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IEEE Guide for the Application of Surge Voltage Protective Equipment on AC Rotating Machinery 1000 V and Greater

IEEE Power Engineering Society

Sponsored by the
Surge Protective Devices Committee



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**Surge Protective Devices Committee
of the
IEEE Power Engineering Society**

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Abstract: The application of surge voltage protective equipment to AC rotating machines rated 1000 V and greater is covered. The guide does not cover motors applied in solid-state switched adjustable speed drives.

Keywords: AC rotating machines, coil insulation, generator insulation, groundwall installation, impulse voltage, insulation strength, insulation withstand, motor insulation, surge arrester, surge voltage, surge withstand, turn installation, winding insulation

The Institute of Electrical and Electronics Engineers, Inc.
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Introduction

(This introduction is not part of IEEE Std C62.21-2003, IEEE Guide for the Application of Surge Voltage Protective Equipment on AC Rotating Machinery 1000 V and Greater.)

This guide started with the publishing of an IEEE transactions paper in 1981 by a Working Group of the Rotating Machinery Committee. That paper, "Impulse Voltage Strength of AC Rotating Machines," made a significant contribution to the ease of protecting electric utility rotating machines from surges. The paper indicated that ac machines could be expected to withstand surge fronts of five microseconds with magnitude equal to the crest of the factory test voltage, and could withstand surge fronts as short as 200 nanoseconds with magnitude equal to two times crest line-to-ground rated voltage. At that time, ac machine manufacturers were usually recommending that large motors be surge protected on the grounds that protection was cheap and failure was costly. It was recognized that most of the knowledge was with the manufacturers, not the users. There was little measured data on the actual surge environment experienced by machines, nor was there measured data of actual withstand voltage or voltage to breakdown of machines in service. In addition, a survey of several thousand motors in industrial service showed that few were equipped with surge protection, and there was almost no evidence of failure due to absence of surge protection. A survey by WG 3.4.9 of Surge Protective Devices Committee found (from a small sample of utility installations) that surge protective capacitors were failing at about the same rate as those motor insulation failures that were not caused by overheating. It was also recognized that capacitor leads as usually installed, and even when of quite short lengths, have sufficient inductance to prevent the capacitor from protecting the machine from steep-front surges. Motor starting surge fronts as short as 200 nanoseconds had been measured.

At the instigation of an Edison Electric Institute committee and with electric utility support, the Electric Power Research Institute (EPRI) undertook a research program to investigate the surge environment being experienced by ac rotating machines, and machine surge withstand strength. The effort was directed to understand and be able to predict whether a particular machine was at risk. Both motors and generators were investigated. Particular attention was given to the problem of steep-front surges produced by full-voltage starting of motors (across-the-line). Much of the field and analytical work was contracted by EPRI to Ontario Hydro. By courtesy of EPRI and Ontario Hydro, and at their expense, IEEE transaction papers were prepared to make the substance of their research generally available to the electric power industry and for preparation of IEEE guides.

Concurrent with the EPRI/Ontario Hydro work, the National Electrical Manufacturers Association (NEMA), the International Electrotechnical Commission (IEC), and the IEEE have developed factory surge test standards for some ac machines.

This guide is intended to aid engineers at all levels of surge protection knowledge in deciding whether particular machines should have surge protection. The guide may be used in estimating the surge withstand capability and switching surge exposure of ac rotating machinery in usual, not extreme exposure, installations.

Participants

At the time this guide was completed Working Group 3.4.9 of the PES Surge Protective Devices Committee had the following membership:

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IEEE Guide for the Application of Surge Voltage Protective Equipment on AC Rotating Machinery 1000 V and Greater

1. Overview

Some rotating machines may require surge protection, especially if they are exposed to lightning or capacitor switching, are started frequently, or are critical to a process. The coil insulation of the stator winding of ac rotating machines has a relatively low impulse strength. The insulation consists of groundwall insulation and turn insulation. The groundwall insulation surrounds all the turns in a coil, insulating between the coil and the stator iron. Turn insulation is around each turn so as to insulate between the several turns in a coil. Stator winding insulation systems of ac machines are exposed to stresses due to the steady-state operating voltages and also to steep-fronted surges of high amplitudes. Both types of voltages stress the groundwall insulation. Steep-fronted surges also stress the turn insulation. If the rise time of the surge voltage is steep (0.1 to 0.2 μ s) most of the surge will appear across the line end-coil that is closest to the line terminal. This is a nonlinear voltage distribution that can damage the turn insulation even though the magnitude of the surge is limited to a value that can be safely withstood by the groundwall insulation.

