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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

IEEE

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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

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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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Contents

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 μs) 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]

[1]EPCC 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).

[2]IEC publications are available from the Sales Department of the International Electrotechnical Commission, Case Postale 131, 3, rue de Varembé, 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 1™-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 43™-2000, IEEE Recommended Practice for Testing Insulation Resistance of Rotating Machinery.

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

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

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

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

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

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

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

IEEE Std 841™-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 930™-1987 (Reaff 1995), IEEE Guide for Statistical Analysis of Electrical Insulation Voltage Endurance Data.

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

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

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

IEEE Std C62.22™-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]

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[3]IEEE 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/).

[4]The IEEE standards or products referred to in this clause are trademarks of the Institute of Electrical and Electronics Engineers, Inc.

[5]NEMA 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 as 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.

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

[7]NEMA 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.

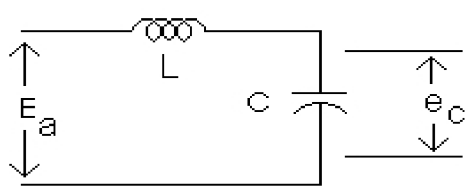

Figure 1—SImple oscillatory circuit

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.

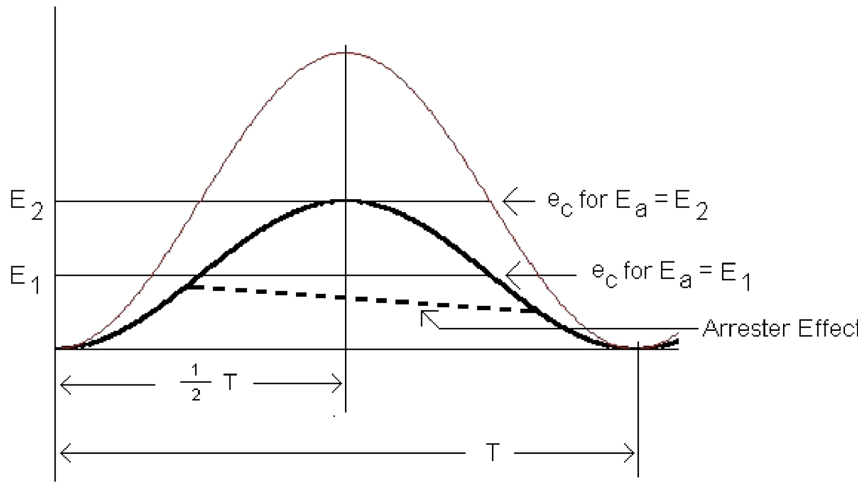

Figure 2—Voltage across the capacitor and as limited by an arrester

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.

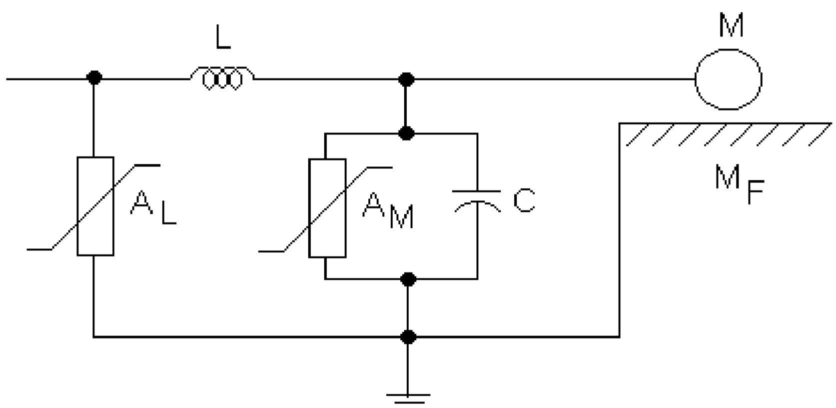

Figure 3—The fundamental machine protective system

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 (10µs) 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 µs 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 µF for machines rated from 2400 to 6900 V, one-quarter µF between 11.5 to 13.8 kV, and one-eighth µF for ratings 14.4 kV and above. To achieve 5 µs rise time, the series inductance (if lumped as in a choke coil or a reactor) should range from 20 µH at 2400 V to 80 µH 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.

4.3 Multi-turn machine impulse voltage withstand strength

The impulse voltage withstand strength of an ac rotating machine is much more difficult to define than it is for a static piece of equipment, such as a power transformer or circuit breaker. The insulation on the windings of the ac rotating machine is limited by space, performance, and economy. The insulation is not immersed in oil; it is dry due to space limitations. Because of the limit on the amount of insulation that can be used, there are two areas of vulnerability in the insulation mechanism. They are as follows:

a) The voltage stresses between the winding and the frame. The magnitude of the voltage surge must be controlled to limit the stress to less than the ground wall withstand strength.

b) The voltage stresses produced between the individual turns in a single coil. The rate-of-rise of the surge is the critical factor in causing this stress. The rate-of rise must be controlled to limit the turn-to turn stress to less than the turn insulation withstand strength.

4.3.1 Source basis for guide

Industry has tried to define the surge insulation strength of ac rotating machines based on these vulnerabilities. Because of the uncertainty in determining the surge insulation strength, until recently there has been little uniformity in the industry for insulation coordination involving ac rotating machines. Numerous papers have been written on the subject. The following material on rotating machine insulation surge withstand strength has been taken from several sources. These sources are:

— IEEE Working Group paper "Impulse Voltage Strength of AC Rotating Machines" [B39]

— NEMA MG-1-1998, parts 20.87 and 21.90 [8]

— IEEE Std 522-1992

— IEC 60034-15: 1995, part 19

— Three papers by Ontario Hydro Research for an EPRI research project on motor steep-front switching surge withstand strength [B21], [B22], [B23].

The material presented in this guide may be used to aid in estimating the surge withstand capability and switching surge exposure of ac rotating machinery in commonly found installations. The manufacturer should be contacted for specific withstand values for machinery of particular interest or importance.

In 1981, an IEEE Working Group paper addressed the impulse voltage strength of ac rotating machines [B39]. That paper was followed by inclusion of machine manufacturer's surge voltage withstand tests in standards such as NEMA MG-1-1998 and IEEE Std 522-1992 (see 4.3.2). Reference [B39] is more conservative than this Guide. Reference [B39] preceded the research upon which much of this guide is based. Reference [B39] indicated a need for surge protection in applications where machines were being operated without protection with little evidence of failures due to surges. It is summarized here because it has been a basis for surge protection recommendations for several decades. Reference [B39] states that AC rotating machines having form-wound coils of multi-turn construction have the capability to withstand impulse voltages whose fronts and amplitudes lie below the envelope of Figure 4.

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

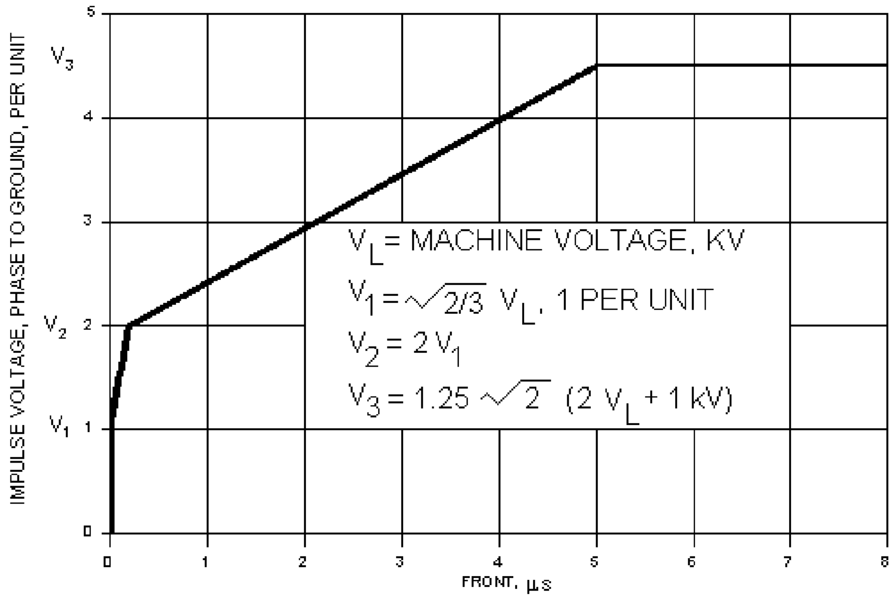

Figure 4—Impulse voltage withstand envelope of 1981 IEEE paper [B39], superseded by standard tests

The three critical points in this figure are defined as follows:

V_3: For surges with front times of five microseconds or longer, the winding insulation can withstand 1.25 times the crest of the fundamental-frequency factory test voltage; that is,

$$1.25(2V_L + 1\text{kV})\sqrt{2}$$

V_2: For surges with front times of two hundred nanoseconds (200 ns), the winding insulation can withstand 2 times the crest phase-to-ground rated voltage.

