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IEEE Std C57.15™

Power transformers –
Part 21: Standard requirements, terminology, and test code for step-voltage regulators

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FOREWORD

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International Standard IEC 60076-21/IEEE Std C57.15-2017 has been prepared by IEC technical committee 14: Power transformers, in cooperation with the Transformers Committee of the IEEE Power and Energy Society[1], under the IEC/IEEE Dual Logo Agreement.

This publication is published as an IEC/IEEE Dual Logo standard. This second edition cancels and replaces IEC 60076-21, published in 2011, and IEEE Std C57.15-2009.

This edition includes the following significant technical changes with respect to IEC 60076-21:2011/IEEE Std C57.15-2009:

a) updated list of normative and bibliography IEC and IEEE references and their associated text;
b) updated tables of preferred ratings for inclusion of maximum system voltage (U_m), nominal system voltage and rated voltage (U_r);
c) inclusion of tables for optional fan-cooled ratings, external dielectric clearances and sound pressure levels;
d) revision of short-circuit requirements for distribution and substation voltage regulators;
e) inclusion of an universal interface between control enclosure and apparatus;
f) inclusion of tap-changer routine and type tests;
g) inclusion of audible sound pressure emissions test procedures;
h) inclusion of tank enclosure integrity type test procedures;
i) update of control environmental IEC reference test standard.

The text of this standard is based on the following documents:

FDIS	Report on voting
14/974/FDIS	14/989/RVD

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

International standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

A list of parts of the 60076 International Standard, published under the general title *Power transformers*, can be found on the IEC website.

The IEC Technical Committee and IEEE Technical Committee have decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

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- withdrawn,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

A bilingual version of this publication may be issued at a later date.

1 A list of IEEE participants can be found at the following URL:
https://standards.ieee.org/standard/C57.15-2017.html

POWER TRANSFORMERS –

Part 21: Standard requirements, terminology, and test code for step-voltage regulators

1 Scope

This document describes electrical, mechanical and test requirements of liquid-immersed, single- and three-phase, 50 Hz and 60 Hz, self and forced-air cooled, distribution, overhead and substation, step-voltage regulators, 1 000 kVA (single-phase units) or 3 000 kVA (three-phase units) and smaller, 34 500 volts and below (2 400 V minimum) and their associated controls.

Requirements, references and definitions relevant to either IEC or IEEE contexts are given and their use is described in Clause 4.

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.

2.1 IEC references

IEC 60050-421, *International Electrotechnical Vocabulary – Chapter 421: Power transformers and reactors*

IEC 60060 (all parts), *High-voltage test techniques*

IEC 60076-2, *Power transformers – Part 2: Temperature rise for liquid-immersed transformers*

IEC 60255-1, *Measuring relays and protection equipment – Part 1: Common requirements*

IEC 60255-21-1, *Electrical relays – Part 21: Vibration, shock, bump and seismic tests on measuring relays and protection equipment – Section One: Vibration tests (sinusoidal)*

IEC 60255-26, *Measuring relays and protection equipment – Part 26: Electromagnetic compatibility requirements*

IEC 60255-27, *Measuring relays and protection equipment – Part 27: Product safety requirements*

IEC 61672-1, *Electroacoustics – Sound level meters – Part 1: Specifications*

2.2 IEEE references

IEEE Std 4™, *IEEE Standard Techniques for High-Voltage Testing*

IEEE Std C37.90.1™, *IEEE Standard Surge Withstand Capability (SWC) Tests for Relays and Relay Systems Associated with Electric Power Apparatus*

IEEE Std C37.90.2™, *IEEE Standard for Withstand Capability of Relay Systems to Radiated Electromagnetic Interference from Transceivers*

IEEE Std C37.90.3™, *IEEE Standard Electrostatic Discharge Tests for Protective Relays*

IEEE Std C57.12.31™, *IEEE Standard for Pole-Mounted Equipment – Enclosure Integrity*

IEEE Std C57.19.00™, *IEEE Standard General Requirements and Test Procedure for Outdoor Power Apparatus Bushings*

IEEE Std C57.91™, *IEEE Guide for Loading Mineral-Oil-Immersed Transformers*

2.3 SAE references

SAE AS50151, *General specification for connectors, electrical, circular threaded, AN type*[2]

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60050-421 and the following apply.

ISO, IEC and IEEE 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
- IEEE Standards Dictionary Online: available at http://ieeexplore.ieee.org/xpls/dictionary.jsp

3.1
ambient sound level
background noise level measured with the voltage regulator de-energized

3.2
ambient temperature
temperature of the medium, such as air, water, or earth, into which the heat of the equipment is dissipated

Note 1 to entry: For self-ventilated equipment, the ambient temperature is the average temperature of the air in the immediate neighbourhood of the equipment.

Note 2 to entry: For air-cooled equipment with forced ventilation, the ambient temperature is taken as that of the in-going air.

3.3
angular displacement
time angle, expressed in degrees, between the line-to-neutral voltage of the unregulated circuit and the line-to-neutral voltage of the corresponding regulated load circuit

2 SAE (Society of Automotive Engineers) international publications are available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096, USA (http://sae.org/).

Note 1 to entry: The connection and arrangement of terminal markings for a three-phase voltage regulator or bank of three single-phase voltage regulators in a wye connection has an angular displacement of zero degrees.

Note 2 to entry: The connection and arrangement of terminal markings for a three-phase voltage regulator or bank of three single-phase voltage regulators in a delta connection has an angular displacement of zero degrees with all voltage regulators in the Neutral tap position and less than ±5° for all other positions with the maximum value occurring when all voltage regulators are on the same extreme tap position.

3.4
autotransformer
transformer in which at least two windings have a common section

3.5
average winding temperature-rise
arithmetic difference between the average winding temperature of the hottest winding and the ambient temperature

3.6
current transformer
instrument transformer intended to have its primary winding connected in series with the conductor carrying the current to be measured or controlled

3.7
diverter switch
switching device used in conjunction with a tap selector to carry, make and break currents in circuits that have already been selected

3.8
excitation current
current flowing in any winding used to excite the voltage regulator when all other windings are open-circuited

Note 1 to entry: Excitation current is usually expressed in percent of the rated current of the voltage regulator.

3.9
equalizer winding
winding on the same magnetic circuit (core) as the excitation and tap windings of a voltage regulator with approximately half the number of turns of each tap section

3.10
intrinsic polarity
polarity is correct if the voltage regulator boosts the voltage in the raise direction and bucks the voltage in the lower direction

Note 1 to entry: The relative polarity of the shunt and series windings of a step-voltage regulator differs in the boost and buck modes between Type A and Type B voltage regulators.

3.11
line-drop compensation
scheme causing the control to vary the regulated circuit voltage by an amount that compensates for the impedance voltage drop in the circuit between the voltage regulator and a predetermined location (sometimes referred to as the regulation point) on the circuit

3.12
liquid
synthetic fluid, natural ester-based fluid, and mineral oil

Note 1 to entry: Some liquids may be unsuitable for use in the arcing environment of a step-voltage regulator.

3.13
liquid-immersed voltage regulator
voltage regulator having its cores and coils immersed in an insulating liquid

3.14
load loss
loss incident to the voltage regulator carrying a specified load

Note 1 to entry: Load loss includes I^2R loss in the current carrying parts (windings, leads, bus bars, bushings), eddy loss in conductors, due to eddy currents and circulating currents (if any) in parallel windings or in parallel winding strands, and stray loss induced by leakage flux in the tank, core clamps, or other structural parts.

3.15
maximum system voltage
U_m
highest RMS phase-to-phase voltage in a three-phase system for which a voltage regulator winding is designed in respect of its insulation

3.16
no-load loss
loss incident to the excitation of the voltage regulator

Note 1 to entry: No-load loss includes core loss, dielectric loss, conductor loss in the winding due to excitation current, and conductor loss due to circulating current in parallel windings. The no-load loss changes with the excitation voltage.

3.17
nominal system voltage
nominal value assigned to a system or circuit of a given voltage for the purpose of convenient designation

Note 1 to entry: The term nominal voltage designates the line-to-line voltage, as distinguished from the line-to-neutral voltage. It applies to all parts of the system or circuit. The system voltage designates the system to which certain operating characteristics are related.

Note 2 to entry: The nominal voltage of a system is near the voltage level at which the system normally operates and provides a per-unit base voltage for system study purposes. To allow for operating contingencies, systems generally operate at voltage levels about 5 % to 10 % below the maximum system voltage for which system components are designed.

3.18
non-vacuum type on-load tap-changer
on-load tap-changer with contacts breaking and making the load and circulating currents with the arcing taking place in a liquid

3.19
on-load tap-changer
OLTC
device for selection of tap connections of a winding, suitable for operation while the voltage regulator is energized or on load

Note 1 to entry: This device can also be called a load tap-changer (LTC) but this is not the preferred usage.

3.20
rated range of regulation
amount the voltage regulator raises or lowers its rated voltage with the range being expressed in per unit, or in percent, of rated voltage, or expressed in kilovolts

3.21
rated voltage
U_r
voltage to which operating and performance characteristics of apparatus and equipment are referred

3.22
rating in kVA
<single-phase voltage regulator> product of the rated load amperes and the rated range of regulation in kilovolts (kV)

3.23
rating in kVA
<three-phase voltage regulator> product of the rated load amperes, maximum rated range of regulation in kilovolts (kV), and the square root of 3

3.24
reactor
preventive autotransformer with the primary purpose of introducing inductive reactance into a circuit

Note 1 to entry: This definition is only valid for reactors used in combination with reactor-type OLTCs. All other reactors, such as short-circuit limiting reactors, are not covered by this definition.

3.25
regulated circuit
circuit on the output (load) side of the voltage regulator, and in which it is desired to control the voltage

Note 1 to entry: The voltage can be held constant at any selected point on the regulated circuit.

3.26
relative polarity
instantaneous polarity of the windings, instrument transformer(s), and utility winding(s), as applicable, designated by an appropriate polarity mark on the diagram of connection on the nameplate

Note 1 to entry: The diagram of connection is in accordance with 7.4.

3.27
series transformer
transformer with a series winding and an excitation winding, in which the series winding is placed in a series relationship in a circuit to change voltage in that circuit as a result of the regulated circuit received from the excitation winding

3.28
series winding
portion of the autotransformer not common to both the unregulated and regulated circuits, but connected in series between the circuits

3.29
selector switch
switching device capable of carrying, making and breaking current, combining the duties of a tap selector and a diverter switch

Note 1 to entry: Selector switches are sometimes called arcing tap switches.

Note 2 to entry: In non-vacuum type selector switches, the selection of tap connections (tap selector duty) and the diversion of the through-current (diverter switch duty) are carried out by the same contacts.

Note 3 to entry: In vacuum type selector switches, the selection of tap connections (tap selector duty) and the diversion of the through-current (diverter switch duty) are carried out by different contacts.

3.30
shunt winding
portion of the autotransformer common to both the unregulated and regulated circuits

3.31
step-voltage regulator
regulating autotransformer in which the voltage of the regulated circuit is controlled in steps by means of taps and without interrupting the load

3.32
tap selector
device designed to carry, but not to make or break, current, used in conjunction with a diverter switch to select tap connections

3.33
Type A step-voltage regulator
step-voltage regulator in which the unregulated circuit is connected directly to the shunt winding of the voltage regulator with the series winding connected to the shunt winding and, in turn, via taps, to the regulated circuit

Note 1 to entry: Refer to Annex C for additional information on step-voltage regulator construction.

3.34
Type B step-voltage regulator
step-voltage regulator in which the unregulated circuit is connected, via taps, to the series winding of the voltage regulator with the series winding connected to the shunt winding, which is connected directly to the regulated circuit

Note 1 to entry: Refer to Annex C for additional information on step-voltage regulator construction.

3.35
unregulated circuit
circuit on the input (source) side of the voltage regulator

3.36
utility winding
winding in a voltage regulator coil providing a voltage supply for the on-load tap-changer motor and/or the control device, for a cooling fan or for a purchaser's specified requirement

3.37
vacuum type on-load tap-changer
on-load tap-changer where vacuum interrupters break and make the load and circulating currents

3.38
voltage supply ratio
ratio of the regulated circuit voltage to the control supply voltage

4 Use of normative references

This document can be used with either the IEC or IEEE normative references, but the references shall not be mixed. The purchaser shall include in the enquiry and order which normative references are to be used. If the choice of normative references is not specified, then IEC standards shall be used, except for step-voltage regulators intended for installation in North America where IEEE standards shall be used.

If only one alternative is given in a certain part of the document, i.e. only IEC reference(s) or only IEEE reference(s), then that/these reference(s) is/are valid independent of the choice of normative references.

5 Service conditions

5.1 Usual service conditions

5.1.1 General

Voltage regulators meeting the requirements of this document shall be suitable for operation at rated kVA under the following usual service conditions.

5.1.2 Temperature

5.1.2.1 Cooling air temperature limit

When air-cooled, the temperature of the cooling air (ambient temperature) does not exceed 40 °C, and the average temperature of the cooling air for any 24 h period shall not exceed 30 °C.

5.1.2.2 Liquid temperature limit

The top liquid temperature of the voltage regulator (when operating) shall not be lower than −20 °C. Liquid temperatures below −20 °C are not considered as usual service conditions.

5.1.3 Altitude

The altitude shall not exceed 1 000 m (3 300 ft).

5.1.4 Supply voltage

The supply-voltage wave shape shall be approximately sinusoidal, and the phase voltages supplying a three-phase voltage regulator shall be approximately equal in magnitude and time displacement.

5.1.5 Load current

The load current shall be approximately sinusoidal. The harmonic factor shall not exceed 0,05 per unit.

5.1.6 Outdoor operation

Unless otherwise specified, voltage regulators shall be suitable for outdoor operation.

5.1.7 Tank or enclosure finish

Temperature limits and tests shall be based on the use of a non-metallic pigment surface paint finish. It should be noted that metallic-flake paints, such as aluminium and zinc, have properties increasing the temperature-rise of voltage regulators, except in direct sunlight. Unless otherwise specified, the tank finish shall conform to Light Gray Number 70, Munsell Notation 5BG 7.0/0.4. Finishing of voltage regulators shall meet requirements specified in IEEE Std C57.12.31.

5.2 Loading at other than rated conditions

IEEE Std C57.91 or IEC 60076-7 [11][3] provides guidance for loading at other than rated conditions including the following:

a) ambient temperatures higher or lower than the basis of rating;

b) short-time loading in excess of nameplate kVA with normal life expectancy;

c) loading resulting in reduced life expectancy.

NOTE IEEE Std C57.91 and IEC 60076-7 [11] are guides rather than standards. They provide the best known general information for the loading of voltage regulators under various conditions based on typical winding insulation systems, and are based upon the best engineering information available at the time of preparation. The guides discuss limitations of ancillary components other than windings, limiting the capability of voltage regulators.

5.3 Unusual service conditions

5.3.1 General

Conditions other than those described in 5.1 are considered unusual service conditions and, when prevalent, should be brought to the attention of those responsible for the design and application of the voltage regulator. Examples of some of these conditions are discussed in 5.3.2 to 5.3.4.

5.3.2 Unusual temperature and altitude conditions

Voltage regulators may be used at higher or lower ambient temperatures or at higher altitudes than specified in 5.1, but special consideration should be given to these applications. Annex A of this document, IEEE Std C57.91, and IEC 60076-7 [11] provide information on recommended practices.

5.3.3 Insulation at high altitude

5.3.3.1 General

The dielectric strength of voltage regulators depends in whole or in part upon the external clearances. It decreases as the altitude increases due to the effect of decreased air density. When specified, voltage regulators shall be designed with larger air spacing using the correction factors of Table 1 to obtain adequate air dielectric strength at altitudes above 1 000 m (3 300 ft).

5.3.3.2 Insulation level

The minimum insulation necessary at the required altitude can be obtained by dividing the standard insulation level at 1 000 m (3 300 ft) by the appropriate correction factor from Table 1.

3 Numbers in square brackets refer to the Bibliography.

Table 1 – Dielectric strength correction factors for altitudes greater than 1 000 m (3 300 ft)

Altitude		Altitude correction factor for dielectric strength
(m)	(ft)	
1 000	3 300	1,00
1 200	4 000	0,98
1 500	5 000	0,95
1 800	6 000	0,92
2 100	7 000	0,89
2 400	8 000	0,86
2 700	9 000	0,83
3 000	10 000	0,80
3 600	12 000	0,75
4 200	14 000	0,70
4 500	15 000	0,67
NOTE An altitude of 4 500 m (15 000 ft) is considered a maximum for voltage regulators compliant with this document.		

5.3.3.3 Bushings

Bushings with additional strike distance or creep distance shall be furnished where necessary for operation above 1 000 m (3 300 ft).

NOTE It is not required for the BIL rating of bushings to be increased to match level of increased creep distance and strike distance.

5.3.4 Other unusual service conditions

5.3.4.1 General

Other unusual service conditions include the following:

a) damaging fumes or vapours, excessive or abrasive dust, explosive mixtures of dust or gases, steam, salt spray, excessive moisture, or dripping water, etc.
b) abnormal vibration, tilting, shock, or seismic conditions;
c) ambient temperatures outside of normal range;
d) unusual transportation or storage conditions;
e) unusual space limitations;
f) unusual maintenance problems;
g) unusual duty or frequency of operation, or high-current short-duration loading;
h) unbalanced alternating currents (AC), voltages, or departure of AC system voltages from a substantially sinusoidal waveform;
i) loads involving abnormal harmonic currents such as those resulting where appreciable load currents are controlled by solid-state or similar devices;

   NOTE 1 Such harmonic currents can cause excessive loss, excessive on-load tap-changer contact wear, and abnormal heating.

j) excitation exceeding either 110 % rated voltage or 110 % rated volts per Hertz;
k) planned short-circuits as a part of regular operating or relaying practice;

l) unusual short-circuit application conditions differing from those described in 6.8.1;

m) unusual voltage conditions (transient overvoltages, resonance, switching surges, etc.), which may require special consideration in insulation design;

n) unusually strong magnetic fields, for example, solar magnetic disturbances can result in the flow of telluric currents in voltage regulator neutrals;

o) parallel operation.

NOTE 2 IEEE Std C57.153 [27] is available as a guide for paralleling voltage regulators.

5.3.4.2 Control

The control, depending on its construction, may be sensitive to altitude considerations. The manufacturer should be consulted where applications exceed 2 000 m (6 600 ft). The control shall withstand an altitude of up to 3 000 m (10 000 ft) without loss of control.

6 Rating data

6.1 Cooling classes of voltage regulators

6.1.1 General

Voltage regulators shall be identified according to the cooling method employed. For liquid-immersed voltage regulators, this identification is expressed by a four-letter code as described in 6.1.2 and 6.1.3.

6.1.2 Liquid-immersed (fire point ≤ 300 °C) air-cooled

Internal cooling medium in contact with the windings is insulating liquid with fire point ≤ 300 °C:

a) liquid-immersed self-cooled (class ONAN);

b) liquid-immersed self-cooled/forced-air-cooled (class ONAN/ONAF).

6.1.3 Liquid-immersed (fire point > 300 °C) air-cooled

Internal cooling medium in contact with the windings is insulating liquid with fire point > 300 °C:

a) liquid-immersed self-cooled (class KNAN);

b) liquid-immersed self-cooled/forced-air-cooled (class KNAN/KNAF).

6.2 Ratings

6.2.1 General

Ratings for step-voltage regulators are continuous and based on not exceeding the temperature limits covered in Table 2. Ratings covered by this document shall be expressed in the terms given in 6.2.2 and as specified in 6.2.3.

Table 2 – Limits of temperature-rise

Item	Type of apparatus [a]	Winding temperature rise by resistance, °C	Hottest-spot winding temperature-rise, °C
(1)	55 °C rise liquid immersed [b]	55	65
(2)	65 °C rise liquid immersed [c]	65	78
(3)	65 °C rise liquid immersed [d]	65	80
(4)	Metallic parts in contact with current-carrying conductor insulation shall not attain a temperature-rise in excess of the winding hottest-spot temperature-rise. The core hot spot temperature shall be limited to 130 °C for the condition of highest core over-excitation, rated load, and the maximum average daily ambient temperature for voltage regulators immersed in dielectric liquid. This is to avoid the problem of gas generation in the core caused by thermal breakdown of the thin liquid film between the core laminations. Under the same operating conditions, the core surface temperatures shall be limited by the temperature capability of the insulation materials in contact with the core surfaces.		
(5)	Metallic parts other than those described in item (4) shall not attain excessive temperature-rise at maximum rated load. Excessive temperature-rise shall be interpreted to mean a temperature-rise resulting in an operating temperature exceeding the temperature limits of the insulation material in contact with the metallic part.		
(6)	The top liquid temperature-rise of the insulating liquid shall not exceed 55 °C (55 °C rise unit) or 65 °C (65 °C rise unit) when measured near the surface of the liquid. (Item (1) and (3))		
(7)	The top liquid temperature-rise of the insulating liquid shall not exceed 60 °C (65 °C rise unit) when measured near the surface of the liquid. (Item (2))		

[a] Apparatus with specified temperature-rise shall have an insulation system proven to possess minimum aging characteristics by an established test.

[b] Apparatus with 30 °C average yearly external cooling air temperature as defined in 5.1.2.1, which may use thermally upgraded insulating paper.

[c] Apparatus with 20 °C average yearly external cooling air temperature as defined in IEC 60076-2.

[d] Apparatus with 30 °C average yearly external cooling air temperature as defined in 5.1.2.1, which utilizes thermally upgraded insulating paper.

6.2.2 Terms in which rating is expressed

The rating of a step-voltage regulator shall be expressed in the following terms:

a) kilovoltampere (kVA);
b) number of phases;
c) frequency;
d) voltage;
e) current;
f) voltage range in percent (Raise and Lower).

Voltage regulators shall be approximately compensated for their internal regulation to provide the specified voltage range at rating in kVA with an 80 % lagging power factor load.

6.2.3 Preferred ratings

Preferred ratings of step-voltage regulators shall be based on operation at a frequency of 60 Hz or 50 Hz and rated voltages as given in Table 3, Table 4, Table 5, and Table 6.

Ratings of single-phase voltage regulators are dependent on the application of two (2) or three (3) voltage regulators applied to support a specific three-phase load. For example, three (3) single-phase voltage regulators rated 333 kVA connected in a wye configuration, support a 10 MVA load.

NOTE National practices can be different for preferred ratings.

Table 3 – Ratings for liquid-immersed 60 Hz step-voltage regulators (single-phase)

Maximum system voltage (U_m) (kV RMS)	Nominal system voltage (kV RMS)	Rated voltage (U_r) (V RMS)	BIL (kV)	Kilovoltamperes (kVA)	Line amperes (A)
6,9	5	2 500/4 330Y	60	50	200
				75	300
				100	400
				125	500
				167	668
				250	1 000
				333	1 332
				416	1 665
11	8,7	5 000/8 660Y	75	50	100
				75	150
				100	200
				125	250
				167	334
				250	500
				333	668
				416	833
17	15	7 620/13 200Y	95	38,1	50
				57,2	75
				76,2	100
				114,3	150
				167	219
				250	328
				333	438
				416	546
				500	656
				667	875
				833	1 093
				1 000	1 312
17	15	13 800	95	69	50
				138	100
				207	150
				276	200
				414	300
				552	400
				667	483
				833	604
				1 000	725

Maximum system voltage (U_m) (kV RMS)	Nominal system voltage (kV RMS)	Rated voltage (U_r) (V RMS)	BIL (kV)	Kilovoltamperes (kVA)	Line amperes (A)
26	25	14 400/24 940Y	150	72	50
				144	100
				288	200
				333	231
				432	300
				576	400
				667	463
				833	578
				1 000	694
36	35	19 920/34 500Y	150	100	50
				200	100
				333	167
				400	201
				667	334
				833	418
				1 000	502
36	35	34 500	200	173	50
				345	100
				518	150
				690	200

Table 4 – Ratings for liquid-immersed 50 Hz step-voltage regulators (single-phase)

Maximum system voltage (U_m) (kV RMS)	Nominal system voltage (kV RMS)	Rated voltage (U_r) (V RMS)	BIL (kV)	Kilovoltamperes (kVA)	Line amperes (A)
7,2	6,6	6 600	75	33	50
				66	100
				99	150
				132	200
				198	300
				264	400
				330	500
				396	600
				462	700
				528	800

Maximum system voltage (U_m) (kV RMS)	Nominal system voltage (kV RMS)	Rated voltage (U_r) (V RMS)	BIL (kV)	Kilovoltamperes (kVA)	Line amperes (A)
12	11	6 350/11 000Y	95	32	50
				64	100
				95	150
				127	200
				190	300
				254	400
				317	500
				381	600
				444	700
				508	800
12	11	11 000	95	55	50
				110	100
				165	150
				220	200
				330	300
				440	400
				550	500
				660	600
				770	700
				880	800
17,5	15	15 000	95	75	50
				150	100
				225	150
				300	200
				450	300
				600	400
				750	500
				900	600
24	22	22 000	150	110	50
				220	100
				330	150
				440	200
				660	300
				880	400
36	33	33 000	170	165	50
				330	100
				495	150
				660	200

Table 5 – Ratings for liquid-immersed 60 Hz step-voltage regulators (three-phase)

Maximum system voltage (U_m) (kV RMS)	Nominal system voltage (kV RMS)	Rated voltage (U_r) (V RMS)	BIL (kV)	Self-cooled		Forced-cooled	
				Kilovoltamperes (kVA)	Line amperes (A)	Kilovoltamperes (kVA)	Line amperes (A)
6,9	5	2 500/4 330Y	60	500	667	625	833
				750	1 000	937	1 250
				1 000	1 334	1 250	1 667
11	8,7	5 000/8 660Y	75	500	577	625	721
				750	866	937	1 082
				1 000	1 155	1 250	1 443
17	15	7 620/13 200Y	95	500	219	625	274
				750	328	937	410
				1 000	437	1 250	546
				1 500	656	2 000	874
				2 000	874	2 667	1 166
				2 500	1 093	3 333	1 458
				3 000	1 312	4 000	1 750
17	15	7 970/13 800Y	95	500	209	625	261
				750	313	937	391
				1 000	418	1 250	523
				1 500	628	2 000	837
				2 000	837	2 667	1 116
				2 500	1 046	3 333	1 394
				3 000	1 255	4 000	1 673
26	25	14 400/24 940Y	150	500	125,5	625	156,8
				750	188,3	937	235,4
				1 000	251	1 250	314
				1 500	377	2 000	502
				2 000	502	2 667	669
				2 500	628	3 333	837
				3 000	694	4 000	926
36	34.5	19 920/34 500Y	150	500	84	625	105
				750	125,5	937	156,8
				1 000	167	1 250	209
				1 500	251	2 000	335
				2 000	335	2 667	446
				2 500	418	3 333	557
				3 000	502	4 000	669

Table 6 – Ratings for liquid-immersed 50 Hz step-voltage regulators (three-phase)

Maximum system voltage (U_m) (kV RMS)	Nominal system voltage (kV RMS)	Rated voltage (U_r) (V RMS)	BIL (kV)	Self-cooled		Forced-cooled	
				Kilovoltamperes (kVA)	Line amperes (A)	Kilovoltamperes (kVA)	Line amperes (A)
7,2	6,6	6 600	75	500	253	625	316
				750	379	937	474
				1 000	505	1 250	631
				1 500	758	2 000	1 010
12	11	6 350/11 000Y	95	500	243	625	304
				750	364	937	456
				1 000	485	1250	607
				1 500	729	2 000	971
12	11	11 000	95	500	262	625	328
				750	394	937	492
				1 000	525	1 250	656
				1 500	787	2 000	1 050
17.5	15	15 000	95	500	111	625	139
				750	167	937	208
				1 000	222	1 250	278
				1 500	333	2 000	444
				2 000	444	2 667	593
				2 500	556	3 333	741
24	22	22 000	150	500	131	625	164
				750	197	937	246
				1 000	262	1250	328
				1 500	394	2 000	525
36	33	33 000	170	500	87	625	189
				750	131	937	164
				1 000	175	1 250	219

6.2.4 Supplementary voltage ratings

6.2.4.1 General

In addition to their rated voltage, as defined in 6.2.3, voltage regulators shall deliver rated kVA output without exceeding the specified temperature-rise per Table 2 at the operating voltages given in Table 7.

Voltage regulators with multi-tapped voltage transformers and/or utility windings may be operated at voltages other than the rated voltage, as specified per the nameplate, and shall deliver rated line amperes without exceeding the temperature limits of Table 2 and as specified per the nameplate.

Table 7 – Supplementary voltage ratings

Rated voltage (V RMS)	**Operating voltage** (V RMS)
7 620/13 200Y	7 200/12 470Y
15 000	14 400

6.2.4.2 Overexcitation

A voltage regulator shall be capable of continuous operation at rated load without damage under conditions of "over fluxing" where the value of voltage divided by frequency (V/Hz) exceeds the corresponding value at rated voltage and rated frequency by no more than 5 %, unless otherwise specified by the purchaser.

At no-load, voltage regulators shall be capable of continuous operation at V/Hz of 110 % of the rated V/Hz. At load current, X times the voltage regulator rated current ($0 \le X \le 1$), the over fluxing shall be limited in accordance with the following Equation (1):

$$\frac{U \times f_r}{U_r \times f} \times 100 \le 110 - 5X \quad (\%) \tag{1}$$

where

U is the system voltage;

f is the system frequency;

U_r is the rated voltage of voltage regulator;

f_r is the rated frequency of voltage regulator.

If the voltage regulator is to be operated at V/Hz in excess of those stated above, this shall be identified by the purchaser in the enquiry.

6.3 Supplementary continuous-current ratings

6.3.1 General

Step-voltage regulators without a series transformer construction rated up to 34,5 kV, inclusive, and rated 668 A and below shall have supplementary continuous-current ratings on intermediate ranges of steps as shown in Table 8. Maximum continuous-current shall be 668 A.

Table 8 – Supplementary continuous-current ratings

Range of voltage regulation (%)	**Continuous-current rating** (%)
10,00	100
8,75	110
7,50	120
6,25	135
5,00	160

6.3.2 Optional forced-air ratings

Optional forced-air ratings are given in Table 9.

Table 9 – Forced-air ratings relationship

Class	Self-cooled ratings		Percent of self-cooled rating with auxiliary cooling
	Single-phase	Three-phase	
ONAN/ONAF KNAN/KNAF	333 kVA and below	1 000 kVA and below	125
ONAN/ONAF KNAN/KNAF	above 333 kVA	above 1 000 kVA	133 1/3

6.4 Taps

Load tap-changing apparatus and windings shall be furnished to provide automatic adjustment of the unregulated circuit voltage on the source side of the voltage regulator. This is to be done with sixteen steps above and sixteen steps below rated voltage. Maximum percent regulation in the Raise and Lower positions is based on the design, Type A or Type B. Minimum range of regulation in the Raise direction shall be 10 %. The output voltage obtainable with a given input voltage is limited by the voltage regulation ranges.

