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INTERNATIONAL STANDARD

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 has been processed through IEC technical committee 14: *Power transformers*.

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

IEEE Std	FDIS	Report on voting
C57.15-2009	14/688/FDIS	14/697/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.

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

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC web site 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- withdrawn,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.

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IEEE Standard Requirements, Terminology, and Test Code for Step-Voltage Regulators

Sponsor

Transformers Committee
of the
IEEE Power & Energy Society

Approved 11 September 2009

IEEE-SA Standards Board

Abstract: Description of design types, tables of 50 Hz and 60 Hz ratings, supplementary ratings, construction, and available accessories are provided. Methods for performing routine and design tests applicable to liquid-immersed single and three-phase step-voltage regulators are described. Winding resistance measurements, polarity tests, insulation power factor and resistance tests, ratio tests, no load loss and excitation current measurements, impedance and load loss measurements, dielectric tests, temperature tests, routine and design impulse tests, short-circuit tests, control tests, calculated data, and certified test data are covered.
Keywords: control, design tests, position indicator, routine tests, series transformer, tap changer, Type A, Type B, voltage regulator

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IEEE Introduction

This introduction is not part of IEEE Std C57.15-2009, IEEE Standard Requirements, Terminology, and Test Code for Step-Voltage Regulators.

The Working Group has undertaken the task to update this standard to:

a) Reflect the latest revisions of referenced documents IEEE Std C57.12.00™ [B13] and IEEE Std C57.12.90™ [B16], and eliminate references to these standards in this standard IEEE Std C57.15-2009 and duplicate applicable text. [1]

b) Adapt the new IEEE approved format to ensure compatibility with the latest ISO and IEC standards.

c) Include references to applicable IEC standards and keep IEEE standard references to a minimum. This assists in setting up document as a possible candidate for a dual logo (IEC/IEEE).

d) Update tables of preferred ratings; include 50 Hz ratings. Ratings of 2.4 kV (45 BIL), 46 kV (250 BIL), and 69 kV (350 BIL) have been removed from the three-phase 60 Hz voltage regulator rating Table 5 (Table 4 in 1999 edition) due to historical inactivity of requests from users for ratings.

e) Add bushing terminal connectors for current ratings of 669 A to 2000 A.

f) Clarify Type A and Type B designs and their resulting voltage regulation per extreme tap positions.

g) Review short-circuit requirements for distribution and substation applications and revise where applicable.

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[1] The numbers in brackets correspond to those of the bibliography in Annex C.

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POWER TRANSFORMERS –

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

1. Overview

1.1 Scope

This standard describes electrical and mechanical requirements of liquid-immersed, single- and three-phase, step-voltage regulators, not exceeding a regulation of 3000 kVA (for three-phase units) or 1000 kVA (for single-phase units). This standard does not apply to load tap-changing power transformers.

1.2 Purpose

This standard is intended as a basis for the establishment of performance, limited electrical and mechanical interchangeability, and general requirements of equipment described. It also assists in the proper selection of such equipment.

1.3 Word usage

When this standard is used on a mandatory basis, the word *shall* indicates mandatory requirements. The words should or ma*y* refer to matters that are recommended or permitted but not mandatory.

2. Normative references

The following referenced documents are indispensable for the application of this standard (i.e., they must be understood and used; therefore, each referenced document is cited in text and its relationship to this standard is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

Where references to both IEC and IEEE standards are made, users shall specify the standard they require, and equipment shall be manufactured to meet that standard.

IEC 60068-2-1, Environmental testing—Part 2-1: Tests—Test A: Cold.[1]

IEC 60068-2-2, Environmental testing—Part 2-2: Tests—Test B: Dry heat.

IEC 60068-2-30, Environmental testing—Part 2-30: Tests—Test Db: Damp heat, cyclic (12 h + 12 h cycle).

IEC 60214-1, Tap-changers—Part 1: Performance requirements and test methods.

IEC 60255-5, Electrical Relays—Part 5: Insulation coordination for measuring relays and protection equipment—Requirements and tests.

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 60255-22-1, Measuring relays and protection equipment—Part 22-1: Electrical disturbance tests—1 MHz burst immunity tests.

IEC 60255-22-2, Measuring relays and protection equipment—Part 22-2: Electrical disturbance tests—Electrostatic discharge tests.

IEC 60255-22-3, Measuring relays and protection equipment—Part 22-3: Electrical disturbance tests—Radiated electromagnetic field immunity.

IEC 60255-22-4, Measuring relays and protection equipment—Part 22-4: Electrical disturbance tests—Electrical fast transient/burst immunity test.

IEC 60255-22-5, Measuring relays and protection equipment—Part 22-5: Electrical disturbance tests for measuring relays and protection equipment—Surge immunity test.

IEC 60255-22-6, Electrical relays—Part 22-6: Electrical disturbance tests for measuring relays and protection equipment—Immunity to conducted disturbances induced by radio frequency fields.

IEEE Std 4™, IEEE Standard Techniques for High-Voltage Testing.[2, 3]

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[1] IEC publications are available from the Central Office of the International Electrotechnical Commission, 3, rue de Varembé, P.O. Box 131, CH-1211, Geneva 20, Switzerland (http://www.iec.ch/). IEC publications are also available in the United States from the Sales Department, American National Standards Institute, 25 West 43rd Street, 4th Floor, New York, NY 10036, USA (http://www.ansi.org/).

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

IEEE Std C57.98™, IEEE Guide for Transformer Impulse Tests.

IEEE Std C57.131™, IEEE Standard Requirements for Load Tap Changers.

3. Definitions

For the purposes of this document, the following terms and definitions apply. *The IEEE Standards Dictionary: Glossary of Terms & Definitions* should be referenced for terms not defined in this clause.[4]

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

NOTE 1—For self-ventilated equipment, the ambient temperature is the average temperature of the air in the immediate neighborhood of the equipment.[5]

NOTE 2—For air cooled equipment with forced ventilation, the ambient temperature is taken as that of the in-going air.

angular displacement of a three-phase voltage regulator or bank of three single-phase voltage regulators: (**A**) The time angle, expressed in degrees, between the line-to-neutral voltage of the reference source voltage terminal and the line-to-neutral voltage of the corresponding load voltage terminal. (**B**) 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. (**C**) 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 when the voltage regulators are on the neutral tap position. When the voltage regulators are on a tap position other than neutral, the angular displacement will be other than zero degrees. The angular displacement with the voltage regulators connected in delta will be less than ±5° for a ±10% range of regulation.

autotransformer: A transformer in which at least two windings have a common section.

average winding temperature rise of a voltage regulator: The arithmetic difference between the average winding temperature of the hottest winding and the ambient temperature.

common winding: That part of the autotransformer winding that is common to both the primary and secondary circuits. *Syn:* **shunt winding.**

[4] *The IEEE Standards Dictionary: Glossary of Terms & Definitions* is available at http://shop.ieee.org/.
[5] Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

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

dielectric withstand voltage tests: Tests made to determine the ability of insulating materials and spacings to withstand specified overvoltages for a specified time without flashover or puncture.

NOTE—The purpose of the tests is to determine the adequacy against breakdown of insulating materials and spacings under normal or transient conditions.

excitation current: The current that flows in any winding used to excite the voltage regulator when all other windings are open-circuited. It is usually expressed in percent of the rated current of the voltage regulator.

impedance drop: The phasor sum of the resistance voltage drop and the reactance voltage drop.

NOTE—For voltage regulators, the resistance drop, the reactance drop, and the impedance drop are, respectively, the sum of the primary and secondary drops reduced to the same terms. They are determined from the load-loss measurements and are usually expressed in per unit or percent of the rated voltage of the voltage regulator. Since they differ at different operating positions of the voltage regulator, two values of impedance shall be considered, in practice, to be the tap positions that result in the minimum and the maximum impedance. Neutral position has the minimum amount of impedance.

impedance voltage of a voltage regulator: The voltage required to circulate rated current through one winding of the voltage regulator when another winding is short-circuited, with the respective windings connected as for a rated voltage operation.

NOTE—Impedance voltage is usually referred to the *series winding,* and then that voltage is expressed in per unit, or percent, of the rated voltage of the voltage regulator.

line-drop compensator: A device that causes the voltage regulating device to vary the output voltage by an amount that compensates for the impedance voltage drop in the circuit between the voltage regulator and a predetermined location on the circuit (sometimes referred to as the *load center*).

liquid: Refers to synthetic fluid, natural ester-based fluid, and mineral oil.

NOTE—Some synthetic fluids may be unsuitable for use in the arcing environment of a step-voltage regulator.

liquid-immersed self-cooled (Class KNAN): A voltage regulator having its core and coil immersed in a liquid with fire point > 300 °C and cooled by the natural circulation of air over the cooling surfaces.

liquid-immersed self-cooled (Class ONAN): A voltage regulator having its core and coil immersed in a liquid with fire point ≤ 300 °C and cooled by the natural circulation of air over the cooling surfaces.

liquid-immersed self-cooled/forced-air-cooled (Classes KNAN/KNAF and KNAN/KNAF/KNAF): A voltage regulator having its core and coils immersed in liquid with fire point > 300 °C and having a self-cooled rating with cooling obtained by the natural circulation of air over the cooling surface and a forced-air-cooled rating with cooling obtained by the forced circulation of air over this same cooling surface.

liquid-immersed self-cooled/forced-air-cooled (Classes ONAN/ONAF and ONAN/ONAF/ONAF): A voltage regulator having its core and coils immersed in liquid with fire point ≤ 300 °C and having a self-cooled rating with cooling obtained by the natural circulation of air over the cooling surface and a forced-air-cooled rating with cooling obtained by the forced circulation of air over this same cooling surface.

liquid-immersed self-cooled/forced-air-cooled/forced-liquid-cooled (Class KNAN/KNAF/KFAF): A voltage regulator having its core and coils immersed in liquid with fire point > 300 °C and having a self-cooled rating with cooling obtained by the natural circulation of air over the cooling surface; a forced-air-cooled rating with cooling obtained by the forced circulation of air over this same air cooling surface; and a forced-liquid-cooled rating with cooling obtained by the forced circulation of liquid over the core and coils and adjacent to this same cooling surface over which the cooling air is being forced-circulated.

liquid-immersed self-cooled/forced-air-cooled/forced-liquid-cooled (Class ONAN/ONAF/OFAF): A voltage regulator having its core and coils immersed in liquid with fire point ≤ 300 °C and having a self-cooled rating with cooling obtained by the natural circulation of air over the cooling surface; a forced-air-cooled rating with cooling obtained by the forced circulation of air over this same air cooling surface; and a forced-liquid-cooled rating with cooling obtained by the forced circulation of liquid over the core and coils and adjacent to this same cooling surface over which the cooling air is being forced-circulated.

liquid-immersed voltage regulator: A voltage regulator in which the core and coils are immersed in an insulating liquid.

liquid-immersed water-cooled (Class KNWF): A voltage regulator having its core and coils immersed in a liquid with fire point > 300 °C and cooled by the natural circulation of the liquid over the water-cooled surface.

liquid-immersed water-cooled (Class ONWF): A voltage regulator having its core and coils immersed in a liquid with fire point ≤ 300 °C and cooled by the natural circulation of the liquid over the water-cooled surface.

liquid-immersed water-cooled/self-cooled (Class KNWF/KNAN): A voltage regulator having its core and coils immersed in liquid with fire point > 300 °C and having a water-cooled rating with cooling obtained by the natural circulation of liquid over the water-cooled surface, and a self-cooled rating with cooling obtained by the natural circulation of air over the air-cooled surface.

liquid-immersed water-cooled/self-cooled (Class ONWF/ONAN): A voltage regulator having its core and coils immersed in liquid with fire point ≤ 300 °C and having a water-cooled rating with cooling obtained by the natural circulation of liquid over the water-cooled surface, and a self-cooled rating with cooling obtained by the natural circulation of air over the air-cooled surface.

load losses: Those losses that are incident to the carrying of a specified load. Load losses include I^2R loss in the current carrying parts (windings, leads, busbars, bushings), eddy losses 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.

load tap changer: A selector switch device, which may include current interrupting contactors, used to change voltage regulator taps with the voltage regulator energized and carrying full load.

no-load (excitation) losses: Those losses that are incident to the excitation of the voltage regulator. No-load (excitation) losses include core loss, dielectric loss, conductor loss in the winding due to exciting current, and conductor loss due to circulating current in parallel windings. These losses change with the excitation voltage.

nominal system voltage: A nominal value assigned to a system or circuit of a given voltage for the purpose of convenient designation. 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 by which the system is designated and to which certain operating characteristics of the system are related. (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.)

platform mounted voltage regulator: A line voltage regulator that is designed for mounting on a platform and has a maximum weight limitation. This step-voltage regulator controls the voltage on the main feeder out of the substation or on laterals off of the main feeder. It is commonly referred to as a *distribution voltage regulator.*

polarity of a voltage regulator: (**A**) The polarity of a voltage regulator is intrinsic in its design. Polarity is correct if the voltage regulator boosts the voltage in the "raise" range and bucks the voltage in the "lower" range. The relative polarity of the shunt winding and the series windings of a step-voltage regulator will differ in the boost and buck modes between Type A and Type B voltage regulators. (**B**) The relative instantaneous polarity of the voltage regulator windings, instrument transformer(s), and utility winding(s), as applicable, will be designated by an appropriate polarity mark on the diagram of connection on the nameplate.

NOTE—The diagram of connection for **(B)** is in accordance with 6.3.

pole-type voltage regulator: A line voltage regulator that is designed for mounting on a pole and has a maximum weight limitation. This step-voltage regulator controls the voltage on the main feeder out of the substation or on laterals off of the main feeder. It is commonly referred to as a *distribution voltage regulator.*

primary circuit of a voltage regulator: The circuit on the input side of the voltage regulator.

rated range of regulation of a voltage regulator: The amount that the voltage regulator will raise or lower its rated voltage. The rated range may be expressed in per unit, or in percent, of rated voltage, or it may be expressed in kilovolts.

rated voltage: The voltage to which operating and performance characteristics of apparatus and equipment are referred.

rated voltage of a step-voltage regulator: The voltage selected for the basis of performance specifications of a voltage regulator.

rated voltage of a winding: The voltage to which operating and performance characteristics are referred.

rated voltage of the series winding of a step-voltage regulator: The voltage between terminals of the series winding, with rated voltage applied to the voltage regulator, when the voltage regulator is in the position that results in maximum voltage change and is delivering rated output at 80% lagging power factor.

rating in kVA of a voltage regulator: (**A**) The rating that is the product of the rated load amperes and the rated "raise" or "lower" range of regulation in kilovolts (kV). If the rated raise and lower range of regulation are unequal, the larger shall be used in determining the rating in kVA. (**B**) The rating in kVA of a three-phase voltage regulator is the product of the rated load amperes and the rated range of regulation in kilovolts multiplied by square root of 3.

reactance drop: The component of the impedance voltage drop in quadrature with the current.

reactor: An electromagnetic device, the primary purpose of which is to introduce inductive reactance into a circuit.

regulated circuit of a voltage regulator: The circuit on the output side of the voltage regulator, and in which it is desired to control the voltage.

NOTE—The voltage may be held constant at any selected point on the regulated circuit.

resistance drop: The component of the impedance voltage drop in phase with the current.

resistance method of temperature determination: The determination of the temperature by comparison of the resistance of a winding at the temperature to be determined, with the resistance at a known temperature.

series transformer: A transformer with a "series" winding and an "exciting" 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 input received from the exciting winding.

series winding: That portion of the autotransformer winding that is not common to both the primary and secondary circuits, but is connected in series between the input and output circuits.

shunt winding: *See:* **common winding.**

station-type voltage regulator: A voltage regulator designed for ground-type installations in substations. This voltage regulator is used for bus or individual feeder regulation. It is commonly referred to as a *substation voltage regulator.*

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

tap: A connection brought out of a winding at some point between its extremities, to permit changing the voltage, or current, ratio.

thermometer method of temperature determination: The determination of the temperature by thermocouple or suitable thermometer, with either being applied to the hottest accessible part of the equipment.

total losses of a regulator: The sum of the no-load and load losses, excluding losses due to accessories.