Steep-fronted surges appearing across machine terminals are caused by lightning strikes, normal circuit breaker operation, switching of power factor correcting capacitors, and for motors, starting, aborted starts, bus transfers, and switching windings (or speeds) in two-speed motors. Turn insulation testing also imposes a high stress on the insulation system.

The crest value and rise time of the surge at the machine depends on the transient event taking place, on the electrical system design, and on the number and characteristics of all other devices in the system. These include, but are not limited to the following:

- The machine
- The cables connecting the machine to the switching device
- The conduit and conduit grounding
- The type of switching device
- The length of the connected switchgear bus
- The number of other circuits connected to that bus

Because of the many variables involved, the surge magnitudes and rise times can be unpredictable. Even though surge withstand capability levels are specified for the windings, it may be desirable for critical applications that surge protective devices also be installed at or very close to the machine terminals. These will slope back, i.e., lengthen, the rise time of the incoming surge so it will distribute more evenly throughout the winding. The relatively low impulse strength of rotating machines indicates that they may need their own surge protective equipment even though they may be partially protected from connected exposed overhead line(s) through apparatus (transformers, regulators, reactors, or cables) whose line side is adequately protected by a surge protective device.

1.1 Scope

This guide covers the application of surge voltage protective equipment to ac rotating machines rated 1000 V and greater. The guide does not cover motors applied in solid-state switched adjustable speed drives. This standard, the first part of two parts, covers the insulation surge withstand strength of motors and generators with windings having form-wound multi-turn coils and the application of surge protection to form-wound multi-turn coil motors. The second part will cover application of surge protection to generators with form-wound multi-turn coils, plus insulation surge withstand strength and surge protection of single-turn coil generators and motors.

1.2 Purpose

This guide is intended to aid engineers at all levels of surge protection knowledge in deciding whether particular machines should have surge protection. The guide may be used in estimating the surge withstand capability and switching surge exposure of ac rotating machinery in usual, not extreme exposure, installations. The manufacturer should be contacted for specific insulation surge voltage withstand values for machinery of particular interest or importance.

For those machines that should be protected, the purpose is to provide guidance in selecting and applying the protective devices. A simple look-up method using tables and a graph is provided for quick estimation of surge rise times and surge voltage levels, and for general use where accuracies in the order of 10% to 15% are acceptable. This method is based on single-phase analysis, neglecting the influence of ground mode surge propagation. A more complex method is provided by formulas to model the three-phase and ground mode propagation. The formulas can be used with calculators or personal computers.

2. References

The use of this guide may be aided when used in conjunction with the following standards. When a referenced standard is superseded by an approved revision, the revision shall apply.

EPCC (Electric Power Coordinating Committee, South Africa) Guide for the Application of Switching Surge Suppressors to Medium Voltage Motors, Aug. 1992.¹

IEC 60034-15: 1995, Rotating Electrical Machines, Part 19: Impulse Voltage Withstand Levels of AC Rotating Machines with Form-Wound Stator Coils.²

¹EPCC publications are available from the South African Institute of Electrical Engineers (SAIEE), P.O. Box 93541, Yeoville, Johannesburg, South Africa, 2143, (<http://www.saiee.org.za>).

²IEC publications are available from the Sales Department of the International Electrotechnical Commission, Case Postale 131, 3, rue de Varembe, CH-1211, Genève 20, Switzerland/Suisse (<http://www.iec.ch/>). IEC publications are also available in the United States from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA.

IEEE Std 1TM-2000, IEEE Recommended Practice for General Principles for Temperature Limits in the Rating of Electric Equipment and for the Evaluation of Electrical Insulation.^{3, 4}

IEEE Std 43TM-2000, IEEE Recommended Practice for Testing Insulation Resistance of Rotating Machinery.

IEEE Std 56TM-1977 (Reaff 1991), IEEE Guide for Insulation Maintenance of Large Alternating-Current Rotating Machinery (10 000 kVA and Larger).

IEEE Std 80TM-2000, IEEE Guide for Safety in AC Substation Grounding.

IEEE Std 117TM-1974 (Reaff 1991), IEEE Standard Test Procedure for Evaluation of Systems of Insulating Materials for Random-Wound AC Electric Machinery.

IEEE Std 367TM-1996, IEEE Recommended Practice for Determining the Electric Power Station Ground Potential Rise and Induced Voltage from a Power Fault.

IEEE Std 432TM-1992 (Reaff 1998), IEEE Guide for Insulation Maintenance for Rotating Electrical Machinery (5hp to less than 10,000 hp).