6.5 Voltage supply ratios

Values of voltage supply ratios are given in Table 10. When a voltage supply ratio is specified that is not a preferred value shown in Table 10, an ancillary transformer may be furnished within the apparatus or control to modify the ratio.

Table 10 – Values of voltage supply ratios

Voltage regulator rating (V **RMS**)	**Values of voltage supply ratios**
2 500	20, 20,8
5 000	40, 41,7
6 350	52,9
6 600	55
7 620	60, 63,5
7 970	66,4
11 000	91,7
13 800	115, 110
14 400	120
15 000	125, 120
19 920	166
22 000	183,3
33 000	275
34 500	287,5

6.6 Insulation levels

Voltage regulators shall be designed to provide coordinated applied-voltage and lightning impulse insulation levels on line terminals, and applied-voltage insulation levels on neutral terminals. The identity of a set of coordinated levels shall be its basic impulse insulation level (BIL), as shown in Table 11.

When single-phase voltage regulators are connected in wye, it is recommended that the neutral ("SL" terminals) of the voltage regulator bank be connected to a grounded neutral of the system. A closed or open delta connection of the voltage regulators is recommended when the system is three-wire ungrounded with the "SL" terminals connected to live phases.

Table 11 – Interrelationships of dielectric insulation levels for voltage regulators

BIL kV	Applied-voltage insulation level (kV RMS)	Impulse levels		
		Full wave	Chopped wave	
		(kV crest)	(kV crest)	Minimum time to flashover (µs)
60	19	60	66	1,5
75	26	75	83	1,5
95	34	95	105	1,8
110	34	110	120	2,0
150	50	150	165	3,0
170	70	170	187	3,0
200	70	200	220	3,0

6.7 Losses

6.7.1 General

The losses specified by the manufacturer shall be the no-load (excitation) loss and load loss, as defined in Clause 3.

6.7.2 Total loss

The total loss of a voltage regulator shall be the sum of the no-load (excitation) loss and load loss.

6.7.3 Tolerance for losses

Unless otherwise specified, the losses represented by a test of a voltage regulator shall be subject to the following tolerances: the no-load loss of a voltage regulator shall not exceed the specified no-load loss by more than 10 %, and the total loss of a voltage regulator shall not exceed the specified total loss by more than 6 %. Failure to meet the loss tolerances shall not warrant immediate rejection but lead to consultation between purchaser and manufacturer about further investigation of possible causes and the consequences of the higher losses.

NOTE Since losses differ at different operating positions of the voltage regulator, care is exercised in the consideration of tap position with losses. Some styles of step-voltage regulators exhibit appreciable change in load loss when boosting versus bucking, or exhibit appreciable change in no-load loss on alternate tap positions. See 6.7.4.

6.7.4 Determination of losses and excitation current

No-load (excitation) loss and excitation current shall be determined for the rated voltage and frequency on a sine-wave basis, unless a different form is inherent in the operation of the apparatus.

Load loss shall be determined for rated voltage, current, and frequency and shall be corrected to a reference temperature equal to the sum of the limiting (rated) winding temperature-rise by resistance from Table 2 plus 20 °C.

Since losses may be very different at different operating positions and with various design options, losses shall be considered in practice as the sum of no-load loss and load loss where:

a) No-load loss is the average of no-load loss in the Neutral position and the adjacent boost position with rated voltage applied to the shunt or series winding for voltage regulators not incorporating a series transformer construction.

NOTE It is apparent, in the case of a Type B step-voltage regulator in the adjacent boost position, the excitation voltage applied at the Source "S" terminal is higher at the shunt winding. Care is exercised to assure rated excitation is present on the shunt winding; this may be accomplished by exciting the voltage regulator from the Load "L" terminal.

b) No-load loss is reported for Neutral position, maximum boost position, and position adjacent-to-maximum boost position for voltage regulators incorporating a series transformer construction.

c) Load loss is the average load loss in both the maximum and adjacent-to-maximum buck positions, and the maximum and adjacent-to-maximum boost positions (that is, four positions) with rated current in the windings.

6.8 Short-circuit requirements

6.8.1 General

Step-voltage regulators shall be designed and constructed to withstand the mechanical and thermal stresses produced by external short-circuits at a maximum value of 25 times the base RMS symmetrical rated load current to a maximum requirement of 16 kA.

a) The first-cycle asymmetrical peak current the voltage regulator is required to withstand shall be determined as shown in Equation (2) and Table 12. The test procedure for demonstrating this mechanical capability for duration of 250 ms is defined in 9.11.

$$I_{sc}\text{ (peak asym)} = k \times I_{sc}\text{ (RMS sym)} \qquad (2)$$

Table 12 – Values of *k*

Base rated kVA	*k*	
	60 Hz	50 Hz
< 250 (single-phase) [c] < 750 (three-phase) [c]	2,26 [a]	2,19 [a]
≥ 250 (single-phase) ≥ 750 (three-phase)	2,60 [b]	2,55 [b]

[a] Value of the first-cycle asymmetrical peak current is based on an X/R ratio of 6 and 5, 60 Hz and 50 Hz, respectively, which are common for distribution circuits.

[b] Value of the first-cycle asymmetrical peak current is based on an X/R ratio of 17 and 14, 60 Hz and 50 Hz, respectively, which are common for substation circuits.

[c] Purchaser may specify the higher 2,60 or 2,55 factor for 60 Hz and 50 Hz ratings, respectively, for specific applications.

b) The short-circuit, thermal withstand capability, shall be based on a symmetrical current with a duration of 2 s calculated by methods described in 9.13.4 not to exceed the limiting temperatures of 6.8.3.

c) Larger kVA sizes with the same voltage rating should be considered if the available fault current exceeds the 25 times base rated current.

It is recognized that short-circuit withstand capability can be adversely affected by the cumulative effects of repeated mechanical and thermal overstressing, as produced by short-circuits and loads above the nameplate rating. Since means are not available to continuously monitor and quantitatively evaluate the degrading effects of such duty, short-circuit tests, when required, should be performed prior to placing the voltage regulator in service.

Voltage regulator components such as leads, bushings, and on-load tap-changers carrying current continuously shall meet all the requirements of 6.8.1. On-load tap-changers are not required to change tap position coincident with a short-circuit condition.

It is recommended that current-limiting reactors be installed by the purchaser, when necessary, to limit the short-circuit current to a maximum of 25 times the base rated full-load current or 16 000 A, whichever is less.

NOTE Short-circuit limiting reactors are not covered by the definition in 3.24.

6.8.2 Mechanical capability demonstration

It is not the intent of 6.8.1 that every voltage regulator design have a short-circuit test to demonstrate adequate construction. When specified, tests of short-circuit mechanical capability shall be performed as described in 9.11.

6.8.3 Thermal capability of voltage regulators for short-circuit conditions

The temperature of the conductor material in the windings of voltage regulators under the short-circuit condition specified in 6.8.1, as calculated by methods described in 9.13.4, shall not exceed 250 °C for a copper conductor or 200 °C for an electrical conductor (EC) aluminium. A maximum temperature of 250 °C shall be allowed for aluminium alloys having resistance to annealing properties at 250 °C, equivalent to EC aluminium at 200 °C, or for application of EC aluminium where the characteristics of the fully annealed material satisfy the mechanical requirements. In setting these temperature limits, the following factors were considered:

a) gas generation from liquid or solid insulation;

b) conductor annealing;

c) insulation aging.

6.9 Sound pressure level for liquid-immersed voltage regulators

The sound pressure level produced by the voltage regulator under a no-load (excitation) condition should not exceed the values specified in Table 13 when measured in accordance with the requirements of 9.12.

Table 13 – Maximum no-load (excitation) sound pressure levels

kVA	Average sound pressure level (dB)
0 – 50	48
51 – 100	51
101 – 300	55
301 – 500	60
501 – 750	61
751 – 1 000	62
1 001 – 1 500	64
1 501 – 2 000	65
2 001 – 2 500	66
2 501 – 3 000	67

6.10 Tests

6.10.1 General

Tests are divided into two categories: routine and type. Routine tests are made for quality control by the manufacturer to verify during production that the product meets the design specifications. Type tests are made to determine the adequacy of the design of a particular type, style, or model of equipment or its component parts. Design adequacy includes but is not limited to: meeting assigned ratings, operating satisfactorily under normal service conditions or under special conditions if specified, and compliance with appropriate standards of the industry. The sequence of routine and type tests can be performed in any order unless otherwise specified in this document.

6.10.2 Routine tests

Routine tests shall be made on all voltage regulators per the following list:

a) leak test;
b) operational test of voltage regulator including all devices. Controlled devices such as on-load tap-changers, position indicators, fans, etc., shall be operated for proper functioning;
c) resistance measurements of all windings (see 9.2);
d) polarity test (see 9.3);
e) ratio test (see 9.4);
f) no-load loss at rated voltage and rated frequency (see 9.5);
g) excitation current at rated voltage and rated frequency (see 9.5);
h) impedance and load loss at rated current and rated frequency (see 9.6);
i) lightning impulse test (see 9.7.3);
j) applied-voltage test (see 9.7.4);
k) induced-voltage test (see 9.7.5);
l) insulation power factor test (see 9.7.6);
m) insulation resistance test (see 9.7.7);
n) on-load tap-changer tests (see 9.8);
o) control system tests (see 9.9).

NOTE Listed tests are not in a required sequence.

6.10.3 Type tests

6.10.3.1 General

The type tests described in 6.10.3.2 to 6.10.3.5 shall be made on representative voltage regulators to substantiate the ratings assigned to all other voltage regulators of basically the same design. Type tests are not intended to be used as a part of normal production. The applicable portion of these type tests may also be used to evaluate modifications of a previous design and to assure the performance has not been adversely affected. Test data from previous similar designs may be used for current designs, where appropriate. Once made, the type tests need not be repeated unless the design is changed to modify performance.

6.10.3.2 Temperature-rise test

Temperature-rise test shall be carried out on one unit of a given rating produced by a manufacturer as a record that this design meets the temperature-rise requirement for a 55 °C or 65 °C winding rise rating. The temperature-rise test shall be carried out at the tap position producing the highest total loss at rated load current for the highest operating voltage per nameplate, supplementary voltage rating (see 6.2.4), and the 160 % or 668 A rating (see 6.3). When a voltage regulator is supplied with ancillary cooling equipment to provide higher kVA ratings, a temperature-rise test shall be carried out at those ratings also. The test shall be carried out in accordance with 9.10.

When specifications state a temperature-rise test may be omitted if there is thermal test data available for a thermal duplicate voltage regulator, then calculated data based upon the thermal test data may be submitted as thermal duplicate test data. A thermal duplicate is a voltage regulator whose thermal design characteristics are identical to a design previously tested, or whose differences in thermal characteristics are within agreed-upon variations, such that the thermal performance of the thermal duplicate voltage regulator shall meet the performance guarantees established by standards or specifications.

6.10.3.3 Lightning impulse test

A lightning impulse test shall be carried out on one unit of a given rating produced by a manufacturer for the purpose of demonstrating the adequacy of the insulating materials' breakdown and spacing under normal conditions. Test shall be carried out in accordance with 9.7.2. Impulse test is to be followed by the application of the low-frequency applied-voltage and induced-voltage tests.

6.10.3.4 Short-circuit test

A short-circuit test shall be carried out on one unit of a rating produced by a manufacturer for the purpose of demonstrating that the unit meets the mechanical requirements of 6.8.2. Where other ratings have the same design configuration, core and coil framing, and clamping as the unit tested, a short-circuit test is not required, and it is adequate to show by calculation the mechanical forces are equal or less than the unit tested. Test is to be carried out in accordance with 9.11.

6.10.3.5 Sound level test

A No-load (excitation) sound level test shall be carried out on one unit of a given rating produced by a manufacturer as a record that this design meets the sound level requirement for the specific power rating specified in Table 13. This test shall be performed by applying rated voltage directly to the excitation winding of the equipment at nominal frequency. The same circuit used for measuring no-load loss shall be adopted for this measurement. The test shall be performed with the voltage regulator fully assembled with all accessories. The test shall be performed at the tap position in which the reactor is energized at its maximum level. Voltage regulators incorporating a series transformer construction shall have their test performed at the tap position in which the reactor and series transformer deliver the maximum No-load (excitation) sound level. This test is to be carried out in accordance with 9.12.

7 Construction

7.1 Bushings

Voltage regulators shall be equipped with bushings having an insulation level not less than the winding terminal to which they are connected, unless otherwise specified.

Bushings for use in voltage regulators shall have impulse and applied-voltage insulation levels as listed in Table 14. Unless otherwise specified, the colour of the bushings shall conform to Light Gray Number 70, Munsell Notation 5BG7.0/0.4, as described in IEEE Std C57.12.31.

Table 14 – Electrical characteristics of voltage regulator bushings

BIL (kV)	**Creep distance** (minimum) mm (in)	**Applied-voltage withstand**		**Impulse full-wave dry withstand** kV crest (1,2 × 50 μs)
		1 min dry (kV **RMS**)	**10 s wet** [a] (kV **RMS**)	
60	90 (3,5)	21	20	60
75	150 (6)	27	24	75
95	255 (10)	35	30	95
110	280 (11)	50	45	110
150	435 (17)	60	50	150
170	660 (26)	70	65	170
200	660 (26)	80	75	200

[a] Wet withstand values are based on water resistivity of 180 Ω·m (7 000 Ω·in) and precipitation rate of 0,085 mm/s (0,2 in/min).

7.2 External dielectric clearances

Table 15 establishes the required minimum external clearances between live parts of different phases and live parts to ground. In the formation of these clearances, it is recognized the bushing ends normally have rounded electrode shapes. It is also expected the conductor clamps are suitably shaped so they do not reduce the withstand strengths, and the arrangement of the incoming conductors does not reduce the effective clearances provided by the voltage regulator bushings. In other words, the clearances were established based upon electrostatic fields not usually being divergent.

Factory dielectric test conditions may require larger clearances than those defined in Table 15.

Table 15 – External dielectric clearances

BIL (kV)	**Minimum clearance between live parts and ground**		**Minimum clearance between live parts of different phases**	
	mm	in	mm	in
60	76	3	76	3
75	89	3,5	102	4
95	114	4,5	127	5
110	152	6	165	6,5
150	203	8	229	9
170	230	9	254	10
200	305	12	330	13

7.3 Terminal markings

Voltage regulator terminals connected to the regulated circuit (load) shall be designated by an "L", and those connected to the unregulated circuit (source) shall be designated by an "S". For example, in the case of a single-phase voltage regulator, the terminals shall be identified by "S", "L", and "SL". In the case of a three-phase voltage regulator, the terminals shall be identified S_1, S_2, S_3, L_1, L_2, L_3, and, if a neutral is provided, S_0L_0.

Single-phase voltage regulators, when viewed from the top, shall have the "S" terminal on the left, followed in sequence in a clockwise direction by the "L" terminal and the common terminal "SL", as shown in Figure 1.

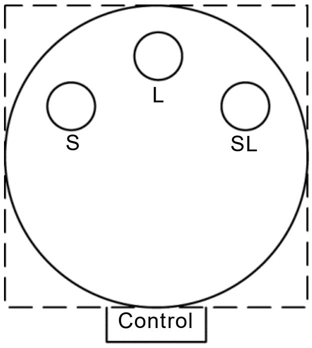
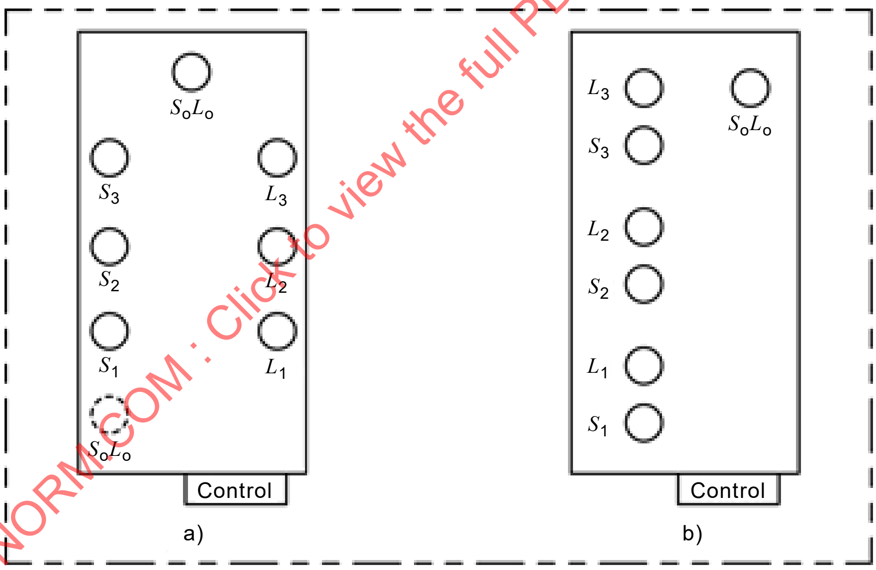


Figure 1 – Single-phase voltage regulators

For three-phase voltage regulators, when facing the voltage regulator on the unregulated circuit side (source), the S_1 terminal shall be in front on the right, and the L_1 terminal shall be directly behind the S_1 terminal, as shown in Figure 2(a), or the S_1 terminal shall be in front on the right, and the L_1 terminal shall be directly to the left of the S_1 terminal, as shown in Figure 2(b). The other terminals shall be located as shown in Figure 2.



NOTE The dotted circle in Figure 2(a) shows alternate location of neutral (S_0L_0) bushing.

Figure 2 – Three-phase voltage regulators with two arrangements of bushings

7.4 Diagram of connections

The manufacturer shall furnish, with each voltage regulator, complete diagrams showing the leads and internal connections and their markings, including polarity markings, and the voltages obtainable with the various connections. These diagrams shall be inscribed on and be part of the nameplate.

Voltage transformers and current transformers shall be indicated on the nameplate. Polarity and electrical location shall be identified.

Any nonlinear devices, capacitors, or resistors installed on the winding assembly or on the on-load tap-changer shall be indicated on the nameplate.

7.5 Nameplates

Two durable metal nameplates shall be furnished with each voltage regulator and shall be affixed to the main tank and on the front of the control enclosure. Unless otherwise specified, they shall be of corrosion-resistant material. The nameplates shall show, at a minimum, the ratings and other essential operating data as specified below:

a) manufacturer's name;
b) type and form designation or the equivalent;
c) cooling class;
d) serial number;
e) month and year of manufacturing (not coded);
f) number of phases;
g) rated kVA;
h) rated current;
i) supplementary continuous-current ratings;
j) rated voltage;
k) voltage transformer ratio;
l) rated range of regulation;
m) rated frequency;
n) impulse level, full wave in kilovolts (kV);
o) untanking weight;
p) total weight;
q) insulating liquid type;
r) volume of insulating liquid (weight of insulating liquid when specified in place of volume);
s) conductor material;
t) average winding rise in degrees Celsius (°C);
u) diagrams as specified in 7.4;
v) installation and operating instructions reference;
w) symmetrical short-circuit withstand ampere rating with time duration;
x) asymmetrical short-circuit withstand, first peak ampere rating (when specified);
y) on-load tap-changer model number and maximum through-current rating;
z) tap-changer motor capacitor rating;
aa) ratio of load current to switched current (if series transformer construction is used).

7.6 Tank construction

7.6.1 General

Voltage regulators shall have a sealed-tank liquid-preservation system. Sealed-tank construction is a construction in which the interior of the tank is sealed to prevent the introduction of external atmosphere into the tank. As a part of the normal operation, a device, as defined in 7.6.2, shall be provided to relieve excess pressure due to normal temperature variation of top liquid and/or due to on-load tap-changer operations. The voltage regulator shall remain effectively sealed for a top liquid temperature range of −20 °C to +110 °C for continuous operation at rated kilovoltamperes and under operating conditions as described in IEEE Std C57.91 and IEC 60076-7[11] without gaskets and O-rings seizing or deteriorating, for the life of the voltage regulator. Excess pressure may also build up slowly due to overloads, or high ambient temperatures, or external secondary faults, or internal incipient faults in the series or shunt windings. This excess pressure should result in an emission of only a negligible amount of liquid.

7.6.2 Pressure-relief valve

The replaceable pressure-relief valve shall be located on the tank above the 110 °C top liquid level, as determined by the manufacturer's calculation. The valve shall be located so it does not interfere with the use of support lugs and lifting lugs. It shall not be located in the quadrant of the tank that contains the control enclosure.

Exposed parts shall be of weather- and corrosion-resistant materials. Gaskets and O-rings shall withstand liquid vapour at 110 °C continuously and under operating conditions as described in IEEE Std C57.91 and IEC 60076-7[11], without seizing or deteriorating, for the life of the voltage regulator.

The valve shall have a pull ring for manually reducing pressure to atmospheric level using a standard hook stick, and shall be capable of withstanding a static pull force of 112 N (25 lbf) for 1 min without permanent deformation. The valve shall withstand for 1 min a static force of 445 N (100 lbf) applied normal to its longitudinal axis at the outermost extremity of the body. When specified, the venting port on the outward side of the valve-head seat shall be protected to prevent entry of dust, moisture, and insects before and after the valve has operated.

Venting and sealing characteristics shall be as follows:

a) venting pressure = 34,5 kPa (5 psig) ± 13 kPa (gauge) (2 psig);
b) resealing pressure = 6,9 kPa (gauge) (1 psig) minimum;
c) zero leakage from reseal pressure to −56 kPa (gauge) (−8 psig);
d) flow at 103 kPa (gauge) (15 psig) = 23,6 l/s [50 standard cubic feet per minute (SCFM)] minimum corrected for air pressure of 101 kPa (14,7 psi) (absolute) and air temperature of 21 °C.

7.6.3 Cover assembly

A cover assembly designed to relieve excessive pressure in the voltage regulator tank shall remain effectively sealed for overloads (IEEE Std C57.91 and IEC 60076-7[11]) and short-circuits (6.8 and IEC 60076-5[10]). The assembly shall relieve pressure at a minimum of 20 kPa (gauge) (3 psig) if designed to reseal, or at a minimum of 138 kPa (gauge) (20 psig) if designed for pressure relief without resealing. Such operation shall occur before other components of the tank are ruptured or displaced, and the cover shall remain in position. Manual means of venting the tank before removal of the cover shall be provided. The flow rate shall be at least equal to that of the pressure-relief device specified in 7.6.2.

7.6.4 Sudden pressure relay

When specified, a sudden pressure relay with a seal-in circuit shall be provided for the indication of voltage regulator faults, and to minimize damage to equipment. The relay shall not actuate under normal voltage regulator operating pressures. The sudden pressure relay may be either a gas space mounted relay or an under liquid relay. Under liquid relays shall actuate under rapidly changing pressures of 10 kPa/s to 38 kPa/s (1,5 psi/s to 5,5 psi/s). The gas space mounted relays shall actuate with a pressure change of 3,5 kPa/s to 21 kPa/s (0,5 psi/s to 3,0 psi/s). These two types of relays shall have their seal-in circuits actuate within three cycles of the rated power frequency after the pressure relay operation.

The sudden pressure relay shall be able to withstand full vacuum or positive pressure of 103 kPa (15 psi) without damage.

7.6.5 Lifting lugs

The lifting lugs shall be permanently attached to and arranged on the tank to provide a balanced lift in a vertical direction for the completely assembled voltage regulator and shall be designed to provide a safety factor of five. The safety factor of five is the ratio of the ultimate stress to the working stress of the material used. The working stress is the maximum combined stress developed in the lifting lugs by the static load of the completely assembled voltage regulator. If the angle of the lifting means interferes with the cover, bushings, arresters or other components, a spreader bar should be provided by the purchaser.

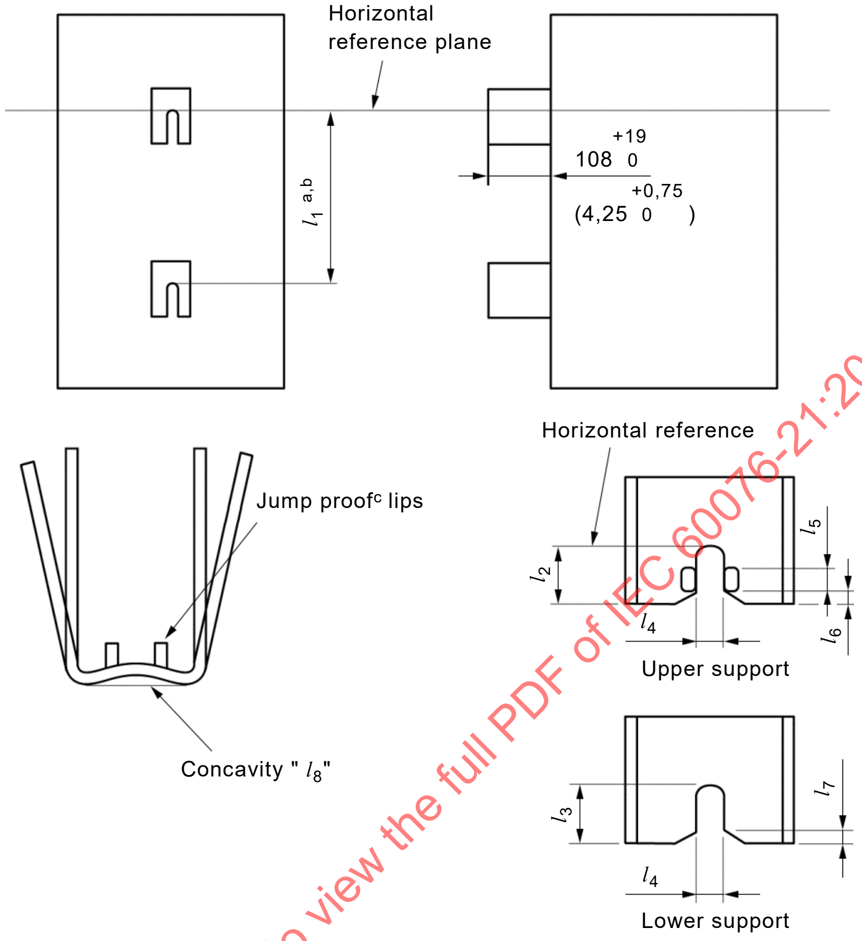
7.6.6 Support lugs

Support lugs for pole mounting shall be provided for ratings 288 kVA and less, with rated line current of 668 A or less. Support lugs shall be designed to provide a safety factor of five when supported in a vertical plane from the top lug only. The safety factor of five shall be as defined for lifting lugs in 7.6.5. Interchangeable mounting to the maximum extent is accomplished by use of Type-B and Type-C support lugs designed in accordance with Figure 3 and Figure 4, respectively. An upper and a lower support lug shall be provided for direct-pole mounting. Type and spacing of support lugs used are dependent on the total weight and height of the voltage regulator.

NOTE 1 Support lug identification and descriptions come from IEEE Std C57.12.20™[19]. Owing to weight restrictions, Type-A support lug is not relevant to voltage regulators.

NOTE 2 Depending on the manufacturer, weights can be significantly different for the same rating. The purchaser is advised to verify the pole is suitable for the weight specified on the voltage regulator's nameplate.

Dimensions in millimetres (dimensions in inches)



Dimensions[d]	Support lug B[e] mm (in)
l_2	44,5 (1,75)
l_3	63,5 (2,50)
l_4[f]	20,2 (0,80)
l_5	15,9 (0,63)
l_6	6,4 (0,25)
l_7	12,7 (0,50)
l_8	6,4 (0,25)

NOTE Unless otherwise noted, all dimensions have a tolerance of ±2 mm (0,063 in).

a "l_1" dimension is 590 mm (23,25 in) or 895 mm (35,25 in) depending on the tank height.

b Slots "l_1" dimension is spaced 20 mm (0,75 in) less than pole bolt spacing.

c Jump-proof lips are on upper support only.

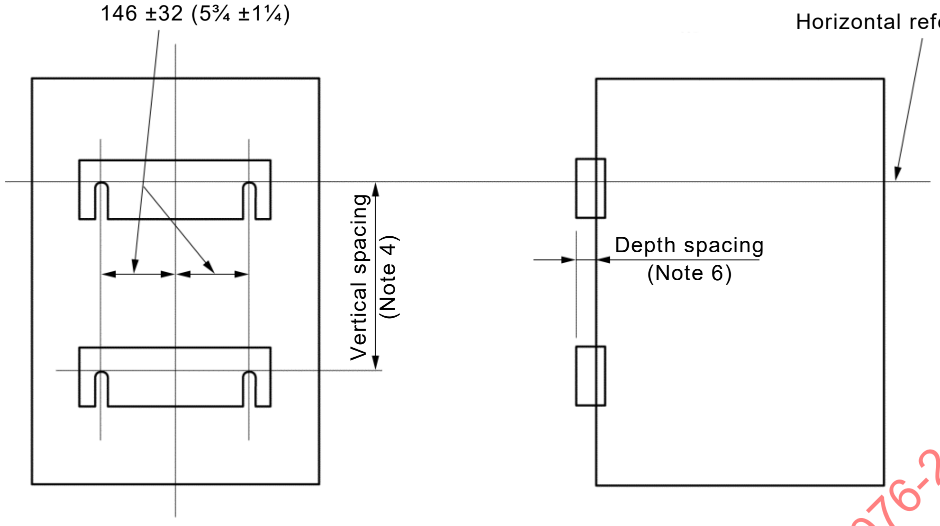
d The dimensions shown shall be maintained to obtain a standard mounting and are not intended to show construction details except for slot dimensions.

e Type-B support lugs use 20 mm (0,75 in) bolts.

f Tolerance for slot dimension "l_4" shall be ±0,4 mm (±0,016 in).

Figure 3 – Type-B support lugs

Dimensions in millimetres (dimensions in inches)



NOTE 1 Support lugs attached to voltage regulator have provisions for bolting on Type-C adapter plates for direct pole mounting.

NOTE 2 Slots can be vertical as well as horizontal and are suitable for 16 mm (0,625 in) bolts.

NOTE 3 Support lug faces are located in one plane.

NOTE 4 Vertical spacing is 914 mm (36 in).

NOTE 5 Type-C adapter plates for direct pole mounting and cluster mounting of voltage regulators are available from pole-line hardware manufacturers. If such adapter plates are to be used, it is suggested the purchaser contact the manufacturer for maximum loading capacities.

NOTE 6 Depth of support lugs is dependent on a manufacturer's design. Bushing profiles on top of cover are to be offset. Some manufacturers incorporate the design specifications of a Type-C adapter plate within their Type-C support lug design for ease of installation.

