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TECHNICAL REPORT

UHV AC transmission systems –
Part 303: Guideline for the measurement of UHV AC transmission line power frequency parameters

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IEC Central Office
3, rue de Varembé
CH-1211 Geneva 20
Switzerland

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

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UHV AC TRANSMISSION SYSTEMS –

Part 303: Guideline for the measurement of UHV AC transmission line power frequency parameters

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IEC TR 63042-303 has been prepared by IEC technical committee 122: UHV AC transmission systems. It is a Technical Report.

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

DTR	Report on voting
122/105/DTR	122/112/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/standardsdev/publications.

A list of all parts in the IEC 63042 series, published under the general title *UHV AC transmission systems*, can be found on the IEC website.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

INTRODUCTION

AC transmission line power frequency parameters are important basic data used for various power system's calculations and applications, including engineering design verification, commissioning, and operation.

Due to the complication of the geological conditions along the corridor of long distance UHV AC transmission lines, it is difficult to obtain accurate transmission line power frequency parameters through theoretical analysis and calculation. To obtain the accurate power frequency parameters, a field measurement is necessary.

This document provides the guidance for measurement of UHV AC transmission lines power frequency parameters which include sequence parameters and phase parameters, etc. The measurement conditions, measurement methods, data process methods, safety requirements, etc. are described.

UHV AC TRANSMISSION SYSTEMS –

Part 303: Guideline for the measurement of UHV AC transmission line power frequency parameters

1 Scope

This part of IEC 63042 specifies measurement methods of UHV AC transmission line power frequency parameters. These measured parameters mainly include sequence parameters, mutual parameters between double-circuit lines, phase parameters and some other related parameters.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC Guide 115:2007, *Application of uncertainty of measurement to conformity assessment activities in the electrotechnical sector*

3 Terms and definitions

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

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

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

3.1
offset frequency method
method that can measure the parameter of transmission line by applying a test power source with a frequency offset from the power frequency

3.2
source terminal
terminal of a transmission line, at which a power source is applied for the parameter measurement

3.3
ending terminal
terminal opposite to the source terminal of a transmission line

3.4
one-terminal measurement method
measurement method, at which only source terminal is measured

3.5
two-terminal synchronous measurement method
measurement method at which both source terminal and ending terminal are measured synchronously

3.6
phase parameter
type of power frequency parameters, which characterize electric and magnetic coupling characteristic for single phase or between two phases, including self-impedance, mutual impedance, self-capacitance and coupling capacitance

3.7
induced voltage
voltage caused by the electromagnetic or electrostatic effect of adjacent energized lines or equipment

3.8
induced current
electric current resulting from the displacement of charge carriers due to an induced voltage

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

4 General

4.1 Background

Due to the complication of the geological conditions along the corridor of long distance UHV AC transmission lines, where soil resistivity and transmission tower size vary, it is difficult to obtain accurate transmission line power frequency parameters through theoretical analysis and calculation. To obtain the accurate power frequency parameters, field measurement is necessary. However, the accuracy of field measurement is influenced by measurement methods due to the distributed characteristic and electromagnetic coupling of UHV AC lines. Therefore, appropriate measurement methods are important to obtain accurate power frequency parameters. In this document, different measurement methods are applied to acquire accurate parameters.

4.2 Measurement items

The recommended parameters which need to be measured are as follows:

- positive-sequence impedance,
- positive-sequence capacitance,
- zero-sequence impedance,
- zero-sequence capacitance,
- mutual impedance and coupling capacitance between double-circuit lines,
- self-impedance of one phase,
- self-capacitance of one phase,
- mutual impedance between two phases,
- coupling capacitance between two phases,
- induced voltage and induced current,
- phase verification and insulation resistance,
- DC resistance.

4.3 Main circuit configuration

Disconnectors at the two terminals of the transmission line should be open during measurement.

Parallel with the transmission line, connected equipment should be disconnected, such as shunt reactors and capacitive transformer.

Series reactors and capacitors used in the transmission line shall be bypassed.

If the transmission line to be measured is composed of overhead lines, cables or gas-insulated lines (GIL), it is recommended to measure the parameters of the overhead lines, cables or GIL, separately.

To eliminate the resistance of the connecting lines for test, two connecting lines, i.e. voltage and current connecting lines, can be applied. If only one connecting line is applied, the obtained line resistance should be reduced by the connecting line resistance. The measurement system should be reliably connected to the substation earthing system.

4.4 Measurement condition

Close attention should be paid to the weather condition along the line during the measurement. The measurement should be stopped if the weather is not suitable for measurement.

Ambient temperature of measuring instrument: −10 °C to +40 °C, relative humidity: ≤ 85 %.

Before starting the measurements, check that all temporary grounding connections have been removed. No work may be done on the lines during the measurements. Make sure that this rule is followed. All local and international safety regulations shall be known and strictly observed. Safety precautions are given in Annex C.

5 Requirement of measuring instrument

5.1 Current transformer

Uncertainty of current transformer (CT) should be equal to or better than 0,5 %. It is obtained based on the method of IEC Guide 115.

5.2 Voltage transformer

Uncertainty of voltage transformer (VT) should be equal to or better than 0,5 %. It is obtained based on the method of IEC Guide 115.

5.3 Measuring instrument of DC resistance

The instrument to measure the DC resistance of a transmission line can be a special instrument or the combination of a DC power source, a DC voltmeter and a DC ammeter.

If the DC resistance measurement meter is used, its uncertainty should be equal to or better than 0,5 %.

If the combination of a DC resistance, a DC power source, a DC voltmeter and a DC ammeter is used, the uncertainty of the DC voltmeter and ammeter should be equal to or better than 0,5 %.

5.4 Offset frequency power source

The offset frequency power source should be capable of supplying sinusoidal signals at a single frequency that can be adjustable. Normally, the power source should generate a sinusoidal signal at $f - \Delta f$ or $f + \Delta f$, where Δf is usually less than 10 Hz, such as 2,5 Hz, 5 Hz or 7,5 Hz.

NOTE ± 5 Hz are two typical values of frequency offset; the frequency of test power source can thus be 45 Hz or 55 Hz for a 50 Hz system.

The total harmonic distortion for the voltage output of offset frequency power source should be within 3 %. It is recommended by IEC 61000-2-4:2002.

5.5 Special measuring instrument of transmission line power frequency parameter

The instrument should meet the requirement as follows:

- The measuring instruments at the source and ending terminals should have the function of synchronous phasor measurement and be capable of sampling single-phase and three-phase voltage and current phasors which include amplitude and phase angle of voltage and current.
- For each measurement, all the measured voltage and current phasors take a GPS PPS as a reference; phase angle of voltage or current is the difference between the measured voltage or current phasor and the reference. The magnitude of voltage or current is amplitude.
- The synchronization error of sampling between the source terminal and ending terminal should be less than 100 ns.
- The measuring instrument should be capable of eliminating signal aliasing and leakage.
- The measuring instrument should be capable of completing data analysis and calculation according to the prescribed method.

6 Conversion of offset frequency measurement results

If there are no induced voltage and induced current on the measured line at power frequency, a power frequency test power source can be directly used.

If there are induced voltage and induced current on the measured line at power frequency, an offset frequency test power source should be used to eliminate the power frequency interference. The offset frequency measurement method is usually used to measure UHV transmission line power frequency parameters. However, the parameters measured by using offset frequency method need to be converted to the parameters at power frequency.

Generally, the two frequencies $f - \Delta f$ and $f + \Delta f$ will be selected for the measurement.

The procedure of offset frequency measurement is as follows:

- Firstly, replace the frequency of power source f by $f - \Delta f$, measure and calculate parameters of the transmission lines at frequency $f - \Delta f$ according to the procedures and equations.
- Secondly, replace the frequency of power source f by $f + \Delta f$, measure and calculate parameters at frequency $f + \Delta f$ according to the procedures and equations.
- Finally, calculate the impedance parameters at power frequency f by

$$z_f = r_f + jx_f = \left(r_{f-\Delta f} + r_{f+\Delta f}\right)/2 + j2\pi f\left(\frac{x_{f-\Delta f}}{2\pi(f-\Delta f)} + \frac{x_{f+\Delta f}}{2\pi(f+\Delta f)}\right)/2 \qquad (1)$$

where

f is the power frequency;

j is the imaginary unit;

z_f is the impedance at frequency f;

r_f is the resistance at frequency f;

$r_{f\text{-}\Delta f}$ is the resistance at frequency $f - \Delta f$;

$r_{f+\Delta f}$ is the resistance at frequency $f + \Delta f$;

x_f is the reactance at frequency f;

$x_{f\text{-}\Delta f}$ is the reactance at frequency $f - \Delta f$;

$x_{f\text{-}\Delta f}$ is the is the reactance at frequency $f + \Delta f$;

$$y_f = g_f + j2\pi f c_f = \left(g_{f-\Delta f} + g_{f+\Delta f}\right) / 2 + j\, 2\pi f\left(c_{f-\Delta f} + c_{f+\Delta f}\right) / 2 \qquad (2)$$

where

y_f is the admittance at frequency f;

j is the imaginary unit;

g_f is the conductance at frequency f;

$g_{f\text{-}\Delta f}$ is the conductance at frequency $f - \Delta f$;

$g_{f+\Delta f}$ is the conductance at frequency $f + \Delta f$;

c_f is the capacitance at frequency f;

$c_{f\text{-}\Delta f}$ is the capacitance at frequency $f - \Delta f$;

$c_{f\text{-}\Delta f}$ is the capacitance at frequency $f + \Delta f$.

7 Measurement of induced voltage and induced current

7.1 General

Induced voltages and currents on the line to be measured can endanger the health of the workers and destroy the measuring instruments. Therefore, the measurement of the induced voltage and current should be the first task of parameter measurement.

7.2 Induced voltage

Induced voltage of three phases should be measured when transmission line is earthed and open-circuit at the ending terminal separately.

As shown in Figure 1, earth the three phases at the ending terminal and disconnect the three phases at the source terminal and measure the induced voltage of each phase at the source terminal by a voltmeter through voltage divider.

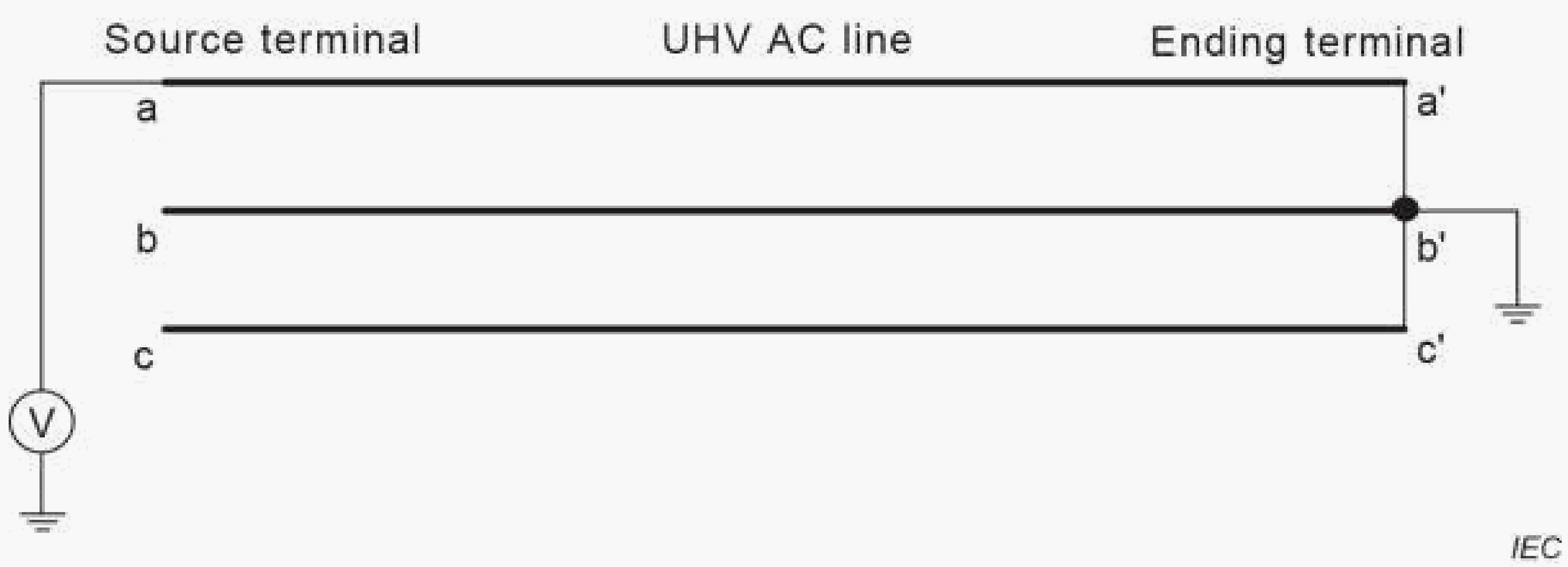


Figure 1 – Measurement of induced voltage

As shown in Figure 2, disconnect the three phases at both terminals and measure the induced voltage of each phase at the source terminal by a voltmeter through voltage divider.