V_1: For a surge with a front time of zero seconds (0 s), the winding insulation can withstand only the crest phase-to-ground rated voltage.

The envelope in Figure 4 was meant to represent the level of phase-to-ground surge voltage that all machine windings could safely withstand. It was applicable to all machines regardless of size and age. It was not intended to represent the insulation breakdown voltage curve.

Subsequently a number of investigations and reports have been prepared on machine breakdown voltage and the probability of breakdown ([B7], [B8], [B9], [B17], [B18], [B21], [B29], [B31], [B47], [B49], [B55], [B58], [B65], [B70]). Another area of research, which was funded in 1987 by EPRI, addressed the probability values of surge voltage peak and rise-times [B56], [B57]. The project purpose was to study problems experienced on a significant number of large ac motors. The project scope included the generation of surges by circuit breaker closing or opening, the propagation of these surges to the motor, surge distribution within windings, and comparisons with the rated withstands of motors.

The findings of this research indicate that the guidelines of [B39] concerning insulation strength are quite conservative. For example, the report [B56] suggests that the insulation withstand strength for a one hundred nanosecond front surge may be 5 pu rather than the 1.5 pu of the [B39] guidelines

Several conclusions of the EPRI report are worth noting. First the insulation withstand of a machine is unique. All machines are not identical; however, they may be grouped by type. Insulation withstand is a function of the insulation system. Another critical conclusion is that the impulse voltage stress is a function of the following:

a) Inter-turn capacitance
b) Turn-to-ground capacitance
c) Reflection coefficient at the coil exit
d) Turn insulation thickness
e) Groundwall insulation thickness
f) Lengths of slot section and overhang section
g) Relative permittivity of coil insulation
h) Number of turns in coil
i) Winding configuration—coil groups and parallels, geometry

This implies that the standardized surges that are sometimes used in design studies are too ideal. The overall conclusion of the EPRI report is that most medium-voltage ac machine windings have turn insulation strong enough to withstand most of the surges that will usually be encountered. Therefore, IEEE Working Group paper [B39] is a quite conservative guide for minimum voltage surge withstand capability. The recent EPRI funded work on ac rotating machine insulation surge withstand strength and insulation coordination has been published in a series of IEEE papers. These serve as the basis for the analysis and application considerations presented in the remainder of this guide, references [B18], [B19], [B21], [B22], [B23], [B24], [B25], [B29], [B30], [B31], [B32], and [B33]. Other useful papers concerned specifically with motors are [B8], [B9], [B16], [B26], [B54], [B55], [B62], [B63], [B64], [B65], [B70], and [B72].

4.3.2 Voltage withstand tests

At the time the IEEE Working Group paper [B39] was published in 1981, the only standard voltage test for motors was the fundamental frequency test. This test is for *steady-state voltage withstand*. The test is one minute of fundamental frequency at twice rated (phase-to-phase) voltage plus 1000 V. Since 1981, NEMA, IEEE, and IEC have established standard tests to prove the *surge withstand strength* of motors. The surge voltage test consists of two tests, one to test the groundwall insulation and the other to test the turn-to-turn insulation.

From NEMA MG-1—Stator windings of ac machines, unless otherwise specified, shall be designed to have a surge withstand capability of 2 pu (per unit) at a rise time of 0.1 to 0.2 μs and 4.5 pu at a rise time of 1.2 μs or longer. One pu is the crest of the rated motor phase-to-ground voltage, which is as follows:

$$1\ \text{pu} = V_{P-P}\sqrt{2/3}$$

When higher surge capabilities are required, the windings shall be designed for a surge withstand capability of 3.5 pu at a rise time of 0.1 to 0.2 μs and 5.0 pu at a rise time of 1.2 μs or longer. This higher capability shall be by agreement between the customer and the manufacturer.

From IEEE Std 522-1992—The overall surge withstand strength of coil insulation in a machine can be defined as follows:

a) Groundwall and turn insulation sufficient to withstand an impulse voltage waveshape falling within an envelope bounded by straight lines between three points on a linear plot with ordinate in per-unit volts and abscissa in microseconds.
   - 1.0 pu volts at front rise time of 0.0 microsecond
   - 3.5 pu volts at front rise time of 0.1 microsecond
   - 5.0 pu volts at front rise time of 1.2 microsecond or longer

b) For testing turn insulation, the rise time of applied impulses should be between 0.1 and 0.2 microsecond. However, if agreed between the manufacturer and user, the impulse envelope described below may be used for testing coils designed for machines that are not likely to be exposed to high magnitude steep fronted surges.
   - 1.0 pu volts at front rise time of 0.0 microsecond
   - 2.0 pu volts at front rise time of 0.1 microsecond
   - 4.33 pu volts plus 1.76 kV (nearly 4.5 pu) at front rise time of 1.2 microsecond or longer

IEC 60034-15: 1995 specifies the following two tests:

a) For the "Ground Wall Insulation BIL (Basic Impulse Insulation Level in IEC terminology): the Wave Shape = 1.2/50 μs, and the wave crest voltage = BIL; where the BIL is:

$$\text{BIL} = 4V_L + 5\text{ kV}$$

where

V_L = rated voltage

b) For the Turn Insulation: Wave Shape = Oscillatory, First crest front time = 0.2 μs, tolerance = +0.3 and –0.1 μs, crest voltage = 0.65 BIL" The IEC "front time" is about 1.25 times the NEMA "rise time."

Table 1—Equivalent surge strengths for rise times 1.2 μs or longer by present standard tests for commonly used motor voltages

Rated Volts	NEMA withstand	IEC BIL
2400	9 kV	15 kV
4160	15 kV	21 kV
13800	51 kV	60 kV

5. Sources of surges

5.1 General

The surge environment for an electric machine is as varied as its application and connection within the electric system. This guide outlines sources of surges resulting from lightning, switching, and faults that are potentially damaging to the machine insulation. Wave fronts of duration longer than five microseconds generally produce uniform turn-to-turn stresses on multi-turn machine insulation systems and are less severe than steep wave fronts. However, the crest magnitude of voltage, whether fast or slow front, must be controlled to below the machine ground-wall insulation withstand strength [B39]. The characterization of the surge environment is useful in order to determine the mitigation methods that should be employed and the protection, if any, that will be required.

A 1986 IEEE survey of data for more than 6000 motors and 65 utilities indicated an average failure rate of 3.12% per year, with 26% of the failures involving groundwall or turn insulation. The remaining non-insulation causes of failures were bearings (41%), rotors (9%), and other causes (24%). The 26% of failures by insulation may not be large when compared with the remaining causes of failure. However, insulation failure may be the result of many different possible causes, making diagnosis and correction of the problem difficult.

5.2 Remote and local origin surges

The origin of a disturbance can be significant because of the amount of surge attenuation and sloping of the wave front, or lack thereof, that may have occurred when the surge arrives at the electric machine terminals. Surges arriving through the external electric supply system will usually be attenuated and modified by the intervening transformers and cables. The surge transfer through a transformer will, because of electrostatic and electromagnetic coupling, produce an oscillatory waveform that may excite natural frequencies in the connected machine supply system. Motor supply cable construction, shield and raceway bonding, and grounding techniques are capable of modifying the incoming surge. [B22], [B23], [B62]. Surge propagation velocity, reflection coefficients, and attenuation losses are affected by the cable geometry, cable materials, and shield configurations.

In this guide, remote surges are those surges occurring at least one voltage transformation removed from the electric machine. Lightning direct strokes to phase conductors, transmission line insulator back flashover, ground potential rise, and capacitor bank switching are typical surges of remote origin.

