short-circuit impedance with metallic return line

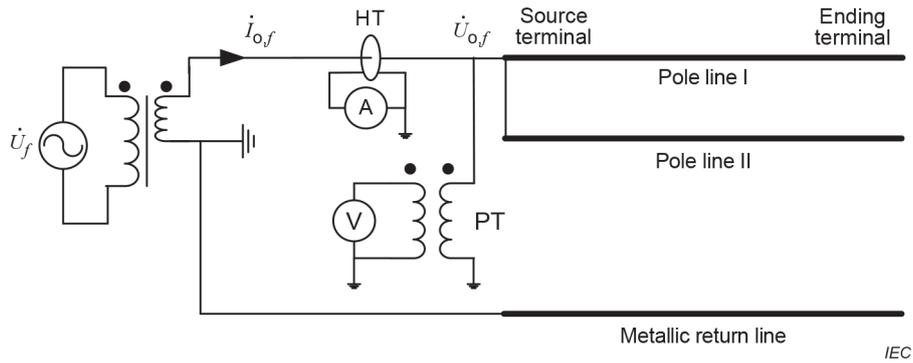


Figure 20 – Measurement of common mode open-circuit impedance with metallic return line

12 Measurement of frequency characteristics of HVDC cable

The DC resistance of HVDC cable is measured by the method given in Clause 8 and the frequency characteristics are measured by the methods given in Clause 9 with the measurement configurations as shown in Figure 21 and Figure 22.

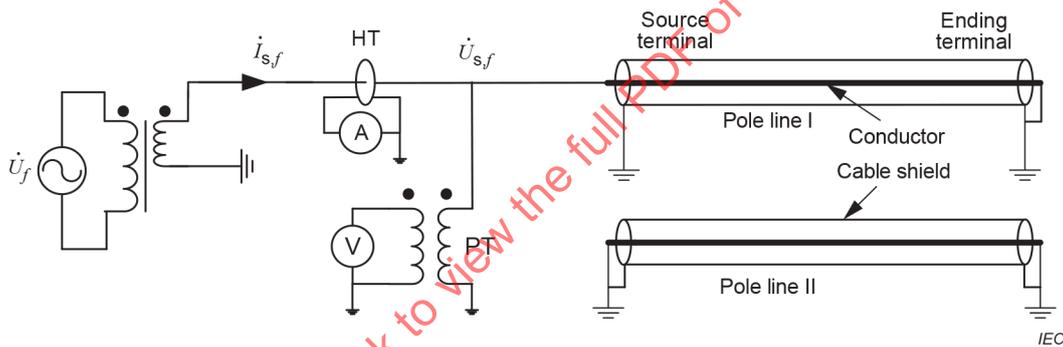


Figure 21 – Measurement of common mode short-circuit impedance of HVDC cable

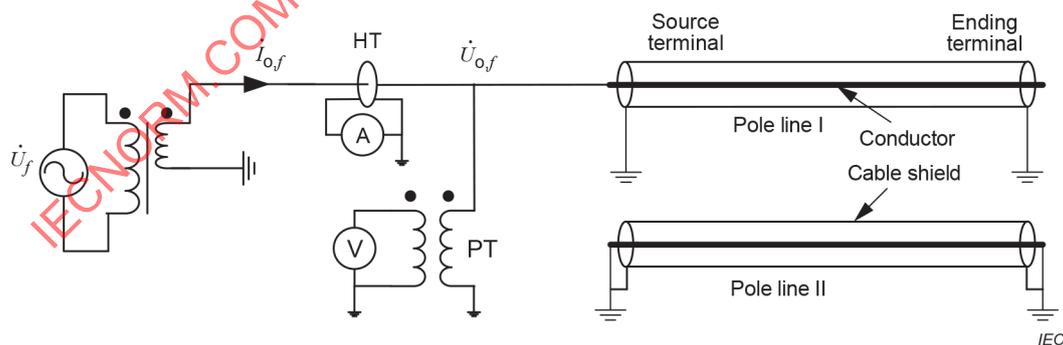


Figure 22 – Measurement of common mode open-circuit impedance of HVDC cable

13 Measurement of earth electrode line parameter

Earth electrode line is used to connect the earth electrode and neutral bus of the converter station, which provides a path for the DC current caused by unbalanced operation of two poles or monopole ground return operation mode. Generally, the earth electrode line is in a parallel-connected two-circuit configuration, as shown in Figure 23.