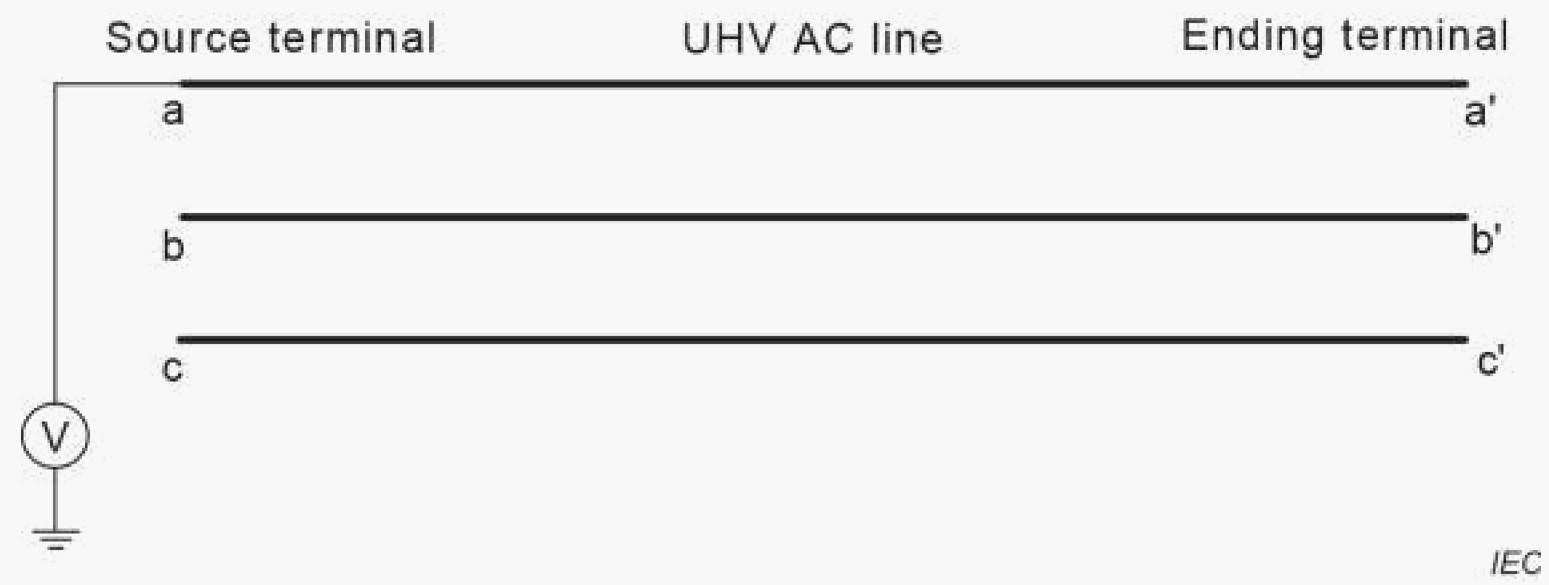


Figure 2 – Measurement of induced voltage

7.3 Induced current

As shown in Figure 3, earth the three phases at the two terminals, and measure the grounding current of each phase and the total current of the three phases at the source terminal by the ammeter.

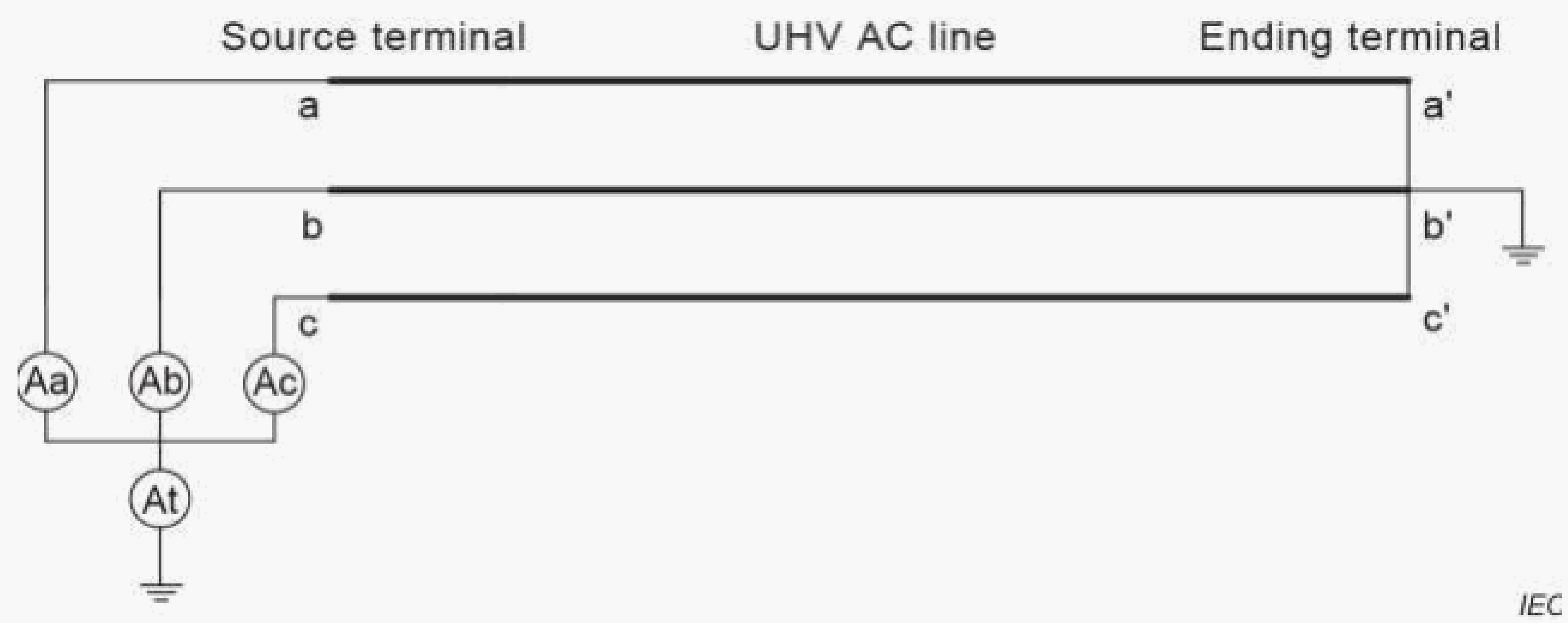


Figure 3 – Measurement of induced current

8 Phase verification and measurement of insulation resistance

8.1 General

Phase verification is used to verify whether the phase labels at two terminals are consistent, and the insulation resistance measurement is applied to obtain the external insulation condition of transmission line. An insulation resistance meter which measuring voltage range is not less than 5 kV can be used as measuring instrument.

8.2 Phase verification

As shown in Figure 4, earth phase a at the ending terminal and disconnect the other phases at the two terminals. Measure the insulation resistance of each phase at the source terminal by the insulation resistance meter. If the insulation resistance of any phase is equal to zero, this phase label is verified to be phase a.

Repeat the same procedure for verification of the other line phases.

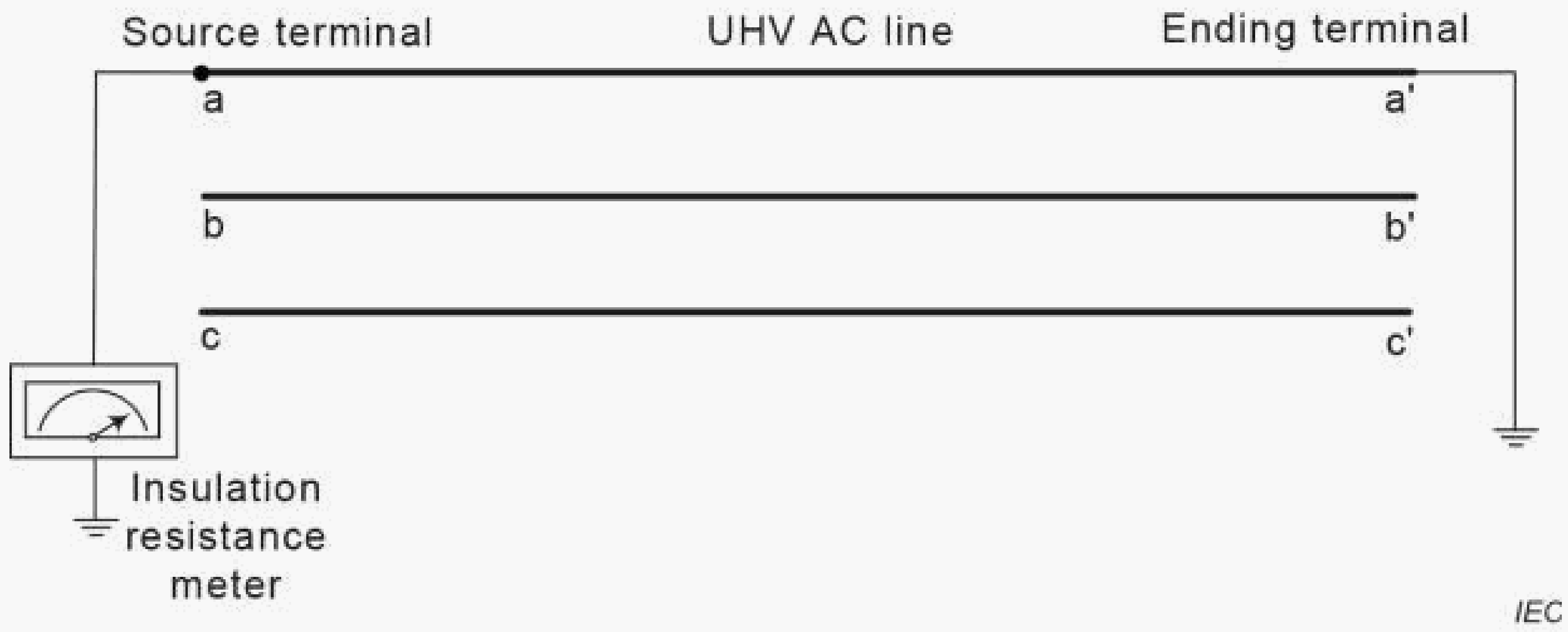


Figure 4 – Phase verification

8.3 Measurement of insulation resistance

As shown in Figure 5, disconnect phase a at both terminals. In order to decrease the induced voltage during measurement, earth the other phases at the source terminal and disconnect them at the ending terminal. Measure the insulation resistance of phase a by the insulation resistance meter at the source terminal.

Repeat the same procedure for insulation resistance measurement of the other line phases.

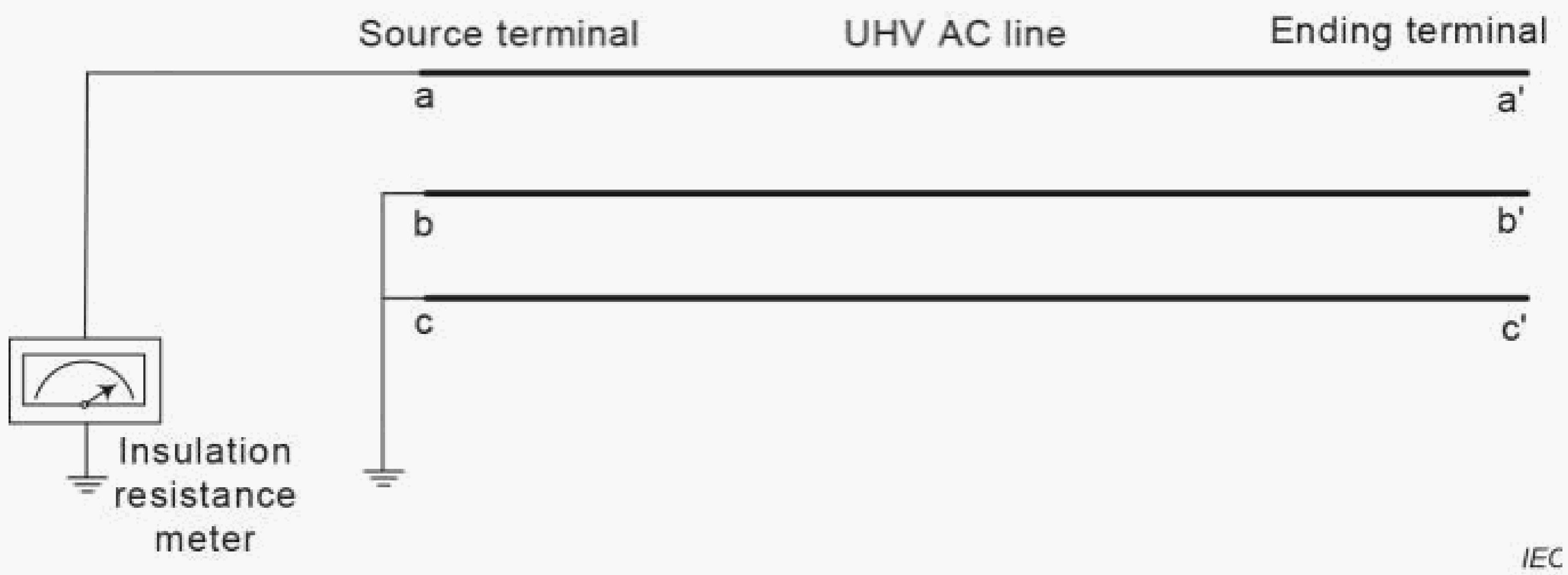


Figure 5 – Measurement of insulation resistance

If a voltage transformer is connected to the transmission line, the voltage transformer shall be disconnected from the line during measurement.

9 Measurement of DC resistance

As shown in Figure 6, disconnect the line to be measured at the source terminal and earth at the ending terminal. Apply a DC power source between phase a and phase b, and measure the DC voltage U_{ab} and the DC current I_{ab}. In order to decrease the induced voltage during measurement, generally earth the measured line at the ending terminal or earth one of the measured two phases at any terminal.