Type A step-voltage regulator: A step-voltage regulator in which the primary circuit is connected directly to the shunt winding of the voltage regulator. It is sometimes referred to as a *straight* design in the industry. The series winding is connected to the shunt winding and, in turn, via taps, to the regulated circuit. In a Type A step-voltage regulator, the core excitation varies because the shunt winding is connected across the unregulated primary circuit. The maximum range of regulation on the *raise* side equals the maximum range of regulation of the *lower* side with 10% being the nominal amount of regulation for the preferred kVA ratings.

NOTE—See Figure 1.

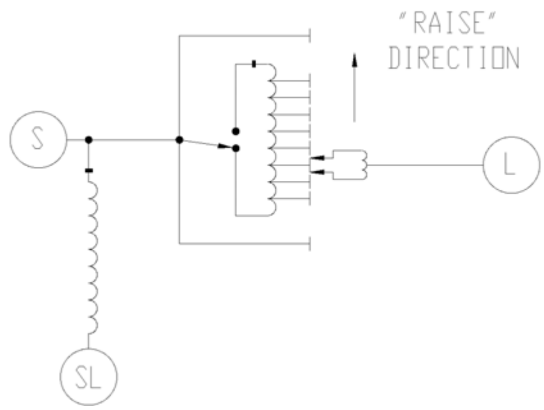


Figure 1—Schematic diagram of single-phase, Type A, step-voltage regulator

Type B step-voltage regulator: A step-voltage regulator in which the primary circuit is connected, via taps, to the series winding of the voltage regulator. It is sometimes referred to as an *inverted* design in the industry. The series winding is connected to the shunt winding, which is connected directly to the regulated circuit. In a Type B step-voltage regulator, the core excitation is constant because the shunt winding is connected across the regulated circuit. The maximum range of regulation of the *raise* side is higher than the maximum range of regulation of the *lower* side with 10% being the nominal amount of regulation of the raise side for the preferred kVA ratings.

NOTE—See Figure 2.

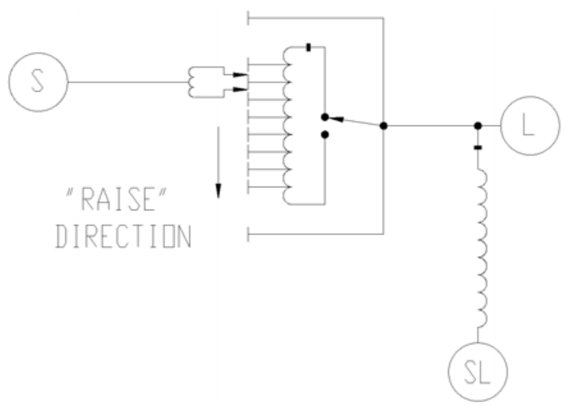


Figure 2—Schematic diagram of single-phase, Type B, step-voltage regulator

utility winding: That part of a voltage regulator coil that provides a voltage supply for the tap changer motor and/or the control, for a cooling fan or for a user's specified requirement.

voltage regulating device: A voltage sensitive device that is used on an automatically operated voltage regulator to control the voltage of the regulated circuit.

voltage supply ratio: The ratio of the regulated line voltage to the control supply voltage.

4. Service conditions

4.1 Usual service conditions

4.1.1 General

Voltage regulators conforming to this standard shall be suitable for operation at rated kilovoltamperes under the usual service conditions given in 4.1.2 through 4.1.7.

4.1.2 Temperature

4.1.2.1 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 does not exceed 30 °C.

4.1.2.2 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.

4.1.2.3 Cooling water temperature limit

When water-cooled, the temperature of the cooling water (ambient temperature) does not exceed 30 °C, and the average temperature of the cooling water for any 24 h period shall not exceed 25 °C. Minimum water temperature shall not be lower than 1 °C, unless the cooling water includes antifreeze suitable for -20 °C operation.

4.1.3 Altitude

The altitude shall not exceed 1000 m (3300 ft).

4.1.4 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.

4.1.5 Load current

The load current shall be approximately sinusoidal. The harmonic factor shall not exceed 0.05 per unit.

4.1.6 Outdoor operation

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

4.1.7 Tank or enclosure finish

Temperature limits and tests shall be based on the use of a nonmetallic pigment surface paint finish. It should be noted that metallic-flake paints, such as aluminum and zinc, have properties that increase 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.[6]

4.2 Loading at other than rated conditions

IEEE Std C57.91 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 that results in reduced life expectancy

NOTE—IEEE Std C57.91 is a guide rather than a standard. It provides the best known general information for the loading of voltage regulators under various conditions based on typical winding insulation systems, and is based upon the best engineering information available at the time of preparation. The guide discusses limitations of ancillary components other than windings that may limit the capability of voltage regulators. When specified, ancillary components and other construction features (cables, bushings, tap changers, liquid expansion space, etc.) shall be supplied such that they in themselves will not limit the loading to less than the capability of the windings.

4.3 Unusual service conditions

Conditions other than those described in 4.1 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 4.3.1 through 4.3.3.

4.3.1 Unusual temperature and altitude conditions

Voltage regulators may be used at higher or lower ambient temperatures or at higher altitudes than specified in 4.1, but special consideration should be given to these applications. Annex A and IEEE Std C57.91 provide information on recommended practices.

4.3.2 Insulation at high altitude

The dielectric strength of voltage regulators that depends in whole or in part upon air for insulation 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 1000 m (3300 ft).

4.3.2.1 Insulation level

The minimum insulation necessary at the required altitude can be obtained by dividing the standard insulation level at 1000 m (3300 ft) by the appropriate correction factor from Table 1.

[6] Information on references can be found in Clause 2.

Table 1—Dielectric strength correction factors for altitudes greater than 1000 m (3300 ft)

Altitude		Altitude correction factor for dielectric strength
(m)	(ft)	
1000	3300	1.00
1200	4000	0.98
1500	5000	0.95
1800	6000	0.92
2100	7000	0.89
2400	8000	0.86
2700	9000	0.83
3000	10 000	0.80
3600	12 000	0.75
4200	14 000	0.70
4500	15 000	0.67

NOTE—An altitude of 4500 m (15 000 ft) is considered a maximum for voltage regulators conforming to this standard.

4.3.2.2 Bushings

Bushings with additional length or creep distance shall be furnished where necessary for operation above 1000 m (3300 ft).

4.3.3 Other unusual service conditions

Other unusual service conditions include the following:

a) Damaging fumes or vapors, 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 that may result where appreciable load currents are controlled by solid-state or similar devices. Such harmonic currents may cause excessive losses, excessive 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 as usual in 5.9.1.

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

n) Unusually strong magnetic fields. It should be noted that solar magnetic disturbances might result in the flow of telluric currents in voltage regulator neutrals.

o) Parallel operation. It should be noted that while parallel operation is not unusual, it is desirable that users advise the manufacturer if paralleling with other voltage regulators is planned, and the characteristics of the transformers or reactors so involved.

4.3.3.1 Control

The control, depending on its construction, may be sensitive to altitude considerations. The manufacturer should be consulted where applications exceed 2000 m (6600 ft). The control shall withstand an altitude of up to 3000 m (10 000 ft) without loss of control.

4.4 Frequency

Step-voltage regulators shall be designed for operation at a frequency of 60 Hz or 50 Hz as specified.

5. Rating data

5.1 Cooling classes of voltage regulators

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 5.1.1 through 5.1.4.

5.1.1 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).

5.1.2 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 KNAN).

b) Liquid-immersed self-cooled/forced-air-cooled (Class KNAN/KNAF).

5.1.3 Liquid-immersed (fire point ≤ 300 °C) water-cooled

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

a) Liquid-immersed water-cooled (Class ONWF).

b) Liquid-immersed water-cooled/self-cooled (Class ONWF/ONAN).

5.1.4 Liquid-immersed (fire point > 300 °C) water-cooled

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

a) Liquid-immersed water-cooled (Class KNWF).

b) Liquid-immersed water-cooled/self-cooled (Class KNWF/KNAN).

5.2 Ratings

Ratings for step-voltage regulators are continuous and based on not exceeding the temperature limits covered in Table 3. Other winding rises may be recognized for unusual ambient conditions specified.

Ratings covered by this standard shall be expressed in the terms given in 5.2.1 and as specified in 5.2.2.

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	55	65
	65 °C rise liquid immersed	65	80
(2)	Metallic parts in contact with current-carrying conductor insulation shall not attain a temperature rise in excess of the winding hottest-spot temperature rise.		
(3)	Metallic parts other than those described in item (2) shall not attain excessive temperature rises at maximum rated load.		
(4)	The temperature rise of the insulating fluid shall not exceed 55 °C (55 °C rise unit) or 65 °C (65 °C rise unit) when measured near the surface of the fluid.		

[a] Apparatus with specified temperature rise shall have an insulation system that has been proven by experience, general acceptance, or an accepted test.

5.2.1 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.

5.2.2 Preferred ratings

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

Table 3—Preferred ratings for liquid-immersed 60 Hz step-voltage regulators (single phase)

Nominal system voltage	BIL (kV)	kVA	Line amperes
2400/4160Y	60	50	200
		75	300
		100	400
		125	500
		167	668
		250	1000
		333	1332
		416	1665
4800/8320Y	75	50	100
		75	150
		100	200
		125	250
		167	334
		250	500
		333	668
		416	833
7620/13 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	1093
		1000	1312
13 800	95	69	50
		138	100
		207	150
		276	200
		414	300
		552	400
		667	483
		833	604
		1000	725
14 400/24 940Y	150	72	50
		144	100
		288	200
		333	231
		432	300
		576	400
		667	463
		833	578
		1000	694
19 920/34 500Y	150	100	50
		200	100
		333	167
		400	201
		667	334
		833	418
		1000	502
34 500	200	173	50
		345	100
		518	150
		690	200

Table 4—Preferred ratings for liquid-immersed 50 Hz step-voltage regulators (single phase)

Nominal system voltage	BIL (kV)	kVA	Line amperes
6600/11430Y	95	33	50
		66	100
		99	150
		132	200
		198	300
		264	400
		330	500
		396	600
		462	700
		528	800
11000	95	55	50
		110	100
		165	150
		220	200
		330	300
		440	400
		550	500
		660	600
		770	700
		880	800
15000/25980Y	150	75	50
		150	100
		225	150
		300	200
		450	300
		600	400
		750	500
		900	600
22000	150	110	50
		220	100
		330	150
		440	200
		660	300
		880	400
33000	170	165	50
		330	100
		495	150
		660	200

Table 5—Preferred ratings for liquid-immersed 60 Hz step-voltage regulators (three phase)

Nominal system voltage	BIL (kV)	Self-cooled		Self-cooled/forced-cooled	
		kVA	Line amperes	kVA	Line amperes
2400/4160Y	60	500	667	625	833
		750	1000	937	1250
		1000	1334	1250	1667
4800	60	500	577	625	721
		750	866	937	1082
		1000	1155	1250	1443
7620/13 200Y	95	500	219	625	274
		750	328	937	410
		1000	437	1250	546
		1500	656	2000	874
		2000	874	2667	1166
		2500	1093	3333	1458
		3000	1312	4000	1750
7970/13 800Y	95	500	209	625	261
		750	313	937	391
		1000	418	1250	523
		1500	628	2000	837
		2000	837	2667	1116
		2500	1046	3333	1394
		3000	1255	4000	1673
14 400/24 940Y	150	500	125.5	625	156.8
		750	188.3	937	235.4
		1000	251	1250	314
		1500	377	2000	502
		2000	502	2667	669
		2500	628	3333	837
		3000	694	4000	926
19 920/34 500Y	150	500	84	625	105
		750	125.5	937	156.8
		1000	167	1250	209
		1500	251	2000	335
		2000	335	2667	446
		2500	418	3333	557
		3000	502	4000	669

Table 6—Preferred ratings for liquid-immersed 50 Hz step-voltage regulators (three phase)

Nominal system voltage	BIL (kV)	Self-cooled		Self-cooled/forced-cooled	
		kVA	Line amperes	kVA	Line amperes
6600/11430Y	95	500	253	625	316
		750	379	937	474
		1000	505	1250	631
		1500	758	2000	1010
11000	95	500	262	625	328
		750	394	937	492
		1000	525	1250	656
		1500	787	2000	1050
15000/25980Y	150	500	111	625	139
		750	167	937	208
		1000	222	1250	278
		1500	333	2000	444
		2000	444	2667	593
		2500	556	3333	741
22000	150	500	131	625	164
		750	197	937	246
		1000	262	1250	328
		1500	394	2000	525
33000	170	500	87	625	189
		750	131	937	164
		1000	175	1250	219

5.2.3 Supplementary voltage ratings

In addition to their rated voltage, as defined in 5.2.2, 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 multitapped 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 for 60 Hz voltage regulators

Number of phases	Rated voltage	Operating voltage
Single phase	7620	7200
	4330	4160
Three phase	5000	4800
	8660	8320
	13 200	12 470
	13 800	13 200

5.3 Supplementary continuous-current ratings

Single-phase step-voltage regulators 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 for single-phase voltage regulators

Range of voltage regulation (%)	Continuous-current rating (%)
10.00	100
8.75	110
7.50	120
6.25	135
5.00	160

Three-phase step-voltage regulators rated up to 13.8 kV, inclusive, and rated 668 A and below shall have supplementary continuous-current ratings on intermediate ranges of steps as shown in Table 9. Maximum continuous current shall be 668 A.

Table 9—Supplementary continuous-current ratings for three-phase voltage regulators

Range of voltage regulation (%)	Continuous-current rating (%)
10.00	100
8.75	108
7.50	115
6.25	120
5.00	130

5.4 Taps

Load tap changing equipment shall be furnished to provide approximately ±10 % automatic adjustment of the unregulated supply on the source side of the voltage regulator. This is to be done in approximately 0.625 percent steps, with sixteen steps above and sixteen steps below rated voltage.

5.5 Operating voltage limits

Voltage regulators, including their controls, shall be suitable for operation within the following limits of voltage provided that the rated load current is not exceeded:

a) A minimum input voltage of 97.75 V times the ratio of voltage transformer.

b) A maximum input voltage at rated load amperes of 1.05 times the rated input voltage of the voltage regulator or 137.5 V times the ratio of voltage transformer, whichever is less.

c) A maximum input voltage at no load of 1.10 times the rated input voltage of the voltage regulator or 137.5 V times the ratio of voltage transformer, whichever is less.

d) A minimum output voltage of 103.5 V times the ratio of voltage transformer.

e) A maximum output voltage of 1.10 times the rated voltage of the voltage regulator or 137.5 V times the ratio of voltage transformer, whichever is less.

f) The output voltage obtainable with a given input voltage is limited also by the voltage regulator voltage range.

Typical examples of the application of these rules to some common ratings of voltage regulators are given in Table 10.