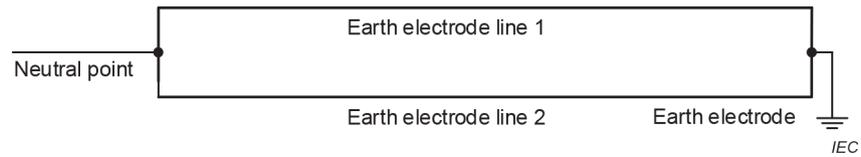


Figure 23 – Equivalent circuit of earth electrode line

The test of induced voltage, induced current, polarity verification, and insulation resistance can be carried out as given in Clause 5. While measuring the DC resistance of earth electrode line, the neutral point is disconnected to measure the series DC resistance of earth electrode line 1 and 2. The effective DC resistance of the complete earth electrode line, consisting of the parallel connection of earth electrode lines 1 and 2, is quarter of the measured value.

Methods given in Clause 9 can be applied to obtain the frequency characteristics of earth electrode line.

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Annex A (informative)

Anti-interference measures

The interference in measurement is generally caused by the capacitive and inductive coupling with adjacent operation AC and DC transmission lines. The parallel resistance R_G , the parallel capacitance C_G and the series resistance R_L are installed at the source terminal of the line as shown in Figure A.1 to reduce the induced voltage and current. In the augmented circuit, R_G reduces the AC and DC induced voltage, C_G reduces the AC induced voltage, and R_L reduces the induced current. Empirically, R_G and R_L are arranged with a resistance in the range of 100 Ω to 200 Ω and C_G is configured with a capacitance of 50 μF .

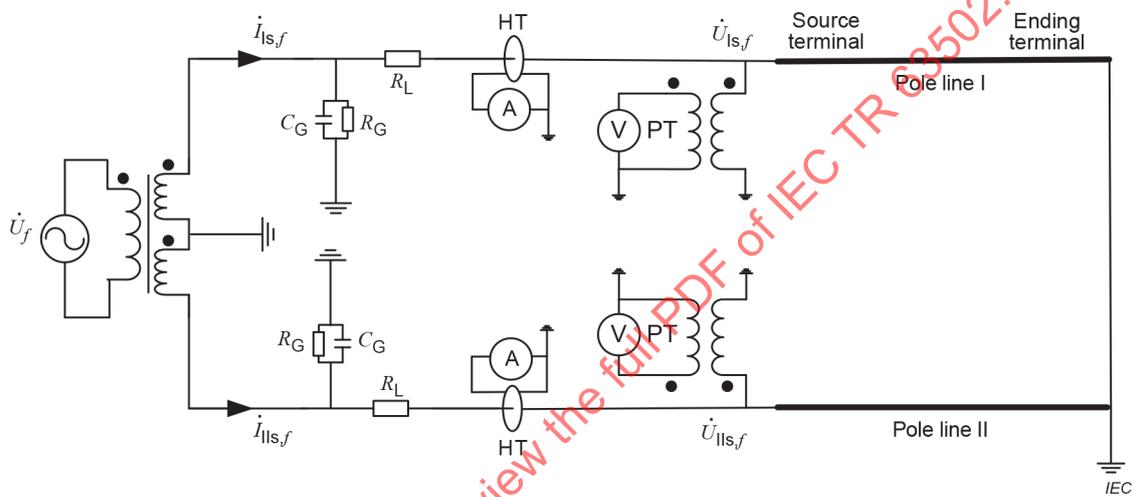


Figure A.1 - Anti-interference measures

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Annex B (informative)

Method for locating faults of transmission line

B.1 Overview

In on-site measurements, due to possible occurrence of short-circuit faults, open-circuit faults, earthing faults and other faults along the transmission line, it is necessary to conduct fault removal before the line parameter measurement. In practical works, measuring personnel generally locates the faults by technically narrowing the intervals where the faults exist, thus improving the work efficiency.