Apply a DC power source between the corresponding phases, and repeat the same measurement procedures for measurement of U_{ca}, U_{bc}, I_{ca} and I_{bc}.

The DC resistance of each phase is then given by the Equations (3) to (5).

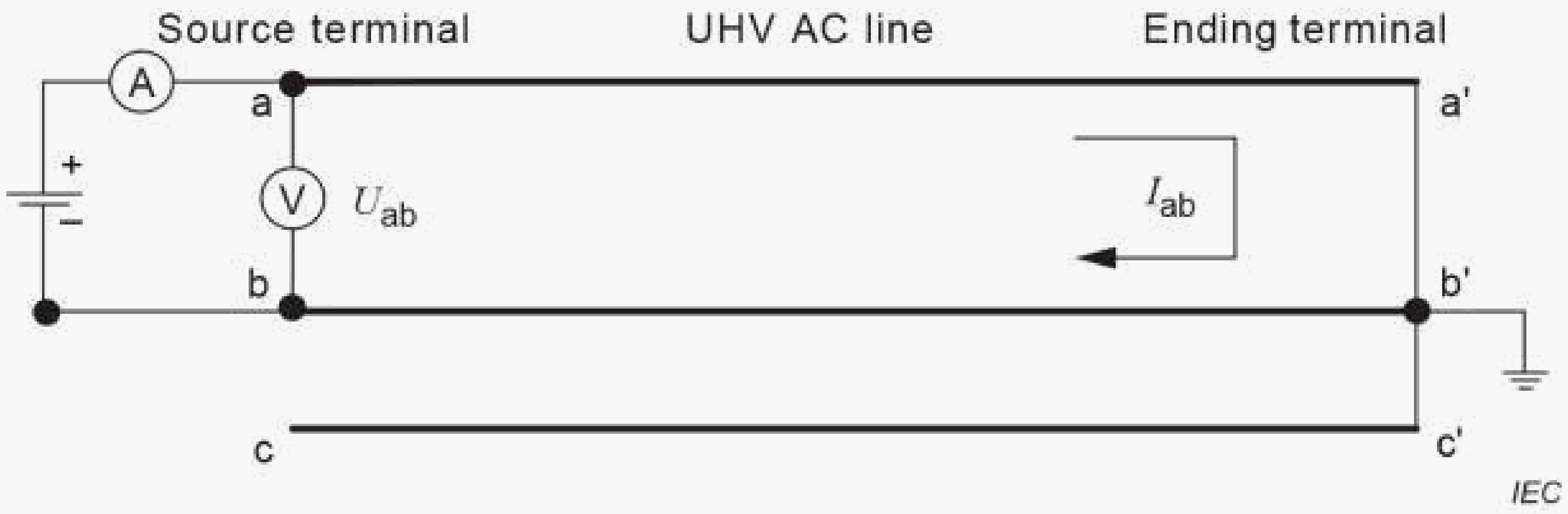


Figure 6 – Measurement of DC resistance

$$R_a = \left(\frac{U_{ab}}{I_{ab}} + \frac{U_{ca}}{I_{ca}} - \frac{U_{bc}}{I_{bc}}\right) / 2 \tag{3}$$

$$R_b = \left(\frac{U_{ab}}{I_{ab}} + \frac{U_{bc}}{I_{bc}} - \frac{U_{ca}}{I_{ca}}\right) / 2 \tag{4}$$

$$R_c = \left(\frac{U_{bc}}{I_{bc}} + \frac{U_{ca}}{I_{ca}} - \frac{U_{ab}}{I_{ab}}\right) / 2 \tag{5}$$

where

R_a is the DC resistance of phase a;

R_b is the DC resistance of phase b;

R_c is the DC resistance of phase c.

The measurement result should be converted to the DC resistance at 20 °C by Equation (6).

$$R_{20} = \frac{R}{1 + (\vartheta - 20)\beta} \tag{6}$$

where

is the average temperature of environment between the source terminal and the ending terminal in °C;

ß is the temperature coefficient of the resistance of the conductor in 1/ °C, for aluminium ß = 0,003 6 (1/ °C);

R is the measured resistance.

10 Measurement of positive-sequence parameter

One terminal measurement method can be used to measure the positive sequence parameters.

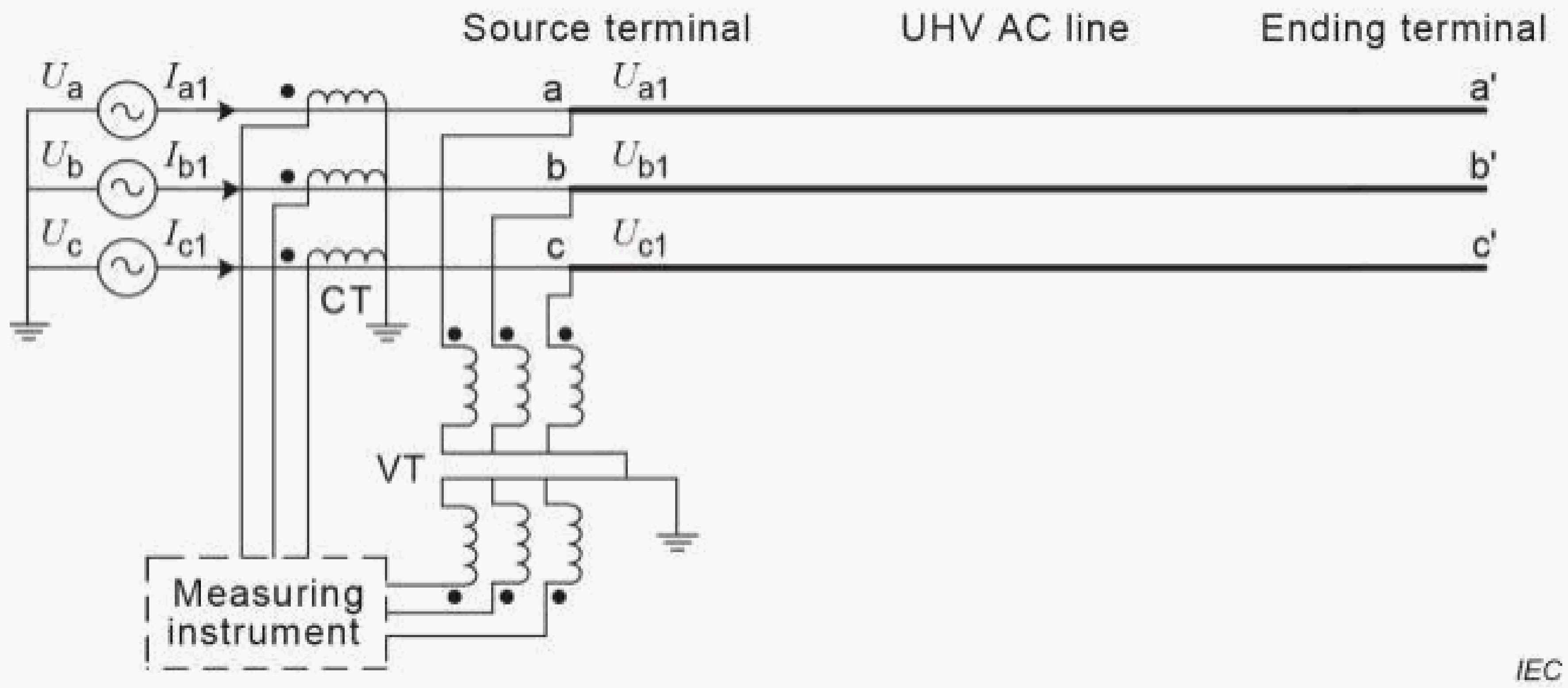
Generally, the ending terminal currents are zero when the three phases are disconnected at the ending terminal, and the ending terminal voltages are zero when three phases are earthed at the ending terminal. Therefore, voltages and currents should be measured at the source terminal when the three phases at the ending terminal are disconnected, and when the lines at the ending terminal are earthed separately. Combined with the conditions mentioned above, positive-sequence impedance and capacitance of the lines can be calculated by transmission line equations [3] [1]. As shown in Figure 7 a) and Figure 7 b), the measurement procedures are as follows.

Firstly, the three phases should be disconnected at the ending terminal and then a three-phase test power source should be applied to the three phases at the source terminal. Measure the three phase voltages U_{a1}, U_{b1}, and U_{c1} and currents I_{a1}, I_{b1}, and I_{c1} at the source terminal.

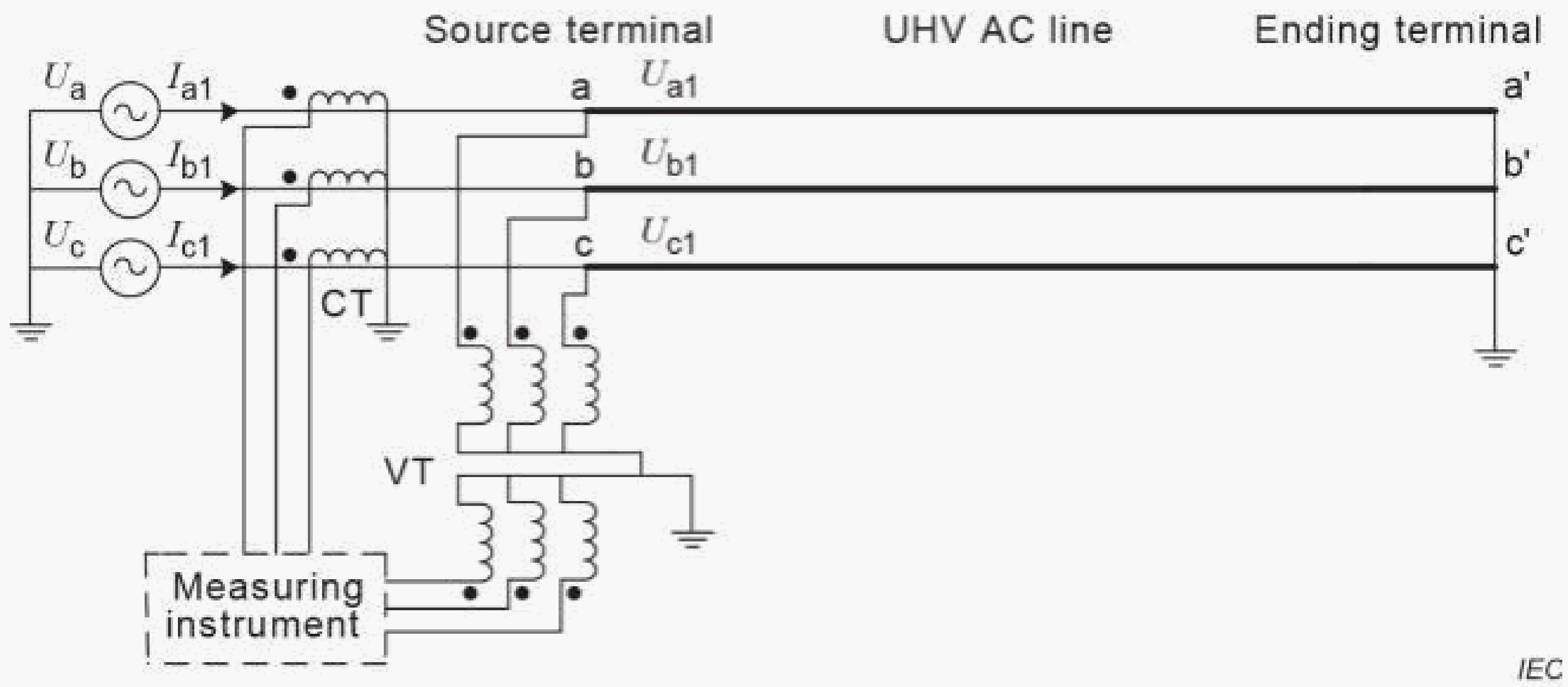
NOTE U_{a1} represents the voltage phasor of phase a, which includes amplitude and phase angle of the voltage. The symbol a′ represents the phase a at the ending terminal.

Secondly, the three phases should be earthed at the ending terminal and then a three-phase test power source should be applied to the three phases at the source terminal. Measure the three phase voltages U_{a2}, U_{b2}, and U_{c2} and currents I_{a2}, I_{b2}, and I_{c2} at the source terminal.

Calculate the positive-sequence component $U_{1,1}$ from U_{a1}, U_{b1}, and U_{c1}, $I_{1,1}$ from I_{a1}, I_{b1}, and I_{c1}, $U_{1,2}$ from U_{a2}, U_{b2}, and U_{c2}, $I_{1,2}$ from I_{a2}, I_{b2}, and I_{c2}



a) The line at the ending terminal is disconnected



b) The line at the ending terminal is earthed

Figure 7 – Measurement of positive-sequence parameter

Positive-sequence impedance and capacitance can be calculated according to the equations in Table 1.

1 Figures in square brackets refer to the Bibliography.

Table 1 – Calculation method of positive-sequence parameters

	Calculation of positive-sequence parameters	
Measured voltage and current	$U_{1,1},\ I_{1,1}$	$U_{1,2},\ I_{1,2}$
Characteristic impedance	$Z_{c,1} = \sqrt{\dfrac{U_{1,1}}{I_{1,1}}\dfrac{U_{1,2}}{I_{1,2}}}$	
Propagation coefficient	$\lambda_1 = \dfrac{\operatorname{arcoth}\sqrt{\dfrac{U_{1,2}}{I_{1,2}}\dfrac{I_{11,}}{U_{11,}}}}{L}$	
Positive-sequence impedance	$z_1 \quad Z_{c,1}\lambda_1$	
Positive-sequence resistance	$r = \mathrm{Re}(z_1)$	
Positive-sequence reactance	$x_1 = \mathrm{Im}(z_1)$	
Positive-sequence admittance	$y_1 = \lambda_1 / Z_{c,1}$	
Positive-sequence capacitance	$c_1 = \dfrac{\mathrm{Im}(y_1)}{\omega}$	

NOTE $\omega = 2\pi f$ represents the angular frequency; L represents the length of transmission line.