Figure 4 – Type-C support lugs

7.6.7 Substation bases

Bases for substation mounting shall be provided for 165 kVA and higher and shall be arranged for rolling or skidding in two directions: parallel to and right angles to one side of the voltage regulator. Voltage regulators with substation base and support lugs shall not have the base interfere with the mounting of the voltage regulator to the pole.

7.6.8 Tank grounding provisions

7.6.8.1 Maximum continuous rating less than 300 A

Tank grounding provisions shall consist, at a minimum, of one steel pad with a 0,5 in-13 NC tapped hole, 11 mm (0,44 in) deep and located near the bottom of the tank.

7.6.8.2 Maximum continuous rating 300 A or greater

Tank grounding provision shall consist, at a minimum, of one unpainted copper-faced steel or stainless-steel pad, 50 mm × 90 mm (2,0 in × 3,5 in), with two holes horizontally spaced on 44,5 mm (1,75 in) centres, tapped for 0,5 inch 13 NC thread and located near the bottom of the tank. Minimum thread depth of each hole shall be 13 mm (0,5 in). Minimum thickness of the copper facing, when used, shall be 0,4 mm (0,015 in).

7.7 Components and accessories

7.7.1 Components for full automatic control and operation

a) Control system

b) Current and voltage transformers or the equivalent for supplying the control system

c) On-load tap-changer equipment consisting of a liquid-immersed arcing tap switch, a tap selector and an arcing switch, or a tap selector with vacuum switch or other current interrupting facility, and motor mechanism

d) Internal power supply for on-load tap-changer motor

e) Provision for disconnecting control power supply

f) Position indicator for the on-load tap-changer with maximum and minimum indicating hands and provision for resetting

   1) Adjustable range of regulation for the Raise and Lower ranges provided for supplementary current ratings per 6.3

   2) Mechanically actuated electric limit switches provided preventing travel beyond the maximum Raise and Lower positions

7.7.2 Accessories for single-phase step-voltage regulators

a) Combination drain and lower filter valve with sampling device

b) Fill plug located at the top of the tank above liquid level

c) Indicator for 25 °C liquid level

d) Bushing terminals shall be either clamp-type or threaded stud, depending on the nameplate line current ratings as shown in Table 16. The clamp-type terminals shall have at least the conductor range stated and shall be capable of accepting an aluminium or copper conductor. Spade terminals shall have a pad with a minimum dimension of 101,6 mm × 101,6 mm (4,0 in × 4,0 in), with four 14,2 mm (0,562 5 in) holes horizontally and vertically spaced on 44,5 mm (1,75 in) centres. Thicknesses of the pad are shown in Table 16. The purchaser has the responsibility of selecting the proper conductor size for use with the clamp-type or spade terminals. When selecting the conductor size, the purchaser should consider factors such as additional current carrying capability with reduced regulation (see 6.3), supplementary voltage ratings (see 6.2.4) and loading at other than rated conditions (see 5.2).

Table 16 – Bushing terminal applications

Nameplate line current rating (A)	Conductor size range or 4-hole spade
150 or less	8–4/0 AWG
151 to 300	2 AWG – 477 kCM
301 to 668	2 AWG – 800 kCM
669 to 1 200	1-1/8–12 UNF-2A with 4-hole spade – 9,5 mm (0,375 in) minimum thickness
1 201 to 2 000	1-1/2–12 UNF-2A with 4-hole spade – 12,7 mm (0,5 in) minimum thickness

7.7.3 Accessories for three-phase step-voltage regulators

a) Combination drain and lower filter valve with sampling device

b) Fill plug located at the top of the tank

c) Indicator for 25 °C liquid level

d) Clamp-type terminals in accordance with single-phase criteria [see item d) in 7.7.2]

e) Provision for thermometer

f) Openings to permit inspection of core and coil and on-load tap-changer

8 Other requirements

8.1 General

Certain specific applications have voltage regulator requirements not covered in Clause 5 to Clause 7. Clause 8 comprises descriptions of the most frequently used requirements for such voltage regulators. They shall be provided only when specified in conjunction with the requirements of Clause 5 to Clause 7. Information in the following subclauses may be specified for some applications.

8.2 Other components and accessories

8.2.1 General

When specified, the other components and accessories listed in 8.2.2 and 8.2.3 may be provided.

8.2.2 Single- and three-phase voltage regulators

a) Control cabinet removable for remote control operation [up to 15 m (50 ft) from the voltage regulator]

b) Universal interface (see Clause 11)

c) Voltage transformer for source side sensing for reverse power flow mode of control

d) Control cabinet heater

e) Remote communication interfaces

f) 5 A secondary rating for current transformer

g) Surge arresters

h) Thermometer with or without alarm contacts

i) Oil level gauge with or without alarm contacts

j) Sight gauge for critical liquid level indication (decal required for designating level at middle of dial)

k) Tank and control enclosure ground connectors

l) Forced air cooling (ONAF or KNAF) with fan motors rated 120 V or 240 V, 50/60 Hz, single-phase, without centrifugal switch, and individually fused or otherwise thermally protected. In addition the following equipment shall be provided:

   1) fan control circuitry including relays and operation switch;

   2) mechanical arrangement and provisions for mounting fans;

   3) thermometer with alarm contacts.

8.2.3 Three-phase voltage regulators

a) Hand operation crank for on-load tap-changer

b) On-load tap-changer compartment separate from the core and coil

c) Remote position indicator[4]

9 Test code

9.1 General

Although the figures with the following test procedures show conventional meters, adequate digital readout measuring devices and digital sampling techniques with computer calculations are considered to be satisfactory alternatives.

9.2 Resistance measurements

9.2.1 General

Resistance measurements are of fundamental importance for the following purposes:

a) calculation of the I^2R component of conductor loss;

b) calculation of winding temperatures at the end of a temperature-rise test;

c) as a quality control test of the manufacturing process;

d) as a base for assessing possible damage in the field.

9.2.2 Determination of cold temperature

9.2.2.1 General

The cold temperature of the winding shall be determined as accurately as possible when measuring the cold-resistance. Cold-resistance measurements shall be made on a voltage regulator only when the liquid or winding temperature is stable. The temperature is considered stable if the top liquid temperature does not vary by more than 2 °C in a 1 h period.

9.2.2.2 Voltage regulator windings immersed in insulating liquid

The temperature of the windings shall be assumed to be the same as the average temperature of the insulating liquid, provided:

a) the windings have been under insulating liquid without excitation and current for a minimum of 3 h before the cold-resistance is measured;

b) the temperature of the insulating liquid has stabilized, and the difference between top and bottom temperatures does not exceed 5 °C.

9.2.2.3 Voltage regulator windings out of insulating liquid

The temperature of the windings shall be recorded as the average of several thermometers or thermocouples inserted between the coils, with care used to see their measuring points are as nearly as possible in actual contact with the winding conductors. It should not be assumed the windings are at the same temperature as the surrounding air.

4 For Selsyn-type systems, care shall be exercised to assure that the conductor size is commensurate with the distance used.

9.2.3 Conversion of resistance measurements

Cold winding resistance measurements are normally converted to a standard reference temperature (T_s) equal to the rated average winding temperature-rise plus 20 °C. In addition, it may be necessary to convert the resistance measurements to the temperature at which the impedance loss measurements were made. The conversions are accomplished by the following Equation (3):

$$R_s = R_m \frac{T_s + T_k}{T_m + T_k} \quad (3)$$

where

R_s is the resistance at desired temperature T_s (Ω);

R_m is the measured resistance (Ω);

T_s is the desired reference temperature (°C);

T_m is the temperature at which resistance was measured (°C);

T_k is 234,5 °C (copper) or 225 °C (aluminium; see Note).

NOTE The temperature 225 °C applies for pure or EC aluminium. T_k can be as high as 230 °C for alloyed aluminium. Where copper and aluminium windings are employed in the same voltage regulator, a value for T_k of 229 °C is applied for the correction of load loss.

9.2.4 Resistance measurement methods

9.2.4.1 Voltmeter-ammeter method

The voltmeter-ammeter method is the most common method used for voltage regulator winding resistance measurements. Resistance-measuring systems employing computer-controlled digital voltmeters, current measuring shunts, and/or digital ammeters of appropriate accuracy are commonly used for cold-resistance measurements and in connection with temperature-rise determinations.

To use this method, the following steps should be taken:

a) Measurement is made with direct current (DC), and simultaneous readings of current and voltage are taken using the connections of Figure 5. The required resistance is calculated from the readings in accordance with Ohm's law. Electronic switching power supplies may be used as voltage sources; however, batteries or filtered rectifiers may also be used, especially in those instances where fewer ripples are desired in the measurement. Automatic recording of the resistance data is recommended so the time to saturation and the variability of the resistance readings after stabilization can be documented.

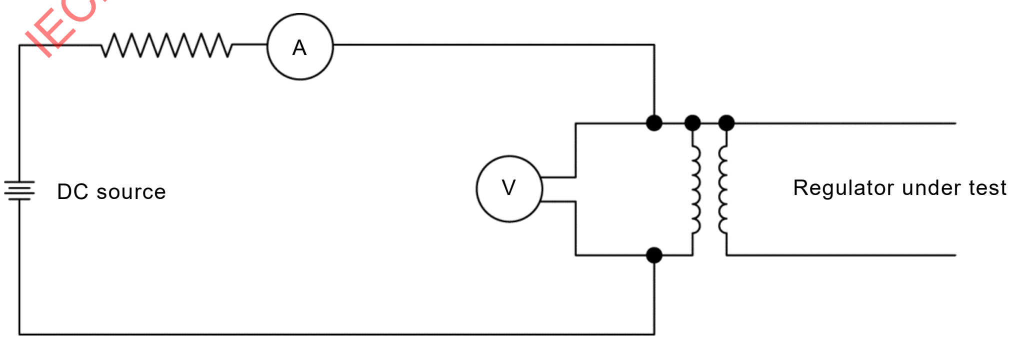


Figure 5 – Connections for voltmeter-ammeter method of resistance measurement

b) The voltmeter leads shall be independent of the current leads and shall be connected as closely as possible to the terminals of the winding to be measured. This step is to avoid including, in the reading, the resistances of current-carrying leads and their contacts and of extra lengths of leads.

c) When making manual resistance measurements:

   1) The voltmeter may be disconnected from the circuit before switching the current on or off, to protect the voltmeter from damage by off-scale deflections. To protect test personnel from inductive kick, the current may be switched off by a suitably insulated switch with a protective circuit to discharge the energy.

   2) Due to inaccuracy of deflecting ammeters and voltmeters, current shunts and digital voltmeters or high-accuracy digital ammeters or other high-accuracy instrumentation should be used.

d) Resistance is recommended to be measured at intervals of 5 s to 10 s, and the readings used shall be after the current and voltage have reached steady-state values.

   When measuring the cold-resistance, preparatory to making a temperature-rise test, note the time required for the readings to become constant. This period of time should be allowed to elapse before taking the first reading when final winding hot-resistance measurements are being made. The residual flux in the cores should be made the same for both the cold-resistance and hot-resistance measurements by saturating the core with direct current prior to the measurement.

   In general, the winding will exhibit a long time constant. To reduce the time required for the current to reach its steady-state value, a noninductive external resistor may be added in series with the DC source. It may then be necessary to increase the source voltage to compensate for the voltage drop in the series resistor. The time is also reduced by passing a direct current through other windings in the same polarity as the winding being tested.

e) It is recommended that ten or more readings, but a minimum of four readings should be used for each cold-resistance measurement, and the average of the resistances calculated from these measurements shall be considered to be the resistance of the circuit. The current used shall not exceed 15 % of the rated current of the winding whose resistance is to be measured. Larger values may cause inaccuracy by heating the winding and thereby changing its temperature and resistance.

9.2.4.2 Bridge method

Bridge methods may be used.

NOTE For resistance values of 1 Ω or more, a Wheatstone bridge (or equivalent) is commonly used; for values less than 1Ω, a Kelvin bridge (or equivalent) is commonly used.

9.3 Polarity test

9.3.1 General

Polarity testing of a voltage regulator is to assure correct polarity of the instrument transformers used in conjunction with the line-drop compensation circuit of the control device. Polarity tests on voltage regulators shall be made in accordance with one of the following methods:

a) inductive kick;

b) ratio meter.

NOTE Testing for additive or subtractive polarity of a main winding, as commonly required for transformers, is not required for voltage regulators. See 3.10.

9.3.2 Polarity by inductive kick

Polarity with regard to the instrument transformers used in voltage regulators may be determined with a low-voltage direct current supply and analogue high-voltage voltmeter. The following procedure may be used to check polarity by means of an inductive kick with direct current:

a) The example shown in Figure 6 is set up for a voltage regulator with a voltage transformer, a current transformer, and a utility winding within the main core and coil assembly. Connect the voltage regulator as shown.

b) Impress a direct voltage of known polarity "S" to "SL", with positive polarity at "S". Wait several seconds while the current stabilizes.

c) Connect a zero-centre-reading direct current voltmeter to the voltage transformer secondary winding, point 1 to point 0 shown in Figure 6.

d) Open the switch. A negative kick response on the voltmeter indicates the polarity is correct as marked.

e) Repeat the test for the current transformer (point 2) and the utility winding (point 3). It may be necessary to place a shunt from "L" to "SL" when testing the current transformer polarity.

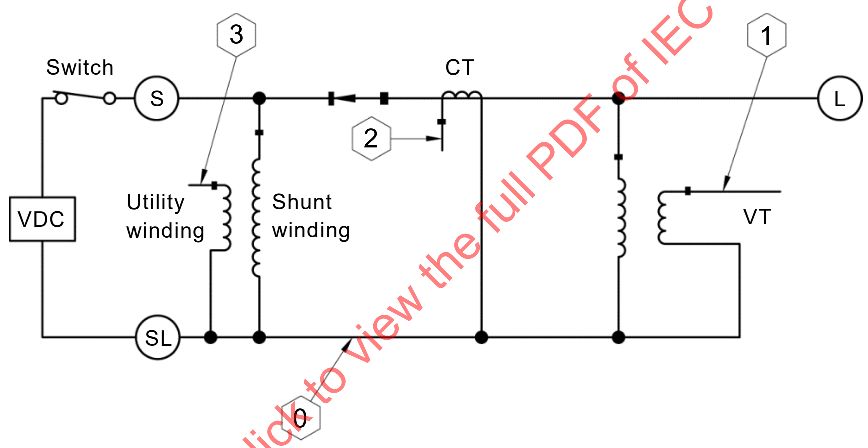


Figure 6 – Voltage regulator connected for polarity testing – Voltage regulator in Neutral position

9.3.3 Polarity by ratio meter

The ratio meter described in 9.4.6.3 can also be used to test polarity.

9.4 Ratio test

9.4.1 General

The turns ratios of a voltage regulator, depending on the design type, can involve one to two core and coil assemblies with two to five individual windings and separate voltage transformer(s) used for control and on-load tap-changer motor supplies. Ratios are made between the number of turns in one winding to the other individual windings of the same core and coil assemblies. The turns ratio of separate voltage transformer(s), if supplied, is made between the turns of the primary and secondary windings.

9.4.2 Taps

The turns ratio shall be determined for all taps as well as for the full winding involved.

9.4.3 Voltage and frequency

The ratio test shall be made at rated or lower voltage and rated or higher frequency.

9.4.4 Three-phase voltage regulators

In the case of three-phase voltage regulators, when each phase is independent and accessible, single-phase power should be used; although, when convenient, three-phase power may be used.

9.4.5 Tolerance for ratio

The turns ratio between windings shall be such that, with the voltage regulator at no load and with rated voltage on the winding with the least number of turns, the voltages of all other windings and all tap connections shall be within 0,5 % of the manufacturer's specified design voltages.

NOTE 1 By design, as per 6.2.2, voltage regulators are approximately compensated for their internal regulation. Also, the voltages of the individual steps are commonly not identical when combined to achieve the maximum range of regulation. The purchaser does not commonly know the extent of the internal compensation or the values of the individual steps. Known design values assist in accurately performing this test.

NOTE 2 For three-phase wye connected voltage regulators, this tolerance applies to the phase-to-neutral voltage.

9.4.6 Ratio test methods

9.4.6.1 Voltmeter method

Two voltmeters shall be used (with voltage transformers when necessary): one to read the voltage of the shunt winding, and the other the series winding.

The two voltmeters shall be read simultaneously.

A second set of readings shall be taken with the instruments interchanged, and the average of the two sets of readings shall be taken to compensate for instrument errors.

Voltage transformer ratios should yield approximately the same readings on the two voltmeters. Compensation for instrument errors by an interchange of instruments shall otherwise not be satisfactory, and it shall be necessary to apply appropriate corrections to the voltmeter readings.

Tests shall be made at not less than four voltages in approximately 10 % steps and the average result shall be taken as the true value. These several values should check within 1 %. Otherwise, the tests shall be repeated with other voltmeters.

When appropriate corrections are applied to the voltmeter readings, tests may be made at only one voltage.

When several voltage regulators of duplicate rating are to be tested, work may be expedited by applying the foregoing tests to only one unit, and then comparing the other units with this one as a standard, in accordance with the comparison voltage regulator method discussed in 9.4.6.2.

9.4.6.2 Comparison method

A convenient method of measuring the ratio of a voltage regulator is by comparison with a voltage regulator of known ratio.

The voltage regulator to be tested is excited in parallel with a voltage regulator of the same nominal ratio, and the two output sides connected in parallel but with a voltmeter or detector in the connection between two terminals of similar polarity (see Figure 7). The voltmeter or detector indicates the difference in voltage. This method is more accurate than the following alternative method.

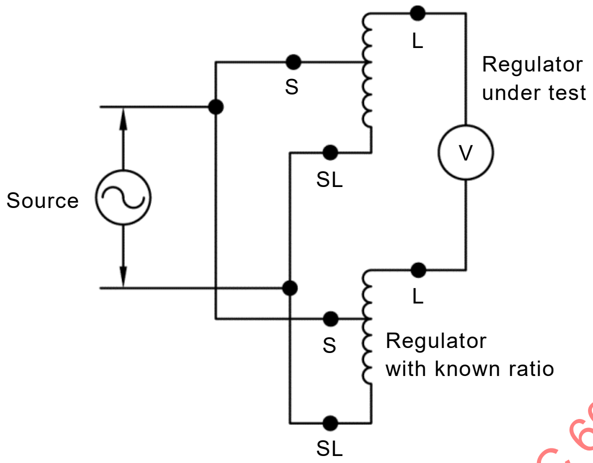


Figure 7 – Voltmeter arranged to read the difference between the two output side voltages

For an alternate method, the voltage regulator to be tested is excited in parallel with a voltage regulator of known ratio, and the voltmeters are arranged to measure the two series winding voltages (see Figure 8). The voltmeters shall be interchanged and the test repeated. The averages of the results are the correct voltages.

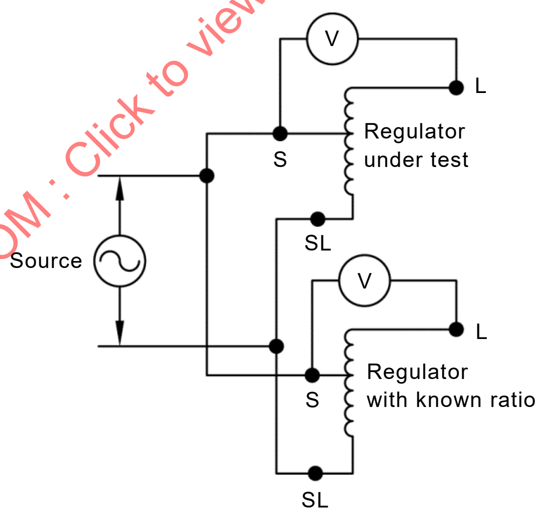


Figure 8 – Voltmeters arranged to read the two series winding voltages

9.4.6.3 Ratio meter

A meter using the basic circuit of Figure 9 may be used to measure the ratio. When detector DET is in balance, the voltage regulator ratio is equal to R/R_1.

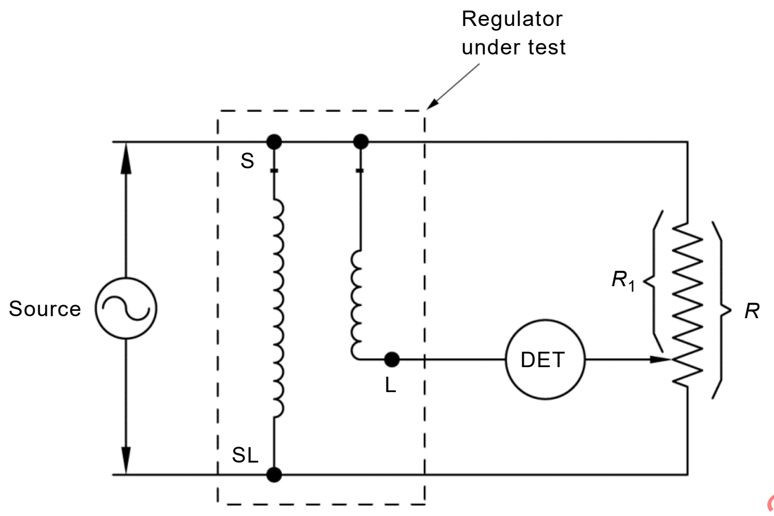


Figure 9 – Basic circuit of ratio meter

NOTE 1 A measurement of ratio using circuits of this type has also been described as a ratio by resistance potentiometer.

NOTE 2 More accurate results can be obtained using a ratio meter providing phase-angle correction.

NOTE 3 The ratio meter can also be used to test polarity.

9.5 No-load loss and excitation current

9.5.1 General

No-load loss is incident to the excitation of a voltage regulator. No-load loss includes core loss, dielectric loss, and conductor loss in the windings due to excitation current, and conductor loss due to circulating current in parallel windings. No-load loss changes with the excitation voltage.

The excitation current (no-load current) includes current flowing in any winding used to excite the voltage regulator when all other windings are open-circuited, and circulating current in parallel windings. The excitation current referred to the shunt winding is generally expressed in percent of the rated load current.

The no-load loss of a voltage regulator consists primarily of the iron loss in the voltage regulator cores and circulating current in parallel windings, both of which are a function of the magnitude, frequency, and waveform of the impressed voltage.

The no-load loss and current are particularly sensitive to differences in wave shape; therefore, a no-load loss measurement varies markedly with the waveform of the test voltage.

The excitation kVA is the product of the rated voltage across the energized winding in kV multiplied by the excitation current in amperes. The ratio of the no-load loss (in kW) to the excitation kVA is the no-load loss power factor of the voltage regulator during the test, and is used in correction for phase-angle error as specified in 9.5.7.

In addition, several other factors affect the no-load loss and excitation current of a voltage regulator. The design-related factors include the type and thickness of core steel, the core configuration, the geometry of core joints, and the core flux density.

Factors that cause differences in the no-load loss of the same design include variability in characteristics of the core steel, mechanical stresses induced in manufacturing, variation in gap structure, core joints, and variability of reactor core gaps.

9.5.2 No-load loss test

9.5.2.1 General

The purpose of the no-load loss test is to measure no-load loss at a specified excitation voltage, frequency and tap position. The no-load loss determination shall be based on a sine-wave voltage, unless a different waveform is inherent in the operation of the voltage regulator. The average-voltage voltmeter method is the most accurate method for correcting the measured no-load loss to a sine-wave basis and is recommended. This method employs two parallel-connected voltmeters: one is an average-responding [but root mean squared (RMS) calibrated] voltmeter and the other is a true RMS-responding voltmeter. The test voltage is adjusted to the specified value as read by the average-responding voltmeter. The readings of both voltmeters are employed to correct the no-load loss to a sine-wave basis, using Equation (4) in accordance with 9.5.3.

9.5.2.2 Connection diagrams

Tests for the no-load loss determination of a single-phase voltage regulator are carried out using the schemes depicted in Figure 10 and Figure 11. Figure 10 shows the necessary equipment and connections when instrument transformers are not required. When instrument transformers are required, the equipment and connections shown in Figure 11 apply. If necessary, correction for loss in a connected measurement instrument may be made by disconnecting the voltage regulator under test and noting the wattmeter reading at the specified test circuit voltage. This loss represents the loss of the connected instruments (and voltage transformer, if used). It may be subtracted from the earlier wattmeter reading to obtain the no-load loss of the voltage regulator under test.

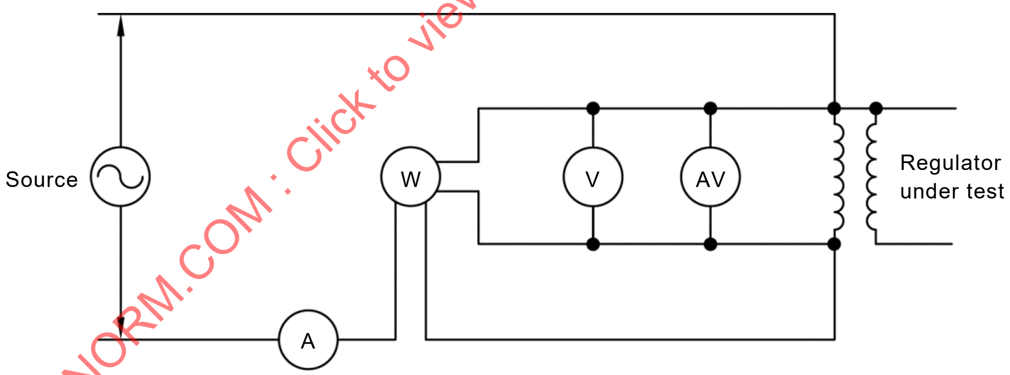


Figure 10 – Connection for no-load loss test of single-phase voltage regulator without instrument transformers

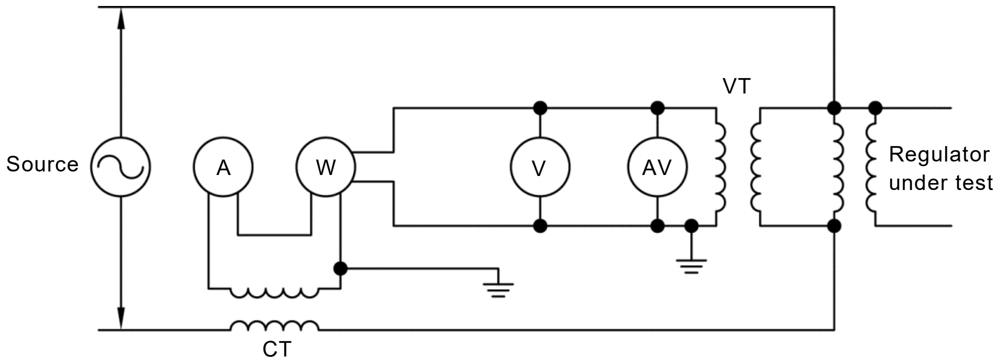


Figure 11 – Connections for no-load loss test of a single-phase voltage regulator with instrument transformers

9.5.2.3 Energized windings

Either the shunt winding or the series winding of the voltage regulator under test may be energized, but it is generally preferred to perform this test using the rated voltage across the shunt winding. The voltage to be maintained during test should result in rated voltage being applied to, or induced into, the shunt winding. In any case, the full winding (not merely a portion of the winding) should be used whenever possible. If, for some unusual reason, only a portion of a winding is excited, this portion shall not be less than 25 % of the winding.

9.5.2.4 Voltage and frequency

The operating and performance characteristics of a voltage regulator are based upon rated voltage and rated frequency, unless otherwise specified. Therefore, the no-load loss test is conducted with rated voltage impressed across the voltage regulator terminals, using a voltage source at a frequency equal to the rated frequency of the voltage regulator under test, unless otherwise specified.

To determine the no-load loss of a single-phase or a three-phase voltage regulator, the frequency of the test source shall be within ±0,5 % of the rated frequency of the voltage regulator under test. The voltage shall be adjusted to the specified value as indicated by the average-voltage voltmeter. Simultaneous values of RMS voltage, RMS current, electrical power, and the average-voltage voltmeter readings shall be recorded. For a three-phase voltage regulator, the average of the three voltmeter readings shall be the desired nominal value.

9.5.3 Waveform correction of no-load loss

The eddy-current component of the no-load loss varies with the square of the RMS value of excitation voltage and is substantially independent of the voltage waveform. When the test voltage is held at the specified value as read on the average-voltage voltmeter, the actual RMS value of the test voltage may not be equal to the specified value. The no-load loss of the voltage regulator corrected to a sine-wave basis shall be determined from the measured value using Equation (4) and Equation (5):

$$P = \frac{P_m}{(P_1 + kP_2)} \tag{4}$$

where

P is the no-load loss corrected for waveform;

P_m is measured no-load loss;

P_1 is the per unit hysteresis loss, referred to P_m;

P_2 is the per unit eddy-current loss, referred to P_m.

$$k = \left(\frac{E_r}{E_a}\right)^2 \quad (5)$$

where

E_r is the test voltage measured by RMS voltage meter;

E_a is the test voltage measured by average-voltage voltmeter.

The actual per-unit values of hysteresis and eddy-current losses should be used if available. A portion of the no load loss of a voltage regulator, depending on tap position, is associated with the reactor circulating current induced by a portion of the series winding. If actual values are not available, it is suggested that these two loss components be assumed equal in value, assigning each a value of 0,5 per unit.

Equation (4) is valid only for test voltages with moderate waveform distortion. If waveform distortion in the test voltage causes the magnitude of the correction to be greater than 5 %, the test voltage waveform shall be improved for an adequate determination of the no-load loss and current.

9.5.4 Test methods for three-phase voltage regulators

Tests for the no-load loss determination of a three-phase voltage regulator shall be carried out by using the three-wattmeter method. Figure 12 is a schematic representation of the equipment and connections necessary for conducting no-load loss measurements of a three-phase voltage regulator where instrument transformers are necessary.

9.5.5 Determination of excitation (no-load) current

The excitation (no-load) current of a voltage regulator consists of current maintaining the rated magnetic flux excitation in the cores of the voltage regulator and circulating current between parallel windings. The excitation current is usually expressed in per unit or in percent of the rated load current of the voltage regulator (where the cooling class of the voltage regulator involves more than one kilovoltampere rating, the lowest kilovoltampere rating is used to determine the base current). Measurement of excitation current is usually carried out in conjunction with the test for no-load loss. RMS current is recorded simultaneously during the test for no-load loss using the average-voltage voltmeter method. This value is used in calculating the per unit or percent excitation current. For a three-phase voltage regulator, the excitation current is calculated by taking the average of the magnitudes of the three line currents.