Local surges, those occurring on the machine voltage system, are important since there may be little, if any, attenuation or sloping of the incoming surge front. Circuit breaker pole timing, current chopping, virtual chopping, prestrikes, and multiple reignitions are significant factors that influence the magnitude and rate-of-rise of surges seen by the connected machine.

5.3 Remote origin surges

5.3.1 Faults and operating conditions

Electric system faults and certain operating conditions can produce transient overvoltages harmful to machine insulation. Restriking ground faults may also impose severe stresses on the insulation system. Faults caused by an insulation failure external to a machine can create steep front surges. Surges with steep fronts or voltage crests of high magnitude, when not attenuated and modified by intervening transformers, switchgear and cables, can impose severe stress on machine insulation systems. Remotely originated surges will be reduced at distribution switchgear by the paralleled surge impedances of multiple outgoing circuits. Faults remote from an electric machine may cause damped resonating overvoltages with the natural frequency of the electric machine system. Sustained ferroresonant overvoltages can occur with connected instrument voltage transformers and distribution transformers with unequal switch pole closing [B60].

5.3.2 Lightning

Direct exposure to lightning is limited for most electric machines because of their location, usually within a plant, building, or area shielded by taller objects. However, a lightning strike to an external supply circuit or to a nearby building tower or earth may expose the machine insulation system to damaging surges impinging on the winding, or by ground potential rise [B34].

5.3.3 Machines within a plant

Machines installed properly within a plant and well shielded from lightning can still be exposed to surges of remote origin through the phase and ground conductors, and also by ground potential rise (GPR) of the station ground grid. The phase conductor surge transfer through a transformer will have electrostatic and electromagnetic coupling and may produce an oscillatory waveform. Of these, the electromagnetic surge transfer is usually the most important to motors. Low secondary surge impedances of 100 Ω or less or secondary capacitances of a few thousand picofarads should essentially eliminate the electrostatically transferred voltage.

5.3.4 Surges transferred through local transformer

The winding and grounding connections of the transformer will affect the magnitude of the surge magnetically coupled into the secondary winding (see Table 2). Table 2 applies to microsecond rise time components of surges and assumes no attenuation or wave front lengthening by the transformer. For single-phase surges through 2-winding transformers, the crest voltage of the secondary surge, E_2, is equal to N times K times the crest of the surge voltage at the primary, E_1, i.e., ($E_2 = N K E_1$), where N is the ratio of secondary phase-to-phase voltage to primary phase-to-phase voltage and K is given in Table 2. (See Hileman [B35].)

Table 2—Single-phase surge magnetic coupling through 2-winding transformer From [B35]

Primary connection	Secondary connection	K for ($E_2 = N K E_1$)
Y grounded	Y grounded	1
Y grounded	Y ungrounded	2/3
Y grounded	Delta	$\sqrt{3}/2$
Y ungrounded	Y	2/3
Y ungrounded	Delta	$1/\sqrt{3}$
Delta	Y grounded	$1/\sqrt{3}$
Delta	Y ungrounded	$1/\sqrt{3}$
Delta	Delta	2/3

For magnetic transfer of two-phase surges and surge transfer through 3-winding transformers, see Hileman, [B35].

5.4 Surges from faults, local origin

Insulation failure anywhere on the same voltage system as a rotating machine can create very steep front surges that may reach the machine with little attenuation. Such insulation failures may occur within another machine, in the leads to a machine, or in the switchgear or other equipment served from the same voltage system.

5.4.1 Machine insulation failure, end-turn insulation fault

Turn insulation breakdown may be caused by a "fringing" ac electrical stress (partial discharges) in the end-winding area for several centimeters away from the slot. Failure of the turn insulation can result in large circulating currents through the faulted coil. Steep-front surges in excess of 8 pu may be required to puncture reasonably good insulation [B70].

Repeated surge voltages stressing single turns or the line-end coils are responsible for some machine insulation failures [B47]. Insulation breakdown may also be a result of inadequate insulation system design and/or manufacturing procedures rather than steep-fronted surges.

5.4.2 Machine insulation failure, internal stator turn winding fault

Power frequency electrical stress may also occur further away from the slot at bracing points between turns in different phases [B70]. Failure of the turn insulation between two phases results in an abnormal field distribution within the machine and in the flow of large transient stator currents exceeding 10 pu while operating at full load and rated power factor. In addition, the asymmetrical connection due to the fault leads to the flow of very high negative phase sequence currents in the stator winding, and consequently also in the rotor damper winding system. A ground wall insulation puncture may result, causing a forced outage of the machine.

5.4.3 Local ground potential rise (GPR)

When a ground fault occurs, the zero-sequence fault current returns to the power system ground source through the earth and also through alternate paths such as neutral conductors, counterpoises, and metallic cable shields [B69]. The ground sources are the grounded, wye-connected windings of power transformers, generator grounds, shunt capacitors, frequency changers, etc. The GPR is the product of the following:

a) The total ground grid impedance at the ground source (substation, electric generating station)

b) The total fault current that flows through the ground grid impedance

For additional information on GPR, see IEEE Std 80-2000, IEEE Std 367-1996, and [B34].

Because a machine is bonded to the ground grid, the frame will be close to the GPR voltage during a ground fault on the machine-voltage system. If, during the fault, a surge arrives over the machine supply cables, the groundwall insulation may be stressed by the sum of the surge and GPR voltages. This is not a likely occurrence. It is not usually considered in the surge protection of a machine.

5.5 Switching surges, local origin

The most frequent and perhaps the most common cause of stress on motor insulation systems are local switching surges. Some motors are switched frequently, i.e., several times a day, and may be located in electric systems exposed to many nearby switching activities. The switching surge exposure is an important consideration in the motor design and application [B60]. Unequal breaker pole closing, prestrikes, reignitions, restrikes, and current chopping are serious threats to motors, not because of high overvoltages but because of the steep fronts and stress on turn insulation [B21], [B22], [B23], [B62]. High-speed bus transfers may also produce switching surges, which should be considered.

5.6 Historical background, motor starting surges

The basic traveling wave lattice diagram approach for tracing a surge between the circuit breaker and the motor, dates back to the 1930s. Boehne measured the surge impedance of machines from the voltage drop they produced in sources of known impedance [B11]. The results were high by today's standards—about 1000 Ω. When compared to motor cable impedances of 20 Ω to 40 Ω, it was clear that the lightning surges he was considering would almost double at the machine. He also recognized the sensitivity of inter-turn stress to the surge rise time. Surge rise times for lightning had been determined by the late 1920s.

Calvert shifted the focus to circuit closing switching surges [B14]. Calvert redefined the surge rise time, which he related to inductance near the switchgear. Rudge measured the impedance of several more machines and found rather lower values, about 200 Ω per parallel path [B67]. He suggested that impedance should scale in proportion to the number of turns per coil, since the coil inductance varies with turns squared while the coil capacitance is largely independent of turns. As a final highlight of the depression years, Schelkunoff developed the theory for copper losses in coaxial cables. This would later be needed to calculate the rise time of surges in long cables [B67].

In the 1950s, Abetti suggested a new way to estimate machine surge impedances based only on nameplate HP and kV [B1]. Fourmarier recognized the larger surges occurring on second pole closing arising from phase-to-phase voltage and the transient remaining from first pole closing [B27]. Baltensperger described and tested the voltage escalation mechanism related to multiple reignitions when opening inductive circuits [B10].

Within the last 20 years, Smith published data for many machines validating Abetti's empirical impedance formula [B69]. Breien and others studied characteristic propagation losses in the cable conductor, the bus, and the switchgear, using low voltage, synthetic and full power tests [B13]. Bacvarov, under EPRI funding, explored methods to calculate the probability of approaching the worst case surge level [B7].

Many references from the early 1970s to the present have studied voltage escalation in vacuum devices on opening such as [B4], [B28], [B30], [B41], [B44], [B47], [B51], [B52], [B59], [B64]. It has been demonstrated that surge levels can, as a worst case, reach 5 pu to 10 pu, which is well beyond the withstand capability of motors. The probabilities of such levels occurring are apparently low, but few general guidelines have emerged to assist the system designer in deciding whether or not to specify arresters or surge capacitors. When capacitors were considered unnecessary, it was probably related to ignorance of the escalation process and its dependence on the particular machine, with the usual installation configuration of small-size motors promoting escalation. The above references are some of the literature covering the surge environment of motors due to switching. For more complete listings, see Annex B and [B37].