Example of transmission line power frequency parameter measurement is given in Annex A.

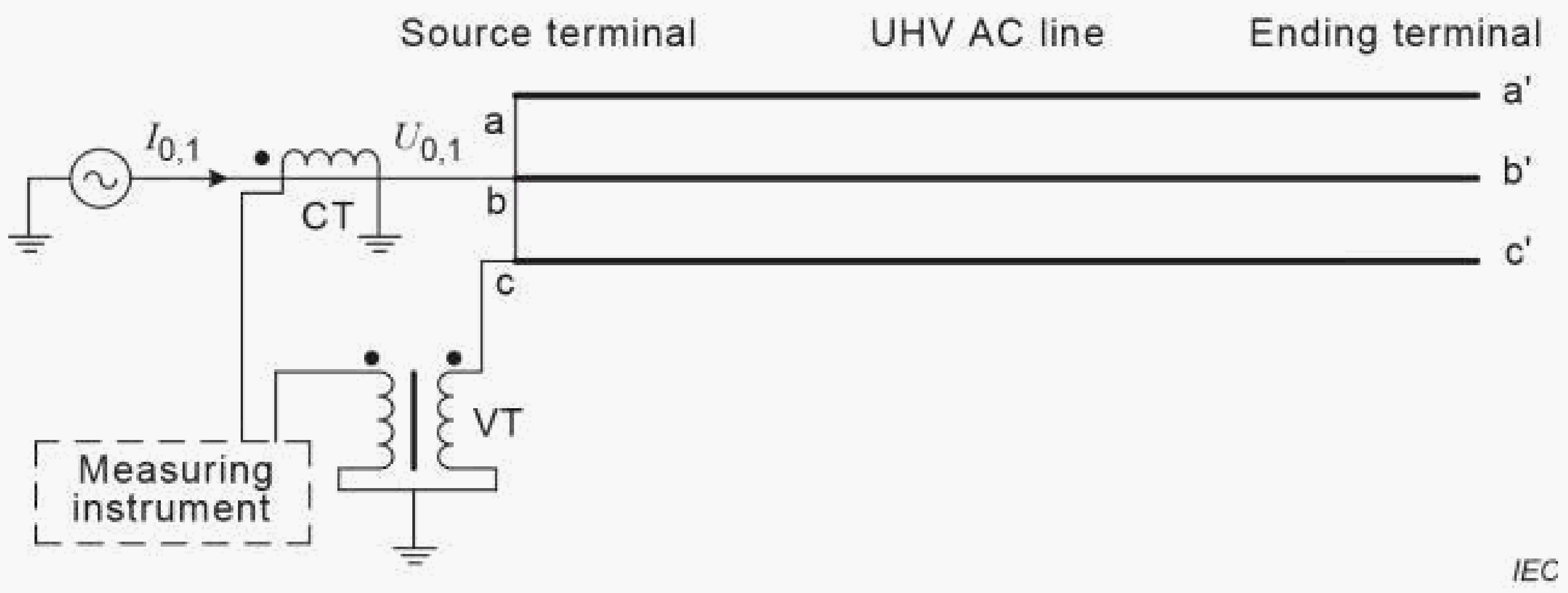
11 Measurement of zero-sequence parameter

The zero-sequence parameters can be also measured by one-terminal measurement method which is the same as for positive-sequence parameters, and calculated by transmission line equations. As shown in Figure 8 a) and Figure 8 b), the measurement procedure is as follows.

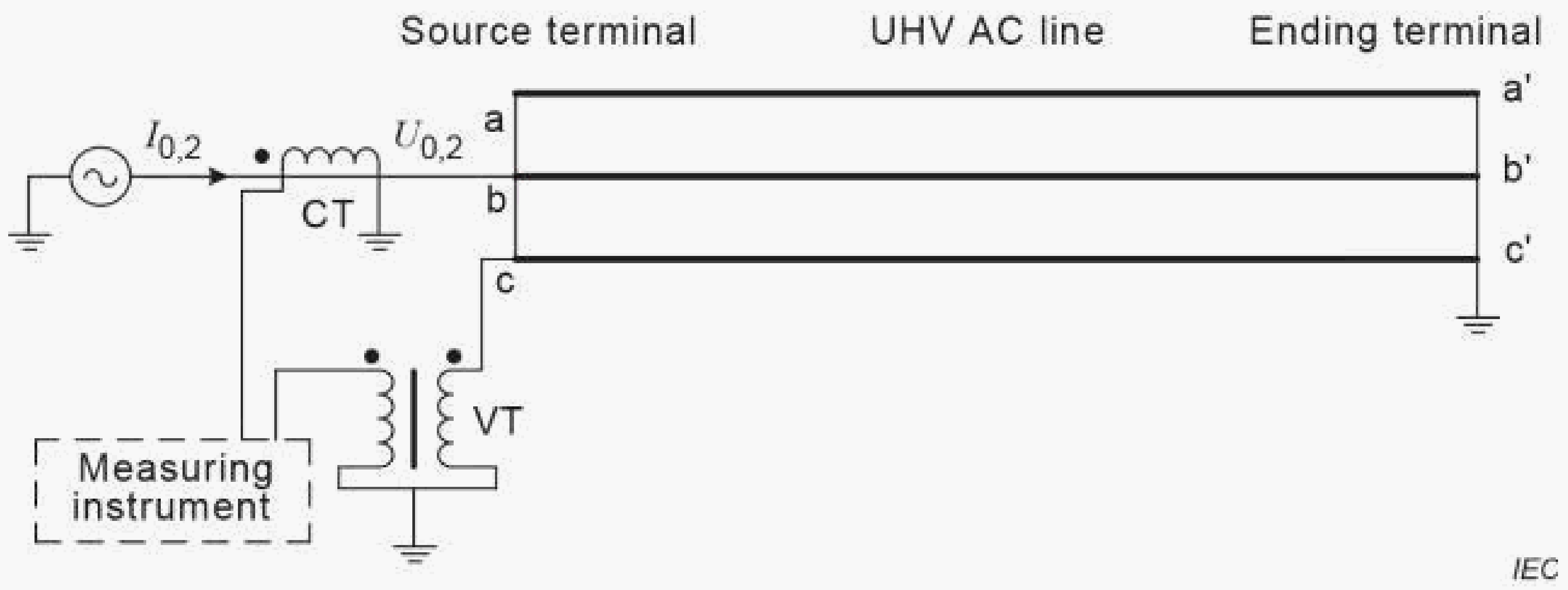
Firstly, the three phases should be disconnected at the ending terminal and then a single phase source should be applied to the three phases shorted at the source terminal. Measure the single phase voltage $U_{0,1}$ and current $I_{0,1}$ at the source terminal.

Secondly, the three phases should be earthed at the ending terminal and then a single phase test power source should be applied to the three phases connected at the source terminal. Measure the single phase voltage $U_{0,2}$ and current $I_{0,2}$ at the source terminal.

For double-circuit transmission lines on the same tower, when measuring the zero-sequence parameter of one circuit transmission line, the two terminals of the other transmission line should be disconnected.



a) The line at the ending terminal is disconnected



b) The line at the ending terminal is earthed

Figure 8 – Measurement of zero-sequence parameter

Zero-sequence impedance and capacitance can be calculated according to the equations in Table 2.

Table 2 – The calculation method of zero-sequence parameters

	Calculation of zero-sequence parameters	
Measured voltage and current	$U_{0,1}$, $I_{0,1}$	$U_{0,2}$, $I_{0,2}$
Characteristic impedance	$Z_{c,0} = \sqrt{\frac{U_{0,1}}{I_{0,1}}\frac{U_{0,2}}{I_{0,2}}}$	
Propagation coefficient	$\lambda_0 = \frac{\operatorname{arcoth}\sqrt{\frac{U_{0,2}}{I_{0,2}}\frac{I_{0,1}}{U_{0,1}}}}{L}$	
Zero-sequence impedance	$z_0 = Z_{c,0}\lambda_0$	
Zero-sequence resistance	$r_0 = \mathrm{Re}(z_0)$	
Zero-sequence reactance	$x_0 = \mathrm{Im}(z_0)$	
Zero-sequence admittance	$y_0 = \lambda_0 / Z_{c,0}$	
Zero-sequence capacitance	$c_0 = \frac{\mathrm{Im}(y_0)}{\omega}$	

12 Measurement of mutual impedance and coupling capacitance between double-circuit transmission lines on the same tower

12.1 General

The measurement principle of the coupling parameters between the double-circuit lines on the same tower is mainly based on the two-phase AC system and its phase-mode transformation. The phase-mode transformation between phase parameter and mode parameter for two-phase systems is given in [4]:

$$z_0 = z_s + z_m \tag{7}$$

$$z_1 = z_s - z_m \tag{8}$$

$$c_0 = c_s + c_m \tag{9}$$

$$c_1 = c_s - c_m \tag{10}$$

where

z_0 is the ground-mode impedance;

z_1 is the line-mode impedance;

c_0 is the ground-mode capacitance;

c_1 is the line-mode capacitance;

z_s is the self-impedance of one phase;

z_m is the mutual impedance between two phases;

c_s is the self-capacitance of one phase;

c_m is the minus of the coupling capacitance between two phases.

Therefore, z_m and c_m are given by

$$z_m = \left(z_0 - z_1\right) / 2 \tag{11}$$

$$c_m = \left(c_0 - c_1\right) / 2 \tag{12}$$

If three phases of each circuit of the double-circuit lines on the same tower are regarded as one phase, double-circuit lines on the same tower can be regarded as two phases of one line. Therefore, the line-mode and ground-mode parameters of two phases of one line can be measured, and the mutual impedance and coupling capacitance between double-circuit lines can be calculated based on the measured line-mode and ground-mode parameters according to Equations (11) and (12). The measurement procedures are described in [5].

12.2 Measurement of line-mode impedance

For each circuit of the measured double-circuit lines, connect three phases of each circuit at the source terminal and short all phases of the double-circuit lines at the ending terminal. Apply a two-phase test power source with identical voltage amplitudes and symmetrical phase angles at the source terminal of the double-circuit lines. Measure the voltages $U_{1,SC}$ and $U_{2,SC}$ and the currents $I_{1,SC}$ and $I_{2,SC}$ at the source terminal, as shown in Figure 9.

NOTE The symmetrical phase angles mean that the difference of phase angles between the two phases is 180°.

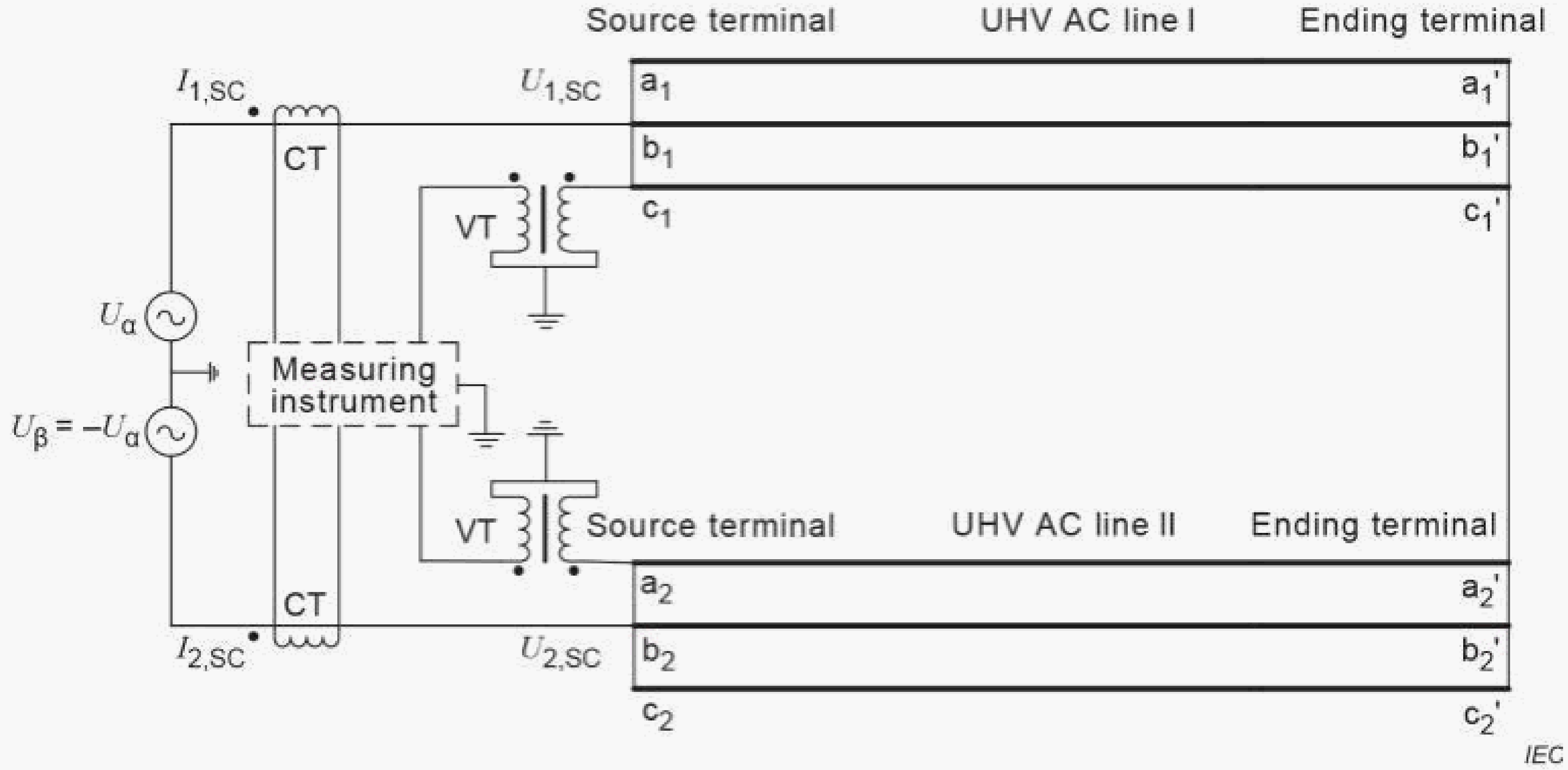


Figure 9 – Measurement of line-mode impedance

12.3 Measurement of line-mode capacitance

For each circuit of the measured double-circuit lines, connect the three phases of each circuit at the source terminal and disconnect all phases at the ending terminal. Apply a two-phase test power source with identical voltage amplitudes and symmetrical phase angles at the source terminal of the double-circuit lines. Measure the voltages $U_{1,OC}$ and $U_{2,OC}$, and the currents $I_{1,OC}$ and $I_{2,OC}$ at the source terminal, as shown in Figure 10.