In practical applications, earthing faults are usually caused by the personal security wire left behind, where the earthing points have an earthing resistance of approximately zero. In other cases of earthing faults, the earthing resistance is unknown, which can bring significant errors using this method.

B.2 Location of earthing faults

The initial location of earthing faults is determined based on the designed DC resistance in per unit length, which is completed by two steps.

As shown in Figure B.1, an earthing point 0 is present. In the first step, by keeping the ending terminal of pole line I opened, and both terminals of the other pole line earthed, the DC resistance R_0 of the pole line I is measured and the approximate distance L_0 is given by Formula (B.1).

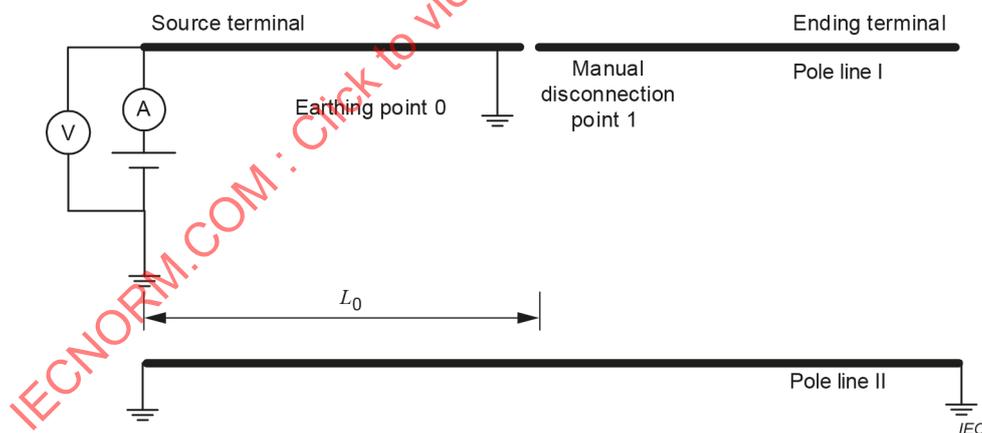


Figure B.1 – Location of earthing faults

$$L_0 \approx \frac{R_0}{r} \quad (\text{B.1})$$

where

r is the designed DC resistance in per unit length;

R_0 is the DC resistance of the measured line;

L_0 is the approximate distance of earthing point 0.

In the second step, as shown in Figure B.1, by keeping the ending terminal opened and setting a manual disconnection point 1 with a distance L_0 from the source terminal, the insulation resistance at the source terminal is measured. If the insulation resistance is 0, the earthing point 0 is in the interval bordered by the source terminal and the manual disconnection point 1, otherwise the earthing point 0 is between the ending terminal and the manual disconnection point 1. Repeat the procedures until the earthing fault is found.

B.3 Location of open-circuit faults

The location of open-circuit faults is determined through insulation resistance measurements. As shown in Figure B.2, by keeping the ending terminal of pole line I opened and setting a manual earthing point 0 at the middle of the line, the insulation resistance is measured using a megohmmeter at the source terminal. If the insulation resistance is 0, the open-circuit point is in the interval bordered by the ending terminal and the manual earthing point. Otherwise, the disconnection point is between the source terminal and the manual earthing point 0. Repeat the procedures until the disconnection point is found.