Table 10 —Typical examples of operating voltage limits including all operating voltage tolerances

Nominal system voltage	Regulator voltage rating (V)		Voltage supply ratio[a]	Input voltage (V)			Output voltage (V)	
	Single phase	Three phase		Minimum	Maximum at rated-load amperes	Maximum at no-load	Minimum	Maximum at rated-load amperes or at no-load
2400	2500	—	20	1955	2625	2750	2070	2750
2400/4160Y	2500	—	20	1955	2625	2750	2070	2750
2400/4160Y	—	4330	34.6	3380	4550	4760	3580	4760
4800	5000	5000	40	3910	5250	5500	4140	5500
7200	7620	—	60	5870	8000	8250	6210	8250
7200	—	8660	60	5870	8250	8250	6210	8250
4800/8320Y	5000	—	40	3910	5250	5500	4140	5500
8320	—	8660	69.3	6775	9090	9525	7170	9525
11000	11000	—	91.7	8960	11 550	12 100	9490	12 100
6600/11 430Y	6600	—	55	5380	6930	7260	5690	7260
12 470	13 800	13 800	104	10 170	14 300	14 300	10 760	14 300
7200/12 470Y	7620	—	60	5870	8000	8250	6210	8250
7200/12 470Y	—	13 800	104	10 170	14 300	14 300	10 760	14 300
7620/13 200Y	7620	—	63.5	6210	8000	8380	6570	8380
7620/13 200Y	7620	—	66.3	6480	8000	8380	6860	8380
7620/13 200Y	—	13 200	110	10 750	13 860	14 520	11 400	14 520
7970/13 800Y	—	13 800	115	11 240	14 490	15 180	11 900	15 180
7970/13 800Y	7970	—	66.3	6480	8360	8760	6860	8760
13 200	13 800	13 800	110	10 750	14 490	15 125	11 400	15 125
14 400	13 800	13 800	120	11 730	14 490	15 180	12 420	15 180
22 000	22 000	—	183.3	17 920	23 100	24 200	18 975	24 200
14 400/24 940Y	14 400	—	120	11 730	15 120	15 840	12 420	15 840
15 000/25 980Y	15 000	—	120	11 730	15 750	16 500	12 420	16 500
19 920/34 500Y	19 920	—	166	16 230	20 920	21 910	17 180	21 910
14 400/24 940Y	—	24 940	208	20 330	26 190	27 435	21 530	27 435
33 000	33 000	—	275	26 880	34 650	36 300	28 460	36 300
19 920/34 500Y	—	34 500	287.5	28 100	36 225	37 950	29 760	37 950
34 500	34 500	—	287.5	28 100	36 225	37 950	29 760	37 950

NOTE—Example values are derived using procedures of 5.5.

[a]Where the listed voltage ratio is provided, an ancillary transformer may be required.

5.6 Voltage supply ratios

Values of voltage supply ratios are given in Table 11. When a voltage supply ratio is specified that is not a preferred value shown in Table 11, an ancillary transformer may be furnished in the unit or control to modify the preferred ratio.

Table 11 —Values of voltage supply ratios

Voltage regulator rating (V)		Values of voltage supply ratios
Single phase	Three phase	
2500		20, 20.8
	4330	34.6, 36.1
5000	5000	40, 41.7
6600		55
7620		60, 63.5
7970		66.4
	8660	69.3, 72.2
11 000		91.7
	13 200	110, 104
13 800	13 800	115, 110
14 400		120
15 000		120
19 920		166
22 000		183.3
	24 940	208
33 000		275
34 500	34 500	287.5

5.7 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 12.

NOTE—When single-phase voltage regulators are connected in wye, the neutral of the voltage regulator bank shall be connected to the neutral of the system. A closed or open delta connection of the voltage regulators is recommended when the system is three-wire ungrounded.

Table 12 —Interrelationships of dielectric insulation levels for voltage regulators used on systems with BIL ratings of 200 kV and below

BIL kV	Applied-voltage insulation level (kV rms)	Impulse levels		
		Full wave	Chopped wave	
		(kV crest)	(kV crest)	Min 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

5.8 Losses

The losses specified by the manufacturer shall be the *no-load (excitation) losses* and *total losses of a regulator,* as defined in Clause 3.

5.8.1 Total losses

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

5.8.2 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 losses of a voltage regulator shall not exceed the specified no-load losses by more than 10%, and the total losses of a voltage regulator shall not exceed the specified total losses 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 will differ at different operating positions of the voltage regulator, care must be exercised in the consideration of tap position with losses. Some styles of step-voltage regulators will exhibit appreciable change in load loss when boosting versus bucking, or will exhibit appreciable change in no-load loss on alternate tap positions. See 5.8.3.

5.8.3 Determination of losses and excitation current

No-load (excitation) losses and exciting 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 losses 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 and load losses where:

a) No-load loss is the average of no-load loss in the neutral and next adjacent boost position with rated voltage applied to the shunt or series winding for voltage regulators that do not include a series transformer.

NOTE—It will be apparent, in the case of a Type B step-voltage regulator that is on the next adjacent boost position, that the excitation voltage applied at the source terminal will be higher at the shunt winding. Care must be exercised to assure that rated excitation is present on the shunt winding; this may be accomplished by exciting the voltage regulator from the load terminal.

b) No-load loss is reported for neutral position, maximum boost position, and position adjacent-to-maximum boost position for voltage regulators that include a series transformer.

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.

5.9 Short-circuit requirements

5.9.1 General

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

a) The first-cycle asymmetrical peak current that the voltage regulator is required to withstand shall be determined as shown in Equation (1) and Table 13.

$$ISC(\text{pk asym}) = KISC(\text{rms sym}) \quad (1)$$

Table 13 —Values of K

Base rated kVA	K	
	60 Hz	50 Hz
< 165 (single phase)	2.26 [a]	2.19 [a]
≥ 165 (single phase) ≥ 500 (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 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 and 50 Hz, respectively, which are common for substation circuits.

b) The short-circuit current shall be assumed to be a duration of 2 s to determine the thermal stresses.

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 load tap changers that carry current continuously shall comply with all the requirements of 5.9.1. 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 user, where 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 1—Larger kVA sizes for the same voltage rating should be considered if the available fault current exceeds the 25 times base rated current.

NOTE 2—User may specify a larger short-circuit withstand value due to unique system parameters. An example as such is a short-circuit withstand of 40 times the base rated load current or 20 000 A whichever is less. Application, limitations, design, and resulting cost are to be agreed upon by the user and the manufacturer.

5.9.2 Mechanical capability demonstration

It is not the intent of this subclause that every voltage regulator design is short-circuit tested to demonstrate adequate construction. When specified, tests of short-circuit mechanical capability shall be performed as described in 8.8.

5.9.3 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 conditions specified in 5.9.1, as calculated by methods described in 8.9.4, shall not exceed 250 °C for a copper conductor or 200 °C for an electrical conductor (EC) aluminum. A maximum temperature of 250 °C shall be allowed for aluminum alloys that have resistance to annealing properties at 250 °C, equivalent to EC aluminum at 200 °C, or for application of EC aluminum 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 fluid or solid insulation

b) Conductor annealing

c) Insulation aging

5.10 Tests

Tests are divided into two categories: routine and design. Routine tests are made for quality control by the manufacturer to verify during production that the product meets the design specifications. Design 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 condition or under special conditions if specified, and compliance with appropriate standards of the industry.

5.10.1 Routine tests

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

a) Resistance measurements of all windings (see 8.1)

b) Ratio test on all tap connections (see 8.2)

c) Polarity test (see 8.3)

d) Operational test of all devices. Controlled devices such as load tap changers, position indicators, fans, pumps, etc., shall be operated for proper functioning.

e) Leak test

f) No-load (excitation) loss at rated voltage and rated frequency (see 8.4)

g) Excitation current at rated voltage and rated frequency (see 8.4)

h) Impedance and load loss at rated current and rated frequency (see 8.5)

i) Lightning impulse test (see 8.6.3)

j) Applied-voltage test (see 8.6.5)

k) Induced-voltage test (see 8.6.6)

l) Insulation power factor test (see 8.6.7)

m) Insulation resistance test (see 8.6.8)

5.10.2 Design tests

The design tests described in 5.10.2.1 through 5.10.2.3 *shall* be made on representative voltage regulators to substantiate the ratings assigned to all other voltage regulators of basically the same design. Design tests are not intended to be used as a part of normal production. The applicable portion of these design tests *may* also be used to evaluate modifications of a previous design and to assure that performance has not been adversely affected. Test data from previous similar designs *may* be used for current designs, where appropriate. Once made, the tests need not be repeated unless the design is changed to modify performance.

5.10.2.1 Thermal tests

Temperature-rise design tests shall be made 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. Temperature tests shall be made at the tap position that produces the highest total loss at rated load current for the highest operating voltage per nameplate, supplementary voltage rating (see 5.2.3), and the 160% or 668 A rating (see 5.3). When a voltage regulator is supplied with ancillary cooling equipment to provide higher kVA ratings, temperature tests shall be made at those ratings also. Tests shall be made in accordance with 8.7.

When specifications state that a thermal test may be omitted if there are 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 comply with performance guarantees established by standards or specifications.

5.10.2.2 Lightning impulse tests

Design lightning impulse tests shall be made on one unit of a given rating produced by a manufacturer for the purpose of demonstrating the adequacy of insulating materials breakdown and spacing under normal conditions. Tests shall be made in accordance with 8.6.2. Impulse tests are to be followed by the application of the low-frequency applied-voltage and induced-voltage tests.

5.10.2.3 Short-circuit tests

Short-circuit tests shall be made on one unit of a rating produced by a manufacturer for the purpose of demonstrating that the unit meets the mechanical requirements of 5.9.2. Where other ratings have the same design configuration, core and coil framing, and clamping as the unit tested, short-circuit tests are not required, and it is adequate to show by calculation that the mechanical forces are equal or less than the unit tested. Tests are to be made in accordance with 8.8.

6. Construction

6.1 Bushings

Voltage regulators shall be equipped with bushings with an insulation level not less than that of 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 color of the bushings shall match 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 (kV)

Regulator 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 (7000 Ω·in) and precipitation rate of 0.085 mm/s (0.2 in/min).

6.2 Terminal markings

6.2.1 Terminal markings for step-voltage regulators

Voltage regulator terminals that are connected to the load shall be designated by an *L*, and those that are connected to the 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 3.

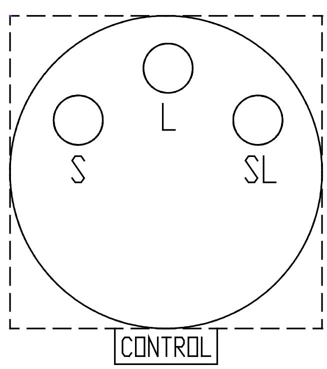


Figure 3—Single-phase voltage regulators

For three-phase voltage regulators, when facing the voltage regulator on the source side, 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 4(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 4(b). The other terminals shall be located as shown in Figure 4.

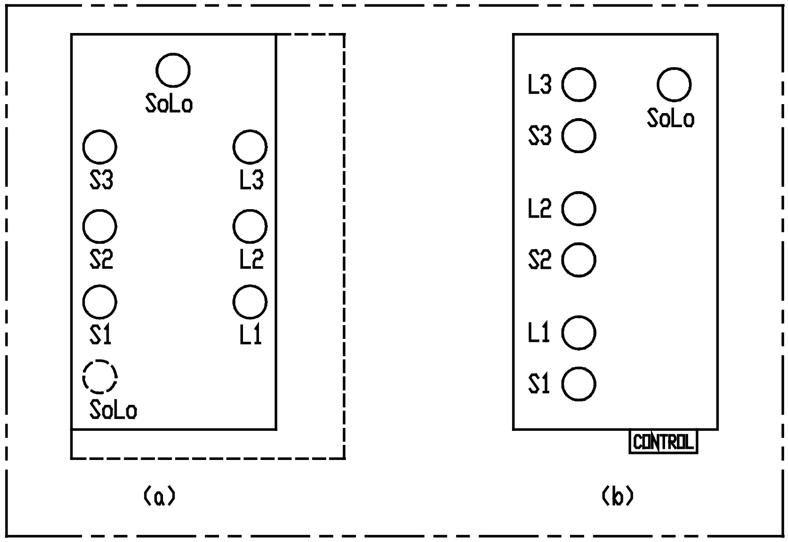


Figure 4—Three-phase voltage regulators

NOTE—The dotted line in Figure 4 shows the location of the control compartment and the tap changing under load equipment. The dotted circle shows alternate location of neutral bushing.

6.3 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 tap changer shall be indicated on the nameplate.

6.4 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 cabinet. 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 as follows:

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 fluid type
r) Volume of insulating fluid
s) Conductor material
t) Average winding rise in degrees Celsius (°C)
u) Diagrams as specified in 6.3
v) Installation and operating instructions reference
w) Symmetrical short-circuit withstand ampere rating with time duration
x) Tap changer model
y) Ratio of load current to switched current (if series transformer is present)

6.5 Tank construction

Voltage regulators shall have a sealed-tank fluid-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 6.5.1, shall be provided to relieve excess pressure due to normal temperature variation of top oil and/or due to tap changer operation. The voltage regulator shall remain effectively sealed for a top fluid 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 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 fluid.

6.5.1 Pressure-relief valve

The replaceable pressure-relief valve shall be located on the tank above the 110 °C top fluid level, as determined by the manufacturer's calculation. The valve shall be located so that 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 device.

Exposed parts shall be of weather- and corrosion-resistant materials. Gaskets and O-rings shall withstand fluid vapor at 110 °C continuously and under operating conditions as described in IEEE Std C57.91, 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 (gage) (2 psig).

b) Resealing pressure = 6.9 kPa (gage) (1 psig) minimum.

c) Zero leakage from reseal pressure to –56 kPa (gage) (–8 psig).

d) Flow at 103 kPa (gage) (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.

6.5.2 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.

6.5.3 Support lugs

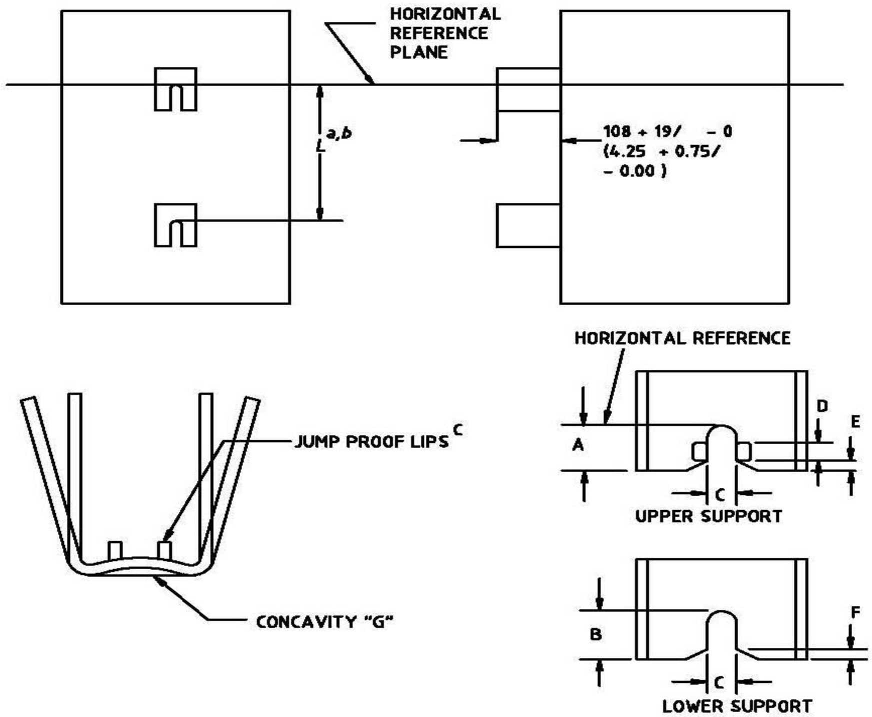
Support lugs for pole mounting shall be provided for ratings 288 kVA and less, with rated line current of 328 A or less. Support lugs shall be designed to provide a safety factor of five when supported in a vertical plane from the top lug only. The safety factor of five shall be as defined for lifting lugs in 6.5.2. Interchangeable mounting to the maximum extent is accomplished by use of Type-B and Type-C support lugs designed in accordance with Figure 5 and Figure 6, 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 comes from IEEE Std C57.12.20™ [B14].[a] Due 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 user is advised to ensure that the pole is suitable for the weight specified on the regulator’s nameplate.

NOTE 3—Some ratings as a standard, depending on manufacturer, will have a substation base along with the support lugs for pole mounting. The substation base must not interfere with the mounting of the voltage regulator to the pole.

[a] The numbers in brackets correspond to those of the bibliography in Annex C.