5.7 Surges during de-energizing motors

De-energizing motors can produce surges that may adversely affect motors under certain conditions, such as when the motor is de-energized before it has come up to speed (aborted starts) or when a vacuum breaker is used to do the switching. When air-magnetic switchgear is used to de-energize a motor that is running under normal operating conditions, no significant surges are produced [B54]. This is true because the back emf of the motor after it is disconnected does not immediately go out-of-phase with the source side voltage. Therefore, the recovery voltage across the breaker is not severe and restrikes do not usually occur. However, when a breaker is tripped before the motor comes up to speed, the back emf is low and the recovery voltage can be severe. Thus, restrikes are likely to occur causing severe surges. These surges can have magnitudes above 2.7 pu with front times of 1 μs or less [B54].

When vacuum breakers are used to switch motors, several problems can occur such as current chopping, virtual current chopping, and multiple reignitions. Current chopping is the forcing of a premature current zero by the switching device. When the load being switched is inductive, the energy stored in the magnetic field at the time of the forcing of a current zero is converted to energy stored in an electric field. If the capacitance of the system is low, this can result in quite high surge voltages. The surge voltage magnitude is proportional to the amount of current chopped and to the surge impedance of the circuit on the load side of the vacuum breaker. The current chopping performance of vacuum breakers has been improved by the development of new contact materials, such as chromium-copper, which chop and interrupt at lower currents. Published data indicate that current chopping overvoltages to ground during switching of normal motor load current do not exceed 3 pu when the vacuum breaker has chromium-copper contacts [B71].

Virtual current chopping occurs because of the ability of vacuum breakers to interrupt at high-frequency current zeroes. When the first phase of a vacuum breaker opens, it is possible to get a reignition or restrike of the current in that phase. This can produce a high-frequency current oscillation in the other two phases that have yet to interrupt. If the superposition of the high-frequency current onto the 60 Hz current results in the total current passing through zero in one of these other phases, then that phase may interrupt. This is very much like chopping the fundamental frequency component of current.

The amount of current that can be virtually chopped is larger than the amount of current that is chopped during normal load current chopping. The surges produced can be severe if a number of parallel load feeders are on-line on the same supply bus [B71]. However, if the surge impedance upstream of the breaker is high or equal compared to the load side, the virtually chopped surges are comparable to or somewhat larger than those produced by normal current chopping [B54]. This phenomenon generally has a low probability of occurrence.

Multiple reignitions in a vacuum breaker are a relatively infrequent occurrence that may result from certain combinations of inductance and capacitance in the circuit. A vacuum breaker can interrupt on the first high-frequency oscillation current zero after the contacts have parted. Therefore, the contacts may still be close together and the dielectric withstand of this small gap may be relatively low. If the system recovery voltage builds up fast, a reignition may occur. When the arc is reestablished, it will not extinguish until the next current zero. This may happen quite quickly because the vacuum breaker is a good interrupter at high-frequency current zeroes. When the arc is extinguished, the contact gap may still be small. Another reignition of the opposite high-frequency polarity may occur. This can be repeated. The surge voltages due to reignitions can build up with each succeeding reignition. The front times of such surges can be short (steep fronts) and can damage motor turn insulation. It is the steep fronts caused by the high frequency with reignition amplification that are likely to puncture turn insulation, rather than just high voltage [B61], [B62], [B64], [B70].

Because some vacuum circuit breakers and interrupters may create high voltages by chopping, prestrikes, or restrikes, some manufacturers have equipped vacuum switchgear with surge limiting arresters on the switchgear bus or on the load side of each outgoing interrupter. For protection of switched machines, the arresters should be on the machine circuit rather than on the bus.

5.8 Full-voltage motor starting, prestrike voltage

A primary source of steep-fronted surges that a motor must repeatedly withstand is the closing of a breaker or contactor to energize the motor. When electrical conduction is established between the closing line and load contacts in an energizing breaker or contactor, the voltage across the contacts just prior to electrical conduction causes a traveling wave or surge to propagate toward the motor at the instant of conduction. The pre-conduction voltage across the contacts is referred to as the prestrike voltage. A recent investigation by EPRI [B21], [B23] has quantified the probability of obtaining prestrike voltages of various magnitudes. This research concentrated on the effect that the closing of a breaker pole has on the prestrike voltage of the next pole to close. When the first pole closes, a surge propagates to the motor and is coupled onto the other two phases with a natural frequency overswing, which is typically 75%. The open poles of the other two phases isolate these winding phases from the supply until those poles establish conduction. The overswing can increase the prestrike voltage of the second pole to close. Likewise, when the second pole closes, the resulting surge can increase the prestrike voltage on the third phase.

In this research project, several motors were tested to develop three-phase equivalent circuit models for the transfer of a surge from the phase that was closed to the other phases. From a consideration of the point on the 60 Hz voltage wave that the first pole may close, it was determined that the maximum prestrike voltage for the second pole to close could be as high as 2.41 pu of peak phase-to neutral voltage, see Clause 3. A similar consideration determined that the maximum prestrike voltage for the third pole to close could be as high as 2.82 pu.

These maximum prestrike voltages result from particular combinations of pole closing times. They do not occur every time a breaker is closed to energize a motor. The research effort quantified the probability of obtaining various magnitudes of prestrike voltage for the second pole to close and the third pole to close. This approach is probabilistically dependent upon the time of closing on the 60 Hz wave. It is a probabilistic worst case determined from the time constants of the empirically derived equivalent circuit.

These probabilities are given in graphical form in Figure 5. The probability of obtaining the maximum possible prestrike voltage of 2.82 pu is one chance in a million. For a motor switched daily over a period of 30 years, approximately 10 000 events, it is probable that a prestrike voltage as large as 2.73 pu may occur. This is within 3% of the maximum value of 2.82 pu. For motors switched weekly over thirty years, or switched monthly over thirty years, the probable maximum prestrike voltages are 2.65 pu, and 2.45 pu respectively. Therefore, for motors switched frequently or daily, a prestrike voltage of 2.82 pu is a reasonable value on which to base surge protection design.

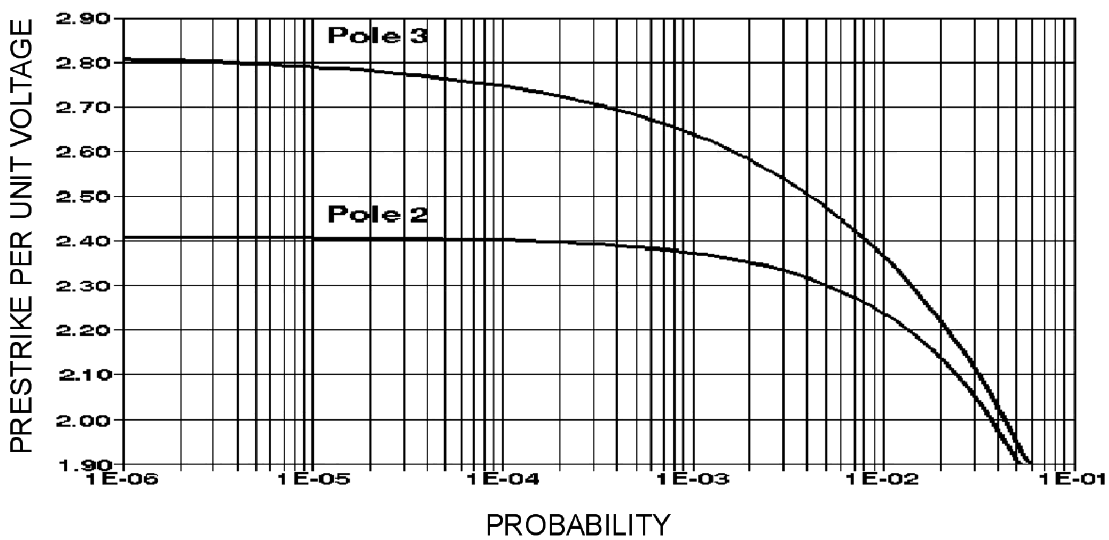

Figure 5—Breaker second and third pole closing prestrike per unit voltage versus probability