IEEE Std 434TM-1973 (Reaff 1991), IEEE Guide for Functional Evaluation of Insulation Systems for Large High-Voltage Machines.

IEEE Std 522TM-1992 (Reaff 1998), IEEE Guide for Testing Turn-to-Turn Insulation on Form-Wound Stator Coils for Alternating-Current Rotating Electric Machines.

IEEE Std 841TM-2001, IEEE Standard for the Petroleum and Chemical Industry—Severe Duty Totally Enclosed Fan-Cooled (TEFC) Squirrel Cage Induction Motors—Up to and Including 500 hp.

IEEE Std 930TM-1987 (Reaff 1995), IEEE Guide for Statistical Analysis of Electrical Insulation Voltage Endurance Data.

IEEE Std 943TM-1986 (1992), IEEE Guide for Aging Mechanisms and Diagnostic Procedures in Evaluating Electrical Insulation Systems.

IEEE Std 1043TM-1996, IEEE Recommended Practice for Voltage-Endurance Testing of Form-Wound Bars and Coils.

IEEE Std C62.11TM-1999, IEEE Standard for Metal-Oxide Surge Arresters for Alternating Current Power Circuits.

IEEE Std C62.22TM-1997, IEEE Guide for the Application of Metal-Oxide Surge Arresters for Alternating Current Systems.

NEMA Std MG-1-1998, Motors and Generators, Parts 20.87 and 21.90.⁵

³IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (<http://standards.ieee.org/>).

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⁵NEMA publications are available from Global Engineering Documents, 15 Inverness Way East, Englewood, Colorado 80112, USA (<http://global.ihs.com/>).

3. Definitions

For the purposes of this guide, the following terms and definitions apply. *The Authoritative Dictionary of IEEE Standards Terms* [B36]⁶ should be referenced for terms not defined in this clause.

NOTE—The following definitions are purposely not alphabetized. Rather, the terms are arranged in such a way as to facilitate an understanding of the technical relationship between them. The terms proceed in order of technical dependency.

3.1 rated voltage (rotating electric machinery): The rms voltage specified at the terminals of a machine, V .

3.2 rated test voltage (rotating electric machinery): The rms fundamental frequency test voltage specified for the rated voltage, V , of the machine in the standard under which the machine is manufactured.⁷

3.3 per unit (pu): The ratio of the actual value of a quantity to the base value of the same quantity.

3.4 per unit surge voltage (rotating electric machinery): The ratio of a surge voltage crest magnitude to the crest value of the machine rated voltage. For a three-phase machine, the divisor (1pu) is the crest value of the rated phase-to-neutral voltage and equals phase-to-phase rated voltage V times the square-root of two divided by the square-root of three ($V\sqrt{2/3}$).

3.5 local surge (rotating electric machinery): A surge that originates on the same voltage system as the machine with no transformation between.

3.6 remote surge (rotating electric machinery): A surge that originates at least one voltage transformation removed from the machine.

3.7 steep-front surge (rotating electric machinery): A voltage surge having a rise time of less than one microsecond.

3.8 turn insulation (rotating electric machinery): The insulation applied to provide electrical separation between the turns of a coil.

NOTE—In the usual case, the insulation encircles each turn. It is sometimes referred to as turn-to-turn insulation.

3.9 ground insulation (rotating electric machinery): Insulation used to insure the electric isolation of the windings from the core and mechanical parts of a machine. It separates the turn insulation from the surrounding slot steel. Ground insulation is sometimes referred to as coil insulation, or groundwall insulation.

3.10 current zero (rotating electric machinery): That instant when an oscillatory current wave passes through zero magnitude.

3.11 normal interruption (rotating electric machinery): A machine circuit interruption by an interrupting device at a current zero of the fundamental frequency current.

3.12 forced current zero (rotating electric machinery): A current wave in the machine circuit forced to zero by an interrupter at other than a fundamental frequency current zero in the interrupted phase and with a forcing duration of several milliseconds but less than a half cycle of fundamental frequency. Example: current-limiting fuse.

3.13 current chopping (rotating electric machinery): A current wave in the machine circuit forced to zero by an interrupter at other than a fundamental frequency current zero in the interrupted phase and with a forcing duration in the order of microseconds or less. Example: vacuum circuit breaker, or a superimposed high-frequency switching surge current with a magnitude greater than the fundamental frequency current.

⁶The numbers in brackets correspond to those of the bibliography in Annex B.

⁷NEMA MG-1 has for many years specified an effective voltage of 1000 V plus twice the machine rated voltage; $2V + 1000$.