DIMENSIONS [d]	SUPPORT lug B [e] mm (in)
A	44.5 (1.75)
B	63.5 (2.50)
C [f]	20.2 (0.80)
D	15.9 (0.63)
E	6.4 (0.25)
F	12.7 (0.50)
G	6.4 (0.25)

NOTE—Unless otherwise noted, all dimensions will have a tolerance of ±2 mm (0.063 in). All dimensions are given in millimeters. Dimensions in parentheses are given in inches.

[a] "L" dimension is 590 mm (23.25 in) or 895 mm (35.25 in) depending on the tank height.

[b] Slots "L" dimension is spaced 20 mm (0.75 in) less than pole bolt spacing.

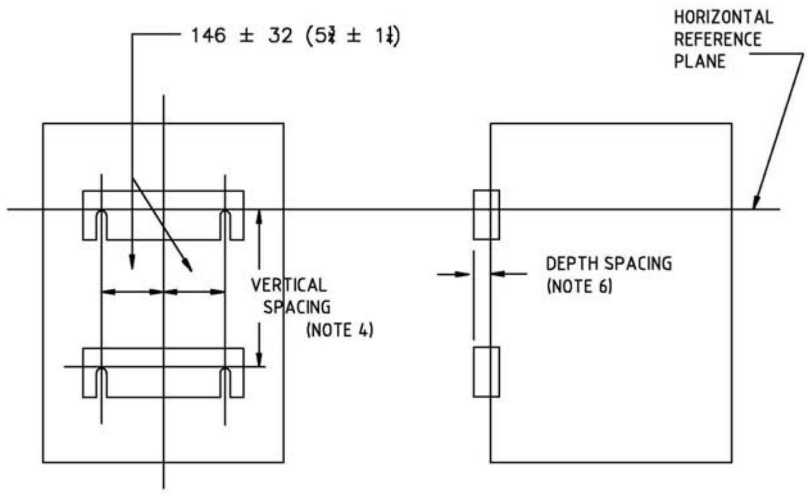
[c] Jump-proof lips on upper support only.

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

[e] "B" lugs to use 20 mm (0.75 in) bolts.

[f] Tolerance for slot dimension "C" shall be ±0.4 mm (±0.016 in).

Figure 5—Support lugs B



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

NOTE 2—Slots can be vertical as well as horizontal and shall be suitable for 16 mm (0.625 in) bolts. Dimension of spacing is given in millimeters. Dimension in parentheses is given in inches.

NOTE 3—Support lug faces shall be in one plane.

NOTE 4—Vertical spacing shall be 914 mm (36 in).

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

NOTE 6—Depth of support lugs is dependent on a manufacturers design. Bushing profiles on top of cover must 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 6—Support lugs C

6.5.4 Moving facilities

Substation voltage regulators shall be arranged for rolling in two directions: parallel to and right angles to one side of the voltage regulator. Bases for substation mounting shall be provided for 165 kVA and higher.

6.5.5 Tank grounding provisions

6.5.5.1 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.

6.5.5.2 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) centers, 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).

6.6 Components and accessories

6.6.1 Components for full automatic control and operation

a) Control system.

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

c) Load tap changer equipment shall consist 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. Equipment shall meet the requirements of either IEEE Std C57.131 or IEC 60214-1 as specified.

d) Internal power supply for tap changer motor.

e) Provision for disconnecting control power supply.

f) Position indicator for the load tap changer with maximum and minimum indicating hands and provision for resetting shall be provided. Adjustable range of regulation for the *raise* and *lower* ranges is to be provided for supplementary current ratings per 5.3. Mechanically actuated electric limit switches shall be provided to prevent travel beyond the maximum raise and lower positions.

6.6.2 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 fluid level.

c) Liquid level indicator.

d) Bushing terminals shall be either clamp-type or threaded stud, depending on the nameplate line current ratings as shown in Table 15. The clamp-type terminals shall have at least the conductor range stated and shall be capable of accepting an aluminum 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 (0.5625 in) holes horizontally and vertically spaced on 44.5 mm (1.75 in) centers. Thickness of the pad is shown in Table 15. The user has the responsibility of selecting the proper conductor size for use with the clamp-type or spade terminals. When selecting the conductor size, the user should consider factors such as additional current carrying capability with reduced regulation (see 5.3), supplementary voltage ratings (see 5.2.3) and loading at other than rated conditions (see 4.2).

Table 15 —Bushing terminal applications

Nameplate line current rating (A)	Conductor size range or 4-hole spade
150 or less	#8–4/0
151 to 300	#2–477 kCM
301 to 668	#2–800 kCM
669 to 1200	1-1/8–12 UNF-2A with 4-hole spade—9.5 mm (0.375 in) minimum thickness
1201 to 2000	1-1/2—12 UNF-2A with 4-hole spade—12.7 mm (0.5 in) minimum thickness

6.6.3 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) Liquid level indicator.

d) Clamp-type terminals in accordance with single-phase criteria [see item d) in 6.6.2].

e) Provision for thermometer.

f) Handholes or openings to permit inspection of core and coil and load tap changer.

7. Other requirements

Certain specific applications have voltage regulator requirements not covered in Clause 4, Clause 5, or Clause 6. Clause 7 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 4 through Clause 6. Information in the following subclauses may be specified for some applications.

7.1 Other supplementary continuous-current ratings

When specified, other supplementary continuous-current ratings, 668 A maximum, for three-phase voltage regulators rated 8660 V and 13 200 V shall be provided as shown in Table 16 (see 5.3).

Table 16 —Other supplementary continuous-current ratings for three-phase voltage regulators

Range of voltage regulation (%)	Continuous-current ratings (%)
10.0	100
8.75	110
7.5	120
6.25	135
5.0	160

7.2 Other components and accessories

When specified, the other components and accessories listed in 7.2.1 and 7.2.2 may be provided.

7.2.1 For all voltage regulators

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

b) Voltage transformer for source side sensing for *reverse power flow* mode of control.

c) Control cabinet heater.

d) Remote communication interface.

e) 5 A secondary rating for current transformer.

f) Surge arresters.

g) Thermometer with or without alarm contacts.

h) Tank and control enclosure ground connectors.

7.2.2 For three-phase voltage regulators

a) Control cabinet heater.

b) Remote communication interface.

c) 5 A secondary rating for current transformer.

d) Surge arresters.

e) Thermometer with or without alarm contacts.

f) Tank and control enclosure ground connectors.

g) Hand operation crank for tap changer.

h) Load tap changer in compartment separate from the core and coil.

i) Remote position indicator.[b]

8. Test code

This clause prescribes methods for performing tests specified in 5.10. The test methods covered are as follows:

a) Resistance measurements (see 8.1)

b) Polarity test (see 8.2)

c) Ratio tests (see 8.3)

d) No-load losses and excitation current (see 8.4)

e) Load losses and impedance voltage (see 8.5)

f) Dielectric tests (see 8.6)

g) Temperature rise (see 8.7)

h) Short-circuit tests (see 8.8)

i) Calculated data (see 8.9)

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

8.1 Resistance measurements

Resistance measurements are of fundamental importance for the following purposes:

a) Calculation of the I^2R component of conductor losses

b) Calculation of winding temperatures at the end of a temperature test

c) As a quality control test of the manufacturing process

d) As a base for assessing possible damage in the field

8.1.1 Determination of cold temperature

The cold temperature of the winding shall be determined as accurately as possible when measuring the cold resistance. The following precautions in 8.1.1.1 through 8.1.1.3 shall be observed.

8.1.1.1 General

Cold resistance measurements shall only be made on a voltage regulator when the liquid or winding temperature is stable. The temperature is considered stable if the top liquid temperature does not vary more than 2 ºC in 1 h period.

8.1.1.2 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 with no excitation and with no current in the windings 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.

8.1.1.3 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 that their measuring points are as nearly as possible in actual contact with the winding conductors. It should not be assumed that the windings are at the same temperature as the surrounding air.

8.1.2 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 (2):

$$R_s = R_m \frac{T_s + T_k}{T_m + T_k} \tag{2}$$

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 (aluminum; see NOTE)

NOTE—The temperature 225 °C applies for pure or EC aluminum. T_k may be as high as 230 °C for alloyed aluminum. Where copper and aluminum windings are employed in the same voltage regulator, a value for T_k of 229 °C should be applied for the correction of losses.

8.1.3 Resistance measurement methods

8.1.3.1 Voltmeter-ammeter method

The voltmeter-ammeter method is the most common method used for voltage regulator winding resistance measurement. 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 7. 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 less ripple is desired in the measurement. Automatic recording of the resistance data is recommended so that the time to saturation and the variability of the resistance readings after stabilization can be documented.

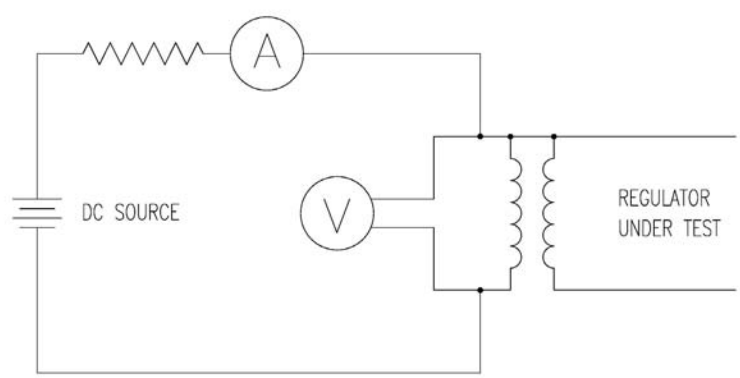


Figure 7—Connections for voltmeter-ammeter method of resistance measurement

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 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 measuring instruments shall have ranges that are close to full scale, to minimize errors of observation.

2) The voltmeter may be disconnected from the circuit before switching the current on or off, to protect the voltmeter from injury 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.

3) 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 heat run, note the time required for the readings to become constant. That 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 and hot resistance measurements by saturating the core with dc 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 non-inductive 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 will also be reduced by passing a dc 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.

8.1.3.2 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 1 Ω, a Kelvin bridge (or equivalent) is commonly used.

8.2 Polarity test

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 panel. Polarity tests on voltage regulators shall be made in accordance with one of the following methods:

a) Inductive kick

b) Ratio bridge

NOTE—Testing for additive or subtractive polarity of a main winding, as commonly required for transformers, is not required for voltage regulators. See Clause 3, *polarity of a voltage regulator.*

8.2.1 Polarity by inductive kick

Various acceptable variations of the inductive kick technique are in common use. The test is structured to ensure that instrument transformers display polarity correctly as per the voltage regulator nameplate. The following procedure may be used to check polarity by means of inductive kick with direct current:

a) The example shown in Figure 8 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-center-reading dc voltmeter to the voltage transformer secondary winding, point 1 to point 0 on Figure 8.

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).

NOTE—It may be necessary to place a shunt from *L* to *SL* when testing the current transformer polarity.

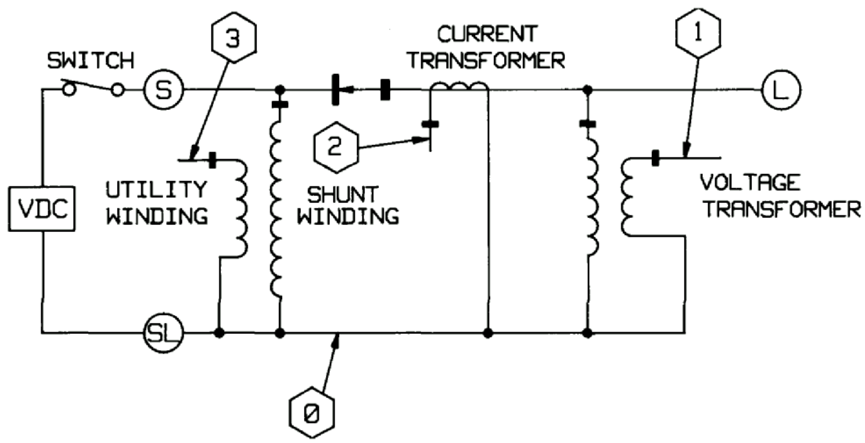


Figure 8—Voltage regulator connected for polarity testing; voltage regulator in neutral position

8.2.2 Polarity by ratio bridge

The ratio bridge described in 8.3.3.3 can also be used to test polarity.

8.3 Ratio tests

8.3.1 General

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

8.3.1.1 Taps

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

8.3.1.2 Voltage and frequency

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

8.3.1.3 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.

8.3.2 Tolerances for ratio

The turns ratios 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—By design, per 5.2.1, 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 user does not commonly know the extent of the internal compensation or the values of the individual steps. These design values must be known to accurately perform this test.

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

8.3.3 Ratio test methods

8.3.3.1 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 will otherwise not be satisfactory, and it will 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 8.3.3.2.

8.3.3.2 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 9). The voltmeter or detector indicates the difference in voltage. This method is more accurate than the following alternative method.

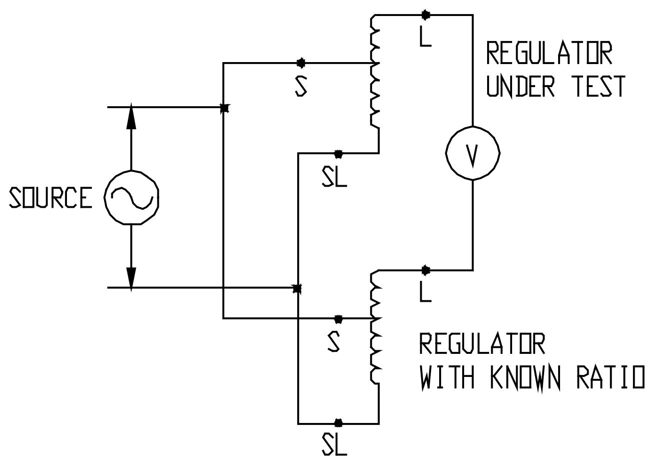


Figure 9—Voltmeter arranged to read the difference between the two output side voltages

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 10). The voltmeters shall be interchanged and the test repeated. The averages of the results are the correct voltages.

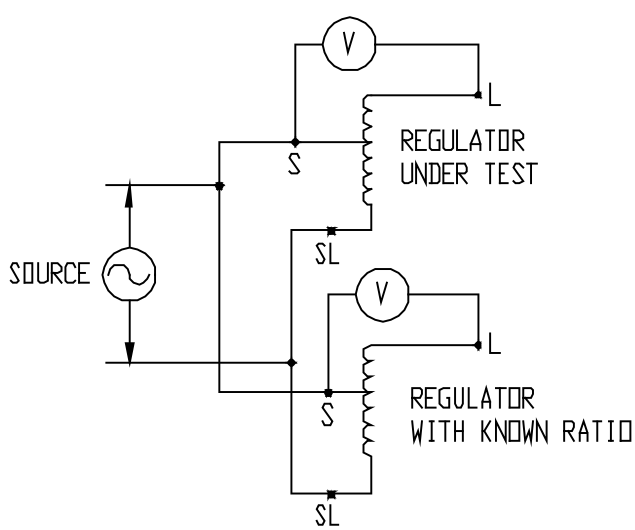


Figure 10—Voltmeters arranged to read the two series winding voltages

NOTE—Readings are repeated after interchanging voltmeters.

8.3.3.3 Ratio bridge

A bridge using the basic circuit of Figure 11 may be used to measure ratio. When detector DET is in balance, the voltage regulator ratio is equal to R/R1.