Once the maximum breaker prestrike voltage is selected, the voltage magnitude and rise time at the motor can be calculated. The EPRI research also proposed an equivalent circuit [B22], of which Figure 6 shows one phase. This circuit can be used to calculate the voltage magnitude and rise time at the motor [B23]. The voltage source V_p is the selected maximum breaker prestrike voltage. The resistor R_s represents the paralleled surge impedances of all other source and load cables connected to the bus from which the motor is being energized. $R_s = (Z_c/n)$ where n is the number of supply and load cables connected to the switchgear bus and Z_c is the cable surge impedance. The length of metal clad switchgear bus and breaker wiring is represented by the inductance L_s, which is usually several microhenries [B22] (see A.2 for typical values). The cable connected to the motor is represented by its surge impedance Z_c and its propagation time. The motor cable surge impedance Z_c may have both line and ground components similar to 60 Hz positive and zero sequences. The initial surge V_s, which propagates toward the motor, has an exponential wave shape with a time constant determined by $L_s/(R_s + Z_c)$. For L_s, see Annex A, Equation A.14 and Equation A.15. The initial surge magnitude is a proportion of the breaker prestrike voltage as determined by the voltage divider formed across the source surge impedance and the cable surge impedance, i.e., $V_s = V_pZ_c/(Z_c + R_s)$. R_s will be much smaller than Z_c when there are several other loads connected to the bus. Consequently, the magnitude of the surge V_s propagating toward the motor will usually be nearly equal to the prestrike voltage V_p.

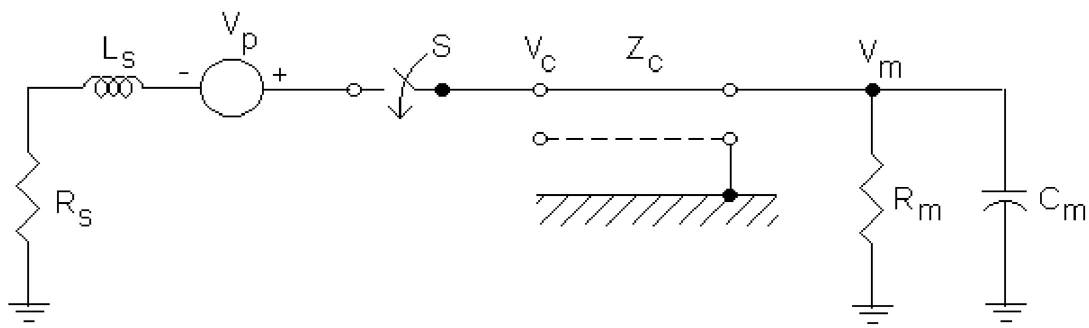

Figure 6—General equivalent single-phase circuit for modeling surge propagation from breaker to motor

The surge rise time is increased by time constants associated with L_s / (R_s + Z_c) and Z_c C_m, where C_m is the motor winding capacitance. To approximate C_m see the discussion in Annex A following Equation A.8, or to calculate C_m see Equation A.18. Note that a decrease in Z_c (for example due to replacing unshielded cables with shielded types), has opposite effects on these time constants. Thus the surge will become steeper only if Z_c C_m is the dominant time constant. Other time constants can be related to dielectric, skin effect, and semi-conductive layer losses in the motor supply cable. The overall rise time is approximated by the sum of these time constants.

Figure 6 may be helpful to understand the way a surge propagates from V_p to V_m. For cable shields grounded only at the motor end as shown in Figure 6, an external component also propagates between the shield and ground. Shields or conduits grounded at only one end may split away part of the surge. After several reflections, this component is shorted to ground and the motor voltage increases, but not in time to contribute to the steep-fronted surge if the cable is longer than about 30 m. For cable shields grounded only at the supply end, a similar splitting takes place at the motor end.

The other elements in the equivalent circuit represent the motor. The capacitor C_m represents one half of the capacitance to ground of the line end coil plus any surge protective capacitor. The resistor R_m represents the equivalent loading resistance of the motor. (See Annex A for formulas for calculating R_m and C_m.) The surge impinging on the motor terminals at the end of the cable will have a longer rise time by the effect of the capacitance C_m. The relative magnitudes of the cable surge impedance and the motor loading resistance determine the surge reflection coefficient and the magnitude of the voltage at the motor.

The worst-case maximum prestrike voltage is a phase-to-ground voltage, which propagates toward the motor and is all or partially reflected back toward the circuit breaker. If the reflection coefficient were 1.0, and if the surge were not reduced by cable shield grounding or coupling to an adjacent cable, the impinging surge would double at the motor terminals. If the reflection coefficient were less, e.g., 0.7 or 0.5, the surge crest at the motor terminals would be 1.7 or 1.5 times the impinging surge.

When the third pole closes a few microseconds after the first pole, the third pole will be at a negative polarity fundamental frequency voltage of –0.71 pu. The first pole voltage will have overswung to a plus polarity of between 1.75 pu to 2.11 pu due to natural frequency oscillation [B21]. When the third pole gap breaks down to conductive contact a negative surge is produced equal to the voltage difference between poles. It is this negative polarity surge of 2.45 to 2.82 pu that impinges on the motor terminals and is reflected.

The surge at the motor terminals results in stress across the turn-to-turn insulation and across the ground wall insulation. The surge at the motor terminal is the sum of the impinging and reflected surge. If the surge front is steep, a rise time much less than a microsecond, most of the surge will be impressed across the turns of only the first coil. If the front is slower, a rise time of several microseconds, the total surge voltage at the terminal will distribute more uniformly through the windings of the motor, and the turn-to-turn stress will be less.

The stress applied to the ground wall insulation will be the sum of the instantaneous fundamental frequency voltage (positive polarity) plus the natural frequency overswing (positive polarity) and the negative polarity surge plus reflection. If a surge of 2.82 pu doubled to 5.64 pu, the ground wall stress would be 3.53 pu, (2.82 × 2 – (2.82 – 0.71)). If the surge reflection coefficient were only 0.5, then the ground wall stress from a 2.82 pu surge would be reduced to 2.12 pu, (2.82 × 1.5 – (2.82 – 0.71)). Usual sizes and constructions of motor cable leads yield cable surge impedances over the range of 15 to 43 ohms. Motor loading resistance R_m may vary from 80 to 800 ohms. Consequently, the reflection coefficient may vary from 0.35 to 0.96 if unmodified by cable shield or raceway grounding.

If surge protective design is based on a less frequently started motor (monthly) with a probable maximum prestrike voltage of 2.45 pu, and a terminal reflection coefficient of 0.75 (cable Z_c = 30 ohm, and motor R_m = 210 ohms), the turn insulation stress would be 4.9 pu (2.45 × 2). The ground wall stress would be 3.16 pu, ((2.45 × 2) – 2.45 – 0.71).

5.9 Limitations of surge capacitor protection

It has been observed that surge capacitors have limited effect in significantly reducing an initial steep front rate-of-rise of voltage at a machine terminal. With a prestrike voltage of greater than 2.5 pu and a front time of 100 ns, the *dV/dt* is 25 pu/µs. For a medium-voltage machine, the available capacitor value is 0.5 uF. The capacitor internal inductance of bushing to ground plane will be about 0.5 uH. Capacitor leads with inter-phase spacing from 0.20 m to 0.45 m will have lead inductance between 0.82 and 0.98 uH/m. A capacitor circuit with one meter leads will have a natural frequency of 185 kHz, which is a quarter cycle front of 1.35 µs. The 100 ns voltage steep front is 13 times as fast. The *L dI/dt* of the capacitor internal and lead inductance will block the current flow into the capacitor and cause most of the voltage front to appear across the machine terminals. It will appear as a 100 ns initial peak on the front of a slower rising voltage controlled by the longer time constant of the supply cable, capacitor and machine inductance. Figure 7 from [B42] illustrates the effect as described. The example in 6.3.2, and Figure 9 through Figure 12 provide a means for estimating the magnitude of the initial sub-microsecond peak voltage.