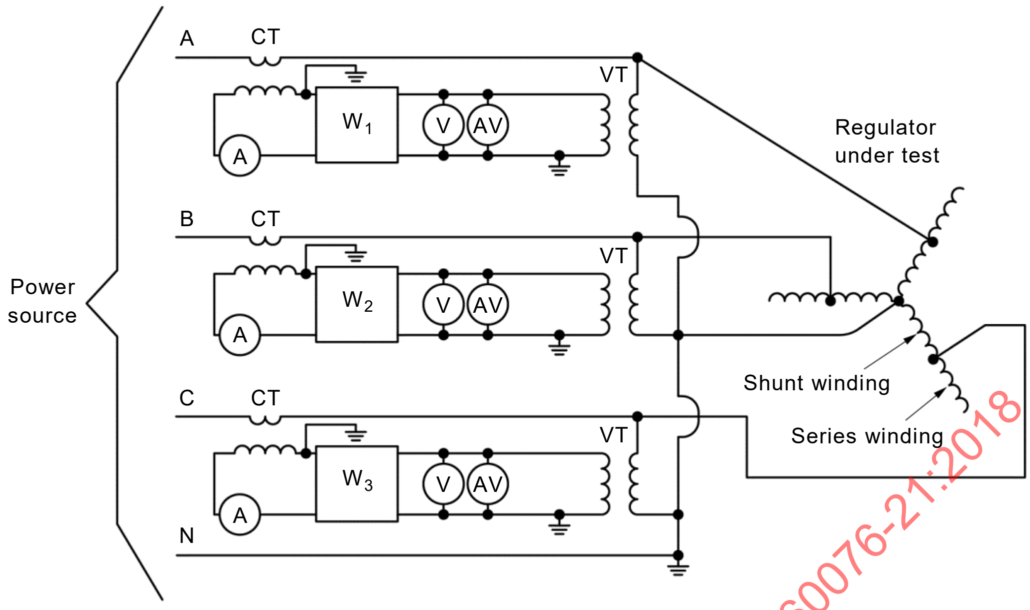


Figure 12 – Three-phase voltage regulator connections for no-load loss and excitation current test using three-wattmeter method

9.5.6 Measurements

At low power factor, such as those encountered while measuring losses of voltage regulators, judicious selection of measurement method and test system components is essential for accurate and repeatable test results. The phase-angle errors in the instrument transformers, measuring instruments, bridge networks, and accessories affect the no-load and load loss test results. Procedures for correcting the losses for metering phase-angle errors are described in 9.5.7.

9.5.7 Correction of loss measurement due to metering phase-angle errors

No-load and load loss errors can be magnitude related, such as instrument transformer ratio errors and meter calibration. Correction of loss measurement due to phase-angle errors in the wattmeters, voltage-measuring circuit and current-measuring circuit shall be applied in accordance with Table 17 using the correction formula in Equation (6):

$$P_\mathrm{c} = P_\mathrm{m} - V_\mathrm{m} A_\mathrm{m} \left[-\varphi W_\mathrm{d} - \varphi V_\mathrm{d} + \varphi C_\mathrm{d} \right] \qquad (6)$$

where

P_c is the wattmeter reading, corrected for phase-angle error (W);

P_m is the actual wattmeter reading (W);

V_m is the voltmeter reading across wattmeter voltage element (V);

A_m is the ammeter reading in wattmeter current element (A);

φW_d is the phase-angle error of wattmeter where applicable (rad);

φV_d is the phase-angle error of voltage transformer (rad);

φC_d is the phase-angle error of current transformer (rad).

Table 17 – Requirements for phase-angle error correction

Apparent loss power factor ($PF = P_m/VA$)	Comments
$PF \le 0{,}03$	Apply phase-angle error correction
$0{,}03 < PF \le 0{,}10$	Apply phase-angle error correction if $\lvert -\varphi W_d - \varphi V_d + \varphi C_d \rvert > 290$ µrad (1 min)
$PF > 0{,}10$	Apply phase-angle error correction if $\lvert -\varphi W_d - \varphi V_d + \varphi C_d \rvert > 870$ µrad (3 min)

In general, instrument transformer phase-angle errors are a function of burden and excitation. Likewise, wattmeter phase-angle errors are a function of the scale being used and the circuit power factor. Thus, the instrumentation phase-angle errors used in the correction formula shall be specific for the test conditions involved. Only instrument transformers meeting 0,3 metering accuracy class, or better, are acceptable for measurements.

Use of Equation (6) is limited to conditions of apparent power factor less than 0,20 and the total system phase-angle less than 20 min. If corrections are required with apparent power factor or system phase error outside this range, the following exact formulas in Equation (7) and Equation (8) apply:

$$\varphi_a = \cos^{-1}\left[\frac{P_m}{V_m A_m}\right] \tag{7}$$

$$P_c = V_m A_m \cos\left[\varphi_a - \varphi W_d - \varphi V_d + \varphi C_d\right] \tag{8}$$

For three-phase measurements, the corrections are applied to the reading of each wattmeter employed. The voltage regulator loss is then calculated to Equation (9) as follows:

$$P_c = \sum_{i=1}^{3} R_v R_a P_{ci} \tag{9}$$

where

P_c is the voltage regulator loss, corrected for phase-angle error (W);

P_{ci} is the corrected wattmeter reading of the ith wattmeter;

R_v is the true voltage ratio of voltage-measuring circuit;

R_a is the true current ratio of current-measuring circuit.

9.6 Load loss and impedance voltage

9.6.1 General

The load loss of a voltage regulator is a loss incident to a specified load carried by the voltage regulator. Load loss includes I^2R loss in the windings due to load current and stray loss due to eddy currents induced by leakage flux in the windings, core clamps, magnetic shields, tank walls, and other conducting parts. Stray loss may also be caused by circulating currents in parallel windings or strands. Load loss is measured by applying a short-circuit across the series winding and applying sufficient voltage across the shunt winding to cause a specified current to flow in the windings. The power loss within the voltage regulator under these conditions equals the load loss of the voltage regulator at the temperature of the test for the specified load current and tap position.

The impedance voltage of a voltage regulator is the voltage required to circulate rated current through the shunt winding while the series winding is short-circuited in a specified tap position. Impedance voltage is usually expressed in per unit or in percent of the rated voltage of the winding across which the voltage is applied and measured. The impedance voltage comprises a resistive component and a reactive component. The resistive component of the impedance voltage, called the resistance drop, is in phase with the current and corresponds to the load loss. The reactive component of the impedance voltage, called the reactance drop, is in quadrature with the current and corresponds to the leakage-flux linkage of the windings. The impedance voltage is the phasor sum of the two components. The impedance voltage is measured during the load loss test by measuring the voltage required to circulate rated current in the windings. The measured voltage is the impedance voltage at the temperature of the test, and the power loss dissipated within the voltage regulator is equal to the load loss at the temperature of the test and at rated load. The impedance voltage and the load loss are corrected to a reference temperature using the equations specified in 9.6.4.2.

The maximum impedance voltage of a step-voltage regulator is generally less than 0,6 % of the rated voltage, stated on the circuit kVA base. Maximum impedance can occur at different tap positions depending on the design type, coil construction and rating. Impedance is minimal in the Neutral position. The impedance voltage varies with tap position and is somewhat higher for a two-core and coil assembly design (series transformer construction).

The impedance kilovoltampere is the product of the impedance voltage across the energized winding in kilovolts and the winding current in amperes. The ratio of the load loss (kW) to the impedance (kVA) at the temperature of test is the load loss power factor of the voltage regulator during the test and is used for correction of phase-angle error as specified in 9.5.7.

9.6.2 Factors affecting the values of load loss and impedance voltage

9.6.2.1 General

The magnitudes of the load loss and the impedance voltage vary depending on the voltage regulator tap position. These changes are due to the changes in the magnitudes of winding currents and associated leakage-flux linkages, as well as changes in stray flux and accompanying stray loss. In addition, several other factors affect the value of load loss and impedance voltage of a voltage regulator. Considerations of these factors partly explain variations in a load loss value and impedance voltage for the same voltage regulator under different test conditions, as well as variations between a load loss value and impedance voltage of different voltage regulators of the same design. These factors are discussed in 9.6.2.2 to 9.6.2.4.

9.6.2.2 Design

The design-related factors include conductor material, conductor dimensions, winding design, winding arrangement, shielding design, and selection of structural materials.

9.6.2.3 Process

The process-related factors impacting the values of load loss and impedance voltage are the dimensional tolerances of conductor materials, the final dimensions of completed windings, phase assemblies, metallic parts exposed to stray flux, and variations in properties of conductor material and other metallic parts.

9.6.2.4 Temperature

Load loss values are also a function of temperature. The I^2R component of the load loss increases with temperature, whereas the stray loss component decreases with temperature. Procedures for correcting the load loss and impedance voltage to the standard reference temperature are described in 9.6.4.2.

9.6.3 Tests for measuring load loss and impedance voltage

9.6.3.1 Preparation

The following preparatory requirements shall be satisfied for accurate test results:

a) To determine the temperature of the windings with sufficient accuracy, the following conditions shall be met, except as stated in the Note below:

   1) The temperature of the insulating liquid has stabilized, and the difference between top and bottom liquid temperatures does not exceed 5 °C.

   2) The temperature of the windings shall be taken immediately before and after the load loss and impedance voltage test in a manner similar to that described in 9.2.2. The average shall be taken as the true temperature.

   3) The difference in winding temperature before and after the test shall not exceed 5 °C.

   NOTE For voltage regulators, where it may not be practical to wait for thermal equilibrium, the method used to determine the winding temperature takes into consideration the lack of thermal equilibrium and the effect of ohmic heating of the winding conductors by load current during the test. The method used can be verified by staging a repeated measurement of the load loss and impedance voltage at a later time when conditions 1 to 3 above are met.

b) The conductors used to short-circuit the series winding of the voltage regulator shall have a cross-sectional area equal to or greater than the corresponding voltage regulator leads.

c) The frequency of the test source used for measuring load loss and impedance voltage shall be within ±0,5 % of the nominal value.

d) The maximum value of correction to the measured load loss due to the test system phase-angle is limited to ±5 % of the measured loss. If more than 5 % correction is required, test methods and/or test apparatus should be improved for an adequate determination of load loss.

9.6.3.2 Load loss and impedance test of a single-phase voltage regulator

A voltage regulator, which basically is an autotransformer, may be tested for load loss and impedance with its internal connections unchanged and with the unit in a specified tap position. The test is made by shorting the unregulated (or regulated) circuit terminals while voltage (at rated frequency) is applied to the other terminals. The voltage is adjusted to cause rated line current to flow. For the purpose of measuring load loss and impedance voltage, it is more common that the series and shunt windings of the voltage regulator are treated as separate windings, the series winding short-circuited and the shunt winding excited. In this situation, where the voltage regulator is connected in a two-winding connection for the test, the current held shall be the rated current of the excited winding based on tap position. The load loss watts and applied voltamperes is the same, regardless of whether the series and shunt windings are treated as separate windings in the two-winding connection or are attached in a autotransformer connection, so long as rated winding current is held in the first case and rated line current in the second case. The impedance voltage measurement from the two-winding connection is revised to reflect the autotransformer connection. Simultaneous readings of the ammeter, voltmeter, and wattmeter are recorded for determination of load loss and impedance voltage. The voltage regulator under test should then be disconnected, and readings of loss taken on the wattmeter representing the loss of the measuring equipment, similar to the procedure in the no-load loss test.

The connections and apparatus needed for the determination of the load loss and impedance voltage of a single-phase voltage regulator are shown in Figure 13 and Figure 14. Figure 13 applies when instrument transformers are not required. When instrument transformers are required, Figure 14 applies.

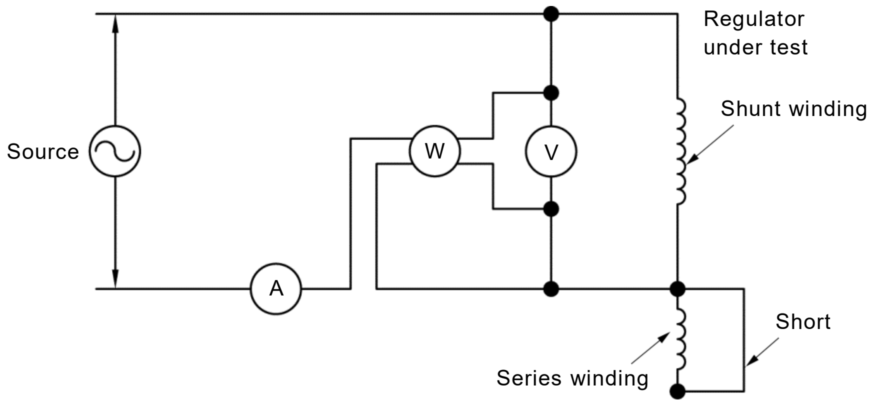


Figure 13 – Single-phase voltage regulator connections for load loss and impedance voltage test without instrument transformers

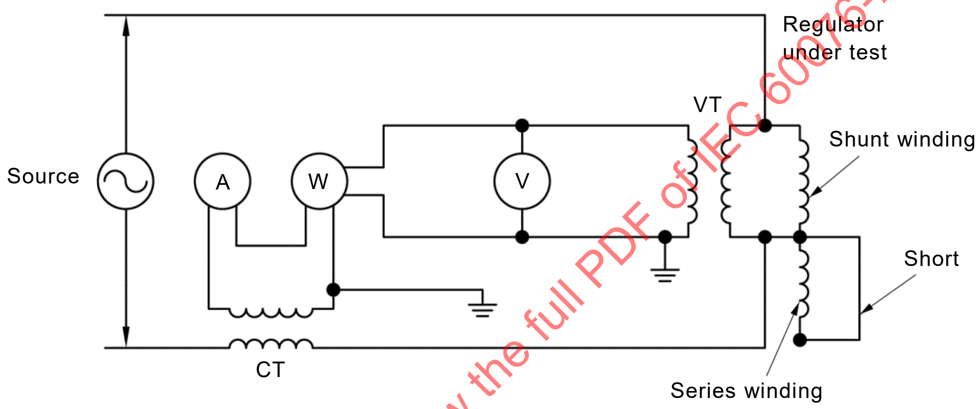


Figure 14 – Single-phase voltage regulator connections for load loss and impedance voltage test with instrument transformers

9.6.3.3 Impedance test of a three-phase voltage regulator

9.6.3.3.1 General

The terminals of the series winding of each phase are short-circuited together, and a three-phase voltage (at rated frequency) at suitable magnitude is applied to the terminals of the shunt windings to cause their rated winding currents to flow for a specified tap position. The procedure is similar to the method described for a single-phase voltage regulator except all connections and measurements are three-phase instead of single-phase. If the three line currents cannot be balanced, their average RMS value should correspond to the desired value, at which time simultaneous readings of wattmeters, voltmeters, and ammeters should be recorded.

9.6.3.3.2 Measurement connections

For three-phase voltage regulators, Figure 15 shows the apparatus and connections using the three-wattmeter method.

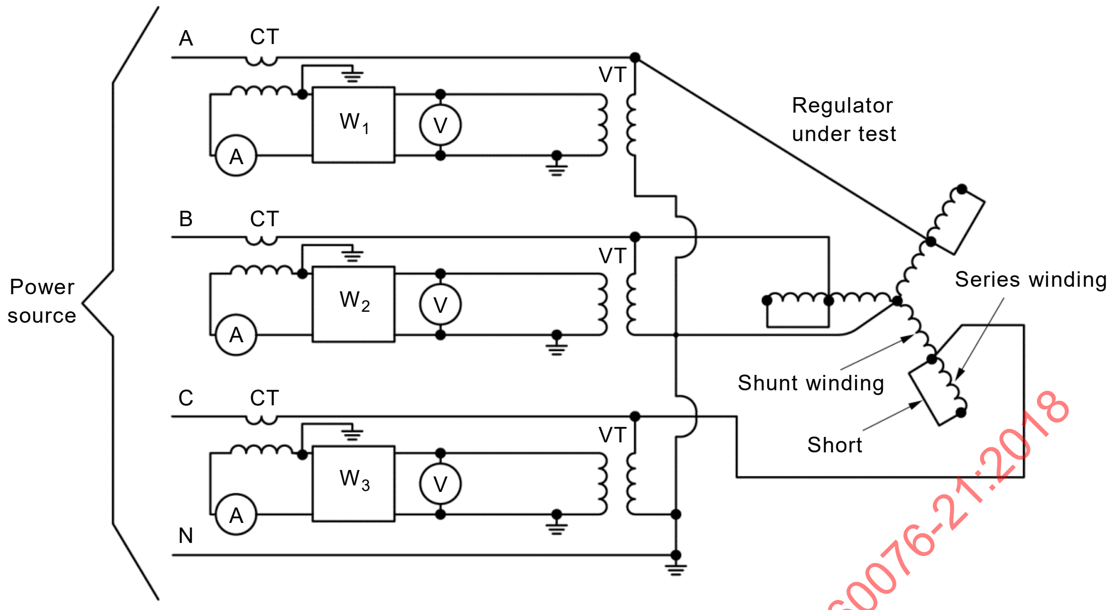


Figure 15 – Three-phase voltage regulator connections for load loss and impedance voltage test using the three-wattmeter method

9.6.4 Calculation of load loss and impedance voltage from test data

9.6.4.1 General

Load loss and impedance voltage measurements vary with temperature and, in general, shall be corrected to a reference temperature. In addition, a load loss measurement value shall be corrected for metering phase-angle error as defined in 9.5.7.

9.6.4.2 Temperature correction of load loss

Both I^2R loss and stray loss of a voltage regulator vary with temperature. The I^2R loss $P_r(T_m)$ is calculated from the ohmic resistance measurements (corrected to the temperature T_m at which the measurement of load loss and impedance voltage was completed) and the current used in the impedance measurement. This I^2R loss subtracted from the measured load loss watts $P(T_m)$ gives the stray loss $P_s(T_m)$ at the temperature at which the load loss test was made, as shown in Equation (10):

$$P_s(T_m) = P(T_m) - P_r(T_m) \tag{10}$$

where

$P_s(T_m)$ is the calculated stray loss at temperature T_m (W);

$P(T_m)$ is the load loss corrected in accordance with 9.5.7, for phase angle error at temperature T_m (W);

$P_r(T_m)$ is the calculated I^2R loss at temperature T_m (W).

The I^2R component of the load loss increases with temperature. The stray loss component diminishes with temperature. Therefore, when it is desirable to convert the load loss from the temperature at which it is measured T_m to another temperature T, the two components of the load loss are corrected separately.

Thus, as shown in Equation (11) and Equation (12):

$$P_r(T) = \frac{P_r(T_m)(T_k + T)}{(T_k + T_m)} \tag{11}$$

$$P_s(T) = \frac{P_s(T_m)(T_k + T_m)}{(T_k + T)} \tag{12}$$

and, then, as shown in Equation (13):

$$P(T) = P_r(T) + P_s(T) \tag{13}$$

where

$P_r(T)$ is I^2R loss (W) at temperature T (°C);

$P_s(T)$ is stray loss (W) at temperature T (°C);

$P(T)$ is load loss (W) corrected to temperature T (°C);

T_k is 234,5 °C (copper) or 225 °C (aluminium; see the following Note).

NOTE The temperature 225 °C applies for pure or EC aluminium. T_k can be as high as 230 °C for alloyed aluminium. Where copper and aluminium windings are employed in the same voltage regulator, a value for T_k of 229 °C is applied for the correction of load loss.

9.6.4.3 Impedance voltage

9.6.4.3.1 General

The impedance voltage and its resistive and reactive components at a specified tap position are determined by the use of Equation (14) through Equation (17):

$$E_r(T_m) = \frac{P(T_m)}{I} \tag{14}$$

$$E_x = \sqrt{E_z(T_m)^2 - E_r(T_m)^2} \tag{15}$$

$$E_r(T) = \frac{P(T)}{I} \tag{16}$$

$$E_z(T) = \sqrt{E_r(T)^2 + E_x{}^2} \tag{17}$$

where

$E_r(T_m)$ is the resistance voltage drop of in-phase component at temperature T_m (V);

$E_r(T)$ is the resistance voltage drop of in-phase component corrected to temperature T (V);

E_x is the reactance voltage drop of quadrature component (V);

$E_z(T_m)$ is the impedance voltage at temperature T_m (V);

$E_z(T)$ is the impedance voltage at temperature T (V);

$P(T)$ is the voltage regulator load loss corrected to temperature T (W);

$P(T_m)$ is the voltage regulator load loss measured at temperature T_m (W).

I is the current in the excited winding (A)

Per unit values of the resistance, reactance, and impedance voltage are obtained by dividing $E_r(T)$, E_x, and $E_z(T)$ by the rated voltage. Percentage values are obtained by multiplying per unit values by 100.

If the voltage regulator is tested as a two-winding transformer, with the series winding short-circuited and the shunt winding excited, the impedance value shall be revised to reflect the autotransformer connection. As an autotransformer, the voltage regulator transfers only the kVA related to the amount of the series winding located in the power circuit between the source and the load. Maximum kVA is transferred and supplied to the load at the maximum boost or buck position depending on the design type. This maximum kVA is 10 % of the kVA supplied to the load when operating at a 10 % range of regulation. This ratio of the rated kVA of the series winding to the output kVA of the voltage regulator is used to convert the effective impedance value of the two-winding connection to the effective impedance value of the autotransformer connection. This conversion is established by Equation (18):

$$Z_{\text{auto}} = Z_{\text{tw}} \frac{P_{\text{series}}}{P_{\text{output}}} \tag{18}$$

where

Z_{tw} is the two-winding (transformer) impedance;

Z_{auto} is the autotransformer (voltage regulator) impedance;

P_{output} is the output kVA supplied by the voltage regulator;

P_{series} is the rated kVA of the series winding at a specific tap position,

9.6.4.3.2 Tolerance for impedance

The impedance of a voltage regulator shall have a tolerance of ±10 % of the specified value. Differences of impedance between duplicate voltage regulators, when two or more units of a given rating are produced by one manufacturer at the same time, shall not exceed 10 % of the specified value.

NOTE The impedance is stated for given tap positions, normally the maximum boost and buck tap positions. The impedance is less at the lower tap positions and is essentially zero at the Neutral tap position except for voltage regulators having a series transformer construction.

9.7 Dielectric tests

9.7.1 General

9.7.1.1 Factory dielectric tests

The purpose of dielectric tests in the factory is to demonstrate the voltage regulator has been designed and constructed to withstand the specified insulation levels.

9.7.1.2 Test requirements

Test levels shall be as outlined in Table 11.

9.7.1.3 Measurement of test voltages

Unless otherwise specified, the dielectric test voltages shall be measured or applied, or both, in accordance with IEEE Std 4 or IEC 60060, with the following exceptions:

a) a protective resistance may be used in series with sphere gaps, on either the live or the grounded sphere. Where unnecessary to protect the spheres from arc damage, it may be omitted;

b) the bushing-type voltage divider method shall be considered a standard method for voltage regulator tests;

c) the rectified capacitor-current method shall be considered a standard method for voltage regulator tests.

9.7.1.4 Dielectric tests in the field

Field dielectric tests are performed in accordance with Annex B.

9.7.1.5 Factory dielectric tests and conditions

9.7.1.5.1 Test sequence

It is preferred that the dielectric tests be performed in the following sequence:

a) lightning impulse test;

b) applied voltage test;

c) induced voltage test.

9.7.1.5.2 Temperature

Dielectric tests may be made at temperatures assumed under normal operation or at the temperatures attained during the tests.

9.7.1.5.3 Assembly

Voltage regulators, including bushings and terminal compartments where necessary to verify air clearances, shall be assembled prior to making dielectric tests. However, assembly of items not affecting dielectric tests, such as radiators and cabinets, is not necessary. Bushings shall, unless otherwise authorized by the purchaser, be those to be supplied with the voltage regulator.

9.7.2 Lightning impulse type test

9.7.2.1 General

Lightning impulse tests, when required as a type test, shall consist of and be applied in the following order: one reduced full wave, one full wave, two chopped waves, and two full waves. The time interval between applications of the last chopped wave and the following full wave should be minimized, without intentional delays, to avoid recovery of dielectric strength. Impulse tests shall be made without excitation.

9.7.2.2 Reduced full-wave test

A reduced full wave is the same as a full wave, except the crest value shall be between 50 % and 70 % of the full-wave value given in Table 11.

9.7.2.3 Full-wave test

The test wave rises to crest in 1,2 μs and decays to half of crest value in 50 μs from the virtual time zero. The crest value shall be in accordance with Table 11, subject to a tolerance of ±3 %, and no flashover of the bushing or test gap shall occur. The tolerance on virtual front time should normally be ±30 %, and the tolerance on time to half of crest shall normally be ±20 %. However, as a practical matter, once the manufacturer has proven they have test equipment limitations, the following shall be considered:

a) The virtual front time shall not exceed 2,5 µs except for windings of large impulse capacitance (low-voltage, high-kilovoltampere and some high-voltage, high-kilovoltampere windings). To demonstrate the large capacitance of the winding causes the long front, the impulse generator series resistance may be reduced. The reduction should cause superimposed oscillations. Only the inherent generator and lead inductances should be in the circuit.

b) The impedance of some windings may be so low that the desired time to the 50 % voltage point on the tail of the wave cannot be obtained with available equipment. For such cases, shorter waves are considered acceptable provided the optimum impulse generator connection is used (i.e. using parallel stages, if applicable, and the largest available capacitance). However, if by using the optimum impulse generator connection, the minimum tail time specified (40 µs) cannot still be achieved, apply a resistor on the grounded terminal of the impulsed winding. The resistor value shall be the minimum necessary to achieve the required minimum tail time of 40 µs and shall not exceed 450 Ω.

   The impulse voltage applied to the resistor should not exceed 80 % of the rated lightning impulse level of the terminal on which the resistor is connected unless the manufacturer has consented.

   In general, the voltage peak appearing across the resistor is considerably delayed compared to the instant of the voltage peak of the applied lightning impulse. Thus, the resulting difference between the applied impulse and the voltage across the resistor (e.g. voltage across the winding) is similar to the one appearing across the winding if the resistor was not used and the terminal was directly grounded. If the resistor applied voltage peak coincides within 10 µs of the voltage impulse peak, then the voltage drop across the winding is significantly reduced and a special procedure should be agreed upon between the manufacturer and the purchaser.

   The use of the Glaninger circuit as described in IEEE Std C57.98 [23] is also an effective method to increase the tail time. If such a circuit is used, care should be exercised on the overswing in the opposite polarity. Overswing in opposite polarity up to 75 % is common.

   NOTE IEEE Std C57.98 [23] and IEC 60076-4 [9] give background information regarding the effect of an added resistor to the dielectric stresses applied to the voltage regulator.

If the calculated tail time for a particular connection and voltage regulator design is such the minimum time to 50 % (e.g. 40 µs) cannot be achieved, the manufacturer shall notify the purchaser of this possibility. The manufacturer shall also state the strategy to be taken to obtain the best achievable wave shape. Notification should be given during the bidding stage for cases where the minimum tail time cannot be obtained for a particular voltage regulator design and/or because of test laboratory limitations. In such cases, shorter wave shapes may be agreed upon between the manufacturer and the purchaser.

The minimum impulse generator energy required to meet the minimum tail time (40 µs) during an impulse test on a particular voltage regulator design and connection can be estimated by using the following Equation 19:

$$E_{\text{min}} = \frac{2\pi f (t_2)^2}{zU^2}\left(\frac{U_{\text{bil}}}{\eta}\right)^2 VA \tag{19}$$

where

E_{min} is the minimum energy required from the impulse generator (J);

f is the power frequency, 60 Hz or 50 Hz;

t_2 is the tail time (s)(t_2 equals 40 µs);

z is the impedance (in per unit), seen from the impulsed terminal;

U is the rated voltage (V, phase to phase);

U_{bil} is the rated BIL of the tested winding (V);

η is the impulse generator efficiency (in per unit) (η = 1,0);

VA is the three-phase volt-ampere rating for which the impedance z is defined.

Preceding equation has been derived from the equations given in IEC 60076-4 [9]. More information about wave shape control can be found in IEEE Std C57.98 [23] and IEC 60076-4 [9]. For single-phase voltage regulators, the three-phase bank power rating and associated phase-to-phase voltage shall be used in the above equation.

9.7.2.4 Chopped-wave test

A chopped wave is inherently a full lightning impulse wave, except the crest value shall be at the required level and the voltage wave shall be chopped at or after the required time to flashover (time to chopping) in accordance with Table 11 but not later than 6 μs after virtual origin. The virtual front time of the chopped wave may be different than the virtual front during full-wave test because of the presence of the chopping gap. Nevertheless, the tolerance on the virtual front time for the chopped-wave test should remain as defined for the full-wave test.

The gap or other equivalent chopping device shall be located as close as possible to the terminals of the voltage regulator without disrupting its electrical field distribution. The distance between the chopping device and the test object shall not exceed a lead length greater than the total height of the voltage regulator (tank plus bushings). The impedance between the tested terminal and the grounded end of the chopping device shall be limited to that of the necessary leads. The voltage zero following the instant of chopping shall occur within 1 μs. However, for some winding designs, the circuit response after chopping may not be oscillatory; it may be overdamped. For such cases, the time interval to the first voltage zero after the instant of chopping may be significantly greater than 1,0 μs.

Only for cases where the overswing to the opposite polarity is greater than 30 % is it permissible to add a series-connected resistor in the chopping circuit to limit the amount of overswing. The resistor shall not decrease the overswing below 30 % of the amplitude of the chopped wave.

The use of a resistor in the chopping circuit may increase the time interval to the first voltage zero after the instant of chopping. If this conflicts with the above requirement regarding the maximum time interval to the first voltage zero after the instant of chopping, the priority shall be given to maximum limit of the time interval. For such cases, it may not be possible to reduce the overswing to the opposite polarity to 30 %.

NOTE This method will increase the likelihood the steepness of the voltage collapse (dv/dt) is as high as possible.

The use of a chopping gap made of sphere gap(s) (single or multiple sphere gaps) is the preferred chopping method since it usually gives faster voltage collapse. The use of a rod-rod chopping gap is also permissible since this more accurately replicates in-service flashover of an air insulator. Notably, the rod-rod gap requires a greater distance between its electrodes for a given operating voltage than does a sphere gap. The extended arc length of the rod-rod gap provides more natural circuit damping than the shorter arc length of a sphere gap.

If the above prescribed maximum lead length to the chopping gap cannot be achieved because of the presence of accessories such as fans or any other voltage regulator accessories, then the shortest possible lead length should be used during tests.

9.7.2.5 Wave polarity

For liquid-immersed voltage regulators, the test waves are normally of negative polarity to reduce the risk of erratic external flashover in the test circuit.