3.14 virtual current chopping (rotating electric machinery): The chopped interruption of current in the machine circuit by a superimposed high-frequency current induced from another phase and with a magnitude greater than the fundamental frequency current in the interrupted phase.

3.15 reignition: A resumption of current between the contacts of a switching device during an opening operation after an interval of zero current of less than 1/4 cycle at normal frequency.

3.16 restrike: A resumption of current between the contacts of a switching device during an opening operation after an interval of zero current at 1/4 cycle at normal frequency or longer.

4. The basic means of machine surge protection

The basic means of protecting machines from surges has been to slow the rate of surge voltage rise by a series circuit of inductance and capacitance, and to limit the voltage that can be impressed on that circuit by surge arresters. The inductance may be only that of the machine leads (supply or output cable) or a transformer. Because the surge is a voltage from phase to ground, the capacitance of the supply or output cable may be only the capacitance to ground, or it may be a surge protective capacitor connected between machine terminals and grounded frame. [B43]

If a constant voltage E_a is suddenly impressed on an inductance L and a capacitance C in series, as in Figure 1, the voltage across the capacitance e_c will be an oscillatory one, oscillating about E_a until the losses in the circuit damp out the oscillations. The period is $T = 2\pi\sqrt{LC}$. It reaches its peak in the time $T/2$. By properly choosing the values of L and C , then a minimum time $T/2$ can be fixed. This alone, however, does not set a limit to the rate-of-rise e_c . The voltage E_a must be limited also. Two values of E_a are shown in Figure 2 to illustrate that if E_a is increased, the rate-of-rise is also increased because $T/2$ remains the same.

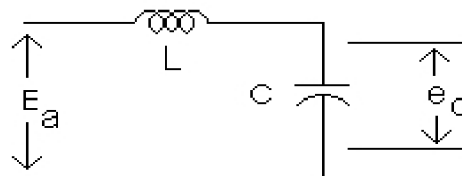


Figure 1—Simple oscillatory circuit

The following three elements are required to limit the rate-of-rise of e_c :

- A capacitance
- An inductance
- A means of limiting E_a

In practice, E_a is fixed by a surge arrester between the surge source and the inductance. The machine is connected in parallel with the capacitance, so that the surge voltage across the capacitor, e_c , is impressed between terminal and machine frame.

These three components do not protect completely. Figure 2 shows that an undamped voltage e_c can rise theoretically to twice the value of E_a by oscillation. In practice, this is not likely because of damping. However, the crest of e_c may exceed E_a by a considerable amount and endanger the groundwall insulation. It will usually be necessary to restrain e_c to a value even less than E_a in order to insure good protection. This is done by applying a second surge arrester, in parallel with the capacitor at the machine terminals. Then, when e_c rises to the discharge voltage of this second arrester, it limits e_c as indicated by the dashed line in Figure 2.

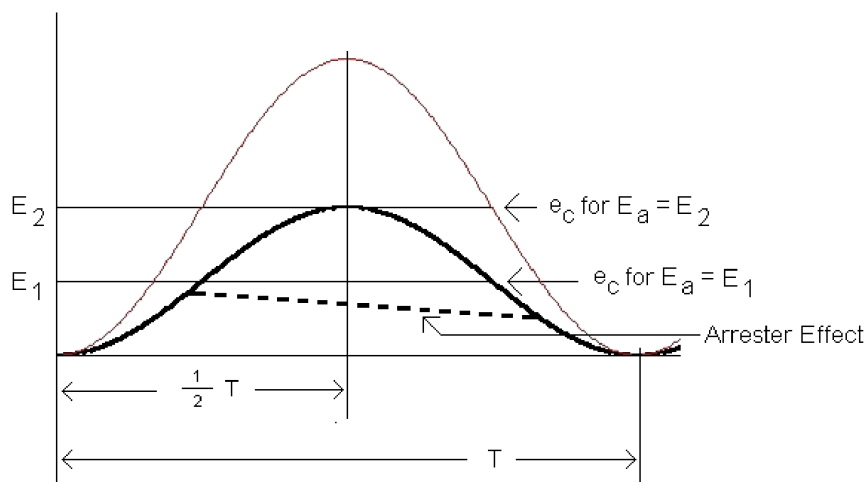


Figure 2—Voltage across the capacitor and as limited by an arrester

4.1 The fundamental protective system

The complete basic protection circuit for rotating machines is shown in Figure 3 [B43]. It consists of four components. Arrester, A_L , limits the incoming voltage. The inductance L and capacitance C lengthen the time to crest and limit the rate-of-rise of the voltage at the machine terminal. Arrester, A_M , limits the magnitude of the voltage from the machine terminal to frame.