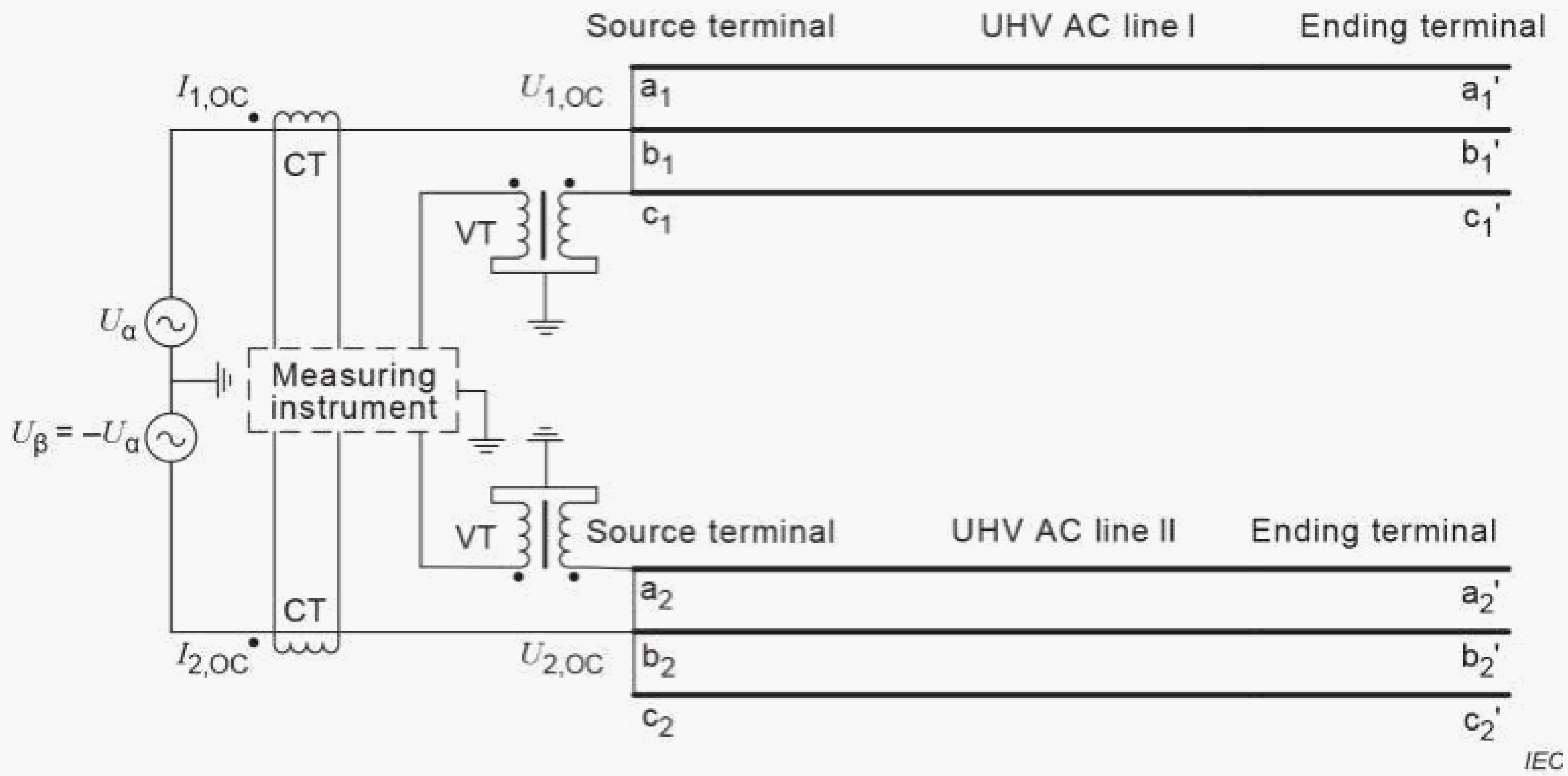


Figure 10 – Measurement of line-mode capacitance

12.4 Measurement of ground-mode impedance

Connect all phases of the two lines at the source terminal and earth all phases of the two lines at the ending terminal.

Apply a single-phase test power source at the source terminal. Measure voltage $U_{0,SC}$ and current $I_{0,SC}$ at the source terminal, as shown in Figure 11.

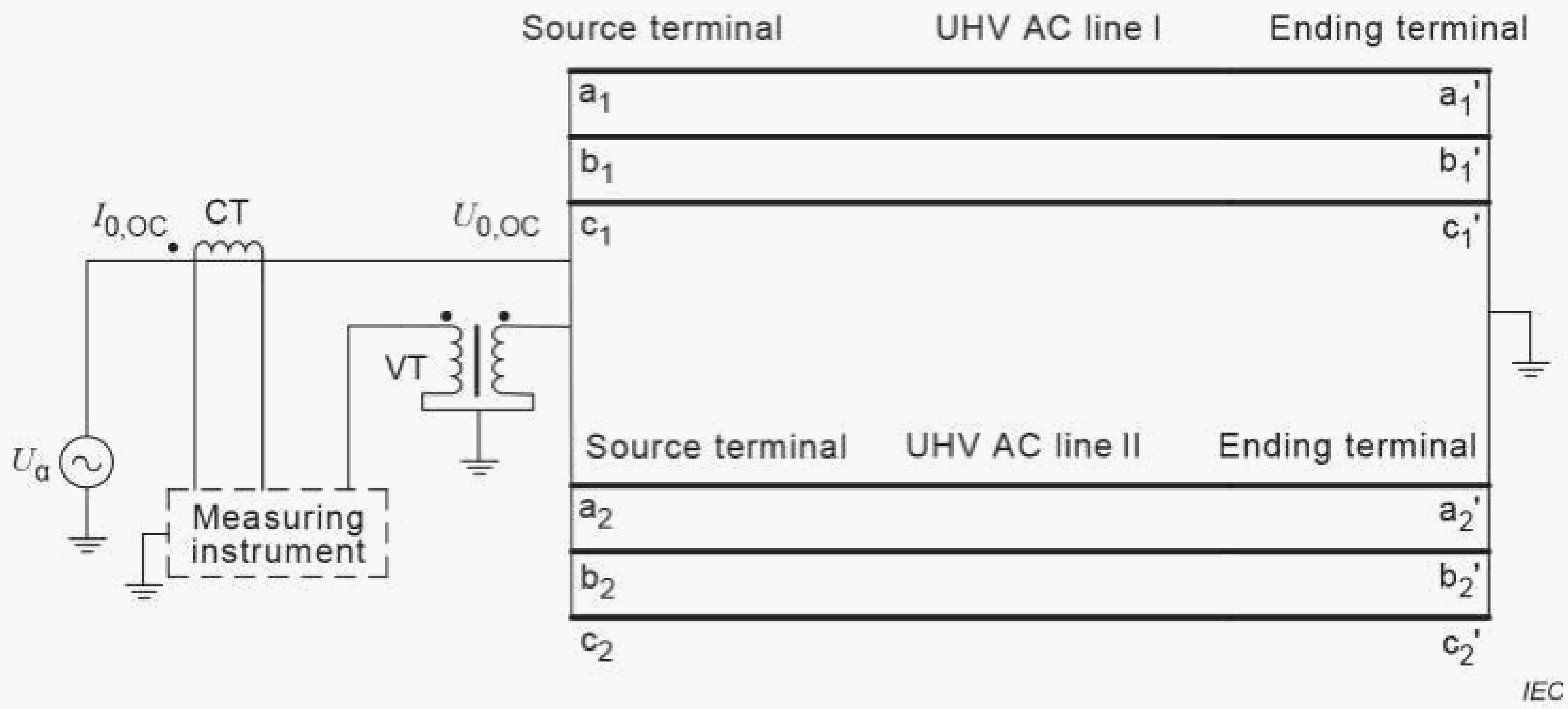


Figure 11 – Measurement of ground-mode impedance

12.5 Measurement of ground-mode capacitance

Connect all phases of the two lines at the source terminal and disconnect all phases of the two lines at the ending terminal. Apply a single-phase test power source at the source terminal. Measure voltage $U_{0,OC}$ and current $I_{0,OC}$ at the source terminal, as shown in Figure 12.

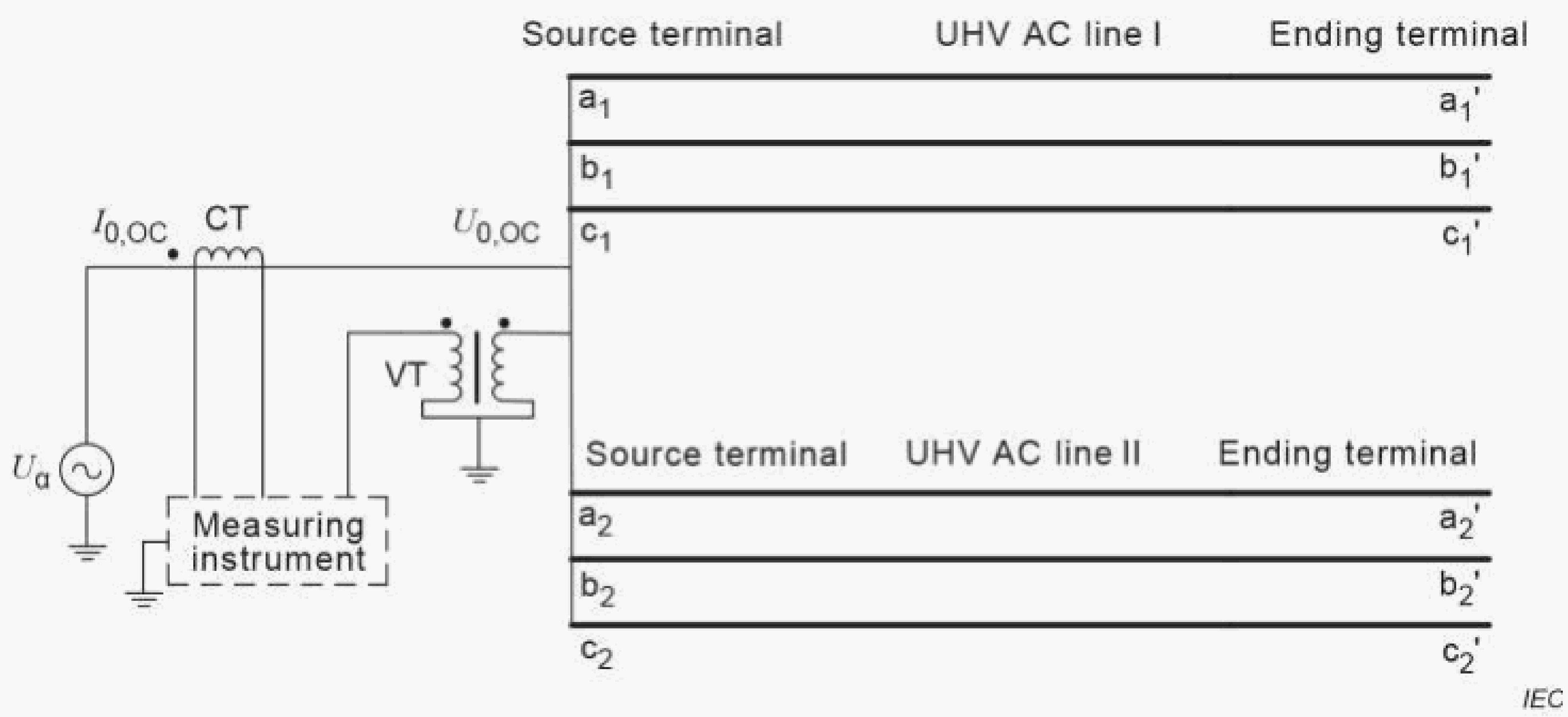


Figure 12 – Measurement of ground-mode capacitance

12.6 Data process

Coupling parameter calculation of double-circuit lines on the same tower is shown in Table 3.