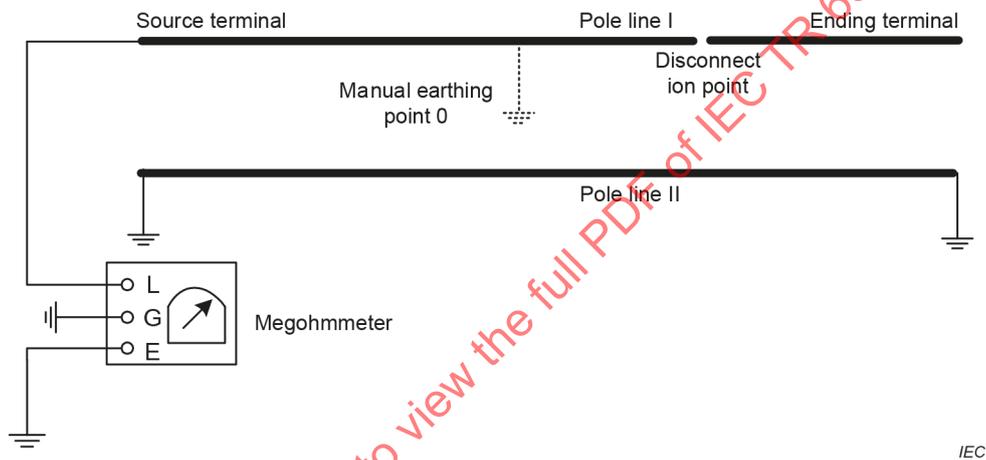


Figure B.2 – Location of open-circuit faults

B.4 Location of bipolar short-circuit faults

The short-circuit faults of the bipolar lines is mainly technically located based on the design value of the DC resistance in per unit length. As shown in Figure B.3, supposing that there is a short-circuited point in the transmission line, the DC resistance between bipolar lines R_{I-II} is measured at the source terminal by keeping the ending terminals of bipolar lines opened.

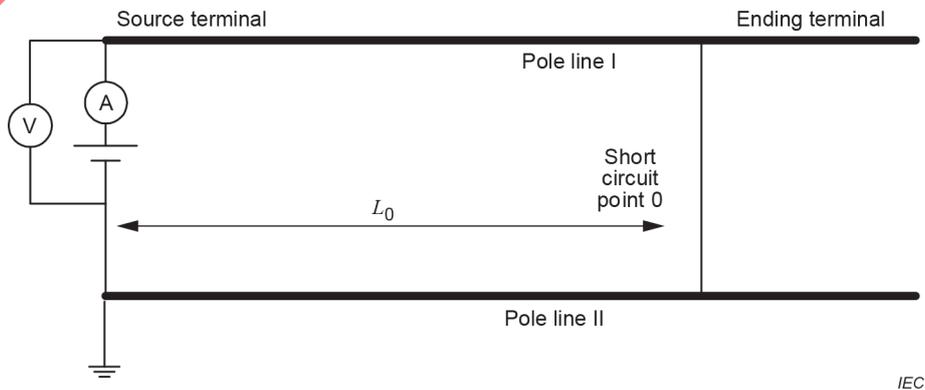


Figure B.3 – Location of bipolar short circuit faults

The approximate distance of short-circuit point 0 L_0 is given by Formula (B.2).

$$L_0 \approx \frac{R_{l-II}}{2r} \quad (\text{B.2})$$

where

r is the designed DC resistance in per unit length;

R_{l-II} is the DC resistance between bipolar lines;

L_0 is the approximate distance of short circuit point 0.

B.5 Location of multiple faults

In the event of multiple faults on the line, the above methods can be conducted in succession until all faults are eliminated.

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Annex C (informative)

Principle of measuring distributed parameters

C.1 Distributed parameter circuit of the transmission line

As shown in Figure C.1, r , l , g and c represent the per-unit length value of resistance, inductance, conductance and capacitance, respectively. Z_D and Z_E denote the terminal impedance and inner impedance of power source, respectively.