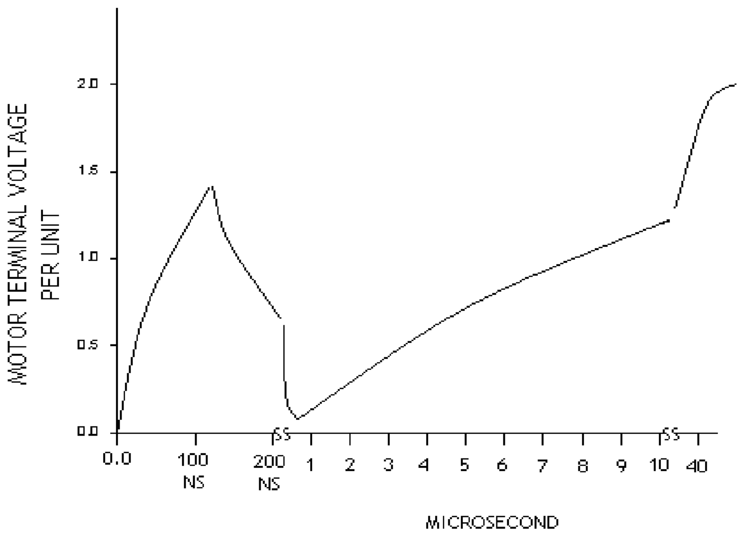

Figure 7—Volt-time plot of sub-microsecond peak caused by capacitor lead and internal inductance
100 ns ramp front, R = 20 Ω, L = 2.5 μH, C = 0.5 μF

6. Motor surge protection

Steep-fronted surges appearing across motor terminals may be caused by lightning strikes, circuit breaker prestrikes and re-strikes, motor starting, aborted starts, bus transfers, switching windings (or speeds) in two-speed motors, or switching of power factor correcting capacitors. Turn insulation testing itself also imposes a high stress on the insulation system [B16], [B21], and [B48].

6.1 Reasons for surge protection of motors started across-the-line (full-voltage start)

Although surge withstand capability levels must be specified for the windings, it is desirable, because of the unpredictable nature of the surge magnitudes and rise times, that for critical applications surge protective capacitors and gapless metal-oxide surge arresters (MOSA) be installed at or very close to the motor terminals. These will lengthen the rise time of the incoming surge, thereby making it more evenly distributed across the entire winding (NEMA MG-1) and thus limiting the maximum surge voltage across the turns.

Even so, for 200 to 50 ns rise times respectively, the inductance of the capacitor and its leads can cause a transient voltage rise and fall of a few nanoseconds duration to reach a peak stress at the motor of 0.75 to 0.90 times, respectively, of the voltage across the switch. After this peak the capacitors will lengthen the rise time of the incoming surge [B42], [B50]. Such motor starting steep front transient peaks may exceed the NEMA tested withstand of 2.0 pu at 0.2 μs for usual motor lead configurations. For example, Table 5 indicates that if shielded cable motor leads are bonded to ground at both ends, when the third phase to close or prestrike closes the circuit a 100 to 200 ns surge rise time may occur. Table 4 indicates that with the shields grounded at both ends, when the third phase closes it can cause a surge voltage of 4 pu to 5 pu at the motor. The *L(di/dt)* of the internal inductance of a protective capacitor and of its external leads can isolate the capacitor from the surge so as to allow 75% to 90% of this surge peak to reach the motor, unless:

— The motor horsepower is quite large (i.e., the motor has a low surge impedance), or

— The motor leads have quite low surge impedance, or
— The capacitor leads are very short (< 0.5 m) and the rise time is longer than 200 ns ([B42]).

After the *L(di/dt)* peak caused by the capacitor leads, the capacitor will charge and lengthen the wave front, distributing it more evenly throughout the winding. Gapless MOSA will limit the crest value without imposing an additional steep-front surge by gap sparkover.

The relatively low impulse strength of motors indicates that they may need their own surge protection even though they may be partially protected from connected exposed overhead line(s) through apparatus (transformers, regulators, reactors, or cables) whose line side is well protected by a surge protective device (see Hileman, [B35]). Some reasons why surge protection may be desirable are as follows:

a) A machine has high exposure to lightning strokes to overhead lines, or is started frequently at full voltage.

b) A machine has high economic importance due to its size and expense to repair or its critical role in maintaining productivity of a plant or process.

c) The life of an important machine may be extended and significant investment deferred by reducing the level of surge stress that can be imposed on the winding insulation.

6.2 Strategies for motor surge protection

If one or more of the following surge protective elements exist for a particular motor application, the need for additional surge protection may not be necessary. Some of these listed elements will be effective for reducing stress on the groundwall insulation and some will be effective for protecting the turn insulation. Some of the elements will be effective for motor starting surges while others will be effective in limiting stress from lightning surges and system switching surges. For a particular machine installation a quantitative evaluation such as is presented in this guide is required to determine whether protective coordination with the insulation withstand is achieved.

a) Effective shielding from lightning strokes to overhead lines supplying the building or plant can reduce the probability of a lightning surge overstress.

b) Gapless metal-oxide surge arresters at the motor terminals can limit the magnitude of voltage stress without creating a steep-front as caused by sparkover of a gapped arrester.

c) Surge capacitors at the motor terminals. (NOTE—Three-phase capacitors have failed much more frequently than single-phase capacitors) [B40]; capacitor internal inductance plus the inductance of leads as long as one meter can isolate the capacitor from the motor during steep-front starting surges, and may not be effective in wavefront sloping [B42]. Surge arrester lead length is not as critical when machine protective arresters are applied together with short lead length capacitors, because the capacitors will lengthen the rise time applied to the arrester lead inductance.

d) Low grounding resistance at the motor-starting switchgear, in the order of one-fifth of the phase mode surge impedance, Z_c+, of the motor supply cable. (Table 6 lists Z_c+ for large and small sizes of 5 kV cable: triplexed shielded in tray, triplexed unshielded in conduit, belted unshielded in tray, and single phase unshielded in tray. This list indicates that for usual cable surge impedances, Z_c+ will vary between 7 to 70 Ω. Low grounding resistance, to be effective, should be in the order of 1.5 Ω for low Z_c+ constructions, and less than 15 Ω for high Z_c+ constructions).

e) Interconnected bonds to ground between the motor frame, the surge arrester, and the surge capacitor.

f) Motor supply cables individually shielded with outer jackets that effectively isolate the shields from the raceway, and the shields bonded at only one end (only at the motor end) to the metallic raceway and to the motor frame and to a low impedance ground or earthing system. (This shield bonding configuration can reduce the surge at the motor by as much as 60% compared to bonding the shields at both ends) [B23].

The surge arrester should be selected to limit the magnitude of the surge voltage to a value less than the motor insulation surge withstand, BIL. The steepness of the surge wavefront at the motor terminals is influenced by two time constants: at the supply end by the effect of system inductance, grounding resistance, and motor cable impedance; at the motor end by cable impedance and motor capacitance. Surge capacitors at the motor increase the time constant and lengthen the time to crest, reducing the steepness of the surge voltage wavefront [B23], [B42], [B50]. As the surge voltage wavefront travels through the winding, the surge voltage between adjacent turns of the same phase will be less for a wavefront having a longer rise time.

Surge protection of all rotating ac machines is not covered here. The two methods developed in [B23] for determining whether surge protection is required for motors started across-the-line are presented as follows:

— A table look-up procedure (6.3.2).

— Equations for a personal computer or pocket calculator (Annex A).

6.3 Practical calculation of full-voltage starting surges at motor terminals

Switching of motors results in steep-fronted surges that can cause a relatively large turn-to-turn stress in windings. Simplified and detailed methods are presented for calculating the surge level and rise time at the motor terminals for particular configurations. The levels are strongly affected by shield or conduit grounding practices and are less dependent on motor size or the number of other loads supplied by the metal-clad bus. The rise times depend mainly on the motor cable impedance, the shield grounding practices, and an equivalent motor capacitance. Less sensitive parameters include switchgear bus length, the breaker position, and cable losses associated with the dielectric, skin effect, and semi-conductive layers.

The material that follows is based upon an updating of [B23], which made public the benefits of an EPRI funded project (see 4.3.1).

The practical methods for calculating surge levels and rise times at motor terminals are discussed in three parts. They begin with 6.3.1, a sensitivity study for a single configuration. This introduces the user to the effect of different parameters. Subclause 6.3.2 follows with a look-up method based on using tables and a graph with an example. These allow rapid estimation of surge rise times and voltage levels with an approximate 10%t accuracy. Then, Annex A presents more accurate three-phase analysis formulas for use with calculators or personal computers. These topics are independent and the simple look-up method can be used without the formulas.