Table 3 – Calculation process and equations of parameters per unit length of double-circuit lines on the same tower

	Line-mode parameters		Ground-mode parameters	
	$Z_{1,1\text{-}2,oc} = \dfrac{U_{1,oc} - U_{2,oc}}{I_{1,oc} - I_{2,oc}}$	$Z_{1,1\text{-}2,sc} = \dfrac{U_{1,sc} - U_{2,sc}}{I_{1,sc} - I_{2,sc}}$	$Z_{0,oc} = \dfrac{U_{0,oc}}{I_{0,oc} / 2}$	$Z_{0,cs} = \dfrac{U_{0,sc}}{I_{0,sc} / 2}$
Characteristic impedance	$Z_{c,1,1\text{-}2} = \sqrt{Z_{1,1\text{-}2,oc} Z_{1,1\text{-}2,sc}}$		$Z_{c,0} = \sqrt{Z_{0,oc} Z_{0,sc}}$	
Propagation coefficient	$\lambda_1 = \dfrac{\text{arcoth}\sqrt{\dfrac{Z_{1,1\text{-}2,oc}}{Z_{1,1\text{-}2,sc}}}}{L}$		$\lambda_0 = \dfrac{\text{arcoth}\sqrt{\dfrac{Z_{0,oc}}{Z_{0,sc}}}}{L}$	
Impedance per unit length	$z_1 = Z_{c,1,1\text{-}2} \lambda_1$		$z_0 = Z_{c,0} \lambda_0$	
Admittance per unit length	$y_1 = \lambda_1 / Z_{c,1,1\text{-}2}$		$y_0 = \lambda_0 / Z_{c,0}$	
Mutual impedance between double-circuit	$z_m = (z_0 - z_1) / 2$			
Coupling capacitance between double-circuit	$c_m = \text{Im}(y_0 - y_1) / 2$			

NOTE L represents the length of transmission line.

13 Measurement of phase parameters

13.1 Measurement of self-impedance

The self-impedance of one phase is generated by the loop formed through one phase ground. In order to eliminate the influence of the other phases during measurement, the other phases at the two terminals should be disconnected. Two-terminal synchronous measurement method is used to obtain the accurate self-impedance [6].

As shown in Figure 13, earth the phase to be measured a_1 of the double-circuit transmission line on the same tower at the ending terminal, while all other phases are disconnected at the two terminals. Apply a single phase test power source to phase a_1 at the source terminal. Measure the voltage $U_{si,1}$ and the current $I_{si,1}$ at the source terminal and the current $I'_{si,1}$ at the ending terminal.

Repeat the same procedures for self-impedance measurement of the other phases.

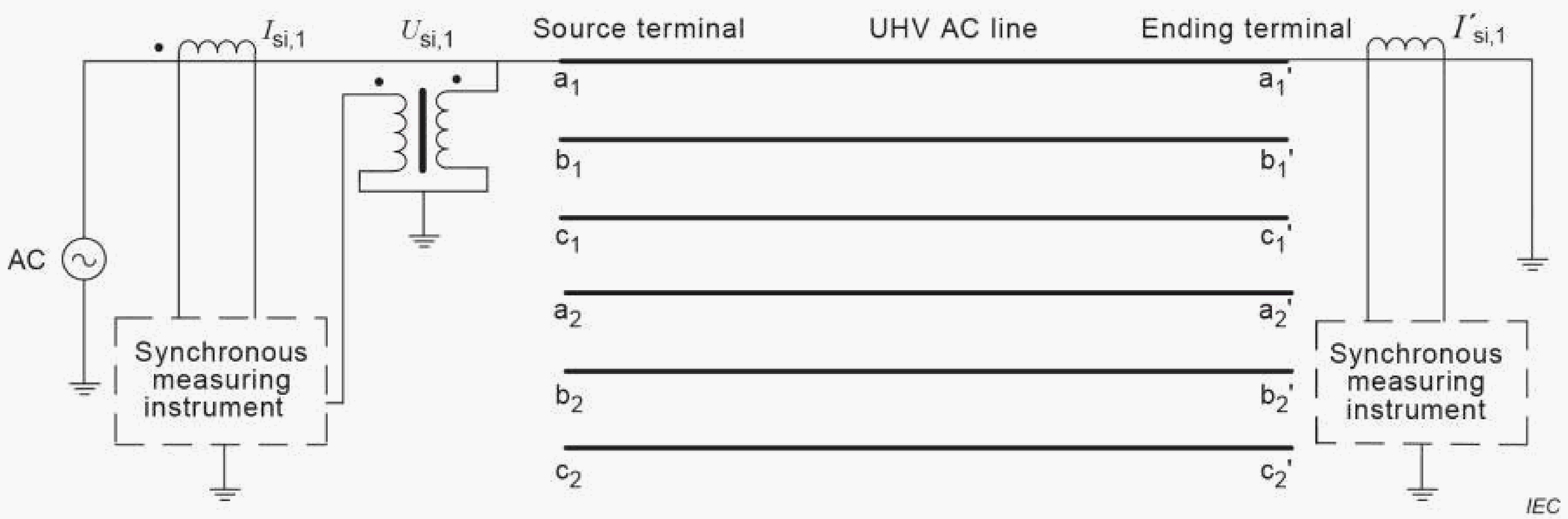


Figure 13 – Measurement of self-impedance by two-terminal synchronous measurement method

Self-impedance can be calculated according to the equations in Table 4.

Table 4 – The calculation of self-impedance

	Calculation of self-impedance
Voltage and current at the source terminal	$U_{si,1}$, $I_{si,1}$
Current at the ending terminal	$I'_{si,1}$
Characteristic impedance	$Z_{c,si} = \dfrac{U_{si,1}}{I'_{si,1}\sinh(\lambda_{0,si}L)}$
Propagation coefficient	$\lambda_{0,si} = \dfrac{\operatorname{arcosh}(I_{si,1}/I'_{si,1})}{L}$
Impedance	$z_{si} = Z_{c,si}\lambda_{0,si}$
Resistance	$r_{si} = \operatorname{Re}(z_{si})$
Reactance	$x_{si} = \operatorname{Im}(z_{si})$

NOTE L represents the length of transmission line.

13.2 Measurement of self-capacitance

Self-capacitance of one phase is the sum of capacitances between one phase and the other phases and capacitance between one phase and earth. When self-capacitance of one phase is measured, in order to avoid the influence of the other phases, the other phases at the two terminals should be earthed. Two-terminal synchronous measurement method is used to obtain the accurate self-capacitance.

As shown in Figure 14, disconnect the phase to be measured a_1 of the double-circuit transmission line on the same tower at the ending terminal, while all other phases should be earthed at the two terminals. Apply a single phase test power source to the measured phase a_1 at the source terminal. Measure the voltage $U_{sc,1}$ and current $I_{sc,1}$ at the source terminal and the voltage $U'_{sc,1}$ at the ending terminal.

Repeat the same procedures for self-capacitance measurement of all other phases.

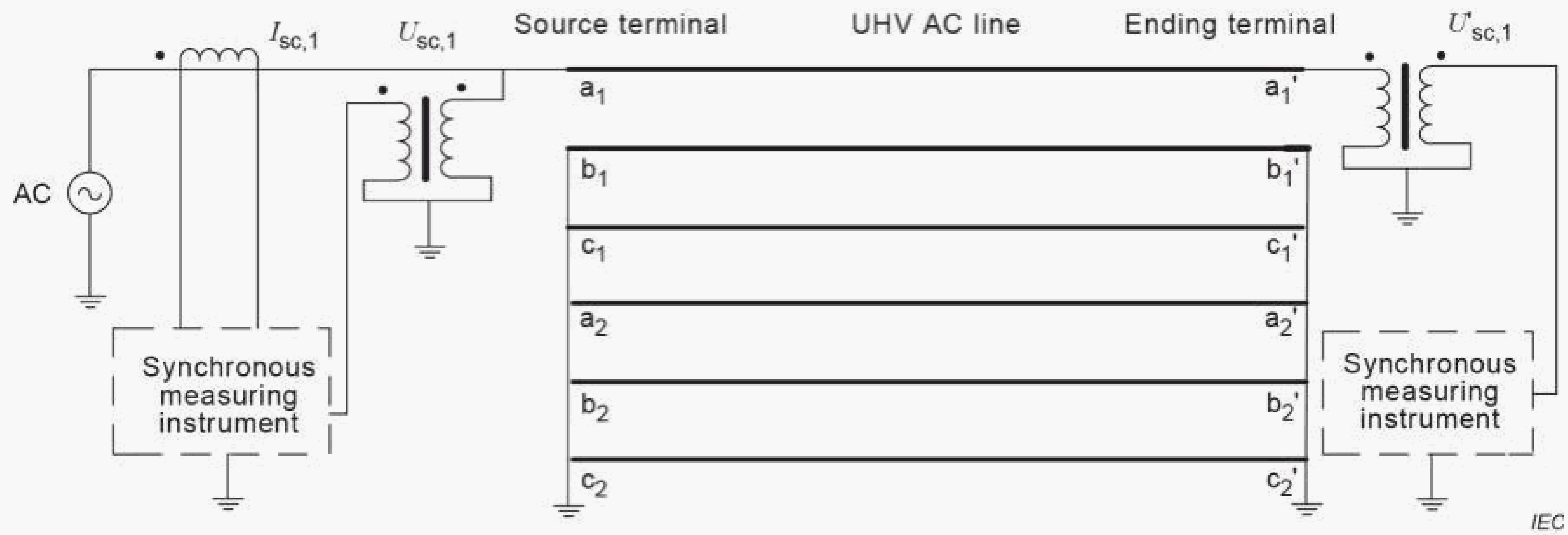


Figure 14 – Measurement of self-capacitance by two-terminal synchronous measurement method

Self-capacitance can be calculated according to the equations in Table 5.

Table 5 – The calculation of self-capacitance

	Calculation of self-capacitance
Voltage and current at the source terminal	$U_{sc,1}$, $I_{sc,1}$
Current at the ending terminal	$U'_{sc,1}$
Characteristic impedance	$Z_{c,sc} = \frac{U'_{sc,1}\sinh(\lambda_{sc}L)}{I_{sc,1}}$
Propagation coefficient	$\lambda_{sc} = \frac{\text{arcosh}(U_{sc,1}/U'_{sc,1})}{L}$
Admittance	$y_{sc} = \lambda_{sc} / Z_{c,sc}$
Capacitance	$c_{sc} = \frac{\mathrm{Im}(y_{sc})}{\omega}$

NOTE $\omega = 2\pi f$ represents the angular frequency; L represents the length of transmission line.

13.3 Measurement of coupling capacitance between two phases

The coupling capacitance is the capacitance between any two phases, including the coupling capacitance between the two phases of the same circuit and the coupling capacitance between two phases of different circuits in double-circuit transmission lines on the same tower. When measuring the coupling capacitance between two phases, the electromagnetic coupling of the other phases has an influence on the measurement. In order to eliminate the influence, it is necessary to use two-terminal synchronous measurement and decoupling calculation method to obtain accurate coupling capacitance.

As shown in Figure 15, for double-circuit lines on the same tower, phase a_1 is disconnected at the ending terminal, while all the other phases should be earthed at the source terminal and disconnected at the ending terminal. Apply a single phase test power source to phase a_1 at the source terminal and measure the voltage U_{11} of phase a_1 at the source terminal and the voltage U_{12} of the phase a_1 at the ending terminal, and the current I_{211} of phase b_1 at the source terminal and voltage U_{212} of phase b_1 at the ending terminal synchronously.

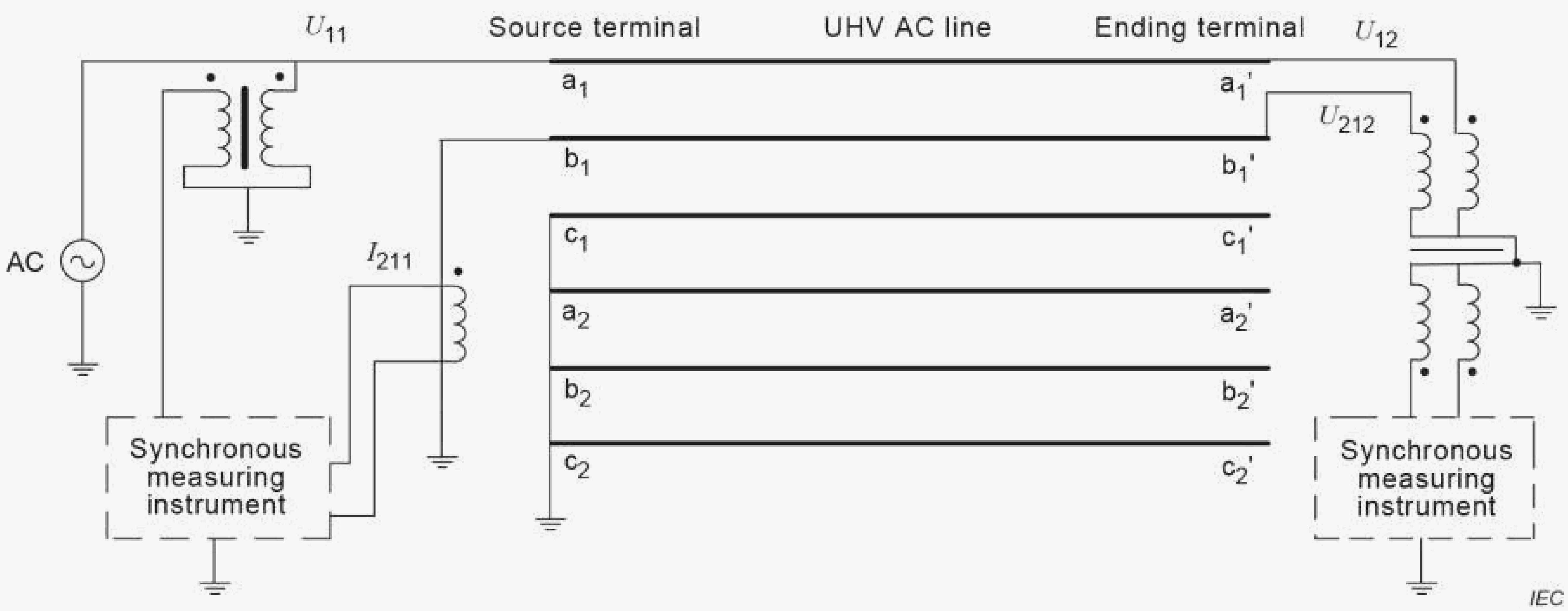


Figure 15 – Measurement of coupling capacitance between two phases

Then, apply a test power source to phase a_1 at the source terminal, and measure the voltage of phase a_1 at the source terminal, the voltage of phase a_1 at the ending terminal, the grounding currents in the phases c_1, a_2, b_2, c_2 as I_{311}, I_{411}, I_{511}, and I_{611} of the other phases at the source terminal and the corresponding voltages U_{312}, U_{412}, U_{512}, U_{612} of the other phases at the ending terminal synchronously.