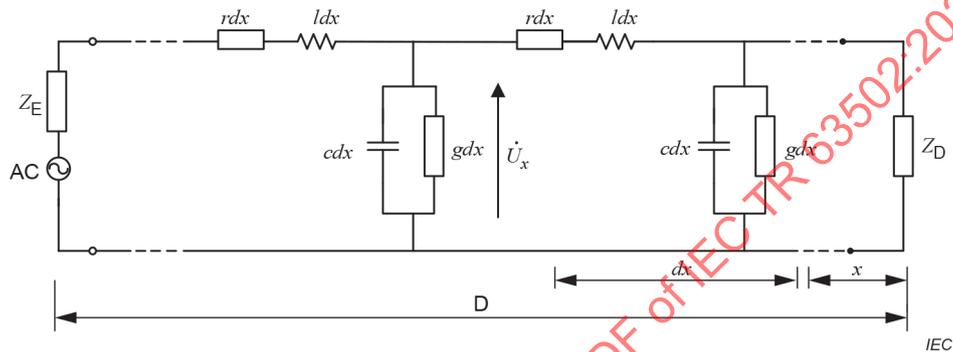


Figure C.1 – Distributed parameter circuit of the transmission line

C.2 Definitions

Impedance per unit length of transmission lines is $z = r + j\omega l$;

Admittance per unit length of transmission lines is $y = g + j\omega c$,

where

Transmission constant is $\gamma = \sqrt{zy}$;

Characteristic impedance is $Z_c = \sqrt{\frac{z}{y}}$.

Therefore,

$$z = \gamma Z_c \tag{C.1}$$

$$y = \frac{\gamma}{Z_c} \tag{C.2}$$

C.3 Telegraph equations

For an evenly distributed transmission line, by ignoring electromagnetic disturbance, the characteristic of voltage and current on the transmission line are given as:

$$\dot{U}(x) = \dot{U}(0)\cosh(\gamma x) + \dot{I}(0)Z_c \sinh(\gamma x) \tag{C.3}$$

$$\dot{I}(x) = \dot{I}(0) \cosh(\gamma x) + \frac{\dot{U}(0) \sinh(\gamma x)}{Z_c} \quad (\text{C.4})$$

in which $\dot{U}(x)$ and $\dot{I}(x)$ denote voltage and current at the point of length x , and $U(0)$ and $\dot{I}(0)$ are the voltage and current at the source terminal of the line.

If a load is introduced at $x = D$ (i.e. the ending terminal of line), where D is length of line, Formula (C.3) and Formula (C.4) are given as:

$$\dot{U}(D) = \dot{U}(0) \cosh(\gamma D) + \dot{I}(0) Z_c \sinh(\gamma D) \quad (\text{C.5})$$

$$\dot{I}(D) = \dot{I}(0) \cosh(\gamma D) + \frac{\dot{U}(0) \sinh(\gamma D)}{Z_c} \quad (\text{C.6})$$

Input impedance is:

$$Z_{\text{in}} = \frac{\dot{U}(D)}{\dot{I}(D)} = \frac{\dot{U}(0) \cosh(\gamma D) + \dot{I}(0) Z_c \sinh(\gamma D)}{\dot{I}(0) \cosh(\gamma D) + \frac{\dot{U}(0) \sinh(\gamma D)}{Z_c}} \quad (\text{C.7})$$

Moreover:

$$\dot{U}(0) = \dot{I}(0) Z_D \quad (\text{C.8})$$

Bring Formula (C.8) into Formula (C.7), therefore:

$$Z_{\text{in}} = \frac{Z_c(Z_D/Z_c + \tanh(\gamma D))}{1 + \tanh(\gamma D) Z_D/Z_c} \quad (\text{C.9})$$

If $\tanh \varepsilon = Z_D/Z_c$, then Formula (C.9) is given as:

$$Z_{\text{in}} = Z_c \frac{\tanh \varepsilon + \tanh(\gamma D)}{1 + \tanh \varepsilon \tanh(\gamma D)} = Z_c \tanh(\gamma D + \varepsilon) \quad (\text{C.10})$$

C.4 Calculation of distributed parameters

When the ending terminal of line is shorted, $Z_D = 0$, $\varepsilon = 0$ in Formula (C.10), then:

$$Z_s = Z_c \tanh(\gamma D + \varepsilon) = Z_c \tanh(\gamma D) \quad (\text{C.11})$$