6.3.1 Sensitivity study for one configuration

The crest value and rise time of the surge at the motor 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 motor, the cables connecting the motor to the switching device, the type of switching device, the length of the busbar in the motor starting switchgear, the number and sizes of all other feeders and motors connected to the same busbar, the type of raceway (whether conduit or tray), and the raceway grounding [B22], [B23].

Table 3 shows the sensitivities of surge voltage level and rise time to parameter variations for a typical motor configuration resulting in fairly severe starting surges. The base system has the following parameters: a 500 HP, 4.2 kV motor is supplied by a 100 m long, XLPE triplexed, shielded, 107 mm^2 (AWG 4/0) cable, shield bonded at both ends, with 15 other loads (feeders connected to the same supply bus). The surge level seen at the motor is given in per unit of peak phase-to-ground voltage and assumes a maximum prestrike voltage of 2.82 pu on third pole closing. The base case has a 5.1 pu surge level and a 125 ns rise time. The calculations were derived from Figure 8 and Table 4 and Table 5 (which follow later) with interpolation to increase the resolution.

Table 3 also shows the normal range of parameter values obtained from a utility survey and visits to several monitored sites. The percentages appearing in the third column are the frequency of occurrence distribution of the parameter value as obtained from the survey. Table 3 is intended to show only overall trends with discussion of the controlling mechanisms. For general analysis, use Table 4 and Table 5 for approximate estimates, or the formulas in Annex A for more accurate analysis.

Table 3—Sensitivity of motor surge level and time constant to many parameters

Parameter	Value/Detail	Frequency	Surge level (pu)	Time constant (ns)
System voltage	480 V	2%	—	—
	2.3 kV	22%	5.0	125
	4.2 kV	48%	5.1	125
	6.6 kV	21%	5.2	85
	13.8 kV	7%	5.4	85
Higher voltage machines with more insulation have higher R_m and Z_c. However R_m increases more, causing surge levels to increase slightly. Higher Z_c reduces the time constant associated with L_s but increases the time constant due to C_m. Here the first effect dominates and the rise time is reduced.				
Number of other loads	5	20%	4.5	115
	10	60%	4.8	120
	15	20%	5.1	125
More loads reduce R_s and increase the bus length as well as L_s.				
Width of metalclad enclosure	30 cm/load ckt	—	5.1	120
	60 cm/load ckt	—	5.1	125
	150 cm/load ckt	—	5.1	140
A wider load circuit enclosure increases bus length and L_s.				
Position of motor breaker	Mid bus	—	5.1	125
	End bus	—	5.1	160
A mid bus breaker sees loads in two directions, reducing L_s.				
XLPE Motor cable length	6 m	—	5.1	100
	100 m	—	5.1	125
	330 m	—	5.1	195
In XLPE cable, skin effect adds about 30 ns per 100 m of length.				
Size, cable conductor	107 mm^2 (AWG 4/0)	—	5.1	125
	177 mm^2 (350 kcmil)	—	5.1	135
	253 mm^2 (500 kcmil)	—	5.2	150
	380 mm^2 (750 kcmil)	—	5.2	165
Larger conductors reduce Z_c increasing the surge level. Depending on L_s and C_m this may increase or decrease the rise time.				

Table 3—Sensitivity of motor surge level and time constant to many parameters *(continued)*

Parameter	Value/Detail	Frequency	Surge level (pu)	Time constant (ns)
Cable insulation type	XLPE, EPR	92%	5.1	125
	PILC	4%	5.1	625
	Cambric	2%	5.1	125
	Air (bus, not cable)	2%	5.1	125
PILC or butyl rubber dielectric losses add about 500 ns per 100 m.				
Construction, motor lead cable	Phases separated, unshielded	—	4.6	95
	Phases separated, shielded	—	5.1	125
	Triplexed, unshielded	—	4.6	95
	Triplexed, shielded	—	5.1	125
	Belted, unshielded	—	4.4	100
Shielding reduces Z_c, thus increasing the surge level. Depending on L_s and C_m, this may increase or decrease the rise time.				
Shield grounding	Both ends	—	5.1	125
	Supply end only	—	5.0	135
	Motor end only	—	2.3	85
Single end shield grounding splits away the surge at one end of the cable. Supply end grounding increases Z_c at the motor only, slightly increasing the C_m time constant. Motor end grounding increases Z_c at the source only, reducing the L_s time constant.				
Motor rating (Hp)	500	—	5.1	125
	1000	—	4.8	135
	3000	—	4.7	165
	10 000	—	4.5	260
Larger motors have a smaller R_m and a larger C_m.				
Surge protection at supply	None	79%	5.1	125
	Capacitors	15%	5.1	345
	Arresters	6%	5.1	125
Capacitors of 0.25 uF are effective. Surge arresters may not be effective against steep fronted surges less than 2.5 pu of MCOV. These voltages are below the usual arrester protective level [IEEE Std C62.22-1997, Table 1].				
Surge protection at motor	None	82%	5.1	125
	Capacitors	4%	5.1	3400
	Arresters	14%	5.1	125
Capacitors can be much more effective at the motor because $Z_c C > R_s C$.				

In summary, designers should pay attention to the following effects:

— Shielded cables bonded only at the motor cause part of the incident surge to split into a component external to the cable, which reduces the surge level at the motor. This assumes a cable length of at least 30 m so the external component will not quickly appear at the motor. However, effective cable impedance is increased at the supply end, which can shorten the time constant.

— Shielded cables bonded only at the supply end increase the impedance seen by the motor capacitance, thus increasing the time constant. Again this assumes a cable at least 30 m long. However, the surge level seen at the motor is hardly reduced since its relatively high impedance takes most of the surge split.

— Unshielded cables have a relatively high surge impedance which can reduce the surge level if the motor impedance itself is not too high. Selecting a cable with thicker insulation also increases the impedance. Higher cable impedance tends to shorten the rise time at the supply end but lengthens it at the motor end.

— For unshielded cables, single end bonding of the conduit can produce effects similar to those noted above for shielded cables, but to a smaller extent. Surge levels can be reduced by feeding fewer loads off one supply bus. Also surge fronts are lengthened by the increased inductance of wider switch compartments. Small motors with low capacitance, fed by shielded cables from a compact metal-clad with many other loads, are most vulnerable.

Grounding at only the motor end with a shielded cable is the single most effective surge-reducing measure.

6.3.2 Look-up tables of surge levels and time constants for estimating the need for surge protection of a motor

Table 4, Table 5, and Table 6 are intended for rapid calculation of the surge level and time constants where accuracies of 10 to 15% are adequate. The results were obtained from formulas, but are presented here in tables, with some sacrifice in generality. For example, the user must choose either 5 or 15 other loads on the supply bus, although this parameter has only a small effect on the surge level and rise time. The surge level is in per unit of peak phase-to-ground voltage and assumes a third pole closing prestrike voltage of 2.82 pu (see Dick, et al, [B21]).

Step 1 is to establish the motor cable type code. All cables individually shielded per phase are type “A.” Unshielded single phase cables with some inter-phase spacing are type “B.” Closely spaced or triplexed unshielded cables are type “C.” Belted cables with intimate phase spacing are type “D.”

Step 2 is to determine the motor cable size code. All 2.3 kV rated cables, 5 kV cables larger than 107 mm^2 (4/0 AWG), and 7.5 kV cables larger than 177 mm^2 (350 kcmil) are size “I.” Others are size “II.”

Step 3 is to obtain a pro-rating factor between 0% and 100%, depending on the motor horsepower (HP) and voltage rating as shown in Figure 8.