9.7.2.6 Impulse oscillograms

All impulses applied to a voltage regulator shall be recorded by an oscilloscope or by a suitable digital transient recorder, unless their crest voltage is less than 40 % of the full-wave level. These oscillograms shall include voltage oscillograms for all impulses and ground-current oscillograms for all full-wave and reduced full-wave impulses. Sweep times should be on the order of 5 µs to 10 µs for chopped-wave tests, 50 µs to 100 µs for full-wave tests, and 100 µs to 600 µs for ground-current measurements.

When reports require oscillograms, those of the first reduced full-wave voltage and current, the first full-wave voltage and current, the two chopped waves, and the last two full waves of voltage and current shall represent a record of the successful application of the impulse test to the voltage regulator.

9.7.2.7 Connections and tap positions for impulse tests of line terminals

9.7.2.7.1 General

The series and shunt windings of a voltage regulator are considered as a single winding for the purpose of the impulse test. The line terminals, "S" and "L", are tied together through a resistor of 450 (1 ± 10 %) Ω to limit induced voltage. Current flowing in this limiting resistor shall not interfere with the ability to detect a staged single-turn fault. A Type A voltage regulator shall have the test applied to the "S" terminal while set in the maximum buck position. A Type B voltage regulator shall have the test applied to the "L" terminal while set in the maximum boost position. The value of the induced voltage on the non-impulsed line terminal shall be in accordance with Table 11, subject to a tolerance of ±10 %. Voltage regulators intended for an open or closed delta connection shall in addition have impulse voltage applied to the "SL" line terminal.

A voltage regulator with a series transformer construction is similar in nature to a Type A or Type B design depending on the location of the series transformer with respect to the shunt transformer and should be tested accordingly. For example, if the shunt transformer is connected between "S" and "SL", the voltage regulator shall be tested as a Type A design; if the shunt transformer is connected between "L" and "SL", the voltage regulator shall be tested as a Type B design.

NOTE Refer to Annex C for additional information on step-voltage regulator constructions.

9.7.2.7.2 Terminals not being tested

Neutral terminals shall be solidly grounded. Line terminals shall be either solidly grounded or grounded through a resistor with an ohmic value not in excess of 450 Ω.

The following factors shall be considered in the actual choice of grounding a terminal:

a) The voltage-to-ground on any terminal not being tested should not exceed 80 % of the full-wave impulse voltage level for that terminal.
b) When a terminal has been specified to be directly grounded in service, it shall be solidly grounded.
c) When a terminal is to be connected to a low-impedance cable connection in service, it shall either be directly grounded or grounded through a resistor with an ohmic value not in excess of the surge impedance of the cable.
d) Grounding through a low-impedance shunt for current measurements may be considered the equivalent of a solid ground.

9.7.2.7.3 Protective devices as an integral part of the voltage regulator

Voltage regulators may have, as an integral part of their design, nonlinear protective devices connected across whole or portions of windings. Operation of these protective devices during impulse testing may cause differences between the reduced full-wave and the full-wave and/or chopped-wave oscillograms. In order to demonstrate these differences are solely caused by the operation of the protective devices and not by a voltage regulator failure, additional reduced full-wave impulse tests at different voltage levels shall be applied to show the effect of the operation of the nonlinear devices on voltage and current oscillograms and its reproducibility.

A nonlinear protective device conveniently accessible, for example, connected externally between the "S" and "L" bushings, may be disconnected and isolated during the impulse testing.

The purpose of the nonlinear protective devices is to limit transient overvoltages, which may be impressed or induced across the windings during lightning impulse surges (high-frequency voltage surges).

NOTE Typical oscillograms depicting the operation of protective devices during impulse testing are shown in IEEE Std C57.98 [23] and IEC 60076-4 [9].

The following test sequence shall be performed:

- one reduced full wave between 50 % and 70 % of the required full-wave impulse level;
- one or more intermediate reduced full waves between 75 % and 100 % of the required full-wave impulse level;
- one full wave at 100 % of the required full-wave impulse level;
- two chopped waves at 100 % of the required chopped-wave impulse level;
- two full waves at 100 % of the required full-wave impulse level;
- one or more intermediate reduced full waves at the same voltage levels as used before the first full-wave test;
- one reduced full wave between 50 % and 70 % of the required full-wave impulse level.

The voltage level to be applied for the intermediate reduced full wave is not specifically given. Only a range is proposed because the threshold operating level of the nonlinear devices is dependent on the voltage regulator's design. Generally, a lightning impulse within a specified voltage range causes the operation of the nonlinear devices. The specific number of intermediate full-wave tests and their voltage levels cannot be given here. The number of intermediate full-wave tests and their respective voltage level for a given voltage regulator should be chosen by the manufacturer and agreed to by the purchaser.

With the exception of the special cases referenced below, the intermediate reduced impulse level shall show the operation of the nonlinear devices and its effect on the current and voltage oscillograms.

In some cases, tests at the required full-wave impulse level with the standardized lightning impulse wave shape do not show the operation of the nonlinear devices. If this is the case, additional intermediate reduced full-wave tests are not necessary and may be waived.

In some other special cases, the operation of the nonlinear devices can be observed only during the chopped-wave impulse tests. If this is the case, the intermediate reduced full-wave tests are also not necessary and may be waived. As explained in item a) under 9.7.2.9.3, comparison of the recorded oscillograms may be done by comparing the two chopped-wave tests together up to the time of chopping. Chopped-wave tests cannot be compared during and after chopping. For such cases, reduced chopped-wave impulses at a test level of approximately 75 % of the required chopped-wave test level may be a useful tool to assess that the differences on the recorded oscillograms are solely caused by the operation of the nonlinear devices. If reduced chopped-wave tests are performed, they should, by agreement, be performed before and after the required chopped-wave tests.

Because of the operation of the nonlinear devices, the comparison of the voltage and current oscillograms shall be made only between two tests performed at the same voltage level, for example, comparing the two 80 % reduced full-wave tests. Each reduced full-wave test performed after a full-wave test shall be compared with the corresponding reduced full-wave test performed prior to the full-wave tests. All three full-wave tests at 100 % shall be compared with each other.

9.7.2.7.4 Current transformer grounding

The secondaries of current transformers, either on bushings or permanently connected to the equipment being tested, shall be short-circuited and grounded.

9.7.2.7.5 Core and tank grounding

The core and tank shall be grounded for all impulse tests.

9.7.2.7.6 Grounding of voltage transformers and utility windings

The secondaries of voltage transformers and utility windings shall be terminated with impedance not to exceed 450 Ω to ground. Current flowing in this limiting resistor shall not interfere with the ability to detect a staged single-turn fault.

9.7.2.8 Impulse tests on voltage regulator neutrals

Impulse tests on the neutral terminal of a voltage regulator or a separate voltage regulator connected in the neutral of a transformer require one reduced and two full waves to be applied directly to the neutral or voltage regulator winding with an amplitude equal to the insulation level of the neutral. The voltage regulator being tested shall be set on the maximum buck or boost position. A wave having a front of not more than 10 µs and a tail of 50 µs to half-crest shall be used except when the inductance of the winding is so low that the desired voltage magnitude and duration to the 50 % point on the tail of the wave cannot be obtained, a shorter wave tail may be used.

9.7.2.9 Detection of failure during impulse test

9.7.2.9.1 General

Given the nature of impulse test failures, one of the most important matters to consider is the detection of such failures. Several indications of insulation failure exist.

9.7.2.9.2 Ground current oscillograms

In the ground-current method of failure detection, the impulse current in the grounded end of the winding tested is measured by an oscilloscope or by a suitable digital transient recorder connected across a suitable shunt inserted between the normally grounded end of the winding and the ground. Any differences in the wave shape between the reduced full-wave and final full-wave detected by comparison of the two current oscillograms may be indications of failure or deviations due to noninjurious causes. They should be fully investigated and explained by new reduced full-wave and full-wave tests. Examples of probable causes of different wave shapes are operation of protective devices, core saturation, or conditions in the test circuit external to the voltage regulator.

The ground-current method of detection is not suitable for use with chopped-wave tests.

9.7.2.9.3 Other methods of failure detection

Other methods of detecting failure include the following:

a) *Voltage oscillograms.* Any unexplained differences between the reduced full-wave and final full-wave detected by comparison of the two voltage oscillograms, or observed by comparing the chopped-waves to each other and to the full-wave up to the time of chopping, are indications of failure.

b) *Failure of gap to sparkover.* In making the chopped-wave test, failure of the chopping gap or any external part to sparkover, although the voltage oscillogram shows a chopped wave, is a definite indication of a failure either within the voltage regulator or in the test circuit.

c) *Noise.* Unusual noise within the voltage regulator at the instant of applying the impulse is an indication of trouble. Such noise should be investigated.

d) *Measurement.* Measurement of voltage and current induced in another winding may also be used for failure detection.

9.7.3 Lightning impulse routine test

9.7.3.1 General

Subclause 9.7.3 defines a routine lightning impulse quality control test suitable for high-volume production-line testing.

9.7.3.2 Connections and tap positions for impulse tests of line terminals

The series and shunt windings of a voltage regulator are considered as a single winding for the purpose of the impulse test. The line terminals, "S" and "L", are tied together through a resistor of 450 (1 ± 10 %) Ω to limit induced voltage. Current flowing in this limiting resistor shall not interfere with the ability to detect a staged single-turn fault. A Type A voltage regulator shall have the test applied to the "S" terminal while set in the maximum buck position. A Type B voltage regulator shall have the test applied to the "L" terminal while set in the maximum boost position. The value of the induced voltage on the non-impulsed line terminal shall be in accordance with Table 11, subject to a tolerance of ±10 %. Voltage regulators intended for an open or closed delta connection shall in addition have impulse voltage applied to the "SL" line terminal.

A voltage regulator with a series transformer construction is similar in nature to a Type A or Type B design depending on the location of the series transformer with respect to the shunt transformer and should be tested accordingly. For example, if the shunt transformer is connected between "S" and "SL", the voltage regulator shall be tested as a Type A design; if the shunt transformer is connected between "L" and "SL", the voltage regulator shall be tested as a Type B design.

NOTE Refer to Annex C for additional information on step-voltage regulator constructions.

9.7.3.3 Procedure

9.7.3.3.1 General

The windings under test are connected to ground through a low-impedance shunt. The tank and core are grounded. This shunt shall consist of either of the following:

a) *Ground-current method.* A suitable resistance shunt or wide-band pulse current transformer is employed to examine the waveform of the ground current.

b) *Neutral impedance method.* A low-impedance shunt, consisting of a parallel combination of resistance and capacitance (RC), is employed. The voltage across this neutral impedance shunt is examined.

An impulse voltage with 1,2 μs × 50 μs wave shape and with specified crest magnitude shall be applied in each test. The tolerances, polarity, and method of determining the wave shape shall be as specified in 9.7.2.3 and 9.7.2.5. During each test, the waveform of the ground current or the voltage wave across the neutral impedance shall be examined.

The required impulse tests shall be applied using either of the following test series described in 9.7.3.3.2 or 9.7.3.3.3.

9.7.3.3.2 Method 1

One reduced full-wave test is performed, followed by one 100 % magnitude full-wave test. The applied-voltage wave in the first test shall have a crest value of between 50 % and 70 % of the assigned BIL. The applied-voltage wave in the second test shall have a crest value of 100 % of the assigned BIL. Failure detection is accomplished by comparing the reduced full-wave test with the 100 % magnitude full-wave test, using either the ground-current waveform or the neutral impedance voltage waveform. A dielectric breakdown causes a difference in compared waveforms. Observed differences in the waveforms may be indications of failure, or they may be due to noninjurious causes. The criteria used to judge the magnitude of observed differences shall be based upon the ability to detect a staged single-turn fault made by placing a loop of wire around the core leg and over the coil.

9.7.3.3.3 Method 2

Two full-wave tests, with crest magnitude equal to the assigned BIL, are applied to the voltage regulator under test. A neutral impedance shunt, using suitable values of resistance and capacitance, is employed to record waveforms for comparison. The waveforms in both tests are compared to pre-established levels. A dielectric breakdown causes a significant upturn and increase in magnitude of the voltage wave examined across the neutral impedance. The pre-established levels are based upon a staged single-turn fault test, made by placing a loop of wire around the core leg and over the coil.

9.7.3.3.4 Failure detection

The failure detection methods for the routine impulse tests described in 9.7.3.3.2 and 9.7.3.3.3 are based on the following two conditions:

a) the voltage regulator connections during the test are such that the series winding is not shorted;
b) chopped-wave tests are not applied.

In addition to these methods of failure detection, other methods of failure detection as described in 9.7.2.9.3 are also indications of failure and shall be investigated.

When the test is complete and the process of failure detection is complete, the waveform records may be discarded.

An exception to the test order given in 9.7.1.5.1, the routine impulse test may be conducted either before or after the low-frequency dielectric tests; however, the preferred sequence is for the impulse test to precede the low-frequency dielectric tests.

9.7.3.4 Terminals not being tested

Neutral terminals shall be solidly grounded. Line terminals shall be either solidly grounded or grounded through a resistor with an ohmic value not in excess of 450 Ω.

The following factors shall be considered in the actual choice of grounding for a terminal:

a) The voltage-to-ground on any terminal not being tested should not exceed 80 % of the full-wave impulse voltage level for that terminal.

b) When a terminal has been specified to be directly grounded in service, it shall be solidly grounded.

c) When a terminal is to be connected to a low-impedance cable connection in service, then that terminal shall either be directly grounded or grounded through a resistor with an ohmic value not in excess of the surge impedance of the cable.

d) Grounding through a low-impedance shunt for current measurements may be considered the equivalent of a solid ground.

9.7.4 Applied-voltage test

9.7.4.1 General

Applied voltage test shall be performed in accordance with the requirements of Table 11.

9.7.4.2 Duration, frequency, and connections

The test shall be performed at low frequency (< 500 Hz) and the duration of the test shall be 1 min.

The winding being tested shall have all its parts joined together and connected to the line terminal of the testing transformer.

All other terminals and parts (including core and tank) shall be connected to ground.

9.7.4.3 Tap connections

The choice of tap position shall be made by the manufacturer.

9.7.4.4 Relief gap

A relief gap set at a voltage of 10 % or more in excess of the specified test voltage may be connected during the applied-voltage test.

9.7.4.5 Application of test voltage

The voltage should be started at one quarter or less of the full value and be brought up gradually to full value. After being held for the time specified in 9.7.4.2, it should be reduced gradually before the circuit is opened.

9.7.4.6 Failure detection

Particular attention should be maintained for evidence of possible failure, such as an indication of smoke and bubbles rising in the insulating liquid, an audible sound as a thump, or a sudden increase in test circuit current. Any such indication should be prudently investigated by observation, by repeating the test, or by other tests to determine whether a failure occurred.

9.7.5 Induced-voltage test

9.7.5.1 Test value and duration

Two times rated turn-to-turn voltage shall be developed in each winding. The induced-voltage test shall be applied for 7 200 cycles, or 60 s, whichever is shorter.

9.7.5.2 Tap connection

A Type A voltage regulator shall have the tap position set at the 15 Lower position. A Type B voltage regulator shall have the tap position set at the 15 Raise position.

A voltage regulator with a series transformer construction is similar in nature to a Type A or Type B design depending on the location of the series transformer with respect to the shunt transformer and should be tested accordingly. For example, if the shunt transformer is connected between "S" and "SL", the voltage regulator shall be tested as a Type A design; if the shunt transformer is connected between "L" and "SL", the voltage regulator shall be tested as a Type B design.

NOTE Refer to Annex C for additional information on step-voltage regulator constructions.

9.7.5.3 Test frequency

As an induced-voltage test applies greater than rated volts per turn to the voltage regulator, the frequency of the impressed voltage shall be high enough to limit the flux density in the core to that permitted by the operating voltage limit established by Equation (1) in 6.2.4.2. The minimum test frequency to meet this condition is shown in Equation (20):

$$\text{Minimum test frequency} = \frac{E_t}{1{,}1 \times E_r} \times \text{rated frequency} \tag{20}$$

where

E_t is the induced test voltage across winding (V);

E_r is the rated voltage across winding (V).

9.7.5.4 Application of voltage

The voltage should be started at one quarter or less of the full value and be brought up gradually to a full value. After being held for the time specified in 9.7.5.1, it should be reduced gradually before the circuit is opened.

9.7.5.5 Need for additional induced-voltage test

When the induced-voltage test on a winding results in a voltage between terminals of other windings in excess of the low-frequency test voltage specified in Table 11, the other winding may be sectionalized and grounded. Additional induced-voltage tests shall then be made to give the required test voltage between terminals of sectionalized windings.

9.7.5.6 Grounded windings

When a voltage regulator has one end of the shunt winding grounded for operation on a grounded-neutral system, special care should be taken to avoid high electrostatic stresses between the other windings and ground.

9.7.5.7 Single-phase testing of three-phase voltage regulators

Three-phase voltage regulators may be tested with single-phase voltage. The specified test voltage is induced, successively, from each line terminal to ground and to adjacent line terminals. The neutrals of the windings may or may not be held at ground potential during these tests. A separate single-phase test or three-phase test may be required when the test voltage between adjacent line terminals is higher than the test voltage from the line terminals to ground.

9.7.5.8 Failure detection

Particular attention should be maintained for evidence of possible failure, such as indication of smoke and bubbles rising in the insulating liquid, an audible sound such as a thump, a sudden increase in test circuit current, or an appreciable increase in partial discharge level. Any such indication should be prudently investigated by observation, by repeating the test, or by other tests to determine whether a failure has occurred.

9.7.6 Insulation power factor tests

9.7.6.1 General

Insulation power factor is the ratio of the power dissipated in the insulation in watts to the product of the effective voltage and current in voltamperes when tested under a sinusoidal voltage and prescribed conditions.

9.7.6.2 Preparation for tests

The test specimen shall have the following:

a) all windings immersed in insulating liquid;
b) all windings short-circuited;
c) all bushings in place;
d) the average temperature of the windings and insulating liquid between 10 °C and 40 °C, preferably as near to 20 °C as practical with the top liquid temperature measured and recorded.

9.7.6.3 Tap connection

The choice of tap position shall be made by the manufacturer.

9.7.6.4 Instrumentation

Insulation power factor may be measured by special bridge circuits or by the voltampere-watt method. The accuracy of measurement should be within ±0,25 %, and the measurement should be made at or near the design operating frequency.

9.7.6.5 Voltage to be applied

The voltage to be applied for measuring insulation power factor shall not exceed half of the low-frequency test voltage given in Table 11 for any part of the winding, or 10 000 V, whichever is lower.

9.7.6.6 Procedure

Insulation power-factor tests shall be made from windings to ground and between windings as shown in Table 18.

Table 18 – Measurements to be made in insulation power factor tests

Method 1–Test without guard circuit [a]	Method 2–Test with guard circuit [a]
Voltage regulators with shunt and series windings only – Shunt and series windings[b] to ground	**Voltage regulators with utility winding** – Shunt and series windings to utility winding and ground – Shunt and series windings to ground, guard on utility winding
Voltage regulators with utility winding – Shunt and series windings to utility winding and ground	

NOTE 1 Although the real significance that can be attached to the power factor of liquid-immersed voltage regulators is still a matter of opinion, experience has shown that the power factor is helpful in assessing the probable condition of the insulation when good judgment is used.

NOTE 2 In interpreting the results of power-factor test values, the comparative values of tests taken at periodic intervals are useful in identifying potential problems rather than an absolute value of power factor.

NOTE 3 The factory power-factor test will be of value for comparison with field power-factor measurements to assess the probable condition of the insulation. It has not been feasible to establish standard power-factor values for liquid-immersed voltage regulators for the following reasons:

a) Experience has indicated that little or no relation exists between power factor and the ability of the voltage regulator to withstand the prescribed dielectric tests.

b) Experience has shown that the variation in power factor with temperature is substantial and erratic so that no single correction curve will fit all cases. The power factor shall be reported along with the top liquid temperature measured and the bottom liquid temperature if available. No temperature correction shall be applied. Temperature correction of the power factor results for trending basis may be applied by the purchaser.

c) The various liquids and insulating materials used in voltage regulators result in large variations in insulation power-factor values.

[a] In this table, the term "guard" signifies one or more conducting elements arranged and connected on an electrical instrument or measuring circuit so as to divert unwanted currents from the measuring means.

[b] Permanently connected windings shall be considered as one winding.

9.7.7 Insulation resistance tests

9.7.7.1 General

Insulation resistance tests shall be made to determine the insulation resistance from windings to ground. The insulation resistance tests are commonly measured in megohms or may be calculated from measurements of applied voltage and leakage current.

The insulation resistance of electrical apparatus is of doubtful significance compared with the dielectric strength. It is subject to wide variation in design, temperature, dryness, and cleanliness of the parts. When the insulation resistance falls below prescribed values, it can, in most cases of good design and where no defect exists, be brought up to the required standard by cleaning and drying the apparatus. Therefore, the insulation resistance may be useful to indicate whether the voltage regulator is in suitable condition for application of dielectric test.

The significance of values of insulation-resistance tests generally requires some interpretation, depending on the design and the dryness and cleanliness of the insulation involved. It is recommended insulation resistance values be measured periodically (during maintenance shutdown) and plotted. Substantial variations in the plotted insulation resistance values should be investigated for cause.

Insulation resistances may vary with applied voltage, and any comparison shall be made with measurements at the same voltage.

Under no circumstances should tests be made while the voltage regulator is under vacuum.

9.7.7.2 Preparation for tests

The test specimen shall have:

a) all windings immersed in insulating liquid;
b) all windings short-circuited;
c) all bushings in place;
d) temperature of windings and insulating liquid near (the reference temperature of) 20 °C.

9.7.7.3 Tap connection

The choice of tap position shall be made by the manufacturer.

9.7.7.4 Instrumentation

Insulation resistance may be measured using the following equipment:

a) a variable-voltage DC power supply with means to measure voltage and current (generally in microamperes or milliamperes);
b) a megohmeter.

NOTE Megohmeters are commonly available with nominal voltages of 500 V, 1 000 V, 2 500 V, and 5 000 V; DC applied-voltage test equipment is available at higher voltages.

9.7.7.5 Voltage to be applied

The DC voltage applied for measuring insulation resistance to ground shall not exceed a value equal to the RMS low-frequency applied voltage allowed in Table 11.

Partial discharges should not be present during insulation resistance tests because they could damage a voltage regulator and may also result in erroneous values of insulation resistance.

NOTE When measurements are to be made using DC voltages exceeding the RMS operating voltage of the windings involved (or 1 000 V for a solidly grounded wye winding), a relief gap can be employed to protect the insulation.

9.7.7.6 Procedure

Insulation-resistance tests shall be made with all circuits of equal voltage above ground connected together. Examples of procedures include the following:

a) voltage should be increased in increments, typically 1 kV to 5 kV, and held for 1 min while current is read;
b) the test should be discontinued immediately if the current begins to increase without stabilizing;
c) after the test has been completed, all terminals should be grounded for a period of time sufficient to allow any trapped charges to decay to a negligible value.

9.8 On-load tap-changer routine tests

9.8.1 General

This subclause applies to routine tests for vacuum and non-vacuum reactor type on-load tap-changers immersed in insulating liquid. The voltage regulator on-load tap-changer is a selector switch capable of carrying, making and breaking current, combining the duties of a tap selector and a diverter switch.

9.8.2 Mechanical test

With the on-load tap-changer fully assembled but without the contacts energized, ten complete cycles (maximum boost to maximum buck and back) of operation shall be performed without failure. A sequence of operations, switching time, of the on-load tap-changer shall be recorded oscillographically. The on-load tap-changer shall not show abnormal contact pressure causing dragging or misalignment, causing abnormal bouncing or jamming during measurement of switching time through its full cycle.

9.8.3 Auxiliary circuits insulation test

The on-load tap-changer auxiliary circuits shall withstand without failure an applied voltage test of 1,5 kV, < 500 Hz from all live terminals to ground for 1 min.

9.9 Control system routine tests

9.9.1 Applied voltage

The control system circuitry shall withstand an applied voltage of 1,5 kV, < 500 Hz from all live terminals to ground for 1 min. The test shall be performed with the control front panel totally disconnected from the control system circuitry. After the test, it shall be determined that no change in performance has occurred.

NOTE To prevent possible excessive damage or failure, use of a resistor to limit the current is suggested.

9.9.2 Operation

All features of the control system shall be operated and checked for verification of proper functioning. The control device shall be checked for calibration at this point.

9.10 Temperature-rise test

9.10.1 General

A temperature-rise test is defined as a test to determine the temperature-rise above ambient of one or more of the voltage regulator's windings, as measured at the terminals. The result for a given terminal pair or winding is the average value of the temperature of the entire circuit; it is not the temperature at any given point in a specific winding. The term "average temperature-rise" refers to the value determined by measurements on a given terminal pair of the winding. It does not refer to the arithmetic average of results determined from different terminal pairs of the voltage regulator.

Conditions under which temperature limits apply are described in 5.1. All temperature-rise tests shall be made under normal (or equivalent to normal) conditions of the means of cooling, as follows:

a) temperature-rise test shall be conducted on a voltage regulator completely assembled and filled to the proper liquid level;
b) the temperature-rise test shall be made in a room free from drafts as practicable defined as a wind speed of 0,5 m/s, or less;
c) when it is not possible or practical to test the voltage regulator as a completed assembly, the voltage regulator shall be tested with the components required to replicate normal means of cooling the voltage regulator during a temperature-rise test. When a voltage regulator is equipped with thermal indicator, or the like, such devices shall be assembled with the voltage regulator.

9.10.2 Test methods

9.10.2.1 General

Tests shall be carried out by one of the following methods:

a) actual loading;

b) simulated loading;

   1) the loading back (opposition) method, in which rated voltage and current are induced in the voltage regulator under test;

   2) the short-circuit method, in which the appropriate total loss is produced by the effect of short-circuit current.

9.10.2.2 Actual loading

Actual loading method is the most accurate method, but energy requirements are excessive for large-voltage regulators. Voltage regulators of small output may be tested under actual load conditions by loading them on a rheostat, bank of lamps, water box, and so forth.

9.10.2.3 Simulated loading

9.10.2.3.1 Loading back method

Some smaller voltage regulators may be tested by connecting their respective shunt and series windings in parallel (see Figure 16 and Figure 17). Voltage regulators shall be tested for the particular combination of design type, connections, and tap position giving the highest average winding temperature-rise. This generally involves those connections and tap position resulting in the highest loss. Supplementary current ratings in accordance with 6.3 shall be used if they are associated with highest average winding temperature-rise.

a) Apply rated voltage at rated frequency to one set of windings. Circulate load current by opening the connections of either pair of windings at one point and impress a voltage across the break just sufficient to circulate rated current at rated frequency for the connection and loading used. The total loss applied during this test shall be the same as the sum of the no-load loss and load loss measured according to 9.5 and 9.6.

b) Measure liquid temperatures, and determine liquid temperature-rise as described in 9.10.4.2.

c) Immediately shut down, and measure the hot-resistance measurements in accordance with 9.10.3.2.

d) When needed to meet the time limit criteria of 9.10.3.2, resume the temperature-rise test for 1 h, holding rated voltage at rated frequency for the connection and loading used. Measure the liquid temperatures, immediately shut down, and measure the hot-resistance of additional terminal pairs in accordance with 9.10.3.2.

e) Determine average winding temperature-rises in accordance with 9.10.4.3.

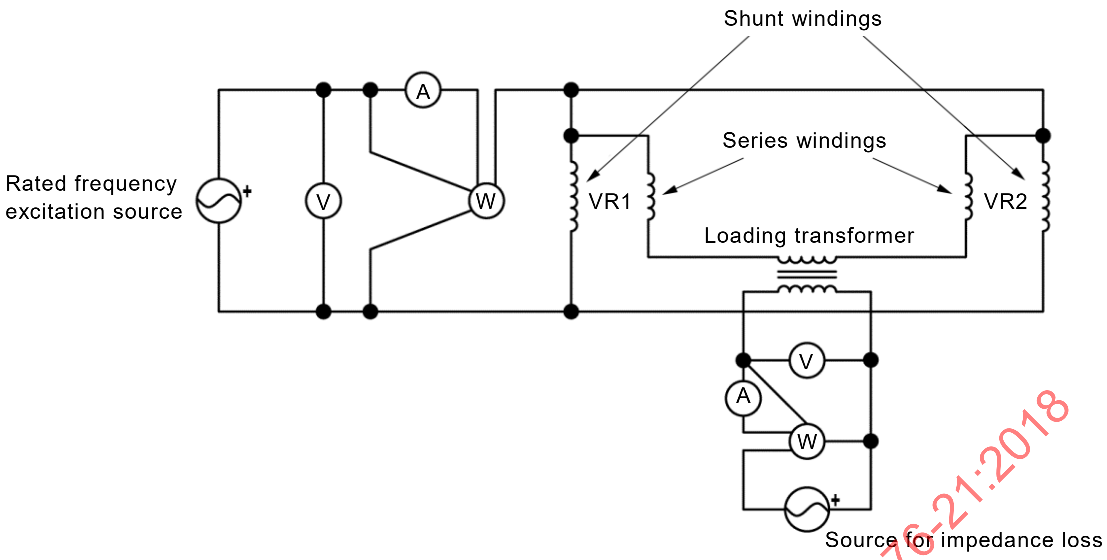


Figure 16 – Example of loading back method: single-phase

It is preferred to use duplicate voltage regulators, but it is not mandatory as long as the voltage regulator under test is energized at the required voltage and current levels. This method provides the closest simulation to actual loading as both the no-load and load losses are present in the voltage regulator. The excitation and loading power sources do not necessarily need to be in phase; the power sources may be in phase or 120 degrees out of phase.

NOTE In the connection scheme shown in Figure 16, even if voltage regulators VR1 and VR2 are duplicates of each other, their respective loading conditions are not identical. VR1 sees an apparent inductive load at nearly zero power factor whereas VR2 sees an apparent capacitive load at nearly zero power factor. As a consequence, the voltage appearing on the series winding of the voltage regulators is different. Voltage on VR1 drops due to its impedance while voltage on VR2 will increase. Therefore, parts of the voltage regulator cores are either over-excited (VR2) or under-excited (VR1) and the no-load loss and sound vary accordingly. Which parts of the core would experience this depends on the construction of the voltage regulators. This test method is not an exact representation of an actual loading of a voltage regulator at a power factor near unity, but is nevertheless a good approximation.