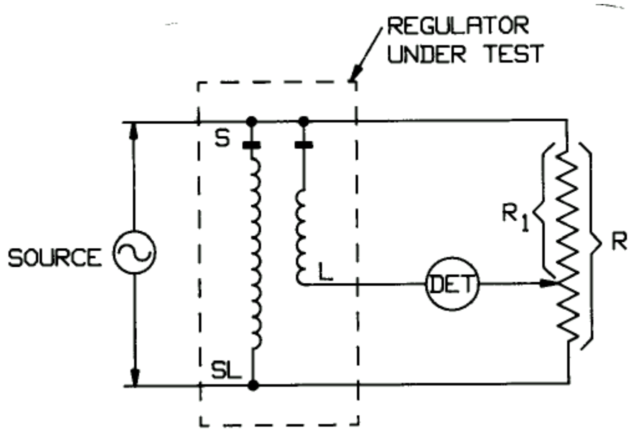


Figure 11 —Basic circuit of ratio bridge

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

NOTE 2—More accurate results can be obtained using a ratio bridge that provides phase-angle correction.

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

8.4 No-load losses and excitation current

8.4.1 General

No-load (excitation) losses are those losses that are incident to the excitation of the voltage regulator. No-load losses include core loss, dielectric loss, and conductor loss in the windings due to excitation current, and conductor loss due to circulating current in parallel windings. These losses change with the excitation voltage.

The excitation current (no-load current) includes current that flows in any winding used to excite the voltage regulator when all other windings are open-circuited, and the 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 the 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, no-load loss measurements will vary markedly with the waveform of the test voltage.

The exciting kVA is the product of the rated voltage across the energized winding in kV multiplied by the exciting current in amperes. The ratio of the no-load losses (in kW) to the exciting 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 8.4.7.

In addition, several other factors affect the no-load losses 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 losses of voltage regulators 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 (preventive autotransformer) core gaps.

8.4.2 No-load loss test

The purpose of the no-load loss test is to measure no-load losses 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 losses 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 losses to a sine-wave basis, using Equation (3) in accordance with 8.4.3.

8.4.2.1 Connection diagrams

Tests for the no-load loss determination of a single-phase voltage regulator are carried out using the schemes depicted in Figure 12 and Figure 13. Figure 12 shows the necessary equipment and connections when instrument transformers are not required. When instrument transformers are required, which is the general case, the equipment and connections shown in Figure 13 apply. If necessary, correction for losses in connected measurement instruments may be made by disconnecting the voltage regulator under test and noting the wattmeter reading at the specified test circuit voltage. These losses represent the losses of the connected instruments (and voltage transformer, if used). They may be subtracted from the earlier wattmeter reading to obtain the no-load loss of the voltage regulator under test.

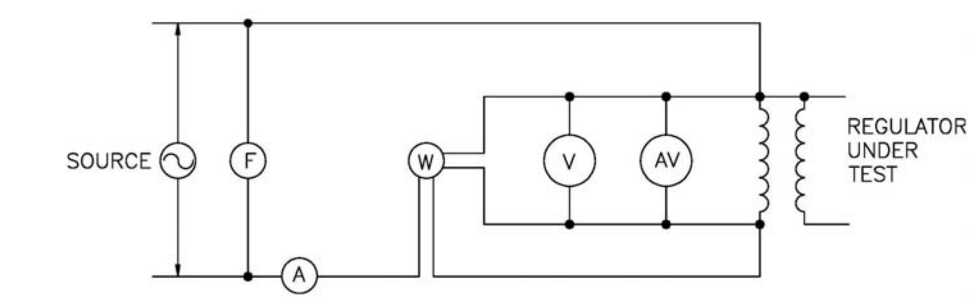


Figure 12 — Connection for no-load loss test of single-phase voltage regulator without instrument transformers

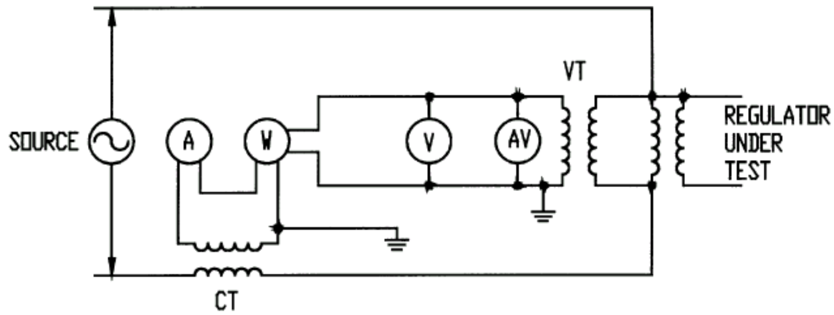


Figure 13 —Connections for no-load loss test of a single-phase voltage regulator with instrument transformers

8.4.2.2 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.

8.4.2.3 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 no-load losses 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.

8.4.3 Waveform correction of no-load losses

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 losses of the voltage regulator corrected to a sine-wave basis shall be determined from the measured value using Equation (3) and Equation (4):

$$P = \frac{P_m}{(P_1 + kP_2)} \tag{3}$$

where

P is the no-load losses corrected for waveform
P_m is measured no-load losses
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

$$k = \left(\frac{E_r}{E_a}\right)^2 \tag{4}$$

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 losses 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 (3) 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 losses and currents.

8.4.4 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 14 is a schematic representation of the equipment and connections necessary for conducting no-load loss measurements of a three-phase voltage regulator when instrument transformers are necessary.

8.4.5 Determination of excitation (no-load) current

The excitation (no-load) current of a voltage regulator consists of the current that maintains the rated magnetic flux excitation in the cores of the voltage regulator and the 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 kVA rating, the lowest kVA rating is used to determine the base current.) Measurement of excitation current is usually carried out in conjunction with the tests for no-load losses. Rms current is recorded simultaneously during the test for no-load losses 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.

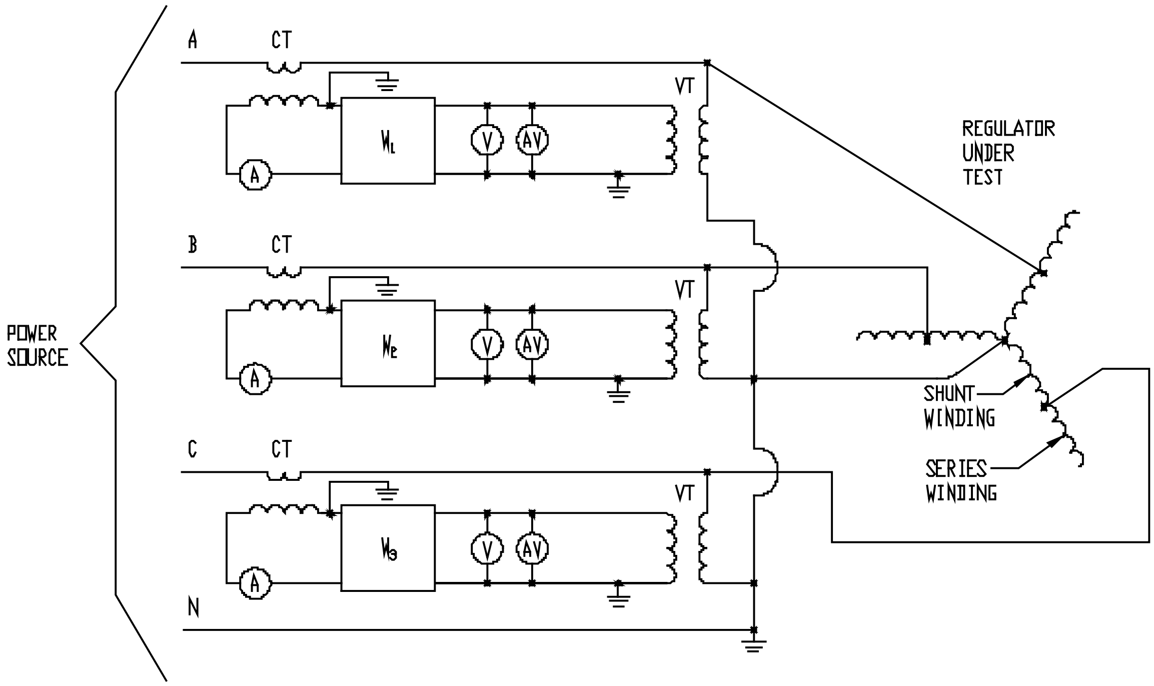


Figure 14 —Three-phase voltage regulator connections for no-load loss and excitation current test using three-wattmeter method

8.4.6 Measurements

At low power factors, 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 8.4.7.

8.4.7 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 measurements due to phase-angle errors in the wattmeter, voltage-measuring circuit and current-measuring circuit shall be applied in accordance with Table 17 using the correction formula in Equation (5):

$$P_c = P_m - V_m A_m \left[-\varphi W_d - \varphi V_d + \varphi C_d \right] \qquad (5)$$

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 ≤ 0.03	Apply phase-angle error correction
0.03 < PF ≤ 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 (5) 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 (6) and Equation (7) apply:

$$\phi_a = \cos^{-1}\left[\frac{P_m}{V_m A_m}\right] \tag{6}$$

$$P_c = V_m A_m \cos\left[\phi_a - \varphi W_d - \varphi V_d + \varphi C_d\right] \tag{7}$$

For three-phase measurements, the corrections are applied to the reading of each wattmeter employed. The voltage regulator loss is then calculated to Equation (8) as follows:

$$P_c = \sum_{i=1}^{N} R_v R_a P_{ci} \tag{8}$$

where

P_c is the voltage regulator losses, corrected for phase-angle error (W)
N is the number of phases (wattmeters) (W)
P_{ci} is the corrected wattmeter reading of the *i*th wattmeter
R_v is the true voltage ratio of voltage measuring circuit
R_a is the true current ratio of current measuring circuit

8.5 Load losses and impedance voltage

8.5.1 General

The load losses of a voltage regulator are losses incident to a specified load carried by the voltage regulator. Load losses include I²R loss in the windings due to load current and stray losses due to eddy currents induced by leakage flux in the windings, core clamps, magnetic shields, tank walls, and other conducting parts. Stray losses may also be caused by circulating currents in parallel windings or strands. Load losses are 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 losses 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 one of two specified windings when the other winding is short circuited while 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 losses. The reactive component of the impedance voltage, called the *reactance drop,* is in quadrature with the current and corresponds to the leakage-flux linkages 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 losses at the temperature of the test and at rated load. The impedance voltage and the load losses are corrected to a reference temperature using the equations specified in 8.5.4.1.

The maximum impedance voltage of a step-voltage regulator generally will be less than 0.6% of the rated voltage, stated on the circuit kVA base. Maximum impedance occurs at various tap positions depending on the design type and rating. Impedance is minimal in the neutral position. The impedance voltage will vary with tap position and may be somewhat higher for a two-core design (series transformer).

The impedance kVA is the product of the impedance voltage across the energized winding in kilovolts times the winding current in amperes. The ratio of the load losses in kilowatts at the temperature of test 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 8.4.7.

8.5.2 Factors affecting the values of load losses and impedance voltage

The magnitudes of the load losses and the impedance voltage will 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 losses. In addition, several other factors affect the values of load losses and impedance voltage of a voltage regulator. Considerations of these factors, partly, explain variations in load loss values and impedance voltage for the same voltage regulator under different test conditions, as well as variations between load loss values and impedance voltage of different voltage regulators of the same design. These factors are discussed in 8.5.2.1 through 8.5.2.3.

8.5.2.1 Design

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

8.5.2.2 Process

The process-related factors that impact the values of load losses 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.

8.5.2.3 Temperature

Load loss values are also a function of temperature. The I^2R component of the load losses increases with temperature, whereas the stray loss component decreases with temperature. Procedures for correcting the load losses and impedance voltage to the standard reference temperature are described in 8.5.4.1.

8.5.3 Tests for measuring load loss and impedance voltage

8.5.3.1 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 fluid temperatures does not exceed 5 °C.

   2) The temperature of the windings shall be taken immediately before and after the load losses and impedance voltage test in a manner similar to that described in 8.1.1. 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 shall take 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 losses and impedance voltage at a later time when conditions 1) through condition 3) 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 losses and impedance voltage shall be within ±0.5% of the nominal value.

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

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

A voltage regulator, which basically is an autotransformer, may be tested for load losses and impedance with its internal connections unchanged and with the unit in a specified tap position. The test is made by shorting the input (or output) 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 losses 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 must be the rated current of the excited winding. The load loss watts and applied voltamperes will be the same, whether series and shunt windings are treated as separate windings in the two-winding connection or are connected in the 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 determinations of load losses and impedance voltage. The voltage regulator under test should then be disconnected, and readings of losses taken on the wattmeter that represents the losses 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 15 and Figure 16. Figure 15 applies when instrument transformers are not required. If instrument transformers are required, which is the general case, then Figure 16 applies.

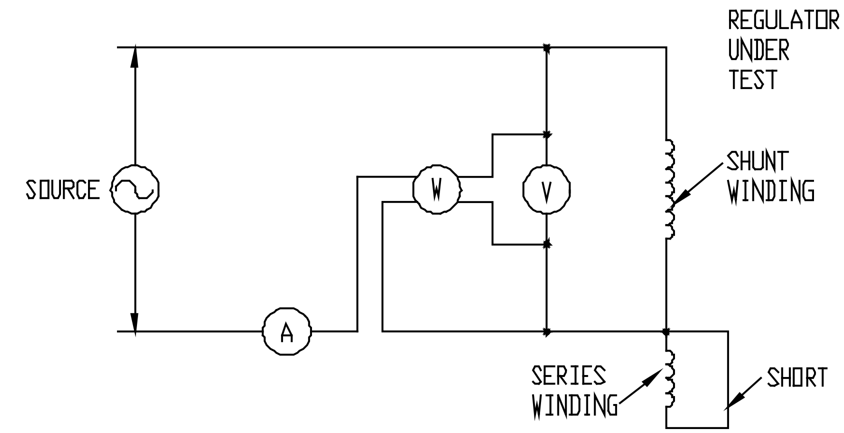


Figure 15 — Single-phase voltage regulator connections for load loss and impedance voltage test without instrument transformers

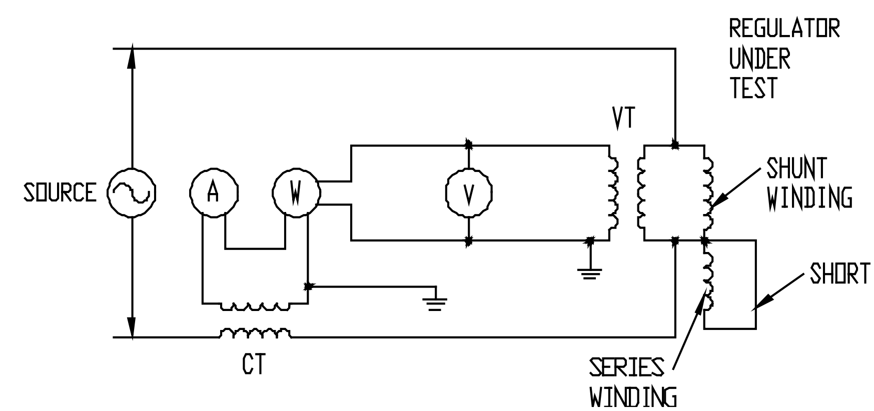


Figure 16 — Single-phase voltage regulator connections for load loss and impedance voltage test with instrument transformers

8.5.3.3 Impedance test of a three-phase voltage regulator

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 that described for a single-phase voltage regulator except that 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.

8.5.3.3.1 Measurement connections

For three-phase voltage regulators, Figure 17 shows the apparatus and connections using the three-wattmeter method.