After that, apply the test power source one by one to phase b_1, c_1, a_2, b_2, c_2 at the source terminal. Similar to the measurement at phase a_1, apply a test power source to the phase to be tested and disconnect this phase at the ending terminal, while all other phases are earthed at the source terminal and disconnected at the ending terminal. Measure the voltage of the phase connected with the test power source at two terminals, the grounding currents of all other phases at the source terminal and the voltages of all other phases at the ending terminal synchronously.

For N-phase system, the calculation equation is shown here:

$$Y_{ij}\left(U_{i1}+U_{i2}\right)-U_{ji2}\,\frac{\tanh\left(\sqrt{z_j y_j}\,L/2\right)}{\sqrt{z_j y_j}\,L/2}\cdot\left(y_j L\right)\sum_{m=1}^{N}Y_{jm}=2I_{ji1},\quad m\neq j \tag{13}$$

where

- i is the phase at which the test power source is applied, take 1 to N-1;
- j is the phase at which the test power source is not applied, take i-1 to N;
- Y_{ij} is the mutual admittance between phase i and phase j;
- z_j is the self-impedance per unit length of phase j;
- y_j is the self-admittance per unit length of phase j.

The N-phase conductor system can list 1 + 2 +3 +…N-1 element equations with 1 + 2 +3 +…N-1 unknowns, and all the mutual admittance Y_{ij} can be obtained by solving the equation set. Then the coupling capacitance per unit length can be calculated.

$$c_{ij}=Y_{ij}/\left(L\cdot j\omega\right) \tag{14}$$

See Annex B for details.

13.4 Measurement of mutual impedance between two phases

Mutual impedance between two phases should be measured after self-impedance, self-capacitance, and coupling capacitance have been measured. Mutual impedance between two phases include mutual impedance between two phases in the same circuit and mutual impedance between two phases of different circuits of double-circuit transmission lines on the same tower. One-terminal measurement method can be used to measure mutual impedance.

As shown in Figure 16, mutual impedance between phase a_1 and phase b_1 of double-circuit transmission lines on the same tower is measured. All phases are earthed at the ending terminal and disconnected at the source terminal. Apply a single phase test power source to phase a_1 at the source terminal, and measure the current I_{a1} of phase a_1 and the voltage U_{b1} of phase b_1 at the source terminal.

Repeat the same measurement procedures for the other phases.

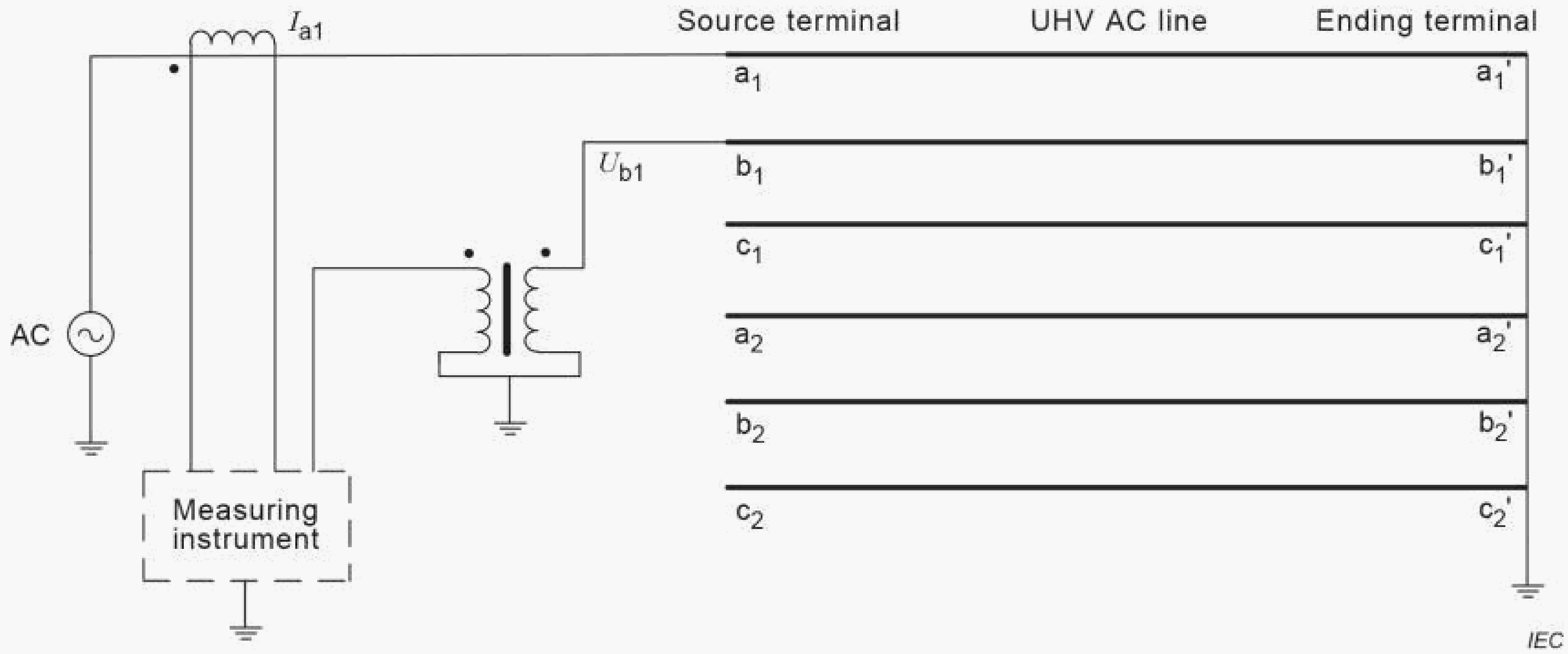


Figure 16 – Measurement of mutual impedance between two phases

For short-distance transmission line, a simple calculation method can be applied without considering the influence of distributed parameter characteristics. The mutual impedance per unit length between two phases can be calculated according to the following equation:

$$z_{mu} = U_{b1} / \left(I_{a1} L \right) \tag{15}$$

where

L is the total length of the measured line.

For transmission lines with length over 150 km, due to the obvious influence of distributed parameter characteristics, the following method should be adopted to calculate the mutual impedance between phase a1 and phase b1.

$$z_{mu,a1b1} = \frac{Z_{mu,a1b1}}{L} = U_{b1} \Bigg/ \left(\frac{\tanh\left(\sqrt{z_{a1} y_{a1}} L\right)}{\sqrt{z_{a1} y_{a1}} L} \cdot \frac{\tanh\left(\sqrt{z_{b1}\left(y_{b1b1} - (y_{b1c1} + y_{b1a2} + y_{b1b2} + y_{b1c2})\right)} L\right)}{\sqrt{z_{b1}\left(y_{b1b1} - (y_{b1c1} + y_{b1a2} + y_{b1b2} + y_{b1c2})\right)} L} \cdot I_{a1} L \right) \tag{16}$$

where

z_{a1} is the self-impedance per unit length of phase a1;

y_{a1} is the self-admittance per unit length of phase a1;

z_{b1} is the self-impedance per unit length of phase b1;

y_{b1b1} is the self-admittance per unit length of phase b1;

y_{b1c1} is the mutual admittance per unit length between phase b1 and phase c1;

y_{b1a2} is the mutual admittance per unit length between phase b1 and phase a2;

y_{b1b2} is the mutual admittance per unit length between phase b1 and phase b2;

y_{b1c2} is the mutual admittance per unit length between phase b1 and phase c2;

All the above mentioned parameters have been measured according to Subclauses 13.1 to 13.3.

Mutual impedance between any two phases is calculated by

$$z_{\mathrm{mu},mn} = \frac{Z_{\mathrm{mu},mn}}{L} = U_{n1} \Bigg/ \left(\frac{\tanh(\sqrt{z_m y_m} L)}{\sqrt{z_m y_m} L} \cdot \frac{\tanh\left(\sqrt{z_n \left(y_{nn} - \sum_{k=1}^{N} y_{nk} L\right)}\right)}{\sqrt{z_n \left(y_{nn} - \sum_{k=1}^{N} y_{nk}\right)} L} \cdot I_{m1} L \right), \quad k \neq m, \ k \neq n \tag{17}$$

where

m is the phase at which the test power source is applied;

n is the phase at which voltage at the source terminal is measured;

k are the phases which are not measured;

z_m is the self-impedance per unit length of phase m;

y_m is the self-admittance per unit length of phase m;

y_n is the self-admittance per unit length of the phase n;

y_{nk} is the mutual admittance per unit length between phase n and phase k.

All the above mentioned parameters have been measured previously.

Annex A
(informative)

Example of transmission line power frequency parameter measurement

A.1 Introduction of transmission line

Transmission line I and II are UHV AC double-circuit transmission lines on the same tower with a total length of each line of 336,6 km.

A.2 Measurement of positive-sequence parameter

A.2.1 Measured data

Based on one-terminal measurement method according to Clause 10, apply a three-phase test power source to the lines at the source terminal. Measure the three phase voltages and currents at the source terminal, and calculate the positive-sequence components of the three phase voltages and currents. Table A.1 shows the positive-sequence components of the voltages and currents at the source terminal of line I.

Table A.1 – Measured data of transmission line I

Measured data		Frequency of test power source 47,5 Hz	Frequency of test power source 52,5 Hz
The lines at the ending terminal are disconnected	Voltage / (V)	455,7 $e^{j10,\ 8°}$	460,4 $e^{-j58,6°}$
	Current / (A)	0,69 $e^{j100,\ 6°}$	0,78 e
The lines at the ending terminal are earthed	Voltage / (V)	113,4 $e^{j98,\ 8°}$	134,0 $e^{j31,3°}_{j38,\ 6°}$
	Current / (A)	1,35 $e^{j10,5°}$	1,43 $e^{-j49,\ 8°}$

A.2.2 Calculation results

The positive-sequence parameters are calculated according to the method in Table 1 of Clause 10. Then convert the parameters to the parameters at power frequency according to Clause 6. The results are shown in Table A.2.

Table A.2 – Positive-sequence parameters of transmission line I

Positive-sequence resistance /(mΩ·km $^{-1}$)	Positive-sequence reactance /(mΩ·km $^{-1}$)	Impedance angle /(°)	Positive-sequence capacitance /(nF·km $^{-1}$)
6,50	252,50	88,53	14,51

The measured DC resistance of transmission line I, shown in Table A.3, can be used as a reference to verify positive-sequence AC resistance. Due to skin effect, the positive-sequence AC resistance is about 10 % larger than the positive-sequence DC resistance.

Table A.3 – DC resistance of line I

DC resistance /(mΩ·km $^{-1}$)		Positive-sequence resistance /(mΩ·km $^{-1}$)
Phase **a**	6,1	6,5
Phase **b**	5,9	
Phase **c**	6,0	

A.3 Measurement of zero-sequence parameter

A.3.1 Measured data

Based on one-terminal measurement method, a single-phase test power source is connected to lines at the source terminal. The single-phase voltages and currents of the line were measured at the source terminal. Table A.4 shows the measured voltages and currents at the source terminal of transmission line I.

Table A.4 – Measured data of transmission line I

Measured data		Frequency of test power source 47,5 Hz	Frequency of test power source 52,5 Hz
The lines at the ending terminal are disconnected	Voltage / (V)	$389,5\ e^{-j61,7°}$	$356,3\ e^{-j134,1°}$
	Current / (A)	$1,01\ e^{j27,5°}$	$1,03\ e^{-j45,2°}$
The lines at the ending terminal are earthed	Voltage / (V)	$185,7\ e^{j134,7°}$	$202,6\ e^{j64,8°}$
	Current / (A)	$2,17\ e^{j55,9°}$	$2,12\ e^{-j14,1°}$

A.3.2 Calculation results

The zero-sequence parameters are calculated according to the method in Table 2 of Clause 11. Then the parameters are converted to the parameters at power frequency according to Clause 6. The results are shown in Table A.5.