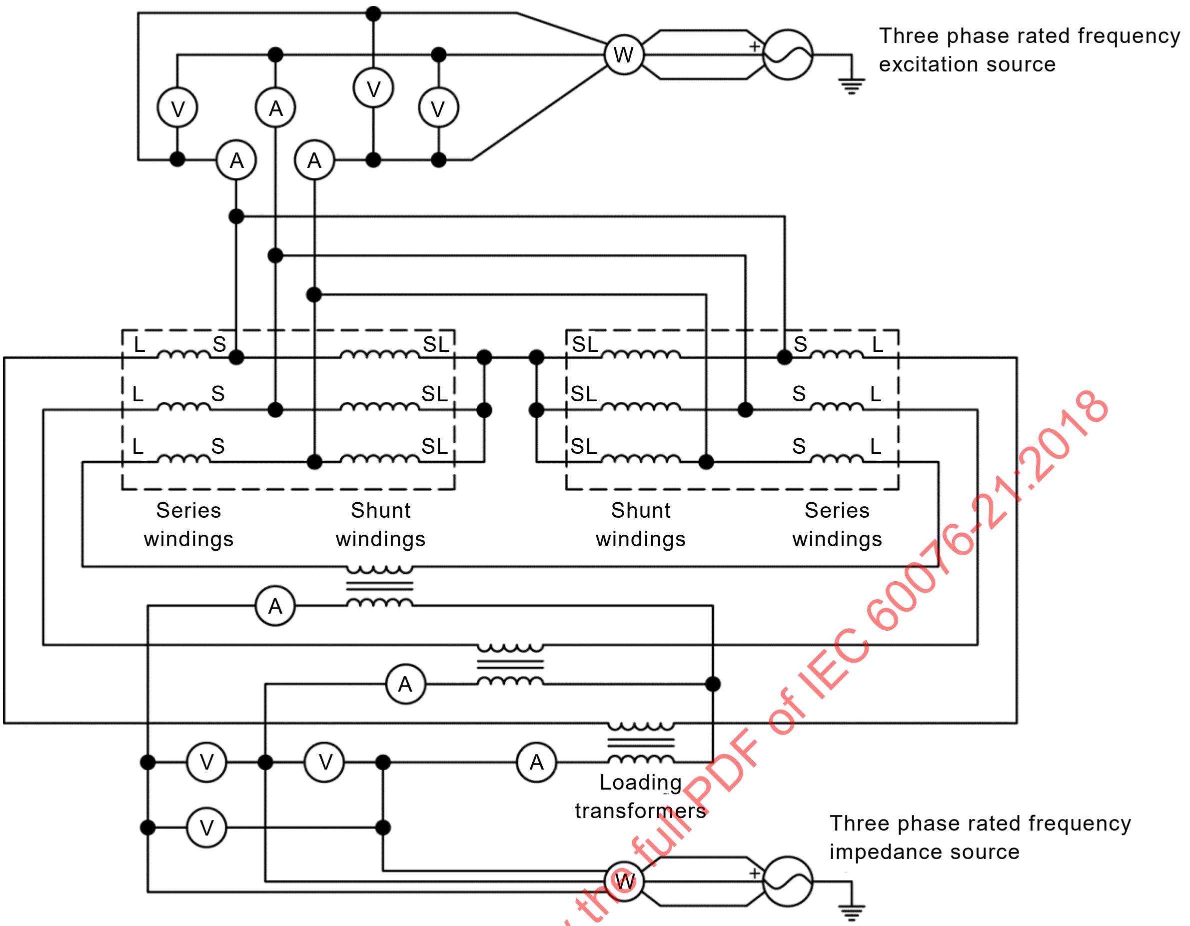


Figure 17 – Example of loading back method: three-phase

For voltage regulators with three windings, the same principles can be applied to load either simultaneously all three windings if the test facility allows it, or separately by pairs of windings. All loads are nearly at zero power factor.

9.10.2.3.2 Short-circuit method

Conduct the short-circuit method as follows:

a) prior to making the total loss run, measure load loss at rated current and frequency for the particular combination of design type, connections, and tap position giving the highest average winding temperature-rise. This generally involves the connection and tap position resulting in the highest loss. Supplementary current ratings in accordance with 6.3 shall be used if they are associated with highest average winding temperature-rise. This thermal connection load loss shall be measured in accordance with 9.6 and referenced to a temperature equal to rated average winding rise plus 20 °C. The required total loss for the total loss run shall be the sum of thermal connection load loss plus no-load loss measured in accordance with 9.5;

b) for the total loss run: short-circuit one or more windings and circulate sufficient current at rated frequency to produce the required total loss as determined in step a) and 9.10.5.3;

c) determine the liquid temperature-rise as described in 9.10.4.2;

d) for the rated current run: reduce the current in the windings to the rated current (or reduced current according to 9.10.5.2) value for the connection and the loading used. Hold the current constant for 1 h. Measure the liquid temperatures and immediately shut down, and measure the hot-resistance in accordance with 9.10.3.2;

e) repeat the rated current run step d) for hot-resistance measurements on additional terminal pairs if needed to meet the time limit criteria of 9.10.3.2;

f) determine average winding rises in accordance with 9.10.4.3.

9.10.3 Resistance measurements

9.10.3.1 Cold-resistance measurements

Cold-resistance measurements shall be taken on all terminal pairs in accordance with 9.2. The same test equipment shall be used for both cold-resistance and hot-resistance measurements. Normally, cold-resistance measurements are taken prior to loading the voltage regulator for temperature-rise test. However, it is permissible to allow the voltage regulator to cool to ambient temperature and perform cold-resistance measurements after the loading test. Whenever it is necessary to make cold-resistance measurements following the temperature-rise test, the cool down time shall be sufficient to allow the criteria in 9.2.2 to be met.

9.10.3.2 Hot-resistance measurements

Fan(s), if available, shall be shut off after the voltage regulator is shut down for hot-resistance measurements. Hot-resistance measurements shall be taken as soon as possible after shutdown, allowing sufficient time for the inductive effects to disappear as indicated from the cold-resistance measurement. To minimize inductive effects when transferring measuring instrument leads from one terminal pair to another, the same relative polarity should be maintained between measuring leads and voltage regulator terminals.

a) The time from instant of shutdown, i.e. time zero, shall be recorded for each resistance measurement.

b) A series of hot-resistance measurements shall be made on each terminal pair under test, and all terminal pairs shall be tested.

c) The first hot-resistance measurement shall be taken as quickly as possible after shutdown and after the inductive effects disappear and in any case, no later than 4 min after shutdown. In order to achieve core saturation in a short time period, the DC power supply voltage shall be large enough to saturate the cores in a short time.

   The DC source should be selected such that it can also provide sufficient current to keep the core saturated without causing excessive heating of windings. A series resistor added to the circuit will decrease time to stabilization.

   When performing winding resistance measurements on a voltage regulator utilizing a series transformer for load tap-changing, care is required to increase the likelihood the whole circuit is saturated before stable readings of the combined winding resistances can be obtained.

d) The hot-resistance versus time data shall be used as the basis for correction to time zero. The cooling curve format shall consist of a series of hot-resistance measurements in accordance with c).

   At least ten resistance measurements shall be made on each terminal pair. All resistance measurements shall be recorded at no longer than 30 s intervals and no less than 10 s intervals.

e) The hot-resistance-time data collected in d) shall be extrapolated to the instant of shutdown using a computerized curve fitting program to determine the hot-resistance-time cooling curve. The hot-resistance-time data collected shall be fitted to an exponential decay curve using the method of least squares.

NOTE 1 Comparative to large voltage regulators, the time constant of small voltage regulators can be short due to thermal characteristics and measuring equipment, which can affect the appropriateness of an exponential decay curve.

NOTE 2 The mean liquid temperature surrounding the winding and the actual location of the winding can result in top and bottom liquid temperatures not giving the intended average winding liquid temperature which could affect the appropriateness of the exponential decay curve.

9.10.4 Temperature measurements

9.10.4.1 Ambient temperature measurement

The ambient temperature shall be taken of the surrounding air, which should not be less than 10 °C nor more than 40 °C. For temperatures within this range, no correction factor shall be applied. Tests may be made at temperatures outside this range when suitable correction factors are available.

The temperature of the surrounding air shall be determined by at least three thermocouples or thermometers in containers spaced uniformly around the voltage regulator under test. They shall be located at about mid-height of the voltage regulator and 1 m to 2 m (3 ft to 6 ft) from the voltage regulator. They shall be protected from drafts and radiant heat from the voltage regulator under test or other sources.

When the liquid time constant of the voltage regulator as calculated according to Equation (21) is 2 h or less, the time constant of the containers shall be between 50 % and 150 % of that of the voltage regulator under test. When the liquid time constant of the voltage regulator under test is more than 2 h, the time constant of the containers shall be within 1 h of the liquid time constant of the voltage regulator under test.

$$\tau_{\text{to,r}} = \frac{C \times \Delta\Theta_{\text{to,r}}}{P_{\text{t,r}}} \tag{21}$$

where

$\tau_{\text{to,r}}$ is the time constant for rated load beginning with initial top-liquid temperature-rise of 0 °C, expressed in h;

$\Delta\Theta_{\text{to,r}}$ is the top-liquid rise over ambient temperature at rated load, expressed in °C;

$P_{\text{t,r}}$ is the total loss at rated load, expressed in W;

$C = 0{,}132\,3 \times$ (weight of core and coil assembly in kilograms)
$+ 0{,}088\,2 \times$ (weight of tank and fittings in kilograms)
$+ 0{,}351\,3 \times$ (litres of oil)

or

$C = 0{,}06 \times$ (weight of core and coil assembly in pounds)
$+ 0{,}04 \times$ (weight of tank and fittings in pounds)
$+ 1{,}33 \times$ (US gallons of oil)

The time constant of a container shall be taken as the time necessary for its temperature to change 6,3 °C when the ambient temperature is abruptly changed 10 °C.

9.10.4.2 Liquid temperature-rise determination

Liquid temperature-rise is the difference between liquid temperature and the ambient temperature. The ultimate liquid temperature-rise above ambient shall be considered to be reached when the top liquid temperature-rise does not vary by more than 2,5 % or 1 °C, whichever is greater, during a consecutive 3 h period.

It is permissible to shorten the time required for the test by the use of initial overloads, restricted cooling, and so on.

The top liquid temperature shall be measured by a thermocouple or suitable thermometer immersed approximately 50 mm (2 in) below the top liquid surface.

The bottom liquid temperature shall be measured by one of the following methods:

a) thermocouples may be attached to an insulated rod and located inside the tank within the liquid flow path from the external cooling means to the bottom of the windings;

CAUTION

Exercise caution when employing this method.
This method may be hazardous for voltage regulators with very high-voltage windings.

b) if heat exchangers or radiators are mounted on a common manifold with a single entrance to the tank, the thermocouples may be located in the piping of the single entrance;
c) if heat exchangers or radiators have multiple entrances into the tank, thermocouples may be installed in the bottom of one radiator or heat exchanger. For accuracy, a radiator or heat exchanger located in the middle of the bank is preferred;
d) if it is not possible to measure the temperature of the liquid inside the tank, radiators, or heat exchangers, surface temperature measurements may be used with the results corrected to account for the temperature difference between the surface and the liquid inside the tank. If surface temperature measurements are made on radiator headers, choose headers one-third or one-half the way in from either end of a bank of radiators. For voltage regulators without radiators, locate the thermocouples on the tank wall at the elevation of the bottom of the winding. Thermocouples located on external cooling surfaces, for the purpose of determining internal liquid temperatures, shall be shielded and insulated so their readings are not significantly affected by the air movement from fan(s), if available, or thermally induced air currents.

The average liquid temperature shall be determined as equal to top liquid temperature minus half the difference in temperature of the moving liquid at the top and the bottom of the cooling means. When bottom liquid temperature cannot be measured directly, the temperature difference may be taken as the difference between the surface temperature of the liquid inlet and outlet. A thermocouple is the preferred method of measuring surface temperature (see 9.10.4.4 for method of measurement). Infrared measurement devices may also be used to measure surface temperatures.

9.10.4.3 Average winding temperature-rise determination

The average winding temperature of a terminal pair corresponding to a winding phase shall be determined from the terminal pair's hot-resistance at shutdown. When the determination of the hot-resistance is not possible (for example, with extremely low-resistance windings), other methods may be used. The average winding temperature of a terminal pair shall be determined by Equation (22):

$$\theta_{\mathrm{w}} = \left(\frac{R_{\mathrm{h}}}{R_{\mathrm{c}}}\right)\left(\theta_{\mathrm{k}} + \theta_{\mathrm{rc}}\right) - \theta_{\mathrm{k}} \tag{22}$$

The average temperature-rise of a terminal pair corresponding to a winding phase shall be determined by Equation (23):

$$\Delta\theta_{\mathrm{w}} = \Delta\theta_{\mathrm{l}} + \theta_{\mathrm{w}} - \theta_{\mathrm{l}} \tag{23}$$

where

$\Delta\theta_w$	is the average winding temperature-rise of a terminal pair (°C);
$\Delta\theta_l = \theta_{l,tl} - \theta_a$	is the liquid temperature-rise as determined from the total loss run (°C);
θ_w	is the average winding temperature of a terminal pair corresponding to hot-resistance R_h (°C);
$\theta_{l,tl}$	is the average liquid temperature at end of total loss run (°C);
θ_l	is the average liquid temperature at shutdown (°C);
θ_a	is the ambient temperature (°C);
θ_{rc}	is the temperature at which cold-resistance R_c was measured (°C);
R_c	is the cold-resistance measured according to 9.2 (Ω);
R_h	is the hot-resistance of a terminal pair (Ω);
θ_k	is 234,5 °C for copper and 225,0 °C for aluminium.

NOTE The temperature 225 °C applies for pure or EC aluminium. θ_k can be as high as 230 °C for alloyed aluminium. Where copper and aluminium windings are employed in the same voltage regulator, a value for θ_k of 229 °C is applied for the correction of load loss.

Average winding rise shall be calculated by using either top liquid rise or average liquid rise. When other than rated winding current is used, the average liquid rise method shall be used to determine winding rises.

a) In the top liquid rise method, the average winding temperature-rise is equal to the top liquid rise, measured during the total loss run, plus the difference between the average winding temperature at shutdown and the top liquid temperature at shutdown.

b) In the average liquid rise method, the average winding temperature-rise is equal to the average liquid rise, measured during the total loss run, plus the difference between the average winding temperature at shutdown and the average liquid temperature at shutdown.

The average winding temperature-rise for each terminal pair corresponding to a winding phase shall be corrected for actual test currents, test losses, and altitude as prescribed in 9.10.5. The corrected average winding temperature-rise shall be reported for each terminal pair of the voltage regulator.

9.10.4.4 Other temperature measurements

When measured, the temperature-rise of metal parts other than windings shall be determined by use of a thermocouple, suitable thermometer, fibre optic temperature sensor, or other appropriate temperature measurement techniques.

A thermocouple is the preferred method of measuring surface temperature. When used for this purpose, the thermocouple should be soldered to the surface. When this is not practical, the thermocouple should be soldered to a thin metal plate or foil approximately 645 mm^2 (1 in^2) in size. The plate should be held firmly and snugly against the surface. The thermocouple should be thoroughly insulated thermally from the surrounding medium.

The surface temperature of metal parts surrounding, or adjacent, to outlet leads or terminals carrying heavy current may be measured at intervals or immediately after shutdown.

9.10.5 Correction of temperature-rise test results

9.10.5.1 General

For any of the loading methods adopted, temperature-rise test results shall be corrected for the predictable effects caused by the following:

a) difference in winding rated current and the winding test current;

b) difference in required loss and test loss;

c) difference in altitude of operation.

9.10.5.2 Correction for differences between winding rated current and test current

When test equipment limitations dictate, it is permissible to hold winding current at a value less than rated current for the winding, but not less than 85 % of rated winding current. When the current held in any of the windings under test differs from the rated current, the observed differences between the average winding temperature at shutdown and the average liquid temperature at shutdown shall be corrected to give the average temperature-rise of the windings at the rated current by using Equation (24):

$$\Delta\theta_{\text{w, c}} = \Delta\theta_{\text{w, o}}\left[\frac{\text{rated current}}{\text{test current}}\right]^{2m} \quad (24)$$

where

$\Delta\theta_{\text{w, c}}$ is the corrected difference between average winding temperature, corrected to shutdown, and the average liquid temperature at shutdown (°C);

$\Delta\theta_{\text{w, o}}$ is the observed difference between average winding temperature corrected to shutdown, and the average liquid temperature at shutdown (°C);

m is 0,8 for class ONAN and ONAF.

The corrected average winding rise is the average liquid rise plus $\Delta\theta_{\text{w, c}}$.

9.10.5.3 Correction of liquid temperature-rise for differences in required total loss and actual loss

This method may be used when actual loss is within 20 % of the required total loss, as in Equation (25):

$$\Delta\theta_{\text{l, c}} = \Delta\theta_{\text{l, o}}\left[\left(\frac{P_{\text{r}}}{P_{\text{t}}}\right)^{n} - 1\right] \quad (25)$$

where

$\Delta\theta_{\text{l, c}}$ is the liquid temperature-rise correction (°C);

$\Delta\theta_{\text{l, o}}$ is the observed liquid temperature-rise (°C);

P_{r} is the required total loss (W);

P_{t} is the actual test loss (W);

n is 0,8 for class ONAN;

n is 0,9 for class ONAF.

Corrected liquid temperature-rise = observed liquid temperature-rise + $\Delta\theta_{\text{l, c}}$.

Corrected average winding temperature-rise = observed winding temperature-rise + $\Delta\theta_{l,\ c}$.

9.10.5.4 Correction of liquid temperature-rise for differences in altitude

When tests are made at an altitude of 1 000 m (3 300 ft) or less, no altitude correction shall be applied to the temperature-rise.

When a voltage regulator tested at an altitude of less than 1 000 m (3 300 ft) is to be operated at an altitude above 1 000 m (3 300 ft), it shall be assumed the liquid temperature-rise increases in accordance with Equation (26):

$$\Delta\theta_a = \Delta\theta_o \left(\frac{A}{A_0} - 1 \right) F \qquad (26)$$

where

$\Delta\theta_a$ is the increase in liquid temperature-rise (°C) at altitude (A) in metres (feet);

$\Delta\theta_o$ is the observed liquid temperature-rise (°C);

A is altitude in metres (feet);

A_0 is 1 000 m (3 300 ft);

F is 0,04 for class ONAN;

F is 0,06 for class ONAF.

NOTE Winding temperature-rise above liquid temperature is not affected by altitude

9.11 Short-circuit test

9.11.1 General

This test code applies to liquid-immersed step-voltage regulators both single- and three-phase.

The code defines a procedure to demonstrate the mechanical capability of a voltage regulator to withstand short-circuit stresses. The prescribed tests are not designed to verify thermal performance.

The short-circuit test procedure described in this document is intended principally for application to new voltage regulators to verify design. Tests may be conducted at the manufacturer's facilities, at test laboratories, or in the field, but it shall be recognized that complete equipment is not usually available in the field for conducting tests and verifying results.

NOTE Some voltage regulators may not be fully tested because of limitations of testing facility (test laboratory, manufacturer's facility, or field test capability). Thermal ability to withstand short-circuit can be demonstrated by calculations as per 9.13.4 or IEC 60076-5[10], upon agreement between the manufacturer and the purchaser. The ability to withstand the dynamic effects of short-circuit is demonstrated by a test; if not possible, it can be demonstrated by calculation and design considerations as per IEC 60076-5[10] upon agreement between manufacturer and purchaser.

9.11.2 Test connections

9.11.2.1 Fault location

The short-circuit may be applied on the voltage regulator's unregulated or regulated circuit terminals as dictated by the available voltage source. The short-circuit shall be applied by means of suitable low-resistance connectors.

In order of preference, the tests may be conducted by either of the following:

a) *pre-set method:* closing a breaker at the voltage supplied terminals applying energy to a previously short-circuited voltage regulator;

b) *post-set method:* closing a breaker, applying a short-circuit to a previously energized voltage regulator.

9.11.2.2 Fault type

For single-phase voltage regulators, a single-phase voltage supply shall be used. For three-phase voltage regulators, a three-phase voltage supply is preferable; as long as the fault current requirements defined in 6.8.1 are met. If this is not possible, a single-phase source with a short-circuit on one phase at a time shall be used.

9.11.2.3 Tap connection for test

One test satisfying the asymmetrical current requirement shall be made with the voltage regulator at the maximum boost position and also at the maximum buck position. Two tests satisfying the symmetrical current requirement shall be made at the maximum boost position and also at the maximum buck position.

9.11.3 Test requirements

9.11.3.1 Symmetrical current requirements

The RMS symmetrical short-circuit current shall have a magnitude as defined in 6.8.1. The base rated load current is the rated self-cooled load current of the voltage regulator.

9.11.3.2 Asymmetrical current requirements

The first-cycle asymmetrical peak current that the voltage regulator is required to withstand shall be as defined in 6.8.1.

In some cases, the inherent X/R ratio of the voltage regulator may be sufficient to impact the asymmetry of the fault as seen by the voltage regulator. The symmetrical current then shall be increased in order for the first cycle peak current to be at the required level for the test.

9.11.3.3 Number of tests

Each phase of the voltage regulator shall be subjected to a total of six tests. Four of these tests shall satisfy the symmetrical current requirements. Two additional tests on each phase shall satisfy the asymmetrical current requirements.

9.11.3.4 Duration of tests

The duration of each test shall be 250 ms of rated frequency current.

9.11.4 Test procedure

9.11.4.1 Fault application

To produce the fully asymmetrical current wave specified in 9.11.3.2, the moment of switching on shall be adjusted by means of a synchronous switch or another controlled switching device.

9.11.4.2 Calibration tests

Calibration tests shall be carried out at less than 70 % of specified current to check the proper functioning of the test setup with regard to the moment of switching on, the current setting, the damping, and the duration. Tests that result in current of 95 % or more of the specified current may be counted toward fulfilment of the required number of tests.

9.11.4.3 Terminal voltage limits

Using the preferred pre-set method, magnetizing inrushes can occur due to saturation of the magnetic core leading to an excessive magnetizing current superimposed on the short-circuit current during the first few cycles. Special precautions shall be taken, for example, pre-magnetization of the core, to prevent the inrush of magnetizing current. It may be required to use the post-set method instead of the preferred pre-set method.

When tests are made using the post-set method, excessive excitation voltages can occur prior to fault initiation unless a large enough power source with low enough source impedance is employed. The no-load voltage supply shall not exceed 110 % of the rated voltage, unless otherwise agreed upon between the manufacturer and the purchaser.

Throughout the course of either test method, the voltage supply at the voltage regulator shall be maintained within a range of 95 % to 105 % of that necessary to produce the required symmetrical short-circuit current as determined in 9.11.3.1.

9.11.4.4 Temperature limits

The top liquid temperature at the start of the test shall be between 0 °C and 40 °C.

9.11.4.5 Current measurements

Current magnitudes shall be measured in the low-resistance connection between the shorted regulated circuit terminals and on the voltage regulator primary circuit terminals connected to the energy source. Oscillograms of currents shall be representative of stresses in the windings.

Whenever possible, record the tank current by connecting the voltage regulator tank to ground through a current measuring device.

NOTE Any appropriate measuring devices can be used, as long that they give correct measurements with appropriate sensitivity, precision, and uncertainty. Those measuring devices can be, for example, current transformers, shunts, or Rogowski coils.

The oscillograms should show a scaled image of the current passing through the primary of the measuring device or a scaled image of the current passing in the corresponding winding. For example, the Rogowski coil voltage output shall be properly treated by digital or analogical means in order to show an image of the real primary current instead of the primary current derivative.

9.11.4.6 Tolerances on required currents

After the measured impedance is taken into account, the measured current (symmetrical or asymmetrical) in the tested phase(s) shall not be less than 95 % of the required current.

9.11.4.7 On-load tap-changer operation

Upon completion of each of the required short-circuit tests; the on-load tap-changer shall be operated from the test position through the Neutral position, and then back to the test position or on to the next test position.

9.11.5 Proof of satisfactory performance

9.11.5.1 General

The voltage regulator under test shall be judged to have performed satisfactorily when the dielectric tests (9.11.5.2) and visual inspection (9.11.5.3) criteria have been satisfactorily met. In 9.11.5.4 to 9.11.5.6, recommended measurements listed can be made during the course of the tests, but are not required unless specified. When the terminal measurements are made and the requirements of 9.11.5.4 to 9.11.5.6 have been met following all tests, it is probable that the voltage regulator has sustained no mechanical damage during the test. A composite evaluation of the degree to which all criteria of 9.11.5.4 to 9.11.5.6 have been met may indicate the need for a greater or lesser degree of visual inspection to confirm satisfactory performance. A decision to waive all or part(s) on the extent of the visual inspection or dielectric test criteria shall be based on discussion and negotiation of all parties involved in specification and performance of a short-circuit test.

9.11.5.2 Dielectric tests

The voltage regulator shall withstand dielectric tests in accordance with 9.7.2, 9.7.4 and 9.7.5 and Table 11 following the short-circuit test.

9.11.5.3 Visual inspection

Visual inspection shall take place after all testing has been concluded owing to the possibility of introducing air and moisture within the assembly. Visual inspection of the core and coils shall not give indication of change occurring with the mechanical condition impairing the function of the voltage regulator. The extent of the visual inspection shall be established on the basis of combined evidence obtained from the measurements described in 9.11.5.4 to 9.11.5.6. The extent of necessary visual inspection may range from an inspection through apertures on the tank (hand hole, manhole) to complete dismantling of the core and coils. The appropriate level of visual inspection shall be based upon discussion and negotiation of all parties involved. The measurements and observations made during the tests and the result of the standard dielectric tests should then be considered during the negotiation.

Visual inspection of the on-load tap-changer shall not indicate any changes impairing the switch function. The extent of this examination shall be established on the basis of operation through the Neutral position after each test. When the on-load tap-changer operates successfully through the Neutral position after each test, then an inspection of the switch as assembled may suffice.

9.11.5.4 Wave shape of terminal voltage and current

No abrupt changes shall occur in the terminal voltage or short-circuit current wave shapes during any test.

9.11.5.5 Leakage impedance

Leakage impedance measured on a per-phase basis after the test series shall not differ from that measured before the test series by more than the percentage variation calculated by the following equation:

$$\Delta IZ = 22{,}5 - 5 \times Z_{\text{auto}} \tag{27}$$

where

Z_{auto} is the result of Equation (18).

The measuring equipment shall have the demonstrated capability of giving reproducible readings within an accuracy of ±0,2 %.

NOTE It can be worthwhile to measure the impedance after each short-circuit. These measurements allow for identifying progressive variations or early substantial impedance changes.

9.11.5.6 Excitation current

Excitation current measured after the test series shall not increase above that measured before the test series by more than 5 % for stacked-type cores. For wound core construction, the increase shall not exceed 25 %.

9.11.5.7 Other diagnostic measurements

Other diagnostic measurements may be made during the course of the tests to evaluate whether any sudden or progressive changes have occurred in the mechanical condition of the voltage regulator. Such results may be useful to understand the response to short-circuit forces, but they shall not form part of the proof criteria.

9.12 Determination of sound level

9.12.1 General

Sound power level of a voltage regulator is composed of the following three components:

a) Sound power at no-load (excitation): this sound component originates in the voltage regulator cores and transmits through the dielectric liquid and structural supports to the tank, where it radiates as airborne sound. The frequency spectrum of main cores sound consists primarily of the even harmonics of the power frequency. For a 60 Hz power system, the main frequency components are 120 Hz, 240 Hz, 360 Hz, and 480 Hz, whereas for a 50 Hz power system, the main frequency components are 100 Hz, 200 Hz, 300 Hz, and 400 Hz.

   The reactor assembly has a number of gaps in the core(s) used to regulate the inductive impedance managing the amount of interrupting kVA seen during the switching cycle. Reactive current is generated during the time the reactor is energized by a tapped section of the series winding and/or the equalizer winding. The highest sound level occurs at the tap position with the highest voltage exciting the reactor assembly.

b) Sound power of the cooling device: The frequency spectrum of this sound component typically consists of broadband fan sound, plus discrete tones (of low levels) at the fan blade passage frequency and its harmonics.

c) Sound power due to load current: This sound component is primarily produced by vibrations of the windings and tank walls when the voltage regulator is loaded. The frequency of this sound component is primarily twice the power frequency (i.e. 120 Hz for a 60 Hz voltage regulator, 100 Hz for a 50 Hz voltage regulator). The magnitude of load sound power is highly dependent on the voltage regulator load. For example, the load sound power level at 60 % of full load is about 9 dB lower than at full load.

NOTE Voltage regulators usually do not require consideration of sound power due to load current.

The sum of no-load (excitation) and cooling device sound power components is typically referred to as the no-load sound power level of a voltage regulator.

Described in this subclause are methods for:

– measuring voltage regulator sound level in terms of A-weighted using both the *sound pressure*, and *sound intensity* measuring methods. Included are methods of correcting the measurements for environmental factors, namely ambient sound and wall sound reflections;

- determining the sound level of the voltage regulator using the measured sound pressure data. Included are methods for:
  - calculating the average sound pressure level;
  - adding no-load and load sound levels;
  - calculating the total sound power level;
- reporting the results in a standard matter.

9.12.2 Applicability

The procedures specified for measuring voltage regulator sound pressure levels or for calculating voltage regulator sound power levels are intended to be applicable to voltage regulators being tested in an indoor or outdoor laboratory, to voltage regulators being tested in a factory, or to voltage regulators that have been installed in substations (either single or in combination with other equipment).

9.12.3 Instrumentation

9.12.3.1 Sound level meter

Sound level measurements shall be made with instrumentation meeting the requirements of ANSI S1.4[3] and IEC 61672-1.

9.12.3.2 Wind screen

A suitable wind screen shall be used when measuring sound.

9.12.3.3 Calibration

Sound-measuring instrumentation shall be calibrated as recommended by the sound level meter manufacturer before and after each set of measurements. When calibration change is greater than 1 dB, sound measurements shall be declared invalid, and the test shall be repeated.

9.12.4 Test conditions

9.12.4.1 Test environment

The test environment, represented by "ambient sound" and "wall sound reflections", can significantly impact the accuracy of the measurement of voltage regulator sound. Therefore, environmental corrections explained in 9.12.6.3.3 and 9.12.6.3.4 shall be made when applicable.

9.12.4.2 Voltage regulator location

The voltage regulator shall be located so that no acoustically reflecting surface is within 3 m (10 ft) of the measuring microphone, other than the floor or ground. When a voltage regulator is to be tested within a semi-reverberant facility, it shall be located in an asymmetrical manner with respect to the room geometry. If the specified conditions cannot be met, the voltage regulator shall be no closer than 3 m (10 ft) from a sound-reflecting surface. When voltage regulator sound is measured in an enclosed space, sound reflections from walls or other large objects can influence the results owing to the sound containing discrete tones affected by room acoustics, room geometry, or reflecting objects. Thus, larger differences may exist between the sound measured in an indoor voltage regulator installation and the sound measured in an acoustical laboratory or an outdoor installation, if the proper correction for "wall sound reflections", as described in 9.12.6.3.4, is not made.