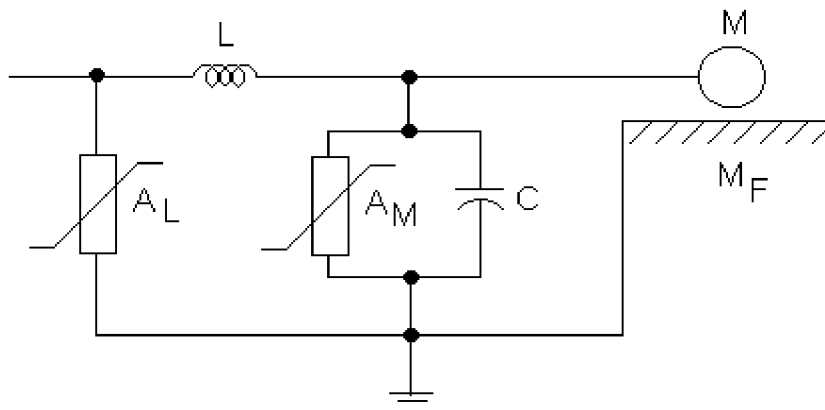


Figure 3—The fundamental machine protective system

The inductance can be a lumped inductance such as a coil or a current-limiting reactor, but is usually a transformer or a length of the incoming line or cable. The capacitance is usually a capacitor, but if the circuits are

in cable, the cable capacitance may be sufficient. The line arrester, A_L , is usually a standard distribution or intermediate class arrester. The arrester at the machine, A_M , is usually one designed especially for this purpose with low discharge voltage. Energy absorption capability has not been a problem for these specially designed rotating machine protection arresters.

The turn-to-turn insulation of most machines newer than 1975 and more than 5000 kVA is designed so that each coil will stand full phase-to-phase rated voltage. However, some smaller motors and older machines were designed for only half this strength. Motors are likely to have had hard usage so that the insulation strength may be impaired. Some motors have as high as 40 turns per coil with 20 turns per coil not uncommon. Turbine generators may have coils with 1 to 3 turns.

The conventional practice prior to 1981 was to lengthen the surge voltage wave front so that the time to reach crest was ten microseconds (10 μ s) or more. This was considered the safe time to reach surge withstand voltage for the machine. Since 1981, a surge front as short as 5 μ s has been accepted as safe for most machines. In the case of modern large machines with one or two-turn coils, surge fronts of three or four microseconds might be safe. However, the extent to which successive impulses may age machine insulation is not known with certainty. The conservative five-microsecond front for all machines is desirable for this reason. It permits a uniform, standardized method of surge protection. There is long experience behind this procedure. Conservatism is advisable in dealing with the protection of machines that may be vital.

The limitation on the rate-of-rise of voltage may be obtained with various combinations of L and C . An accepted practice is to use a lumped capacitance of one-half μ F for machines rated from 2400 to 6900 V, one-quarter μ F between 11.5 to 13.8 kV, and one-eighth μ F for ratings 14.4 kV and above. To achieve 5 μ s rise time, the series inductance (if lumped as in a choke coil or a reactor) should range from 20 μ H at 2400 V to 80 μ H at 14.4 kV.

Caution should be observed in applying surge protective capacitors to achieve slow enough rates of rise. Capacitors are not fully effective in slowing the rise of steep front surges such as may occur during full-voltage starting of motors. This is discussed in 5.9 and 6.1. An example in 6.3.2 illustrates the problem and provides a means for estimating the reduced effectiveness of surge protective capacitors for motor starting surges.

4.2 Risk analysis

An analysis of risk is appropriate when considering whether a particular machine requires surge protection. Such an analysis should usually include the importance of the service provided by the machine or the process; the exposure of the machine to potentially damaging surges; the anticipated machine failure rate and maintenance-inspection schedule; the expected cost of outage and repair; the cost of surge protection; and the expected failure rate of that protection.

In 1989, an IEEE Working Group reported a survey on failures of surge protective capacitors and silicon-carbide arresters on ac rotating machines [B40]. Although the sample size was small, these conclusions appeared valid.

- Three-phase capacitors fail much more frequently than single-phase capacitors.
- The reported motor insulation Mean-Time-Between Failures (MTBF) for failures not caused by insulation overheating is nearly the same as the reported MTBF for single-phase surge protective capacitors [B3].
- Outage time and repair expense would be much less for surge protective capacitor failure.
- No failures of silicon-carbide machine protective arresters were reported.