Table A.5 – Zero-sequence parameters of transmission line I

Zero-sequence resistance /(mΩ·km $^{-1}$)	Zero-sequence reactance /(mΩ·km $^{-1}$)	Impedance angle /(°)	Zero-sequence capacitance /(nF·km $^{-1}$)
127,0	738,0	80,24	8,03

A.4 Measurement of phase parameter

A.4.1 General

According to the measurement methods of Clause 13, the phase parameters of transmission lines I and II are measured and calculated. The results are shown in Table A.6, Table A.7 and Table A.8. In the tables, a_1, b_1 and c_1 represent the phase a, phase b and phase c of line I, and a_2, b_2 and c_2 represent the phase a, phase b and phase c of line II.

A.4.2 Capacitance matrix

The self-capacitance and coupling capacitance of line I and II are calculated, as shown in Table A.6, where the diagonal data are self-capacitances and off-diagonal data are coupling capacitances.

Table A.6 – The capacitance matrix of transmission line I and II

Phase labels	Self-capacitance and coupling capacitance / (nF/km)					
	a_1	b_1	c_1	a_2	b_2	c_2
a_1	12,7	1,880	1,918	0,598	0,956	1,033
b_1		12,7	1,970	1,075	0,599	0,958
c_1			12,9	0,949	1,001	0,674
a_2				12,9	1,881	1,936
b_2					12,6	1,960
c_2						12,6

A.4.3 Impedance matrix

The self-impedance and mutual impedance of line I and line II are calculated, as shown in Table A.7 and Table A.8. The diagonal data are self-impedance and the off-diagonal data are coupling impedance, where X denotes reactance, R denotes resistance.

Table A.7 – The resistance matrix of transmission line I and II

Phase labels	R (mΩ/km)					
	a_1	b_1	c_1	a_2	b_2	c_2
a_1	49,0	41,31	41,17	41,21	43,09	42,87
b_1		48,08	41,90	39,13	41,56	39,58
c_1			48,27	40,47	39,57	41,49
a_2				47,52	40,54	40,23
b_2					47,71	41,73
c_2						47,43

Table A.8 – The reactance matrix of transmission line I and II

Phase labels	X (mΩ/km)					
	a_1	b_1	c_1	a_2	b_2	c_2
a_1	410,6	155,54	158,44	124,12	137,77	141,24
b_1		414,2	160,70	138,93	127,66	136,98
c_1			416,4	138,81	138,14	127,22
a_2				404,1	151,55	152,51
b_2					406,9	152,54
c_2						401,5

Annex B
(informative)

Derivation process of measurement and calculation for coupling capacitance between two phases

Due to the influence of capacitance between lines and earth, the measurement of the coupling capacitance between two phases which is longer than 200 km should adopt the two-terminal synchronous measurement method.

Figure B.1 shows the schematic diagram of π-type equivalent circuit measurement of the 3-phase system. Based on Figure B.1, the equation of coupling capacitance of N-phase line system is deduced. By ignoring conductance in admittance, only the susceptance is taken into consideration.

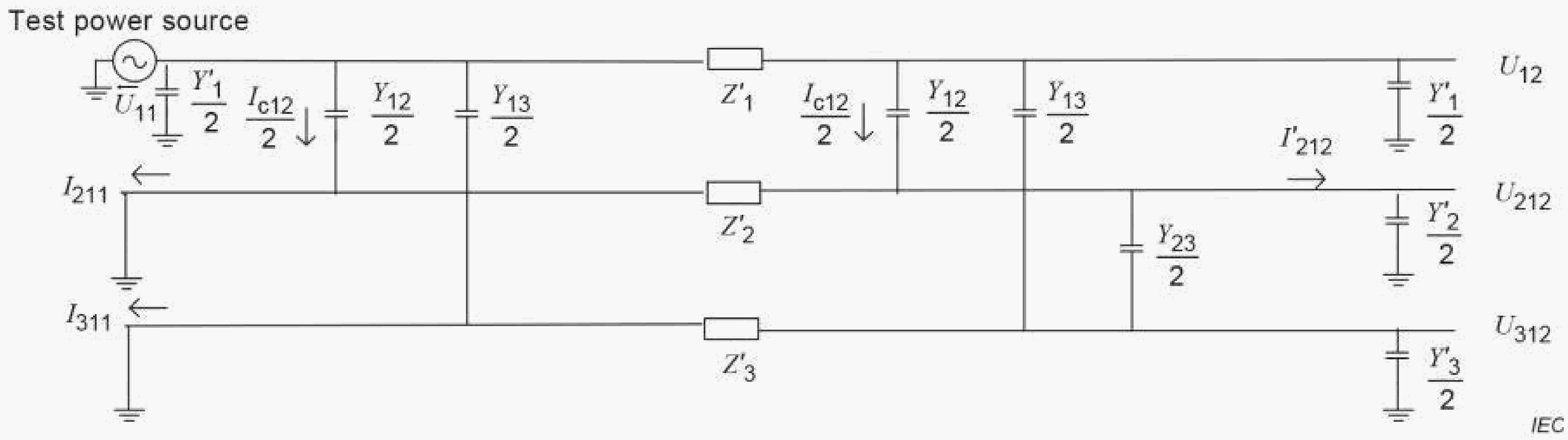


Figure B.1 – The π-equivalent circuit of 3-phase system during measurement

In Figure B.1, phase 1 should be disconnected at the ending terminal, while the other two phases are earthed at the source terminal and disconnected at the ending terminals. Apply a test power source to phase 1 at the source terminal. Measure the voltages of the phase 1 at the two terminals, while measuring the currents of the other two phases at the source terminal and the voltages of the other two phases at the ending terminal.

Y_{12} is the mutual admittance between phase 1 and phase 2;

I_{c12} is the sum of current I_{211} at the source terminal and current I'_{212} at the ending terminal of phase 2.

Equation (B.1) can be obtained from Figure B.1.

$$I_{211}+I'_{212}=U_{11}\cdot\frac{Y_{12}}{2}+(U_{12}-U_{212})\cdot\frac{Y_{12}}{2} \quad \text{(B.1)}$$

Equation (B.2) can be obtained from Figure B.1.

$$I'_{212}=U_{212}\cdot Y'_2/2 \quad \text{(B.2)}$$

By substituting Equation (B.2) into Equation (B.1), we can obtain Equation (B.3).

$$Y_{12}=\frac{I_{211}+U_{212}(Y'_2/2)}{(U_{11}+U_{12}-U_{212})/2} \quad \text{(B.3)}$$

In the subscript of U_{abc}, the first number a represents phase number 1, 2, 3, 4, 5 or 6 of the line. The second number b represents the phase at which the test power source is applied. The third number c represents the source terminal or ending terminal, 1 denotes source terminal and 2 denotes ending terminal. For example, U_{212} represents the voltage of the ending terminal of phase 2 when a power source is applied to phase 1. The subscript for the currents is identical.

Since U_{212} is the induced voltage, far less than $U_{11} + U_{12}$, U_{212} in the denominator can be ignored. Y'_2 is the total admittance between phase 2 and earth. The total self-admittance of phase 2 is Y'_{22}. Then, Y'_2 can be obtained by Equation (B.4):

$$Y_2' = Y_{22}' - Y_{21} - Y_{23} \tag{B.4}$$

If the total self-admittance of the equivalent circuit with distributed parameters in the phase 2 is Y_2, then the total self-admittance Y'_{22} in the π equivalent circuit can be obtained by the conversion from the total self-admittance Y_2 of the equivalent circuit with distributed parameters. The conversion method is shown by Equation (B.5)

$$Y_{22}' = k_2 Y_2 = k_2 (y_2 L) \tag{B.5}$$

where

$$k_2 = \frac{\tanh(\sqrt{z_2 y_2} L / 2)}{\sqrt{z_2 y_2} L / 2}$$

where

z_2 is the self-impedance per unit length;

y_2 is the self-admittance per unit length,

both measured previously.

By substituting Equation (B.5) into Equation (B.4) and Equation (B.3), the mutual admittance of phase 1 and phase 2 can be obtained by:

$$Y_{12}\left(U_{11} + U_{12}\right) - U_{212}\left(k_2\left(y_2 L\right) - Y_{21} - Y_{23}\right) = 2 I_{211} \tag{B.6}$$

where $Y_{12} = Y_{21}$. There are the two unknown mutual admittances Y_{21} and Y_{23} in the equation and therefore it cannot be solved.

Similarly, the mutual admittance equations between phase 1 and phase 3, phase 2 and phase 3 are shown in Equation (B.7) and Equation (B.8) separately.

$$Y_{13}\left(U_{11} + U_{12}\right) - U_{312}\left(k_3\left(y_3 L\right) - Y_{31} - Y_{32}\right) = 2 I_{311} \tag{B.7}$$

$$Y_{23}\left(U_{21} + U_{22}\right) - U_{322}\left(k_3\left(y_3 L\right) - Y_{31} - Y_{32}\right) = 2 I_{321} \tag{B.8}$$

where $Y_{13} = Y_{31}$ and $Y_{23} = Y_{32}$.

By solving Equations (B.6), (B.7) and (B.8), the mutual admittance Y_{12}, Y_{13} and Y_{23} can be obtained, and the coupling capacitance per unit length is

$$c_{ij} = Y_{ij} / (L \cdot j\omega) \tag{B.9}$$

The above method is extended to the measurement and calculation of coupling capacitance of N-phase line system, and the mutual admittance equation between any phase i and phase j is given in Equation (B.10).

$$Y_{ij}(U_{i1} + U_{i2}) - U_{ji2}\left(\frac{\tanh(\sqrt{z_j y_j} L/2)}{\sqrt{z_j y_j} L/2} \cdot (y_j L) - \sum_{m=1}^{N} Y_{jm}\right) = 2I_{ji1} \tag{B.10}$$

with $m \neq j$, i from 1 to N-1, and j from i+1 to N.

For a N-phase line system, N-element equations with N unknowns can be listed, all the mutual admittances are solved and then the coupling capacitances can be calculated.

For the double-circuit transmission lines on the same tower, the following 15-element equations can be listed to obtain the coupling capacitance.

When the test power source is applied to phase 1, Equation (B.11) can be obtained.

$$Y_{1j}(U_{11} + U_{12}) - U_{j12}\left(\frac{\tanh(\sqrt{z_j y_j} L/2)}{\sqrt{z_j y_j} L/2} \cdot (y_j L) - \sum_{m=1}^{N} Y_{jm}\right) = 2I_{j11},\ j = 2,3,4,5,6 \tag{B.11}$$

When the power source is applied to phase 2, Equation (B.12) can be obtained.

$$Y_{2j}(U_{21} + U_{22}) - U_{j22}\left(\frac{\tanh(\sqrt{z_j y_j} L/2)}{\sqrt{z_j y_j} L/2} \cdot (y_j L) - \sum_{m=1}^{N} Y_{jm}\right) = 2I_{j21},\ j = 3,4,5,6 \tag{B.12}$$

When the power source is applied to phase 3, Equation (B.12) can be obtained.

$$Y_{3j}(U_{31} + U_{32}) - U_{j32}\left(\frac{\tanh(\sqrt{z_j y_j} L/2)}{\sqrt{z_j y_j} L/2} \cdot (y_j L) - \sum_{m=1}^{N} Y_{jm}\right) = 2I_{j31},\ j = 4,5,6 \tag{B.13}$$

When the power source is applied to phase 4, Equation (B.14) can be obtained.

$$Y_{4j}(U_{41} + U_{42}) - U_{j42}\left(\frac{\tanh(\sqrt{z_j y_j} L/2)}{\sqrt{z_j y_j} L/2} \cdot (y_j L) - \sum_{m=1}^{N} Y_{jm}\right) = 2I_{j41},\ j = 5,6 \tag{B.14}$$

When the power source is applied to phase 5, Equation (B.15) can be obtained.

$$Y_{5j}(U_{51} + U_{52}) - U_{j52}\left(\frac{\tanh(\sqrt{z_j y_j} L/2)}{\sqrt{z_j y_j} L/2} \cdot (y_j L) - \sum_{m=1}^{N} Y_{jm}\right) = 2I_{j51},\ j = 6 \tag{B.15}$$

Annex C
(informative)

Safety precautions

During the parameter measurement of a transmission line, power frequency induced voltage and current could exist. Sometimes the induced voltage could be over tens of kilovolts and induced current could be hundreds of amperes or higher. It is noteworthy that the induced voltage is extremely high when both terminals are disconnected. High frequency induced voltage and current endanger the safety of operators and measuring instrument, while they increase the difficulty of separating between offset frequency measuring signal and power frequency induced voltage and current signal. Safety measures should thus be taken to minimize the induced voltage and current.

- In order to decrease the induced current of the measuring circuit, impedance can be connected in series between the test power source and the measured line. In order to decrease the AC component of the induced voltage, a capacitor can be connected to the ground between the test power source and the measured line.
- To ensure safety during measurements, operators shall wear personal protective equipment, such as insulation shoes, gloves, mats, safety belts, etc.
- Transmission lines shall be solidly grounded when the measuring mode is changed, in order to ensure the safety of instruments and personnel. The grounding wire of the test circuit shall be solidly grounded when not measured. Any wire used in the measurement shall be insulated and shall be able to withstand induced voltage and current.
- It is necessary to install a protective gap between the grounding wire and the down-lead to protect operators and measuring equipment from lightning strokes.
- The substation earthing grid should serve as protective grounding, neutral point grounding and short-circuit grounding. The grounding point of the transmission tower is prohibited to be the grounding point of the measurement.
- Personnel participating in the measurement shall follow the safety codes of electric utilities and take adequate protective measures. Safety measures shall be checked to meet regulatory requirements.

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