9.12.4.3 Determination of total sound level of a voltage regulator

9.12.4.3.1 No-load (excitation) sound level

When measuring no-load (excitation) sound level, the voltage regulator shall be connected and energized at rated voltage and rated frequency across its excitation (shunt) winding or sections of its series winding. The on-load tap-changer shall be set in the tap position in which the reactor is energized at its maximum level.

The rated voltage shall be measured with a voltmeter responsive to the average value of the voltage but scaled to read the RMS value of a sinusoidal wave having the same average value. The voltmeter shall be connected between the terminals of the energized windings.

Fan(s) shall be operated as appropriate for the rating being tested. When cooling devices are not connected to the voltage regulator, it shall be so noted on the data sheet. When suitable cooling device sound level data is available, the data may be appropriately added to the measured voltage regulator sound level, if agreed to by the manufacturer and the purchaser. The addition of cooling device sound level to measured voltage regulator sound level shall be clearly noted on the data sheet.

Sound measurements shall begin after the voltage regulator being tested is energized and steady-state sound level conditions are established. Measurements may be made immediately on voltage regulators in continuous operation.

9.12.4.3.2 Load current sound level

Similar to load loss measurements (9.6), the load sound level at rated current is measured by applying a short-circuit across either the unregulated or regulated circuit terminals and applying sufficient voltage across the other terminals resulting in the rated current flowing in the windings. The load current sound level shall be measured at rated frequency and at the maximum boost position. Since load current sound level may be a contributor to the total sound level of the voltage regulator at higher loads, the load current sound level shall be measured at the ONAF measuring contour when available.

When test equipment limitations dictate, or when the ambient sound level is not sufficiently lower than load current sound level of the voltage regulator at full load, it is permissible to measure load current sound of the voltage regulator at a different current than rated current. When the test current differs from the rated current, but is within the range of equation validity (60 % to 130 % of rated current), Equation (28) can be used to convert the value of the measured load current sound level to the corresponding level at rated current.

$$L_{p,r} = L_{p,t} + 40\log_{10}\left(\frac{I_r}{I_t}\right) \tag{28}$$

where

$L_{p,r}$ is the rated load current sound level of the voltage regulator;

$L_{p,t}$ is the measured load current sound level of the voltage regulator at the test current;

I_r is the rated current;

I_t is the test current.

9.12.5 Microphone positions

9.12.5.1 Reference sound-producing surface

The reference sound-producing surface of a voltage regulator is a vertical surface following the contour of a taut string stretched around the periphery of the voltage regulator or integral enclosure (see Figure 18). The contour shall include radiators, corrugated fins, cooling tubes, fans, control enclosures; but it shall exclude bushings and minor extensions, such as valves, position indicators, oil gauges, thermometers, junction terminal boxes, universal interface enclosures, and projections at or above cover height.

Dimensions in metres (dimensions in feet)

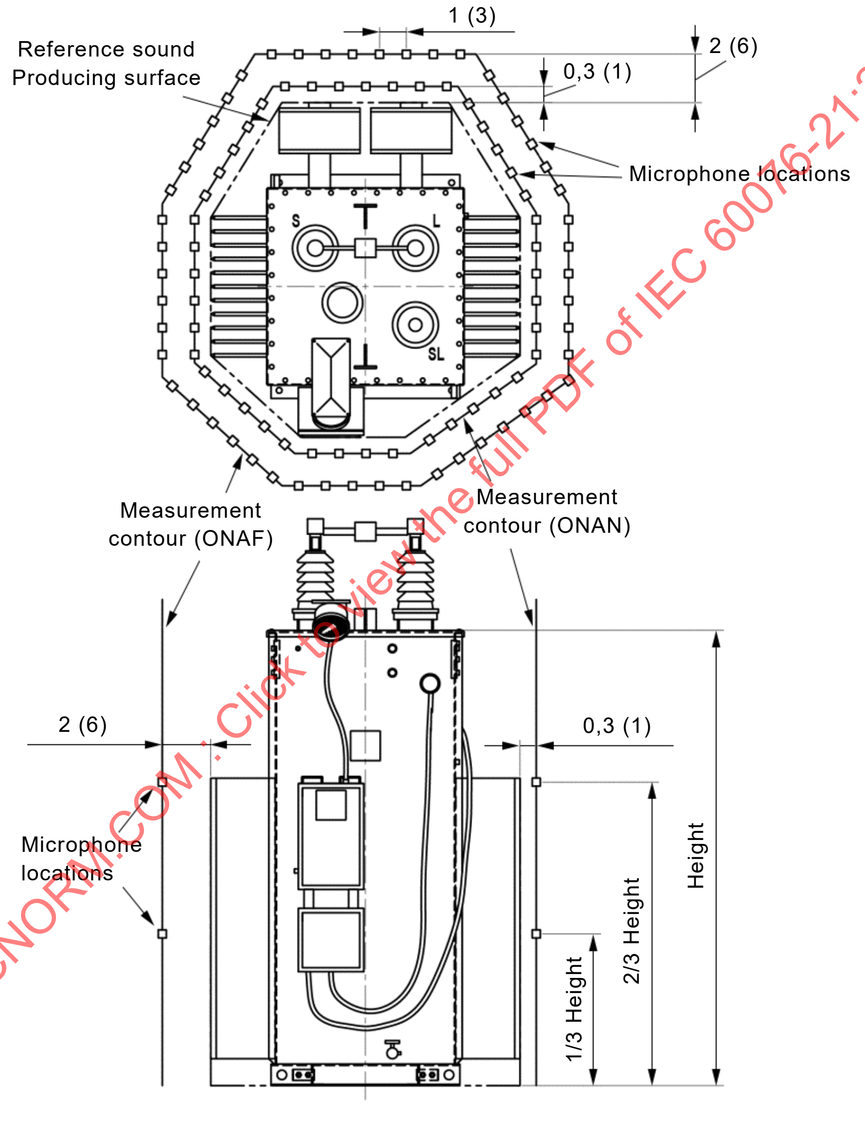


Figure 18 – Microphone location for measuring sound level

9.12.5.2 First measurement position

The first microphone location shall coincide with the main drain valve. Additional microphone locations shall be at 1 m (3 ft) intervals in a horizontal direction, proceeding clockwise as viewed from above along the measurement surface defined in 9.12.5.1.

9.12.5.3 Number of microphone locations

No fewer than four microphone locations shall be used. For small voltage regulators, intervals of less than 1 m (3 ft) may result. When fans are not in operation, the microphone shall be spaced 0,3 m (1 ft) from the reference sound-producing surface (ONAN contour). When fans are in operation, the microphone shall be located 2 m (6 ft) from the reference sound-producing surface (ONAF contour), refer to Figure 18.

9.12.5.4 Height of microphone locations

For voltage regulators having an overall tank or enclosure height of less than 2,4 m (7,9 ft), measurements shall be made at half height. For voltage regulators having an overall tank or enclosure height of 2,4 m (7,9 ft) or more, measurements shall be made at one-third and at two-thirds height.

9.12.6 Sound level measurements

9.12.6.1 General

The sound level of a voltage regulator can be measured using either the sound pressure or the sound intensity measuring method. When using the sound pressure measuring method, corrections for ambient sound, wall sound reflections, and near-field effect are to be made as explained in 9.12.6.3. Since the sound intensity measuring method allows measurement of only the sound radiating from the voltage regulator, these corrections need not be made. Instead, a correction, specified in 9.12.6.4.2, shall be made when ambient sound and wall sound reflections are such that they affect the accuracy of the measurements.

Voltage regulator sound level shall be measured in conformance with 9.12.3 to 9.12.5 using A-weighted sound level measurements.

9.12.6.2 A-weighted sound level measurements

The A-weighted sound level shall be measured with a sound level meter set to the A-weighted network.

9.12.6.3 Sound level measurements using the sound pressure method

9.12.6.3.1 General

Measured sound pressure levels shall be corrected for ambient sound, wall sound reflections, and near-field effects. The correction for ambient sound shall be made using the procedure described in 9.12.6.3.3. The correction for wall sound reflections shall be performed by subtracting the sound reflection correction "K" as calculated by Equation (29) in 9.12.6.3.4. The correction for the near-field effect shall be made per 9.12.6.3.5. The reported final test data shall include the measured sound levels along with the corrections used in determining the final value(s).

9.12.6.3.2 Measuring ambient sound pressure level

The ambient sound pressure level shall be established by averaging the ambient sound pressure levels measured immediately preceding and immediately following the sound measurements of an energized voltage regulator. The ambient sound shall be measured at a minimum of four locations, and the instruments shall be in conformance with 9.12.3. However, additional measurements may be made if agreed to by the manufacturer and purchaser or if the ambient measurements vary by more than 3 dB around the voltage regulator. At least one of the locations for measuring ambient sound pressure level shall be on the centre of each face of the measurement surface. Ambient sound pressure level corrections may be made at each microphone location before the average voltage regulator sound pressure level is computed. Ambient sound pressure levels shall be measured using the same A-weighted bandwidth specified for measuring the voltage regulator sound. The ambient sound pressure level corrections shall be made with the identical frequency bandwidths used to measure the combined voltage regulator and ambient sound pressure level.

9.12.6.3.3 Correction for ambient sound level

Measurements shall be made in an environment having an ambient sound pressure level at least 5 dB below the combined voltage regulator and ambient sound pressure level. When the ambient sound pressure level is 5 dB, or more, below the combined voltage regulator and ambient sound pressure level, the corrections shown in Table 19 shall be applied to the combined voltage regulator and ambient sound pressure level to obtain the voltage regulator sound pressure level. When the difference between the ambient sound pressure level and the combined voltage regulator and ambient sound pressure level is less than 5 dB, and it is desired only to know the sound pressure level the voltage regulator does not exceed, a correction of −1,6 dB may be used. Alternatively, the manufacturer may attempt to reduce the ambient sound during the test.

Table 19 – Ambient sound pressure level correction

Ambient sound pressure level and the combined voltage regulator and ambient sound pressure level difference (dB)	**Correction to be added to the combined voltage regulator and ambient sound pressure level** (dB)
5	−1,6
6	−1,3
7	−1,0
8	−0,8
9	−0,6
10	−0,4
over 10	0,0

9.12.6.3.4 Wall sound reflection correction "K"

This correction accounts for the influence of undesired sound reflections from test room boundaries (walls, ceiling, and floor) and reflecting objects near the voltage regulator. The magnitude of "K" depends principally on the ratio of the voltage regulator sound measuring surface "S" to the sound absorption area of the test room "A". The sound reflection correction "K" shall be calculated using Equation (29), or obtained from Figure 19 using the calculated value of "A/S".

$$K = 10 \log_{10}\left(1 + \frac{4}{(A/S)}\right) \tag{29}$$

The value of "A", in square metres, is given by Equation (30):

$$A = \alpha S_v \tag{30}$$

where

α is average acoustic absorption coefficient (from Table 20);

S_v is total area of the surface of the test room (walls, ceilings and floors), in square metres.

The sound measuring surface area "S" is the vertical area (in square metres or square feet) enveloping the voltage regulator (measurement surface) on which the sound measurement points are located plus the horizontal plane bounded by the vertical measurement surface. The measurement surface area is approximately equal to 125 % of the vertical area enveloping the voltage regulator. Therefore, the sound measuring surface area "S", is calculated using the following Equation (31):

$$S = 1{,}25 \times h \times l_{\text{m}} \tag{31}$$

where

h is the height of the voltage regulator tank, in metres;

l_{m} is the length of the sound measuring contour, in metres.

The empirical factor of 1,25 accounts for the sound radiated by the voltage regulator cover.

The maximum value allowed for this sound reflection correction is 4 dB. This is equivalent to allowing sound reflection equivalent to 1,5 times the sound radiated from the voltage regulator. In cases of high wall sound reflections, the voltage regulator manufacturer could, if applicable/feasible, move the voltage regulator to a larger test area/room, or outdoors.

NOTE The sound level reflection correction described above is based on IEC 60076-10 [12] for voltage regulator sound measurements.

Table 20 – Approximate values of the average acoustic absorption coefficient

Description of room	Average acoustic absorption coefficient, α
Nearly, or partly empty, room with smooth hard walls	0,1
Industrial room with machinery and no sound absorbing material on walls or ceiling	0,2
Industrial room with a small amount of sound absorbing material on ceiling or walls	0,3
Room with substantial amount of sound absorbing materials on both ceilings and walls	0,4
Sound room or room with an open side	0,5

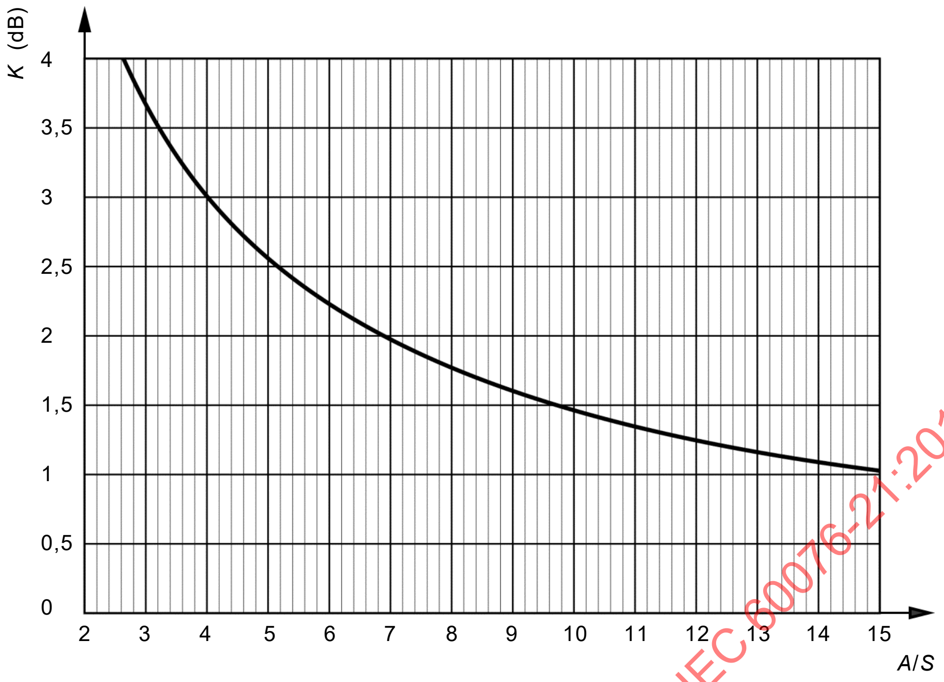


Figure 19 – Sound reflection correction factor "K" calculated as per Equation (29)

9.12.6.3.5 Near-field correction

This correction compensates for the measuring error caused by the near-field reactive sound power around the voltage regulator at the ONAN sound measuring contour. The value to be used for this correction is −1,0 dB for the ONAN measurements. No correction is to be made to the ONAF measurements.

9.12.6.4 Sound pressure level measurements using the sound intensity method

9.12.6.4.1 General

As stated earlier, in 9.12.6, measurements using the sound intensity method do not need to be corrected for ambient sound or wall sound reflections. However, ambient sound and/or wall sound reflections, when high, affect the accuracy of the measurements using this method. Under those conditions, the correction, described below, shall be made.

9.12.6.4.2 Environmental correction

The sound intensity measuring equipment provides two measured values for the sound level of the voltage regulator; one using the sound pressure method "L_P", and one using the sound intensity method "L_I". The sound intensity method of measurements is based on ISO 9614-1[28] and ISO 9614-2[29]. Under favourable environmental conditions (reasonable levels of ambient sound and wall sound reflections), the difference between the two measured values of the sound level of the voltage regulator is typically ≤ 4 dB. Under these conditions, no correction, to the measurements using the sound intensity method, is needed. However, when the environmental conditions are such that this difference (L_P – L_I) is > 4 and ≤ 6 dB, the following correction shall be made per Equation (32) or (33):

$$4 < (L_P - L_I) \le 5\,\text{dB, corrected } L_I = \text{Measured } L_I + 1 \quad (32)$$

$$5 < (L_P - L_I) \leq 6\,\text{dB, corrected } L_I = \text{Measured } L_I + 2 \quad (33)$$

where L_P and L_I are average sound levels measured using the sound pressure and sound intensity measuring methods, respectively.

When the environmental conditions are such that (L_P – L_I) > 6 dB, using the sound intensity method would be considered invalid. Alternatively, the voltage regulator sound could be measured using the sound pressure method while following the recommended corrections described in 9.12.6.3. Alternatively, as above environmental conditions are typically caused by high ambient sound and/or high wall sound reflections, the voltage regulator manufacturer could attempt to reduce the ambient sound and/or move the voltage regulator into a larger test area/room, if feasible.

9.12.7 Determination of sound level of a voltage regulator

9.12.7.1 Average sound pressure level (L_p)

The average voltage regulator sound pressure level (measured either by the sound pressure or the sound intensity method) shall be computed by logarithmically averaging the ambient-corrected sound pressure levels measured at each microphone location and for each A-weighted frequency band using Equation (34):

$$L_p = 10 \times \log_{10}\left\{\frac{1}{N}\sum_{i=1}^{N} 10^{(L_i/10)}\right\} \quad (34)$$

where

L_i is the sound pressure level measured at the ith location for the A-weighted sound level (dB);

N is the total number of sound measurements.

9.12.7.2 Determination of total sound pressure level of a voltage regulator

9.12.7.2.1 Addition of no-load (excitation) and load current sound levels

The total sound pressure level of a voltage regulator at a certain operating condition of voltage, current, and cooling stage, can be calculated by logarithmically adding the measured sound pressure levels of no-load (excitation) and load current corresponding to this operating condition. It can be calculated using Equation (35) below:

$$L_{pt} = 10 \times \log_{10}\left(10^{0,1L_{pnl}} + 10^{0,1L_{pl}}\right) \quad (35)$$

where

L_{pt} is the total sound pressure level of the voltage regulator at the specified operating condition;

L_{pnl} is the no-load (excitation) sound pressure level of the voltage regulator at the specified operating condition;

L_{pl} is the load current sound pressure level of the voltage regulator at the specified operating condition.

9.12.7.2.2 Determination of total sound pressure level of a voltage regulator at different loading conditions

The determination of the total sound pressure level of a voltage regulator at different loading conditions requires the following measurements:

a) no-load (excitation) sound with no fans running; at ONAN contour;
b) no-load (excitation) sound with half of the fans running; at ONAF contour;
c) no-load (excitation) sound with all fans running; at ONAF contour;
d) load current sound with no fans running; at ONAF contour.

Subclause 9.12.4.3.2 and Equation (28) shall be used to determine the load current sound level at a specific load using the load current sound level measured at a different loading condition.

Equation (35) shall be used to determine the logarithmic sum of no-load (excitation) and load current sound levels.

For the determination of the total sound level of the voltage regulator at a specific loading condition, the following procedure shall be used:

<u>At top power rating of voltage regulator</u>

Total sound level = logarithmic sum of the measured no-load (excitation) sound level with all fans operating and load current sound level at the top power rating.

<u>At a load up to the ONAN rating of voltage regulator</u>

Total sound level = logarithmic sum of the measured ONAN no-load (excitation) sound level and load current sound level at the specified loading condition corrected to the ONAN contour using the adder ($10 \cdot \log_{10}$(ONAF contour/ONAN contour)) where (ONAF contour/ONAN contour) is the ratio of the lengths of the two contours.

<u>At an intermediate load between the ONAN rating and top rating of the voltage regulator</u>

Total sound level = logarithmic sum of the measured no-load (excitation) sound level at the corresponding cooling stage and load current sound level at the specified loading condition.

The above calculations would not be needed when the purchaser requires adherence to the specified no-load (excitation) sound pressure levels in Table 13.

9.12.7.3 Sound power level calculation (L_w)

The sound power level shall be computed for each A-weighted frequency band using Equation (36):

$$L_w = L_p + 10 \times \log10(S) \tag{36}$$

where

L_w is the sound power level of the voltage regulator, in dB(A);

L_p is the sound pressure level of the voltage regulator, in dB(A).

Refer to Equation (31) for the calculation of the sound measuring surface area "S".

9.12.8 Presentation of results

Reports describing voltage regulator sound ratings shall include, as a minimum, the following data and Figure 20 (for sound pressure method measurements) and Figure 21 (for sound intensity method measurements), as applicable:

a) a statement the measurements were made and reported as described in this document;

b) a detailed description of all deviations from this document;

c) a description of the voltage regulator being tested, including rated power, voltage, voltage ratio, tap position, and connections;

d) measured voltage at the start of the no-load (excitation) sound level test and measured current at the start of the load current sound level test;

e) the name of the voltage regulator manufacturer, the location of manufacturer, the voltage regulator type, the serial number, the date and time of the test, and the name of the engineer giving the approval for the test;

f) a description of the sound-measuring instruments including the name of manufacturer, model, serial number, and calibration source as well description of the microphone, and the calibration method;

g) a description of the test environment, including a dimensioned sketch, showing the position of the voltage regulator with respect to other objects, location of the measuring surface, the microphone positions, and sound reflecting or absorbing surfaces;

h) the descriptor specified by the purchaser and manufacturer for sound level measurement;

i) clear descriptions of the sound level measured for any of the following operating conditions:

   1) voltage regulator fully equipped with its auxiliaries in service;

   2) voltage regulator fully equipped with its auxiliaries not in service;

   3) cooling devices in service with voltage regulator not energized;

j) the measurement surface area and the distance between the measurement microphone locations and the voltage regulator;

k) when using the sound pressure method:

   1) ambient sound pressure levels measured at each location;

   2) combined voltage regulator and ambient sound pressure level measured at each location and the logarithmical average sound pressure level;

   3) average A-weighted voltage regulator sound pressure levels corrected for ambient sound conditions, wall sound reflections, and near-field effects;

l) when using the sound intensity method:

   1) voltage regulator sound pressure level measured at each location and the logarithmical average sound pressure level;

   2) average A-weighted voltage regulator sound pressure levels corrected for environmental conditions if needed;

m) A-weighted sound power level of the voltage regulator.

Sound level data shall be rounded to the nearest whole decibel; values of 0,5 and above being rounded to the next higher integer.

Measuring position	(voltage regulator + ambient) Sound level		Ambient sound level at > 4 points	
	1/3 Height	2/3 Height	1/3 Height	2/3 Height
1				
2				
3				
4				
5				
•				
•				
n				
Logarithmic average sound level of (voltage regulator + ambient)				dB (A)
Logarithmic average sound level of ambient				dB (A)
Sound level of voltage regulator (corrected for ambient sound level)				dB (A)
Near-field correction				dB (A)
Measured sound level corrected for ambient sound level, wall sound reflection, and near-field effect				dB (A)

Figure 20 – Measurements using the sound pressure method

Measuring position	Sound pressure		Sound intensity			
	1/3 Height	2/3 Height	1/3 Height		2/3 Height	
			Level	±	Level	±
1						
2						
3						
4						
5						
•						
•						
n						
Logarithmic average sound pressure measurements						dB (A)
Logarithmic average sound intensity measurements						dB (A)
(Pressure – Intensity) index						dB (A)
Environmental correction						dB (A)
Measured sound level corrected environmental correction						dB (A)

Figure 21 – Measurements using the sound intensity method

9.13 Calculated data

9.13.1 Reference temperature

The reference temperature for determining load loss, voltage regulation, and efficiency shall be equal to the sum of the rated average winding temperature-rise by resistance plus 20 °C.

9.13.2 Loss and excitation current

9.13.2.1 Determination of no-load loss and excitation current

No-load loss and excitation current shall be determined for the rated voltage and frequency on a sine-wave basis unless a different form is inherent in the operation of the voltage regulator.

9.13.2.2 Load loss

Load loss shall be determined for rated voltage, current, and frequency and shall be corrected to the reference temperature (9.13.1).

9.13.2.3 Total loss

Total loss is the sum of the no-load loss and load loss.

9.13.3 Efficiency

The efficiency of a voltage regulator is the ratio of its useful power output to its total power input, exclusive of fans, and other ancillary devices. See Equation (37).

$$\eta = \left(\frac{P_o}{P_i}\right) = \frac{(P_i - P_l)}{P_i} = 1 - \left(\frac{P_l}{P_i}\right) = 1 - \left[\frac{P_l}{(P_o + P_l)}\right] \tag{37}$$

where

η is the efficiency;

P_o is the output (W);

P_i is the input (W);

P_l is the loss (W).

When specified, efficiency shall be calculated on the basis of the reference temperature for the average winding temperature-rise of the voltage regulator. If fans are supplied, the power requirements shall be provided as supplementary data.

9.13.4 Calculation of winding temperature during a short-circuit

The final winding temperature, T_f, at the end of a short-circuit of duration, t, shall be calculated as shown in Equations (38) to (43), on the basis of all heat stored in the conductor material and its associated turn insulation. T_f shall not exceed the limiting temperature in 6.8.3. All temperatures are in degrees Celsius.

$$T_f = (T_k + T_s) \times m \times (1 + E + 0{,}6m) + T_s \tag{38}$$

where

$$m = \frac{(W_s t)}{[C \times (T_k + T_s)]}$$

These equations are approximate formulas, and their use should be restricted to values of m = 0,6 or less.

For values of m in excess of 0,6, the following more nearly exact equation should be used:

$$T_f = (T_k + T_s)\left[\sqrt{\varepsilon^{2m} + E(\varepsilon^{2m} - 1)} - 1\right] + T_s \tag{39}$$

where

T_f is final winding temperature;

T_k is 234,5 °C (copper) or 225 °C (aluminium).

NOTE The temperature 225 °C applies for pure or EC aluminium. T_k can be as high as 230 °C for alloyed aluminium. Where copper and aluminium windings are employed in the same voltage regulator, a value for T_k of 229 °C is applied for the correction of load loss.

T_s is the starting temperature equal to:

a) 30 °C ambient temperature plus the average winding rise plus the manufacturer's recommended hottest-spot allowance, or

b) 30 °C ambient temperature plus the limiting winding hottest-spot temperature-rise specified for the appropriate type of voltage regulator;

ε is the base of natural logarithm, 2,718;

E is the per unit eddy-current loss, based on resistance loss, W_s, at the starting temperature.

$$E = E_r\left[\frac{T_k + T_r}{T_k + T_s}\right]^2 \tag{40}$$

where

E_r is the per-unit eddy-current loss at reference temperature;

T_r is the reference temperature, which is 20 °C ambient temperature plus rated average winding rise;

W_s is the short-circuit resistance loss of the winding at the starting temperature, in watts per weight of conductor material.

$$W_s(\text{W/kg}) = \frac{W_r N^2}{M_{kg}}\left[\frac{T_k + T_s}{T_k + T_r}\right](2{,}2) \text{ or } W_s(\text{W/lb}) = \frac{W_r N^2}{M_{lb}}\left[\frac{T_k + T_s}{T_k + T_r}\right] \tag{41}$$

where

W_r is the resistance loss of winding at rated current and reference temperature (W);

N is the ratio of symmetric short-circuit magnitude to normal rated current;

M_{kg} is the mass of winding conductor, in kilograms;

M_{lb} is the mass of winding conductor, in pounds;

C is the average thermal capacitance per mass of conductor material and its associated turn insulation (W_s/°C). It shall be determined by iteration from either of the following empirical equations:

$$C = 384 + 0{,}049\,6(T_s + T_f) + 110\frac{A_i}{A_c} \text{ for copper} \tag{42}$$

$$C = 893 + 0{,}220(T_s + T_f) + 360\frac{A_i}{A_c} \text{ for aluminium} \tag{43}$$

where

A_i is the cross-sectional area of turn insulation;

A_c is the cross-sectional area of conductor.

9.13.5 Certified test data

Minimum information to be included in certified test data:

a) order data;
   1) purchaser;
   2) purchaser's order number;
   3) manufacturer's production order number and serial number;
b) rating data;
   1) type;
   2) cooling class;
   3) number of phases;
   4) frequency;
   5) insulating medium;
   6) temperature-rise;
   7) winding ratings: voltage, voltampere, BIL, all temperature-rise ratings specified, including future ratings*;
   8) harmonic factor if other than standard*;
c) test and calculated data (by individual serial number; if the results are from another voltage regulator "type" tested, provide serial number, kV and kVA ratings, and date of test);
   1) date of test;
   2) winding resistances*;
   3) losses: no-load, load, and total;
   4) losses: cooling fans *;
   5) impedances in percent (%);
   6) excitation current in percent (%);
   7) applied-voltage test value;
   8) induced-voltage test value;
   9) routine impulse test value;
   10) ratio test results*;
   11) polarity test results*;
   12) insulation power factor in percent (%);
   13) insulation resistance (megger) test value*;
   14) other special test (defined by purchaser) results*;
   15) lightning impulse type test data*;
   16) thermal performance data*;
      i) ambient temperature;
      ii) tap position, total loss, and line currents for total loss run;
      iii) final bottom and top liquid temperature-rise over ambient for total loss run for each test;

iv) average winding temperature-rise over ambient for each winding for each test;

v) calculated winding hottest spot temperature-rise over ambient for maximum rating;

17) short-circuit test data*;

18) sound level test data*;

19) enclosure integrity test data*;

20) on-load tap-changer type test data*;

21) control type test data*;

22) zero-sequence impedance (calculated when specified)*;

23) dissolved gas in liquid analysis*;

24) lift and support lug safety factor*;

Items identified with an asterisk (*) are not required for voltage regulators unless specified by the purchaser.

d) certification statement and approval.

Number of significant figures of reported data should reflect the level of confidence of the data accuracy.

All temperature sensitive data should be reported after correcting to reference temperature (9.13.1).

Other significant information, such as tap position during loss tests, induced-voltage test, test connection used, and any particular method used when alternatives are allowed, should be included.

NOTE Other drawings, such as nameplate and outline, can be made a part of certified test data in place of duplicating the same information.

10 Component tests

10.1 General

Component tests are not included as part of the testing as per Clause 9 for the complete voltage regulator.

10.2 Enclosure integrity

10.2.1 General

An enclosure integrity test for the purposes of demonstrating mechanical force withstand requirements shall be made on voltage regulators with cylindrical enclosures. Where other ratings have the same tank and cover configuration, a test is not required, and it is satisfactory to show by calculation the mechanical forces are equal or less than the unit tested.

NOTE The enclosure integrity test establishes minimum mechanical force withstand requirements, however, it does not establish requirements for withstanding an abnormal fault condition such as bypassing a voltage regulator off of the Neutral position while energized.

10.2.2 Static pressure

The completely assembled voltage regulator enclosure shall be of sufficient strength to withstand an internal pressure of 49 kPa (gauge) (7 psig) without permanent deformation to the enclosure. The voltage regulator shall be of sufficient strength to withstand an internal pressure of 138 kPA (gauge) (20 psig) without rupturing or displacing components (excluding the cover gasket and gasket liquid leaks) of the voltage regulator.