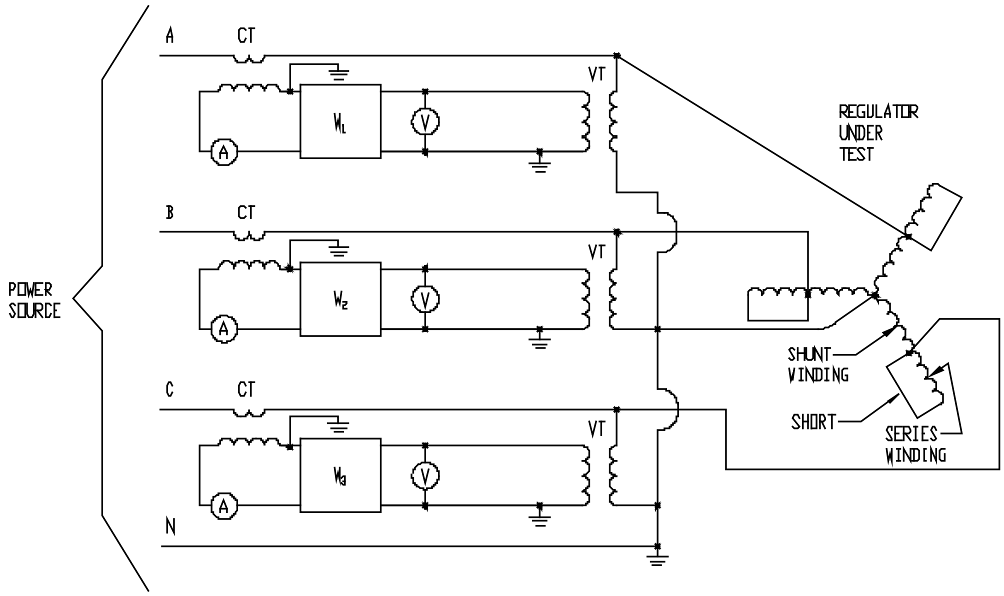


Figure 17 —Three-phase voltage regulator connections for load loss and impedance voltage test using the three-wattmeter method

8.5.4 Calculation of load losses and impedance voltage from test data

Load losses and impedance voltage measurements vary with temperature and, in general, shall be corrected to a reference temperature. In addition, load loss measurement values shall be corrected for metering phase-angle error as defined in 8.4.7.

8.5.4.1 Temperature correction of load losses

Both I^2R losses and stray losses of a voltage regulator vary with temperature. The I^2R losses $P_r(T_m)$ of a voltage regulator are calculated from the ohmic resistance measurements (corrected to the temperature T_m at which the measurement of load losses and impedance voltage was done) and the current that was used in the impedance measurement. These I^2R losses subtracted from the measured load loss watts $P(T_m)$ give the stray losses $P_s(T_m)$ of the voltage regulator at the temperature at which the load loss test was made, as shown in Equation (9):

$$P_s(T_m) = P(T_m) - P_r(T_m) \tag{9}$$

where

$P_s(T_m)$ is the calculated stray losses at temperature T_m (W)
$P(T_m)$ is the voltage regulator load losses corrected in accordance with 8.4.7, 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 losses increases with temperature. The stray loss component diminishes with temperature. Therefore, when it is desirable to convert the load losses from the temperature at which it is measured T_m to another temperature T, the two components of the load losses are corrected separately.

Thus, as shown in Equation (10) and Equation (11):

$$P_r(T) = \frac{P_r(T_m)(T_k + T)}{(T_k + T_m)} \tag{10}$$

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

Then, as shown in Equation (12):

$$P(T) = P_r(T) + P_s(T) \tag{12}$$

where

$P_r(T)$ is I^2R loss (W) at temperature T (°C)
$P_s(T)$ is stray losses (W) at temperature T (°C)
$P(T)$ is voltage regulator load losses (W) corrected to temperature T (°C)
T_k is 234.5 °C (copper) or 225 °C (aluminum; see NOTE)

NOTE—The temperature 225 °C applies for pure or EC aluminum. T_k may be as high as 230 °C for alloyed aluminum. Where copper and aluminum windings are employed in the same voltage regulator, a value for T_k of 229 °C should be applied for the correction of losses.

8.5.4.2 Impedance voltage

The impedance voltage and its resistive and reactive components at a specified tap position are determined by the use of Equation (13) through Equation (16):

$$E_r(T_m) = \frac{P(T_m)}{I} \tag{13}$$

$$E_x = \sqrt{E_z(T_m)^2 - E_r(T_m)^2} \tag{14}$$

$$E_r(T) = \frac{P(T)}{I} \tag{15}$$

$$E_z(T) = \sqrt{E_r(T)^2 + E_x^{\,2}} \tag{16}$$

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 losses corrected to temperature T (W)
$P(T_m)$ is the voltage regulator load losses 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 must be revised to reflect the autotransformer connection. As an autotransformer the voltage regulator transfers only the kVA that is 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 type of design. This maximum kVA is generally 10 % of the kVA supplied to the load. 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 (17):

$$Z_{auto} = Z_{tw} \frac{P_{series}}{P_{output}} \tag{17}$$

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

8.5.4.2.1 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 will be stated for a given tap position, normally the extreme tap position. The impedance will be less at lower tap positions and may be essentially zero at the Neutral tap position.

8.6 Dielectric tests

8.6.1 General

8.6.1.1 Factory dielectric tests

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

8.6.1.2 Test requirements

Test levels shall be as outlined in Table 12.

8.6.1.3 Measurement of test voltages

Unless otherwise specified, the dielectric test voltages shall be measured or applied, or both, in accordance with IEEE Std 4 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 potential 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.

8.6.1.4 Dielectric tests in the field

Field dielectric tests will be performed in accordance with Annex B.

8.6.1.5 Factory dielectric tests and conditions

8.6.1.5.1 Test sequence

Lightning impulse voltage tests shall precede the low-frequency tests.

8.6.1.5.2 Temperature

Dielectric tests may be made at temperatures assumed under normal operation or at the temperatures attained under conditions of routine test.

8.6.1.5.3 Assembly

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

8.6.2 Design lightning impulse test procedures

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

8.6.2.1 General

Impulse tests shall be made without excitation.

8.6.2.1.1 Reduced full-wave test

A reduced full wave is the same as a full wave, except that the crest value shall be between 50% and 70% of the full-wave value given in Table 12.

8.6.2.1.2 Chopped-wave test

This wave is inherently a full lightning impulse wave, except that the crest value shall be at the required level and the voltage wave shall be chopped at or after the required time to sparkover (time to chopping) in accordance with Table 12 but not later than 6.0 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 1.0 µs. However, for some winding designs it may be possible that the circuit response after chopping will 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%, it is permissible to add a series-connected resistor in the chopping circuit to limit the amount of overswing. When a resistor is added in the chopping circuit, 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 the use of a resistor in the chopping circuit does conflict with the preceding requirement of 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 1—This method will ensure that the steepness of the voltage collapse (dv/dt) is as high as possible.

NOTE 2—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 electrode 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.

NOTE 3—If the above prescribed maximum lead length to the chopping gap cannot be achieved because of the presence of accessories such as coolers or any other voltage regulator accessories, then the shortest possible lead length should be used during tests.

8.6.2.1.3 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 12, 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, 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 that 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 that:

   The optimum impulse generator connection is used (use of parallel stages if applicable, largest available capacitance);

   Moreover, 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.

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

   2) IEEE Std C57.98 and IEC 60076-4 [B5] give background information regarding the effect of an added resistor to the dielectric stresses applied to the voltage regulator.

   3) In general, the voltage peak appearing across the resistor is considerably delayed compared to the instant of the voltage peak of the applied lightening 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 that would appear across the winding if the resistor was not used and the terminal directly grounded. If the resistor applied-voltage peak coincides within 10 µs of the voltage peak, then the voltage drop across the winding is significantly reduced and a special procedure should be agreed upon between the manufacturer and the user.

   4) The use of the Glaninger circuit as described in IEEE Std C57.98 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.

If the calculated tail time for a particular connection and voltage regulator design is such that 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 at the end of the electrical design 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 manufacturer and purchaser.

NOTE—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:

$$E_{\min} = \frac{2 \times \pi \times f \times (t_2)^2}{z \times \mathrm{V}^2} \times \frac{(\mathrm{V_{BIL}})^2}{\eta} \times \mathrm{VA}$$

where

$E_{min.}$	is minimum energy required from the impulse generator (J)
f	is power frequency, 60 Hz or 50 Hz
t_2	is tail time (s); t_2 equals 40 µs
z	is impedance in p.u. seen from the impulsed terminal
V	is winding rated voltage (V)
V_{BIL}	is rated BIL of the tested winding (V)
η	is impulse generator efficiency in p.u.: $\eta = 1.0$
VA	is power rating in voltamperes for which the impedance z is defined

Note that the preceding equation has been derived from the equations given in IEC 60076-4 [B5]. More information about wave shape control can be found in IEEE Std C57.98 and IEC 60076-4 [B5].

8.6.2.1.4 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.

8.6.2.1.5 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 last two chopped waves, and the last full wave of voltage and current shall represent a record of the successful application of the impulse test to the voltage regulator.

8.6.2.2 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 Ω ± 10% 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 source (*S*) terminal while set in the maximum buck position. A Type B voltage regulator shall have the test applied to the load (*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 12, subject to a tolerance of ±10%. Voltage regulators intended for delta connections shall in addition have impulse voltage applied to the *SL* line terminal.

8.6.2.2.1 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 each terminal:

a) The voltage-to-ground on any terminal that is 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, then that terminal 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.

8.6.2.2.2 Protective devices that are 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-waves oscillograms. In order to demonstrate that 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 that is conveniently accessible, e.g., 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). Typical oscillograms depicting the operation of protective devices during impulse testing are shown in IEEE Std C57.98.

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 (see NOTE 1)
- One full wave at 100% of the required full-wave impulse level
- Two chopped waves at 100% of the required chopped-wave impulse level
- One full wave 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

With the exception of the special cases given in NOTE 2 and NOTE 3, the intermediate reduced impulse level shall show the operation of the nonlinear devices and its effect on the current and voltage oscillograms.

NOTE 1—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 voltage regulator design dependent. Generally, a lightning impulse within that specified voltage range will cause 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 user.

NOTE 2—In some cases, tests at 100% of the required full-wave impulse level with the standardized lightning impulse wave shape will not show the operation of the nonlinear devices. If this is the case, additional intermediate reduced full-wave wave tests are not necessary and may be waived.

NOTE 3—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) in 8.6.2.4.2, 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 an 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. Because it is not possible to compare a single 100% full-wave test with other reduced full-wave tests as it is the case for voltage regulators not having nonlinear devices, it is needed to perform two 100% full-wave impulse tests for comparing them. All reduced full-wave tests performed after the full-wave tests shall be compared with its corresponding reduced full-wave test performed prior to the full-wave tests.

8.6.2.2.3 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.

8.6.2.2.4 Core and tank grounding

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

8.6.2.2.5 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.

8.6.2.3 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 that, 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.

8.6.2.4 Detection of failure during impulse test

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.

8.6.2.4.1 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 means of 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 wave and full-wave test. 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.

8.6.2.4.2 Other methods of failure detection

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.

8.6.3 Routine lightning impulse test procedures

For voltage regulators, the impulse tests specified in 8.6.2 are design tests. This subclause defines a routine quality control test that is suitable for high-volume production-line testing.

8.6.3.1 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 Ω ± 10% 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 12, subject to a tolerance of ±10%. Voltage regulators intended for delta connections shall in addition have impulse voltage applied to the *SL* line terminal.

8.6.3.2 Procedure

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 wideband 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 R-C, 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 8.6.2.1.3 and 8.6.2.1.4. 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 8.6.3.2.1 or 8.6.3.2.2.

8.6.3.2.1 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 will cause 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.

8.6.3.2.2 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 R and C, is employed to record waveforms for comparison. The waveforms in both tests are compared to preestablished levels. A dielectric breakdown will cause a significant upturn and increase in magnitude of the voltage wave examined across the neutral impedance. The preestablished 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.

8.6.3.2.3 Failure detection

The failure detection methods for the routine impulse tests described in 8.6.3.2.1 or 8.6.3.2.2 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 8.6.2.4.2 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.

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.

8.6.3.3 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 each terminal:

a) The voltage-to-ground on any terminal that is 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, then that terminal 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.

8.6.4 Low-frequency tests

Low-frequency tests shall be performed in accordance with the requirements of 5.7 and Table 12.

The low-frequency insulation levels are developed by the applied-voltage and induced-voltage tests described in 8.6.5 and 8.6.6, or combinations thereof.

8.6.5 Applied-voltage tests

8.6.5.1 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 and to the other terminal of the testing transformer.

8.6.5.2 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.

8.6.5.3 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 8.6.5.1, it should be reduced gradually before the circuit is opened.

8.6.5.4 Failure detection

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

8.6.6 Induced-voltage tests

8.6.6.1 Test value and duration

The induced-voltage tests may involve either single- or three-phase excitation. Two times rated turn-to-turn voltage shall be developed in each winding. The induced-voltage test shall be applied for 7200 cycles, or 60 s, whichever is shorter.

8.6.6.2 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 limits established in Table 10 and 5.5. The minimum test frequency to meet this condition is shown in Equation (18):

$$\text{Minimum test frequency} = \frac{E_t}{1.1 \cdot E_r} \cdot \text{rated frequency} \tag{18}$$

where

E_t is the induced test voltage across winding (V)
E_r is the rated voltage across winding (V)

8.6.6.3 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 8.6.6.1, it should be reduced gradually before the circuit is opened.

8.6.6.4 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 induced test voltage specified in 8.6.4, 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 windings that were sectionalized.

8.6.6.5 Grounded windings

When a voltage regulator has one 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.

8.6.6.6 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.

8.6.6.7 Failure detection

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

8.6.7 Insulation power factor tests

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.

8.6.7.1 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 should be between 10 °C and 40 °C, but preferably as near to 20 °C as practical. The top liquid temperature shall be measured and recorded.

8.6.7.2 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 voltage regulator design operating frequency.

8.6.7.3 Voltage to be applied

The voltage to be applied for measuring insulation power factor shall not exceed half of the applied voltage given in Table 12 for any part of the winding, or 10 000 V, whichever is lower.

8.6.7.4 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 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 — Utility winding to shunt and series winding and ground — Utility winding to ground, guard on shunt and series windings
Voltage regulators with utility winding — Shunt and series windings to utility winding and ground — Utility winding to ground — Shunt and series winding to ground	

[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.

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 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 is of value when compared 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 fluid temperature measured and the bottom fluid temperature if available. No temperature correction shall be applied. Temperature correction of the power factor results for trending basis may be applied by the user.

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

8.6.8 Insulation resistance tests

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

NOTE 1—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.

NOTE 2—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. When a user decides to make insulation resistance tests, it is recommended that insulation resistance values be measured periodically (during maintenance shutdown) and plotted. Substantial variations in the plotted insulation resistance values should be investigated for cause.

NOTE 3—Insulation resistances may vary with applied voltage, and any comparison shall be made with measurements at the same voltage.

NOTE 4—Under no circumstances should tests be made while the voltage regulator is under vacuum.

8.6.8.1 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.

8.6.8.2 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, 1000 V, 2500 V, and 5000 V; dc applied-voltage test equipment is available at higher voltages.

8.6.8.3 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 12.

NOTE 1—Partial discharges should not be present during insulation resistance tests because they can damage a voltage regulator and may also result in erroneous values of insulation resistance.

NOTE 2—When measurements are to be made using dc voltages exceeding the rms operating voltage of the windings involved (or 1000 V for a solidly grounded wye winding), a relief gap may be employed to protect the insulation.

8.6.8.4 Procedure

Insulation resistance tests shall be made with all windings 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.

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.

8.7 Temperature-rise tests

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 4.1. All temperature-rise tests shall be made under normal (or equivalent to normal) conditions of the means of cooling, as follows:

a) Temperature-rise tests shall be conducted on voltage regulators that are completely assembled and filled to the proper liquid level.
b) The temperature-rise tests shall be made in a room that is as free from drafts as practicable.
c) When it is not possible, or practical to test the voltage regulator as a completed assembly, the voltage regulator shall be tested with those components required to ensure normal means of cooling the voltage regulator during temperature-rise test. When the voltage regulators are equipped with thermal indicators, or the like, such devices shall be assembled with the voltage regulator.

8.7.1 Test methods

Tests shall be made by one of the following methods:

a) Actual loading
b) Simulated loading
    1) The short-circuit method, in which appropriate total losses are produced by the effect of short-circuit current.
    2) The loading back (opposition) method, in which rated voltage and current are induced in the voltage regulator under test.

8.7.1.1 Actual loading

Actual loading method is the most accurate of all methods, 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.

8.7.1.2 Simulated loading

8.7.1.2.1 Short-circuit method

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 taps that give the highest average winding temperature rise. This will generally involve those connections and taps resulting in the highest losses. Supplementary current ratings in accordance with 5.2.3 and 5.3 shall be used if they are associated with highest average winding temperature rise. This thermal connection load loss shall be measured in accordance with 8.5 and referenced to a temperature equal to rated average winding rise plus 20 °C. The required total losses for the total loss run shall be the sum of thermal connection load loss plus no-load loss measured in accordance with 8.4.
b) Total loss run: Short-circuit one or more windings and circulate sufficient current at rated frequency to produce the required total losses as determined in step a) and 8.7.4.2.
c) Determine liquid temperature rises as described in 8.7.3.2.
d) Rated current run: Reduce the current in the windings to the rated current (or reduced current according to 8.7.4.1) 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 resistances in accordance with 8.7.2.2.

e) Repeat step d) for hot resistance measurements on additional terminal pairs if needed to meet the time limit criteria of 8.7.2.2.

f) Determine average winding rises in accordance with 8.7.3.3.

8.7.1.2.2 Loading back method

Duplicate voltage regulators may be tested by connecting their respective shunt and series windings in parallel (see Figure 18 and Figure 19). Voltage regulators shall be tested and load losses measured at rated current and frequency for the particular combination of design type, connections, and taps that give the highest average winding temperature rise. This will generally involve those connections and taps resulting in the highest losses. Supplementary current ratings in accordance with 5.2.3 and 5.3 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 8.4 and 8.5.

b) Measure liquid temperatures and determine liquid temperature rises as described in 8.7.3.2.

c) Immediately shut down and measure the hot resistance in accordance with 8.7.2.2.

d) When needed to meet the time limit criteria of 8.7.2.2, resume the heat run for 1 h, holding rated voltage at rated frequency for the connection and loading used. Measure the liquid temperatures and immediately shut down and measure the hot resistance of additional terminal pairs in accordance with 8.7.2.2.

e) Determine average winding temperature rises in accordance with 8.7.3.3.

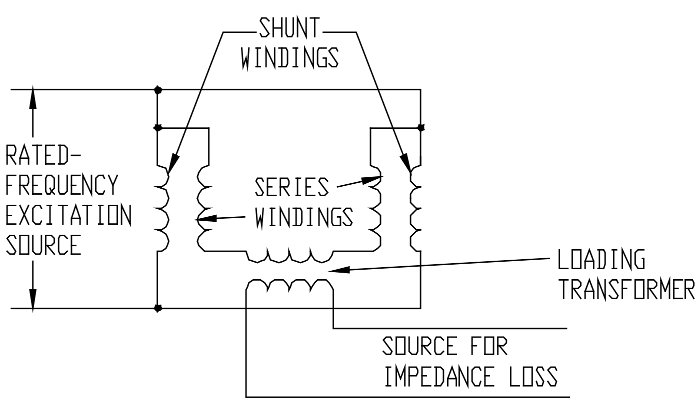


Figure 18 — Example of loading back method: Single phase

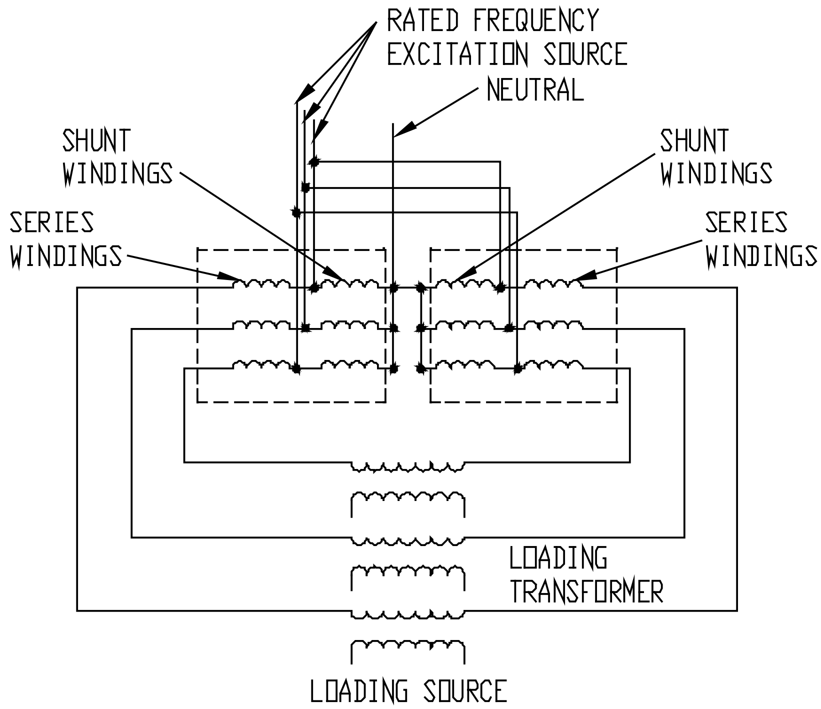


Figure 19 — Example of loading back method: three phase

8.7.2 Resistance measurements

8.7.2.1 Cold-resistance measurements

Cold-resistance measurements shall be taken on all terminal pairs in accordance with 8.1. 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 8.1.1 to be met.

8.7.2.2 Hot-resistance measurements

When the voltage regulator is shut down for hot-resistance measurements, fans and cooling water shall be shut off. Fluid pumps may be shut off or left running during shutdown. 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 shall be recorded for each resistance measurement.

b) At least one resistance measurement shall be taken on all terminal pairs within 4 min after shutdown.

c) A series of at least four resistance measurements shall be made on one terminal pair corresponding to a phase of a winding.

d) Resistance-time measurements in accordance with item c) shall be made on all windings.

e) The resistance/time data collected in item c) shall be corrected to the instant of shutdown using a resistance-time cooling curve determined by plotting data on suitable coordinate paper, or by using a curve fitting program.

f) The resistance/time data obtained on one phase of a winding shall be used to determine the correction to shutdown for the other phases of the same winding, provided the first measurement on each of the other phases has been taken within 4 minutes after shutdown.

8.7.3 Temperature measurements

8.7.3.1 Ambient temperature measurement

8.7.3.1.1 Air-cooled voltage regulators

For air-cooled voltage regulators, the ambient temperature shall be taken as that 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 (19) 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.

$$\tau_{TO,R} = \frac{C \times \Delta\Theta_{TO,R}}{P_{T,R}} \tag{19}$$

where

$\tau_{TO,R}$ is the time constant for rated load beginning with initial top-liquid temperature rise of 0 °C, hours
$\Delta\Theta_{TO,R}$ is the top-liquid rise over ambient temperature at rated load, °C
$P_{T,R}$ is the total loss at rated load, watts

$$\begin{aligned} C = {} & 0.0272 \times (\text{weight of core and coil assembly in kilograms}) \\ & + 0.01814 \times (\text{weight of tank and fittings in kilograms}) \\ & + 5.034 \times (\text{liters of liquid}) \end{aligned}$$

or :

$$\begin{aligned} C = {} & 0.06 \times (\text{weight of core and coil assembly in pounds}) \\ & + 0.04 \times (\text{weight of tank and fittings in pounds}) \\ & + 1.33 \times (\text{gallons of liquid}) \end{aligned}$$

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

8.7.3.1.2 Water-cooled voltage regulators

For water-cooled voltage regulators, the flow rate in liters per minute (gallons per minute) and the temperature of the incoming and outgoing water shall be measured.

The ambient temperature shall be taken as that of the incoming water that should not be less than 20 °C nor more than 30 °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.

8.7.3.2 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 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 so that the thermocouples are in 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 that their readings are not significantly affected by the air movement from fans 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 8.7.3.4 for method of measurement). Infrared measurement devices may also be used to measure surface temperatures.

8.7.3.3 Average winding temperature-rise determination

The average winding temperature of a terminal pair corresponding to a winding 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 (20):

$$\theta_w = \left(\frac{R_h}{R_c}\right)(\theta_k + \theta_{rc}) - \theta_k \tag{20}$$

The average temperature rise of a terminal pair corresponding to a winding phase shall be determined by Equation (21):

$$\Delta\theta_w = \Delta\theta_l + \theta_w - \theta_l \tag{21}$$

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 liquid temperature at end of total loss run (°C)
- θ_l is the 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 8.1 (Ω)
- R_h is the hot resistance (Ω)
- θ_k is 234.5 °C for copper and 225.0 °C for aluminum

NOTE—225 °C applies for pure or EC aluminum. θ_k may be as high as 230 °C for alloyed aluminum. Where copper and aluminum windings are employed in the same voltage regulator, a value for θ_k of 229 °C should be applied for the correction of losses.

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 quantity (average winding temperature at shutdown minus top liquid temperature at shutdown).

b) In the average liquid rise method, the average winding temperature rise is the average liquid rise, measured during the total loss run, plus the quantity (average winding temperature at shutdown minus 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 8.7.4. The corrected average winding temperature rise shall be reported for each terminal pair of the voltage regulator.

8.7.3.4 Other temperature measurements

When measured, the temperature rise of metal parts other than windings shall be determined by use of a thermocouple, suitable thermometer, fiber 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 mm² (1 in²). 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.

8.7.4 Correction of temperature-rise test results

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

8.7.4.1 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 lower 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 (22):

$$\Delta\theta_{w,c} = \Delta\theta_{w,o}\left[\frac{\text{rated current}}{\text{test current}}\right]^{2m} \tag{22}$$

where

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

$\Delta\theta_{w,o}$ 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, ONAF, OFAF, and OFWF

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

8.7.4.2 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 (23):

$$\Delta\theta_{l,c} = \Delta\theta_{l,o}\left[\left(\frac{P_r}{P_T}\right)^n - 1\right] \tag{23}$$

where

$\Delta\theta_{l,c}$ is the liquid temperature-rise correction (°C)
$\Delta\theta_{l,o}$ 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
is 0.9 for Class ONAF, OFAF, and OFWF

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

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

8.7.4.3 Correction of liquid temperature rises for differences in altitude

When tests are made at an altitude of 1000 m (3300 ft) or less, no altitude correction shall be applied to the temperature rises.

When a voltage regulator tested at an altitude of less than 1000 m (3300 ft) is to be operated at an altitude above 1000 m (3300 ft), it shall be assumed that the liquid temperature rise will increase in accordance with Equation (24):

$$\Delta\theta_A = \Delta\theta_o\left(\frac{A}{A_0} - 1\right)F \tag{24}$$

where

$\Delta\theta_A$ is the increase in liquid temperature rise (°C) at altitude A m (feet)
$\Delta\theta_o$ is the observed liquid temperature rise (°C)
A is altitude meters (feet)
A_0 is 1000 m (3300 ft)
F is .04 for self-cooled mode
is .06 for forced-air-cooled mode

NOTE—Winding temperature rise above liquid temperature is not affected by altitude.

8.8 Short-circuit tests

8.8.1 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. Conformance to short-circuit thermal requirements shall be by calculation in accordance with 8.9.4.

The short-circuit test procedure described in this standard is intended principally for application to new voltage regulators to verify design. Tests may be conducted at manufacturer's facilities, 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.

8.8.2 Test connections

8.8.2.1 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, but the regulated circuit fault is preferred because it closely represents the system fault condition. 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) Closing a breaker at the source terminal to apply energy to the previously short-circuited voltage regulator, pre-set method.

b) Closing a breaker at the faulted terminal to apply a short circuit to the previously energized voltage regulator, post-set method.

8.8.2.2 Fault type

For three-phase voltage regulators a three-phase supply is preferable, as long as the fault current requirements defined in 5.9.1 can be met. If this is not possible, an alternate single-phase source can be used:

a) Single-phase source with short-circuit on one phase at a time (applies to all single-phase voltage regulators).

8.8.2.3 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.

8.8.3 Test requirements

8.8.3.1 Symmetrical current requirements

The rms symmetrical short-circuit current shall have a magnitude as defined in 5.9.1. The base rated load current is the rated self-cooled load current of the voltage regulator.

NOTE—The user may specify a larger short-circuit withstand value due to unique system parameters. An example as such is a short-circuit withstand of 40 times the base rated load current or 20 000 A whichever is less. Application, limitations, design, and resulting cost are to be agreed upon by the user and the manufacturer.

8.8.3.2 Asymmetrical current requirements

The first-cycle asymmetrical peak current that the voltage regulator is required to withstand shall be as defined in 5.9.1.

8.8.3.3 Number of tests

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

8.8.3.4 Duration of tests

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

8.8.4 Test procedure

8.8.4.1 Fault application

To produce the fully asymmetrical current wave specified in 8.8.3.2, the moment of switching on shall be adjusted by means of a synchronous switch or another controlled switching device.

8.8.4.2 Calibration tests

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

8.8.4.3 Terminal voltage limits

When tests are to be made by applying a short circuit to the energized voltage regulator, the no-load source voltage shall not exceed 110% of the rated voltage, unless otherwise approved by the manufacturer.

Throughout the course of any test, the voltage at the voltage regulator primary circuit terminals shall be maintained within a range of 95% to 105% of that necessary to produce the required symmetrical short-circuit current as determined in 8.8.3.1.

NOTE—When choosing the test voltage the possibility of over-excitation and high inrush current shall be considered. All reasonable precautions shall be taken in order to reduce these inrushes.

8.8.4.4 Temperature limits

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

8.8.4.5 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. The symmetrical peak current shall be established as half of the peak-to-peak envelope of the current wave, measured at the midpoint of the second cycle of test current. The first cycle peak asymmetrical current shall be measured directly from the oscillograms of the terminal currents.

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

NOTE 1—Any appropriate measuring devices may be used, as long that they give correct measurements with appropriate sensitivity, precision, and uncertainty. Those measuring devices may be, for example, current transformers, shunts, or Rogowski coils.

NOTE 2—The oscillograms shall 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.

8.8.4.6 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.

8.8.4.7 Tap-changing switch operation

Upon completion of each of the required short-circuit tests, the 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.

8.8.5 Proof of satisfactory performance

The voltage regulator under test shall be judged to have performed satisfactorily when the visual inspection (8.8.5.1) and dielectric test (8.8.5.2) criteria have been satisfactorily met. In 8.8.5.3 through 8.8.5.5, 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 8.8.5.3 to 8.8.5.5 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 8.8.5.3 to 8.8.5.5 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 short-circuit tests.

NOTE—The proof of satisfactory performances is determined by visual inspection and the standard dielectric tests defined in Table 12. It may be advisable to proceed to a visual inspection before undertaking standard dielectric test.

8.8.5.1 Visual inspection

Visual inspection of the core and coils shall give no indication that any change in mechanical condition has occurred that will impair 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 8.8.5.3 through 8.8.5.5. 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 test should then be considered during the negotiation.

Visual inspection of the tap changer shall indicate no change that will impair the switch function. The extent of this examination shall be established on the basis of operation through neutral after each test. When the tap changer operates successfully through neutral after each test, then an inspection of the switch as assembled may suffice.

8.8.5.2 Dielectric tests

The voltage regulator shall withstand standard dielectric tests in accordance with 8.6, at the full specification level following the short-circuit test.

8.8.5.3 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.

8.8.5.4 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 22.5%.

The measuring equipment shall have the demonstrated capability of giving reproducible readings within an accuracy of ±0.2%.

NOTE—It may be worthwhile to measure impedance after each short circuit. These measurements will allow identifying progressive variations or early substantial impedance changes.

8.8.5.5 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%.

8.8.5.6 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.

8.9 Calculated data

8.9.1 Reference temperature

The reference temperature for determining load losses, voltage regulation, and efficiency shall be equal to the sum of the rated average winding temperature rise by resistance plus 20 °C.