10.2.3 Dynamic pressure

The completely assembled voltage regulator enclosure shall be capable of passing the fault current tests as defined in 10.2.4.

10.2.4 Type test for fault current capability of a voltage regulator enclosure

10.2.4.1 Objective

This test procedure has been designed to determine the ability of a voltage regulator enclosure to withstand a jolt- or impulse-type application of internal pressure. It is recognized that the test conditions should ultimately be described in terms of the energy applied, with the pressure wave defined by the rate of rise, peak pressure, duration, and total energy under the curve. However, at this time, sufficient information is not available to describe an applicable pressure wave. For the interim period, until such knowledge is available, this test procedure is based upon defining the electrical conditions associated with generating a particular jolt or impulse pressure wave, which shall be used as a measure of the enclosure strength. This test procedure is not intended to include all possible conditions occurring in service under fault conditions, but rather to establish a meaningful test repeatable and capable of duplication in various laboratories and test situations.

Some faults can quickly develop high pressures inside the voltage regulator enclosure. The rate of pressure rise and the ultimate pressure may vary for different faults. This type test is to be made on a new voltage regulator tank and cover configuration, subjected to no more than two tests or pressure shots, to demonstrate its capability to withstand pressure changes owing to specified test parameters.

10.2.4.2 General requirements

The new tank and cover configuration to be tested shall be complete with its core and coil assemblies, reactor, tap-changer, bushings, etc. The test shall be conducted at ambient temperature with an initial internal pressure from 14 kPa to 17 kPa (gauge) (2 psig to 2,5 psig). The voltage regulator enclosure being tested shall be securely supported solely by its support lugs, platform bolt-down provisions or substation mounting provisions. The test current shall be symmetrical. A new tank and cover shall be used for each test duty consisting of two tests. The second test is accomplished by reusing, "as specified by the manufacturer," all of the original components inside the enclosure. Provisions shall be made for venting in a safe manner any internal pressure remaining after each test.

If specified by the purchaser, the manufacturer shall provide a test report. This report shall describe tests on representative production samples of each enclosure diameter with its minimum designed air space.

10.2.4.3 Test duty – Arcing fault inside a voltage regulator enclosure

10.2.4.3.1 First test

Test duty with a high-current arcing fault shall be conducted on each tank diameter with its minimum designed air space. The minimum designed air space shall consider production tolerances.

A simulated internal fault shall be provided. This fault shall consist of a 25 mm (1 in) arc gap mounted horizontally and located 25 mm (1 in) above the core clamps. This gap shall be bridged initially by a copper wire having a diameter smaller than 1,0 mm (0,039 4 in). The gap shall be connected between two of the voltage regulator bushing terminals or from one of the bushing terminals to ground. The mounting blocks or terminals of the gap shall consist of copper-bearing material and shall have flat surfaces from 6 mm to 20 mm (0,25 in to 0,75 in) in diameter or in width. These mounting blocks or terminals shall be designed to maintain this

25 mm (1 in) arc gap for the duration of the test. The voltage regulator core and coil assemblies, reactor and tap-changer shall not be electrically connected into this test circuit. The power source shall be at least 7,2 kV and adjusted to supply a current of 8 000 RMS symmetrical amperes.

As this arcing fault is not self-clearing, back-up protection or proper test circuit timing shall be provided to clear the circuit in approximately 1 cycle (16,7 ms at 60 Hz or 20 ms at 50 Hz). A cut-out with up to a 25 K fuse link or appropriate timing of a test circuit breaker shall be used to provide back-up protection. A current-limiting device, such as a current-limiting fuse, shall not be included in the back-up protection.

10.2.4.3.2 Second test

For the second test, the test described in 10.2.4.3.1 shall be repeated on the same voltage regulator enclosure.

10.2.4.4 Test results

For a voltage regulator enclosure to pass the test duty, it shall satisfy all of the following criteria:

a) no mechanical components from the voltage regulator enclosure shall be propelled or dropped during the tests. Bushings shall remain in place and intact;
b) there shall be no rupture of the enclosure casing or seams;
c) there shall be less than one litre (one quart) of liquid emitted;
d) there shall be no expulsion of flaming liquid during the tests;
e) no liquid shall continue to leave from the inside of the voltage regulator enclosure after the completion of the test;
f) the voltage regulator enclosure shall not be dislodged from its mounting.

The amount of liquid emitted, criteria c), shall be measured when there is no observable deformation by measuring the liquid level before and after test. For other cases, weighing the voltage regulator before and after the test or a pan can be used. The test report shall state which method is used and the minimum sensitivity of the method.

10.3 On-load tap-changer

10.3.1 General

This subclause applies to type tests for vacuum and non-vacuum reactor type on-load tap-changers immersed in insulated liquid.

NOTE Type tests for on-load tap-changers of other basic technologies will be per agreement of the purchaser and the manufacturer using standard IEC 60214-1 [13] or IEEE Std C57.131 [26] as a reference.

Up to the maximum rated through-current of the on-load tap-changer, there are different assigned combinations of values of rated through-current and corresponding rated step voltage. When a value of rated step voltage is referred to a specific value of rated through-current, it is called the 'relevant rated step voltage'.

10.3.2 Type tests

10.3.2.1 General

The following type tests shall be performed on samples of the relevant on-load tap-changer after its final development or on equivalent components provided the manufacturer can demonstrate the relevant test conditions and results are not influenced by testing only components instead of the complete on-load tap-changer.

NOTE No differentiation has to be made with respect to the test supply with frequencies of 50 Hz or 60 Hz. The tests can be carried out with either frequency.

a) Temperature-rise of contacts test (10.3.2.2)
b) Switching tests (10.3.2.3)
c) Short-circuit test (10.3.2.4)
d) Reactor test (10.3.2.5)
e) Mechanical test (10.3.2.6)
f) Dielectric tests (10.3.2.7)

10.3.2.2 Temperature-rise of contacts test

Test shall be performed to verify the temperature-rise above the insulating liquid, surrounding each type of contact carrying through-current continuously, does not exceed 20 °C rise when the contacts have reached a steady temperature, carrying 1,2 times the maximum rated through-current. Contacts tested are those carrying current continuously and are opened and closed at some instant during service or maintenance.

NOTE Contacts operating in vacuum do not need to be measured.

The type test shall be performed in the position in which the highest total current flows through the on-load tap-changer. The current is calculated on the following basis:

a) through-current equalling 1,2 times the maximum rated through-current;
b) circulating current equalling 50 % of the maximum rated through-current (or otherwise specified by the manufacturer and stated in the type test report;
c) power factor equalling 80 %.

The test shall be performed at a starting temperature of not more than 40 °C and not less than 10 °C.

The temperature of the surrounding medium shall be measured at not less than 25 mm below the contacts.

The temperature shall be measured by thermocouples or other suitable means positioned in a manner to accurately reflect the actual contact temperature as near the point of contact as possible. The measuring device should be embedded into the contact or brazed or welded on to the contact so it is measuring the bulk temperature of the contact and not the temperature of the interface between the contact and cooling medium.

The temperature condition is considered to be steady when the difference of the temperature between the contact and the surrounding medium does not change more than 1 K over an hour.

The cross-section and insulation of the conductor carrying the current into the on-load tap-changer or components under test shall be stated.

10.3.2.3 Switching tests

10.3.2.3.1 General

Switching tests that include service duty and breaking capacity tests shall have the following provisions:

Service duty test

a) Maximum circulating current of reactor equalling 50 % of the maximum rated through-current (or otherwise specified by the manufacturer and stated in the type test report).

b) Power factor equalling 80 %.

Breaking capacity test

a) Maximum circulating current of reactor equalling 50 % of the maximum rated through-current (or otherwise specified by the manufacturer and stated in the type test report).

b) Power factor equalling 0 %.

For vacuum type on-load tap-changers, the breaking capacity test shall be performed after the completion of the service duty test using the identical test sample.

Contacts and liquid in the case of liquid-immersed on-load tap-changers shall not be renewed during the tests.

In the case of three-phase switches, it is normally sufficient to test the contacts of one phase.

The arrangement for testing shall be such that, except where otherwise specified, the switched current, the recovery voltage, or the product of these shall not, in any case, be less than 95 % of the calculated values.

10.3.2.3.2 Service duty test

The contacts of the on-load tap-changer shall be subjected to a number of operations corresponding to N, tap-change operations in normal service when carrying a current corresponding to not less than the maximum rated through-current and the relevant rated step-voltage. The number of tap-change operations, N, to be carried out depends on the type of on-load tap-changer. For non-vacuum type on-load tap-changers, N shall be 50 000 tap-change operations. In the case of vacuum type on-load tap-changers, N shall be equal to 1,2 times the number of tap-change operations between maintenance according to the manufacturer, but N shall not be less than 50 000 operations. This number of operations shall be declared by the manufacturer.

Comparison of oscillograms taken at regular intervals during the test shall show there is no significant alteration in the characteristics of the on-load tap-changer in such a way as to compromise the operation of the apparatus. Twenty (20) oscillograms shall be taken at the start of the test, and twenty (20) after each succeeding quarter of N $(N/4)$ operations, making a total of 100 oscillograms.

After the test, inspections of contact wear shall take place, the results of these leaving no doubt as to the suitability of the on-load tap-changer for service.

NOTE 1 The results of this test can be used by the manufacturer to demonstrate the contacts used for making and breaking current are capable of performing, without replacement of the contacts, the number of tap-change operations declared by the manufacturer at the maximum rated through-current and at the relevant rated step voltage.

NOTE 2 Generally, it is sufficient to compare the series of oscillograms taken at the beginning and at the end of the test.

In order to approximate to service conditions, non-vacuum type on-load tap-changers shall have the test performed at not more than eight tap-change operations, these being centrally disposed about the change-over selector (mid-position plus/minus four (4) positions, without dead positions).

In the case of vacuum type on-load tap-changers, the breaking action will take place within the vacuum interrupters and does not depend on the tap-changer position. Therefore, the above-mentioned approximation to the service conditions is not required.

10.3.2.3.3 Breaking capacity tests

Forty operations shall be performed at a current corresponding to twice the maximum rated through-current at its relevant rated step voltage.

In order to approximate to service conditions, non-vacuum type on-load tap-changer shall have the test performed at not more than eight tap-change operations, these being centrally disposed about the change-over selector (mid-position plus/minus four (4) positions, without dead positions).

In case of vacuum type on-load tap-changers, the breaking action will take place within the vacuum interrupters and depends not on the tap-changer position. Therefore, the above mentioned approximation to the service conditions is not required.

The oscillograms taken for each operation shall indicate that in no case is the arcing time such as to jeopardize the operation of the apparatus.

For vacuum type on-load tap-changers, the breaking capacity test shall be performed after the completion of the service duty test using the identical test sample.

10.3.2.4 Short-circuit test

All dissimilar designed contacts of a new on-load tap-changer, carrying current continuously, shall be subjected to short-circuit currents, each of 2 (1 ± 10 %) s in duration.

In the case of three-phase on-load tap-changers, it is sufficient to test the contacts of one phase only unless otherwise specified.

Three applications shall be made using an asymmetrical current determined per 6.8.1 using the maximum rated through-current of the tap-changer as the base RMS symmetrical current. The value of the symmetrical short-circuit test current to be applied shall be a maximum value of 25 times the maximum RMS symmetrical rated through-current of the tap-changer or 16 kA, whichever is less. The contacts shall not be moved between these applications.

When it is not possible to obtain the three asymmetrical current applications per 6.8.1, the symmetrical RMS value of the short-circuit test current shall be increased so that the rated asymmetrical peak current is obtained for the three applications, resulting in the test duration being reduced. The product of the square of the increased RMS current and the shorter test duration shall not be less than the product of the square of the rated short-circuit RMS current and the two-second (2 s) duration.

The open-circuit voltage for the test shall be at least 50 V.

At the conclusion of the test, the contacts shall not have been damaged so as to prevent continued correct operation at maximum rated through-current. This has to be proven by a no-load operation, oscillographically recorded, breaking any created weld. Comparison of this oscillogram with those obtained before the test shall show suitability for service.

Other current-carrying parts shall not show signs of permanent mechanical distortion, which can influence the normal operation of the on-load tap-changer.

The short-circuit current is divided into two equal parts at the tap selector or selector switch contacts. Therefore, the current carried by each contact is 50 % of the full test current.

10.3.2.5 Reactor test

Reactors are normally tested in accordance with the specification for the voltage regulator with which the on-load tap-changer is intended for use.

Attention should be taken in the design of the reactor to avoid high inrush currents during switching.

10.3.2.6 Mechanical test

The on-load tap-changer shall be assembled and immersed in a test tank filled with clean dielectric liquid, and operated as for normal service conditions. The contacts shall not be energized and the full range of taps shall be utilized until a minimum of 500 000 tap-change operations have been performed. At least 50 000 tap-change operations shall be carried out on the change-over selector.

If the number of operations carried out during the service duty test is higher than or equal to the requested 500 000 operations during mechanical endurance test, it is allowed to use these operations for the verification of the 500 000 operations, provided that all test conditions fit.

Half the number of operations shall be performed at a temperature of not less than 75 °C and half at a lower temperature, for example during the heating or cooling period, with daily temperature cycles being permitted.

Ten timing oscillograms shall be taken at the start and finish of the mechanical endurance test. Comparison of these timing oscillograms shall show no significant difference.

One hundred operations shall be performed at 110 °C to demonstrate the capability to withstand the voltage regulator liquid temperatures during emergency loading as specified in IEEE Std C57.91 or IEC 60076-7 [11]. The operation shall be oscillographically recorded. Comparison of these oscillograms with those obtained at the start and the end of the mechanical endurance test shall show suitability for service.

One hundred operations shall be performed at −20 °C with the on-load tap-changer oscillographically recorded. Comparison of these oscillograms with those obtained in accordance with the previous paragraph shall show suitability for service. The viscosity at −20 °C of the liquid used in this test shall be stated. Tests with a higher viscosity alternative liquid may not be applicable at −20 °C. The manufacturer shall be consulted on the minimum allowable temperature.

During the test, there shall be no failure or undue wear of the contacts or mechanical parts leading to mechanical failure if the operation is continued.

10.3.2.7 Dielectric tests

10.3.2.7.1 General

The dielectric requirements for the on-load tap-changer depend on the voltage regulator rating to which it is to be connected. The on-load tap-changer shall have the appropriate insulation level, as well as the connecting leads between the on-load tap-changer and the windings of the voltage regulator.

The on-load tap-changer shall be immersed in a test tank filled with clean dielectric liquid before the tests are performed.

10.3.2.7.2 Nature of tests

The insulation level of the on-load tap-changer shall be proved by dielectric tests performed at the following distances:

a) to earth;
b) between phases (where applicable);
c) between the first and last contacts of the tapped winding;
d) between any two adjacent contacts.

10.3.2.7.3 Test voltages

Test voltage levels for applied voltage, impulse full wave and chopped wave are found in Table 11.

10.3.2.7.4 Application of test voltages

For the dielectric tests, the on-load tap-changer shall be assembled, arranged and dried-out in a manner similar to that used in service. It is not, however, necessary to include leads for connecting the on-load tap-changer to the windings of a voltage regulator. If using leads, they should be an approximation of those in service.

For test a) of 10.3.2.7.2, the live parts of each phase shall be short-circuited and connected to the voltage source.

For tests b), c), and d), appropriate withstand values of full and chopped wave lightning impulse voltage, and applied voltage, shall be declared by the manufacturer.

The preferred testing sequence is as follows:

a) full wave lightning impulse test;
b) chopped wave lightning impulse test;
c) applied voltage test.

10.3.2.7.5 Full wave lightning impulse test

The test shall be performed in accordance with 9.7.2.3, at the required value.

10.3.2.7.6 Chopped wave lightning impulse test

The test shall be performed in accordance with 9.7.2.4, at the required value.

10.3.2.7.7 Applied-voltage test

The test shall be performed in accordance with 9.7.4, at the required value.

10.4 Control system

10.4.1 General

The control system of a voltage regulator is composed of sensing apparatus to provide signals proportioned to the system voltage within the control voltage operating range and load current, and a control device interpreting the output of the sensing apparatus, relating this input to conditions desired by the operator, and to automatically command the voltage regulator to function to hold the output thereby required.

The total control system is furnished as a complete package with the voltage regulator; however, the usual stand-alone nature of the control device portion of the control system makes it appropriate to consider the control system in a unified context.

10.4.2 Control device construction

10.4.2.1 Setpoint adjustment ranges

The control device shall permit parameter adjustments as follows:

a) voltage level setting adjustable from at least 108 V to 132 V (related to system voltage-by-voltage supply ratio as defined in Table 10);

b) bandwidth setting adjustable from at least 1,0 V to 6,0 V (total range);

c) actuation time delay setting adjustable from at least 10 s to 120 s. The time delay applies only to the first required change if subsequent changes are required to bring the system voltage within the bandwidth setting;

d) line-drop compensation adjustment including independently adjustable resistance and reactance in the range of at least −24 V to +24 V.

NOTE The voltage refers to line-drop compensation at the nominal control base voltage of 120 V and rated base current of 0,2 A. It is not required to provide negative resistance and negative reactance compensation simultaneously.

10.4.2.2 Components and accessories

The following components and accessories will be provided as part of the control device:

a) *Voltage test terminals.* Measurement of voltage is proportional to voltage regulator output voltage and shall not change by more than ±1 % after connecting a burden of 25 VA at 0,7 power factor across the test terminals, unless otherwise specified. This is not included in the specification of accuracy of the control relays.

b) *Manual-automatic control switch.*

c) *Manual raise/lower switch.*

d) *Neutral position indicator.* Display shall be independent of the on-load tap-changer position indicator

e) *External voltage source terminals*

f) *Internal/external power switch.* Switch allows the control to be energized from the voltage regulator's internal voltage supply or from an external voltage source. Voltage regulator windings shall not be able to be energized by an external voltage source being connected to the external source terminals while the power switch is in the external power position.

g) *Operations counter.* Accumulated number of on-load tap-changer operations is shown.

h) *High- and low-band limit indicators.*

10.4.3 Accuracy

10.4.3.1 General

The control system of a voltage regulator shall have an overall system error not exceeding ±1 %. The accuracy requirement is based on the combined performance of the control device and sensing apparatus, including instrument current and voltage transformers, utility windings, transducers, and so forth, with the voltage and current input signals of a sinusoidal wave shape.

Since it is not practical to test the overall control system accuracy, it is permissible to individually test the control system components and then add their accuracies together to arrive at the overall control system accuracy. Accuracy tests are type tests not made on every unit. The test voltage and current signals should have a sinusoidal wave shape. No analytical correction is permitted to remove effects of harmonics in the accuracy test results.

10.4.3.2 Voltage source

The voltage source accuracy shall be determined on a nominal secondary voltage base of 120 V and a burden of 10 VA.

10.4.3.3 Current source

The current source accuracy shall be determined on a nominal 0,2 A secondary current and a burden of 3,5 VA.

10.4.3.4 Control device

10.4.3.4.1 General

The accuracy of the control device shall be determined based on test digressions at an ambient temperature of 25 °C, rated frequency, a nominal input voltage of 120 V and a base current of 0,2 A at unity power factor and at zero power factor lagging.

The user should be made aware that harmonic distortion of the control device input voltage and/or current can result in differences in the sensed average or RMS magnitude, which affects the overall accuracy of the control device and control system. Such differences may be inherent in the product design and do not constitute an additional error in the context of control accuracy.

10.4.3.4.2 Errors

Each individual error-producing parameter is stated in terms of its effect on the response of the control device and is determined separately with the other parameters held constant. Errors causing the control device to hold a higher voltage level than the reference value are plus errors and those causing a lower voltage level are minus errors. The overall error of the control device is the sum of the individual errors as separately determined; the overall error causes a divergence from the voltage level setting.

10.4.3.4.3 Factors for accuracy determination of control device

The greater magnitude of the sum of the positive or negative errors of the following three areas shall constitute the accuracy of the control device:

a) variations in ambient temperature of the control environment between −30 °C and 65 °C;

b) frequency variation of ±0,25 % in rated frequency;

c) line-drop compensation:

   1) resistance compensation of 12 V and an in-phase base current of 0,2 A with reactance compensation of zero;

   2) resistance compensation of 12 V and a 90° lagging base current of 0,2 A with reactance compensation of zero;

   3) reactance compensation of 12 V and an in-phase base current of 0,2 A with resistance compensation of zero;

   4) reactance compensation of 12 V and a 90° lagging base current of 0,2 A with resistance compensation of zero.

10.4.4 Type tests

10.4.4.1 General

Type tests shall be carried out to insure required accuracy and ability to operate under a normal service condition. The control device and voltage regulator shall continue to operate properly and not cause any unintentional tap-change during or after the tests.

10.4.4.2 Control device accuracy

10.4.4.2.1 Procedure for determination of accuracy of control device

This subclause outlines procedures for determining values of errors contributed by the factors described in 10.4.3.4.3. The voltage and current sources applied may be as free of harmonics or other distortions as the test facility permits.

10.4.4.2.2 Test for errors relating to voltage level

With the control device set at a voltage level of 120 V and at an ambient temperature of 25 °C, energize the control device for 1 h using a 120 V source at rated frequency. The control is calibrated at this point. Errors in voltage level in the following three tests will determine the control device accuracy:

a) *Tests for error in voltage level due to temperature.* The control device shall be tested over a temperature range of −30 °C to 65 °C in not more than 20 °C temperature increments. The air temperature surrounding the control device shall be held constant and uniform within ±1 °C of each increment for a period of not less than 1 h before taking a test reading. Tests are carried out at rated frequency with zero current in the line-drop compensation circuit.

b) *Tests for error in voltage level due to frequency.* The control device shall be tested over a sufficient range of frequencies to accurately determine the error over the specified range of rated frequency, ±0,25 %. Tests are made at a constant temperature of 25 °C with zero current in the line-drop compensation circuit.

c) *Tests for errors in voltage level due to line-drop compensation.* Four tests shall be made at rated frequency and a constant temperature of 25 °C and a voltage level setting of 120 V. Determine the voltage level required to balance the control with 0,2 A in the compensator circuit of the control under the conditions specified in Table 21.

Table 21 – Voltage level values for select line-drop compensation

Test	Set LDC-R (V)	Set LDC-X (V)	Current phasing	Determine error relative to expected voltage
1	12	0	In-phase	132,0 ∠ 0° V
2	0	12	In-phase	119,4 ∠ 0° V
3	12	0	90° lagging	119,4 ∠ 0° V
4	0	12	90° lagging	132,0 ∠ 0° V

Use the individual test error (plus or minus), which produces the largest overall error magnitude when summed as per 10.4.3.4.2.

10.4.4.3 Set point display deviations

10.4.4.3.1 General

Deviation of set point display for voltage level, bandwidth, line-drop compensation, and time delay settings are not considered as a portion of the errors in determining the accuracy classification.

10.4.4.3.2 Voltage level display deviation

The difference between the actual voltage level value and the displayed value at any setting over the range of 120 (1 ± 10 %) V shall not exceed ±1 %.

10.4.4.3.3 Bandwidth display deviation

The difference between the actual bandwidth voltage and the displayed value shall not exceed ±10 % of the displayed value setting.

10.4.4.3.4 Line-drop compensation display deviation

The arithmetic difference between the actual line-drop compensation voltage expressed as a percent of 120 V and the displayed value of any setting of either the resistance or reactance element of line-drop compensation (expressed as a percent of 120 V, with 0,2 A in the line-drop compensation circuit) shall not exceed ±1 %.

10.4.4.3.5 Time delay display deviation

The difference between the actual time delay and the value of any setting shall not exceed ±2 s or ±10 %, whichever is greater. An integrating-type circuit shall be initiated without a stored delay.

10.4.4.4 Environmental tests per IEC 60255-1

10.4.4.4.1 Temperature

The control shall meet all requirements specified herein when operated in an operating environment (air temperature, solar radiation, and other heat sources) with temperature range −40 °C to +65 °C. Control device components shall withstand a temperature range −40 °C to +85 °C without loss of control. This requirement includes powering up of a control not in service or a control disconnected from the primary power source and does include the effects of any internal heat source (i.e. self-heating).

The following tests shall be completed:

a) IEC 60255-1, cold, −40 ºC, 96 h;

b) IEC 60255-1, dry heat, +65 ºC, 96 h.

10.4.4.4.2 Humidity

Tests are to be conducted as per IEC 60255-1, 25 °C to 55 °C, 6 cycles.

10.4.4.4.3 Vibration

Tests shall be completed as per IEC 60255-21-1 (Class 1).

10.4.4.5 Insulation coordination tests

Tests shall be completed as per IEC 60255-27, impulse voltage ±5 kV, dielectric test (2 kV).

10.4.4.6 Electromagnetic compatibility (EMC) tests

10.4.4.6.1 Electrostatic discharge immunity

Tests shall be completed either as per IEEE Std C37.90.3 (testing shall be completed for all voltage levels specified, highest level being 8 kV contact discharge and 15 kV air discharge) or as per IEC 60255-26 (2 kV, 4 kV and 6 kV contact discharge and 2 kV, 4 kV and 8 kV air discharge) as specified.

10.4.4.6.2 Radiated interference immunity

Tests shall be completed per either IEEE Std C37.90.2 (20 V/m unmodulated, 35 V/m modulated) or IEC 60255-26 (10 V/m unmodulated, 18 V/m modulated) as specified.

10.4.4.6.3 Surge withstand capability

Tests shall be completed either as per IEEE Std C37.90.1 or as per IEC 60255-26 (Zone A) as specified.

10.4.4.6.4 Surge immunity

Tests shall be completed as per IEC 60255-26 (Zone A).

10.4.4.6.5 Conducted interference immunity

Tests shall be completed as per IEC 60255-26.

10.4.4.6.6 Voltage dips and interruptions immunity

Tests shall be completed per IEC 60255-26.

10.4.4.7 On-load tap-changer compatibility type test

10.4.4.7.1 General

This procedure shall be followed to validate acceptable operational functionality of a manufacturer's control when used in conjunction with any manufacturer's on-load tap-changer. As modifications are made to the control or on-load tap-changer, it is imperative that functionality is validated for the set.

10.4.4.7.2 Test procedure set up

a) Refer to the manufacturer's control instruction manual for description of proper control configuration and operation.

b) Supply control with external voltage as per Table 22 with the power switch in the External position.

Table 22 – Control supply voltage

Frequency	Control supply voltage
60	103
	120
	132,5
50	103
	120
	132,5

c) Select on-load tap-changer model in the control, if applicable.

d) Reset operations counter to zero (0).

e) Begin a test sequence from one of the maximum tap positions, 16 Raise or 16 Lower.

f) Each cycle of a test sequence is equal to thirty-two (32) operations in either the boost or buck direction, maximum position to maximum position.

g) Complete test sequences in 10.4.4.7.3 (Manual test sequence) and 10.4.4.7.4 (Automatic test sequence) for all applied voltage levels identified in Table 22.

h) Verify that the tap position, displayed by the control, matches the tap position shown by the mechanical position indicator. Reset tap position displayed by the control to correspond with mechanical position indicator, if necessary.

i) Record test results.

10.4.4.7.3 Manual test sequence, five hundred twelve (512) operations (16 cycles)

a) Place control switch in manual position.

b) Verify and record operations count at the end of each cycle of thirty-two (32) operations.

c) Pause for a minimum of five (5) seconds between cycles.

d) Operations of the first eight (8) cycles are initiated one step at a time while monitoring the tap position displayed by the control.

e) Attempt to make five (5) additional operations at the end of the first eight (8) cycles verifying the operations counter is not indexing.

f) Operations of the last eight (8) cycles are driven without a pause while monitoring the tap position displayed by the control.

10.4.4.7.4 Automatic test sequence, five hundred twelve (512) operations (16 cycles)

a) Set bandwidth to 1,0 V.

b) Set time delay to 5 s.

NOTE If a minimum value of 5 s is not available, the minimum value of a specific control is acceptable.

c) Place Control switch in Automatic position.

d) Begin a test sequence from one of the maximum tap positions, 16 Lower or 16 Raise.

e) Set Voltage Level to 100 V for an "out of band high" condition for buck operation cycles and 135 V for an "out of band low" condition for boost operation cycles.

f) After the time delay elapses, allow the on-load tap-changer to operate until a maximum position is reached while monitoring the tap position displayed by the control.

g) Verify the tap position and record operations count at the end of each cycle of thirty-two (32) operations.

10.4.4.7.5 Test summary

Successful pass completion of "Manual" and "Auto" test sequences is determined by not having the following:

a) misoperations;

b) out of sequence displayed tap positions;

c) inaccurate operations count totals.

Failures or inconsistent test results should be noted and analyzed.

10.4.4.8 Devices to be tested

The devices making up the control system vary depending on the requirements of the purchaser. The requirements for tests as per 10.4.4.4 to 10.4.4.6 vary with the application. The following examples spell out certain specifics:

a) A voltage regulator with control mounted on the tank or on the pole at ground level below the voltage regulator and with no circuits except the power conductors and a cable from the voltage regulator to the control. (The control system is both the control and the voltage regulator. Since there are no other control conductors connected to the system, there are no tests as per 10.4.4.4 to 10.4.4.6 required. The power system line conductor connections are otherwise covered and hence fall beyond this requirement.)

b) A voltage regulator mounted as in item (a) but with potential device, control, or metering conductors being connected into the control. (These conductors would be subject to 10.4.4.4 to 10.4.4.6 test requirements.)

c) A control enclosure mounted remotely with potential device, control, or metering connections to the control. (Here, all conductors connected to the control, including those to the voltage regulator, would be subject to 10.4.4.4 to 10.4.4.6 test requirements.)

d) If the foregoing examples do not adequately cover the application, the manufacturer and purchaser shall agree on the connection scheme and the tests to be applied.

11 Universal interface

11.1 Connection between control enclosure and apparatus

A universal interface, when specified, shall be made available between the voltage regulator control enclosure and apparatus. This is accomplished by way of an auxiliary enclosure. The auxiliary enclosure shall include the following features:

a) universal interface receptacle;

b) a means of shorting the current transformer secondary; either mechanically or electronically;

c) terminal boards and wiring for managing signals between voltage regulator apparatus and control enclosure;

d) minimum IP rating of 24 (NEMA 3R);

e) capacitor for the tap-changer motor (if not included within the control enclosure);

f) grounding provision shall be provided for metal enclosures. For proper control operation and improved safety, interface enclosure shall be grounded using the same ground used for the voltage regulator apparatus and control enclosure.

NOTE 1 Refer to NEMA Standards Publication 250-2003 [30] or IEC 60529 [15] for details regarding the various degrees of protection provided by electrical circuitry enclosures.

NOTE 2 Other types of enclosures are available that are more resistant to dust and water. These options can be specified by the purchaser based on discussions with the manufacturer.