8.9.2 Losses and excitation current

8.9.2.1 Determination of no-load losses and exciting current

No-load losses and exciting 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.

8.9.2.2 Load losses

Load losses shall be determined for rated voltage, current, and frequency and shall be corrected to the reference temperature (8.9.1).

8.9.2.3 Total losses

Total losses are the sum of the no-load losses and the load losses.

8.9.3 Efficiency

The efficiency of a voltage regulator is the ratio of its useful power output to its total power input, exclusive of pumps, fans, and other ancillary devices. See Equation (25).

$$\eta = \left(\frac{P_o}{P_i}\right) = \frac{(P_i - P_L)}{P_i} = 1 - \left(\frac{P_L}{P_i}\right) = 1 - \left[\frac{P_L}{(P_o + P_L)}\right] \tag{25}$$

where

η is efficiency
P_o is output (W)
P_i is input (W)
P_L is losses (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 pumps or fans are supplied, the power requirements shall be provided as supplementary data.

8.9.4 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 Equation (26) through Equation (31), 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 5.9.3. All temperatures are in degrees Celsius.

$$T_f = (T_k + T_s)m(1 + E + 0.6m) + T_s \tag{26}$$

where

$$m = \frac{(W_s t)}{[C(T_k + T_s)]}$$

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:

$$T_f = (T_k + T_s)\left[\sqrt{\varepsilon^{2m} + E(\varepsilon^{2m} - 1)} - 1\right] + T_s \tag{27}$$

where

- T_f is final winding temperature
- T_k is 234.5 °C (copper) and 225 °C (aluminum)

  NOTE—225 °C applies for pure or EC aluminum. T_k may be as high as 230 °C for alloyed aluminum. Where copper and aluminum windings are employed in the same voltage regulator, a value for T_k of 229 °C should be applied for the correction of losses.

- T_s is the starting temperature equal to
  a) A 30 °C ambient temperature plus the average winding rise plus the manufacturer's recommended hottest-spot allowance, or
  b) A 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

$$E = E_r\left[\frac{T_k + T_r}{T_k + T_s}\right]^2 \tag{28}$$

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

$$W_s(\mathrm{W/kg}) = \frac{W_r N^2}{M_{kg}}\left[\frac{T_k + T_s}{T_k + T_r}\right](2.2) \text{ or } W_s(\mathrm{W/lb}) = \frac{W_r N^2}{M_{lb}}\left[\frac{T_k + T_s}{T_k + T_r}\right] \tag{29}$$

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:

$$C = 174 + 0.0225\left(T_s + T_f\right) + 110\frac{A_i}{A_c} \text{ for copper} \tag{30}$$

$$C = 405 + 0.1\left(T_s + T_f\right) + 360\frac{A_i}{A_c} \text{ for aluminum} \tag{31}$$

where

A_i is the cross-sectional area of turn insulation
A_c is the cross-sectional area of conductor

8.9.5 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 “design” 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 and pumps *
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 test value *
14) Other special test (defined by user) results *
15) Design impulse test data *
16) Thermal performance data *
    i) Ambient temperature
    ii) Tap position, total loss, and line currents for total loss run
    iii) Fluid flow in winding (directed and non-directed)
    iv) Final bottom and top fluid temperature rise over ambient for total loss run for each test
    v) Average winding temperature rise over ambient for each winding for each test
    vi) Calculated winding hottest spot temperature rise over ambient for maximum rating
17) Short-circuit test data *
18) Control design test data *
19) Zero-sequence impedance (calculated when specified) *
20) Regulation (calculated when specified) *
21) Dissolved gas in fluid analysis *
22) Audible sound level *

d) Certification statement and approval

NOTE 1—Items identified with an asterisk (*) are not required for voltage regulators unless specified by the user.

NOTE 2—Number of significant figures of reported data should reflect the level of confidence of the data accuracy.

NOTE 3—All temperature sensitive data should be reported after correcting to reference temperature (defined in 8.9.1).

NOTE 4—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 5—Other drawings, such as nameplate and outline, may be made a part of certified test data in place of duplicating the same information.

9. Control systems

9.1 General

The control system of a voltage regulator is composed of sensing apparatus to provide signals proportioned to the system voltage and load current, and a control device that interprets the output of the sensing apparatus, relates 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.

9.2 Control device construction

9.2.1 Setpoint adjustment ranges

The control device shall permit parameter adjustment 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 11).

b) Bandwidth setting adjustable from at least 1.5 V to 3.0 V (total range).

c) Actuation time delay setting adjustable from at least 15 s to 90 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 adjustable in the range of at least –24 V to +24 V. (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.)

9.2.2 Components and accessories

The following components and accessories will be provided as part of the control device:

a) Test terminals for measuring voltage proportional to voltage regulator output voltage. (The test terminal voltage should not be changed more than ±1% by 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(es).

d) Neutral position indicator independent of the tap changer position indicator.

e) External source terminals.

f) Internal/external power switch to allow 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 position).

g) Operations counter to indicate accumulated number of tap changer operations.

h) High and low band limit indications.

9.3 Control system requirements

9.3.1 Accuracy

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 design tests that are 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.

9.3.1.1 Sensing apparatus

9.3.1.1.1 Voltage source

The voltage source accuracy shall be determined on a nominal secondary voltage base of 120 V and a burden of 10 VA.

9.3.1.1.2 Current source

The current source accuracy shall be determined on a nominal 0.2 A secondary current and a burden of 3.5 VA.

9.3.1.2 Control device

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.

NOTE—The user should be 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 will affect 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.

9.3.1.2.1 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.

9.3.1.2.2 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

9.4 Tests

9.4.1 Design tests

Design tests shall be made 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.

9.4.1.1 Accuracy

9.4.1.1.1 Procedure for determination of accuracy of control device

This subclause outlines procedures for determining values of errors contributed by the factors described in 9.3.1.2.2. The voltage and current sources applied may be as free of harmonics or other distortions as the test facility permits.

9.4.1.1.2 Tests for errors in 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 of 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 made 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 19.

Table 19 —Voltage-level values for select line-drop compensation settings

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 per 9.3.1.2.1.

9.4.1.2 Set point marks

Deviation of set point marks 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.

9.4.1.2.1 Voltage level marking deviation

The difference between the actual voltage level value and the marked value at any setting over the range of 120 V ± 10% shall not exceed ±1%.

9.4.1.2.2 Bandwidth marking deviation

The difference between the actual bandwidth voltage and the marked value shall not exceed ±10% of the marked value set.

9.4.1.2.3 Compensator marking deviation

The arithmetic difference between the actual compensation voltage expressed as a percent of 120 V and the marked value of any setting of either the resistance or reactance element of the compensator (expressed as a percent of 120 V, with 0.2 A in the compensator circuit) shall not exceed ±1%.

9.4.1.2.4 Time delay set marking deviation

The difference between the actual time delay and the marked value of any setting shall not exceed ±2 s or ±10%, whichever is greater, when initiated with no stored delay in an integrating-type circuit.

9.4.1.3 Environmental tests

9.4.1.3.1 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 60068-2-1, cold, –40 ºC, 96 h
b) IEC 60068-2-2, dry heat, +65 ºC, 96 h

9.4.1.3.2 Humidity

Tests are to be conducted per IEC 60068-2-30, 55 ºC, 6 cycles.

9.4.1.3.3 Vibration

Tests shall be completed per IEC 60255-21-1 (Class 1).

9.4.1.4 Insulation coordination tests

Tests shall to be completed per IEC 60255-5, impulse voltage (category III), dielectric test (2 kV).

9.4.1.5 Electrostatic discharge test

Tests shall be completed per either IEEE Std C37.90.3 or IEC 60255-22-2 as specified. Testing shall be completed for all voltage levels specified, highest level being 8 kV contact discharge, 15 kV air discharge.

9.4.1.6 RFI and interference tests

9.4.1.6.1 Radiated RFI

Tests shall be completed per either IEEE Std C37.90.2 or IEC 60255-22-3 as specified.

9.4.1.6.2 Surge withstand capability

Tests shall be completed per either IEEE Std C37.90.1 or both IEC 60255-22-1 and IEC 60255-22-4 (Class A) as specified.

9.4.1.6.3 Surge immunity

Tests shall be completed per IEC 60255-22-5.

9.4.1.6.4 Conducted immunity

Tests shall be completed per IEC 60255-22-6.

9.4.1.7 Devices to be tested

The devices that make up the control system vary depending on the requirements of the user. The requirements for tests per 9.4.1.4 through 9.4.1.6 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 would be both control and the voltage regulator. Since there are no other control conductors connected to the system, there is are no tests per 9.4.1.4 through 9.4.1.6 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 9.4.1.4 through 9.4.1.6 test requirements.)

c) A control mounted remotely with potential device, control, or metering connections to the control device. (Here, all conductors connected to the control, including those to the voltage regulator, would be subject to 9.4.1.4 through 9.4.1.6 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.

9.4.2 Routine tests

9.4.2.1 Applied voltage

The control enclosure circuitry shall withstand an applied voltage of 1.5 kV, <500 Hz from all terminals to ground for 1 min. The test shall be performed with the control front panel totally disconnected from the control enclosure circuitry. After the test, it shall be determined that no change in performance has occurred.

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

9.4.2.2 Operation

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

Annex A

(informative)

Unusual temperature and altitude conditions

A.1 Unusual temperatures and altitude service conditions

Voltage regulators may be applied at higher ambient temperatures or at higher altitudes than specified in this standard, but performance may be affected and special consideration should be given to these applications.

A.2 Effect of altitude on temperature rise

The effect of the decreased air density due to high altitude is to increase the temperature rise of voltage regulators since they are dependent upon air for the dissipation of heat due to losses.

A.3 Operation at rated kVA

Voltage regulators may be operated at rated kVA at altitudes greater than 1000 m (3300 ft) without exceeding temperature limits, provided the average temperature of the cooling air does not exceed the values of Table A.1 for the respective altitudes.

NOTE 1—See 4.3.2 for voltage regulator insulation capability at altitudes above 1000 m (3300 ft).

NOTE 2—Operation in low ambient temperature with the top liquid at a temperature lower than –20 °C may reduce dielectric strength between internal energized components below design levels.

Table A.1—Maximum allowable average temperature of cooling air for carrying rated kVA[a]

Method of cooling apparatus	1000 m (3300 ft)	2000 m (6600 ft)	3000 m (10 000 ft)	4000 m (13 200 ft)
	°C			
Liquid-immersed self-cooled	30	28	25	23
Liquid-immersed forced-air-cooled	30	26	23	20

[a] It is recommended that the average temperature of the cooling air be calculated by averaging 24 consecutive hourly readings. When the outdoor air is the cooling medium, the average of the maximum and minimum daily temperatures may be used. The value obtained in this manner is usually slightly higher, by not more than 0.3 °C, than the true daily average.

A.4 Operation at less than rated kVA

Voltage regulators may be operated at altitudes greater than 1000 m (3300 ft) without exceeding temperature limits, provided the load to be carried is reduced below rating by the percentages given in Table A.2 for each 100 m (330 ft) that the altitude is above 1000 m (3300 ft).

Table A.2—Rated kVA correction factors for altitudes greater than 1000 m (3300 ft)

Types of cooling	Derating factors [% per 100 m (330 ft) above 1000 m (3300 ft)]
Liquid-immersed air-cooled	0.4
Liquid-immersed water-cooled	0.0
Liquid-immersed forced-air-cooled	0.5

Annex B

(informative)

Field dielectric tests

B.1 Tests on bushings

When tests are required on bushings separately from the regulators, the tests shall be made in accordance with IEEE Std C57.19.00™ [B18].

B.2 Dielectric tests in the field

Field dielectric tests may be warranted on the basis of detection of combustible gas or other circumstances. However, periodic dielectric tests are not recommended because of the severe stress imposed on the insulation.

Where field dielectric tests are required, low-frequency applied-voltage and induced-voltage tests shall be used. The line-to-ground or line-to-line voltage stress imposed shall not exceed 150% of normal operating stress or 85% of full test voltage, whichever is lower. The duration of the tests shall be the same as that specified in 8.6.5 and 8.6.6 for applied-voltage and induced-voltage tests, respectively.

Annex C

(informative)

Bibliography

[B1] Accredited Standards Committee C2-2007, National Electrical Safety Code® (NESC®).[c]

[B2] ANSI C84.1, American National Standard Voltage Ratings (60 Hz) for Electric Power Systems and Equipment.[d]

[B3] ASTM D 117, Standard Methods of Testing and Specifications for Electrical Insulating Oils of Petroleum Origin.[e]

[B4] ASTM D 3487, Specifications for Mineral Insulating Oil Used in Electrical Apparatus.

[B5] IEC 60076-4, Power transformers—Part 4: Guide to the lightning impulse and switching impulse testing—Power transformers and reactors.[f]

[B6] IEC 60214-2, Tap Changers—Part 2: Application Guide.

[B7] IEC 61000-4-8, Electromagnetic compatibility (EMC)—Part 4-8: Testing and measurement techniques—Power frequency magnetic field immunity test.

[B8] IEC 61000-4-9, Electromagnetic compatibility (EMC)—Part 4-9: Testing and measurement techniques—Pulse magnetic field immunity test.

[B9] IEC 61000-4-10, Electromagnetic compatibility (EMC)—Part 4-10: Testing and measurement techniques—Damped oscillatory magnetic field immunity test.

[B10] IEC 61000-4-11, Electromagnetic compatibility (EMC)—Part 4-11: Testing and measurement techniques—Voltage dips, short interruptions and voltage variations immunity tests.

[B11] IEEE Std 62™, IEEE Guide for Diagnostic Field Testing of Electric Power Apparatus—Part 1: Oil Filled Power Transformers, Regulators, and Reactors.[g, h]

[B12] IEEE Std 315™, IEEE Standard Graphic Symbols for Electrical and Electronics Diagrams (Including Reference Designation Letters).

[B13] IEEE Std C57.12.00™, IEEE Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers.

[B14] IEEE Std C57.12.20™, IEEE Standard for Overhead Type Distribution Transformers, 500 kVA and Smaller: High Voltage, 34 500 V and below; Low Voltage, 7970/13 800y V and below.

[B15] IEEE Std C57.12.80™, IEEE Standard Terminology for Power and Distribution Transformers.

[c] The NESC is available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, Piscataway, NJ 08854, USA (http://standards.ieee.org/).
[d] ANSI publications are available from the Customer Service Department, American National Standards Institute, 25 W. 43rd Street, 4th Floor, New York, NY 10036, USA (http://www.ansi.org/).
[e] ASTM publications are available from the American Society for Testing and Materials, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959, USA (http://www.astm.org/).
[f] IEC publications are available from the Central Office of the International Electrotechnical Commission, 3, rue de Varembé, P.O. Box 131, CH-1211, Geneva 20, Switzerland (http://www.iec.ch/). IEC publications are also available in the United States from the Sales Department, American National Standards Institute, 25 West 43rd Street, 4th Floor, New York, NY 10036, USA (http://www.ansi.org/).
[g] IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, Piscataway, NJ 08854, USA (http://standards.ieee.org/).
[h] The IEEE standards or products referred to in Annex C are trademarks owned by the Institute of Electrical and Electronics Engineers, Incorporated.

[B16] IEEE Std C57.12.90™, IEEE Standard Test Code for Liquid-Immersed Distribution, Power, and Regulating Transformers.

[B17] IEEE Std C57.13™, IEEE Standard Requirements for Instrument Transformers.

[B18] IEEE Std C57.19.00™, IEEE Standard General Requirements and Test Procedure for Outdoor Power Apparatus Bushings.

[B19] IEEE Std C57.98™, IEEE Guide for Transformer Impulse Tests.

[B20] IEEE Std C57.104™, IEEE Guide for the Interpretation of Gases Generated in Oil-Immersed Transformers.

[B21] IEEE Std C57.106™, IEEE Guide for Acceptance and Maintenance of Insulating Oil in Equipment.

Annex D

(informative)

IEEE List of Participants

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