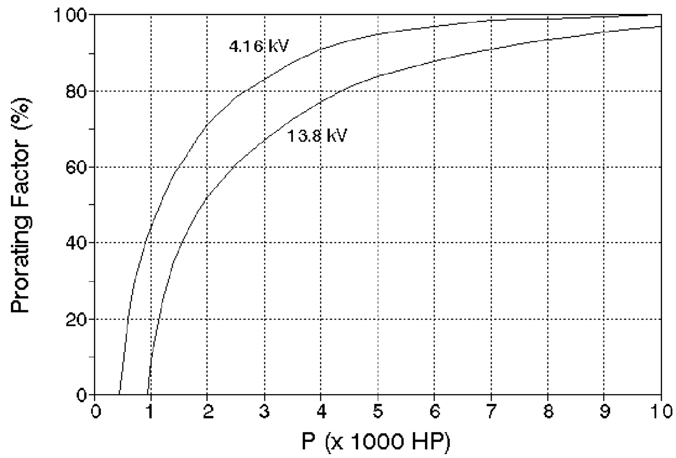

Figure 8—Motor size pro-rating factor for Table 4

Step 4 is to find the surge levels. Table 4 lists surge levels when third pole to close causes 2.82 pu prestrike voltage (first pole to close equals 1.0 pu volts) Dick, et al, [B23]. Use Table 4 to find the surge levels corresponding to the cable codes, the number of other loads present and the motor pro-rating factor [which is applied between the left hand (0%) and right hand (100%) columns].

**Table 4—Motor surge level in per unit (pu) from [B23]
HP ProRate% from Figure 8**

Cable type code	Cable size code I		Cable size code II	
	15 loads	**5 loads**	**15 loads**	**5 loads**
1. Cable shields, conduit, or tray bonded both ends				
HP ProRate	**0%–100%**	**0%–100%**	**0%–100%**	**0%–100%**
A	5.2 – 4.9	4.6–4.4	5.1–4.4	4.5–3.9
B	4.8–3.5	4.3–3.1	4.5– 2.9	4.0–2.6
C	4.8–3.6	4.3–3.2	4.6–3.1	4.1–2.8
D	4.7–3.6	4.2–3.2	4.5–3.1	4.0–2.8
2. Cable shields bonded at supply end only				
HP ProRate	**0%–100%**	**0%–100%**	**0%–100%**	**0%–100%**
A	5.1–4.4	4.5–3.9	4.9–3.8	4.4–3.4
3. Cable shields bonded at motor end only				
HP ProRate	**0%–100%**	**0%–100%**	**0%–100%**	**0%–100%**
A	1.8–1.7	1.7–1.6	2.6– 2.2	2.4–2.1

Step 5 is to use Table 5 in a similar fashion to find the rise time. Here the motor size is pro-rated between 0% and 100% by dropping two zeros in the horsepower rating, that is 500 HP is 5% and 10 000 HP is 100% with the voltage rating being ignored. Again the pro-rating is applied between the two columns. The number of other loads on the supply bus has only a small effect and has not been included here as a parameter. The rise time should be further increased by 30 ns per 100 m of motor cable to account for cable losses. When PILC cable is used, this should be increased to 500 ns per 100 m. Surge capacitors, C_s, give an additional lengthening of the rise time by $C_s Z_c$ where 10 Ω could be used as a conservative lower bound for Z_c. However, the combined inductance of the surge capacitor with its connecting leads can interfere with the effectiveness of the capacitor, as is discussed later.

Look-Up Example of this procedure—For two figure significant accuracy consider this configuration: a 500 HP, 4.2 kV motor is supplied by a 100 m, XLPE triplexed, shielded, 107 mm^2 (AWG 4/0) cable, shield bonded at both ends, 15 other loads on the same bus. The resulting cable type code is "A," size code "II," and Figure 8 gives a motor pro-rating value of about 2% for Table 4. From Table 4, the surge level is 5.1 + 2% (4.4 – 5.1) = (5.1 – 0.014) = 5.1 pu. To calculate the surge rise time, 500 HP gives a pro-rating value of 5%. Table 5 gives a rise time of 66 + 5% (243 – 66) = (66 + 8.85) = 75 ns. The total rise time is 105 ns after adding 30 ns for skin effect loss. The 5.1 pu at 105 ns exceeds the NEMA withstand test of 2.0 pu at 100 to 200 ns, and 4.5 pu at 1.2 μs. Consider now how to protect this motor.

Table 5 Motor surge level constants (ns) [B23]

HP ProRate% from HP / 100 =%		
Cable type code	**Cable size code I**	**Cable size code II**
1. Cable shields, conduit, or tray bonded both ends		
HP ProRate	**0%–100%**	**0%–100%**
A	134–207	66–243
B	49–508	51–736
C	53–430	52–605
D	63–384	59–518
2. Cable shields bonded at supply end only		
HP ProRate	**0%–100%**	**0%–100%**
A	138–332	72–422
3. Cable shields bonded at motor end only		
HP ProRate	**0%–100%**	**0%–100%**
A	60–126	46–223

Unbond and isolate the supply cable shields from ground at the supply switchgear end. This will reduce the voltage to 2.6 pu (Table 4) and the rise time to (46 + 9 + 30) = 85 ns (Table 5). These still exceed the NEMA surge withstand test of 2.0 pu at 100 ns. Add machine surge protective capacitors to reduce the steepness of the surge front. Select capacitor leads such that the sub-microsecond peak across the capacitor leads (85 ns) does not exceed the 2.0 pu withstand (See previous discussion in 5.9 and 6.1).

Figure 9 through Figure 12 [B42] provide a means to estimate the sub-microsecond peak across the capacitor leads. For usual capacitor lead conductors and height above the ground plane, the lead inductance will be between 1.25 and 1.40 μH/m. For this estimate use 1.25 μH/m. The internal inductance of the capacitor is approximately the height of the terminal above the ground plane, about 0.5 μH. Motor supply cable modal impedances from [B22] are given in Table 6 below for sizes 42 mm^2 (#1 AWG) and 380 mm^2 (750 kcmil). It is conservative to use Z_c+ from Table 6 for Z_c. For other cable sizes pro-rate the impedance for the range between 42 and 380 mm^2. For 67 mm^2 (#2/0 AWG), use 20%; for 107mm^2 (#4/0 AWG), use 40%; for 177 mm^2 (350 kcmil), use 60%; for 253 mm^2 (500 kcmil), use 80%.

For 4/0 cable, Configuration 1, the phase mode surge impedance Z_c+ from Table 6 is:

19 + 40% (7 – 19)) = (19 – 4.8) = 14 Ω. Use Figure 9 for supply cable with Z_c = 13 Ω.

Table 6—Typical cable modal surge impedances (ohms) [B22]

	Z_{co}		Z_{c+}		Z_e	
Size						
mm^2	42	380	42	380	42	380
AWG/kcmil	#1	750	#1	750	#1	750
Configuration						
1	19	7	19	7	20	14
2	132	91	48	30	56	56
3	250	170	34	21	190	190
4	113	71	71	45	190	190
Configuration 1 5kV, XLPE, Triplexed Shielded Cable in Tray						
Configuration 2 5kV, Butyl Rubber, Unshielded Triplexed Cable in Conduit						
Configuration 3 5kV, XLPE, Belted Unshielded Cable in Tray						
Configuration 4 5kV, XLPE, Single Phase Unshielded Cable in Tray						

Using Figure 9—To limit the 85 ns surge peak that is caused by inductance of the capacitor and capacitor leads to 2.0 pu, the ordinate value on an interpolated 85 ns curve must be no greater than (2.0 / 2.6) = 0.77 pu. This occurs at about 2.0 μH. (For interpolation, see next paragraph.) Subtracting the 0.5 μH of the capacitor, the leads must have an inductance of 1.50 μH or less. At 1.25 μH/m, the capacitor lead length should not exceed 1.2 m (1.50μH / 1.25μH/m = 1.2 m). To provide protective margin, shorter is better.

In Figure 9, interpolating by eye at L = 2.0 μH, E = 0.85 pu at 50 ns, and 0.73 pu at 100 ns. At 85 ns, E = 0.73 + (0.85 – 0.73) × [(100 – 85) / (100 – 50)] = 0.73 + 0.036 =0.77 pu.

After the initial 85 ns peak the voltage will fall to the capacitor charge volts (near zero) and rise with a time constant of Z_c+ × C, where 14 Ω × 0.5 μF of the capacitor equals a 7 μs time constant.

This is longer than 5 μs so the switching surge will distribute evenly through the motor windings. At three time constants, 21 μs, the rise will be 2.6 (1 – ε^{-3}) = 2.47 pu.

With only a 2.47 pu rise at 21 μs, no surge arresters are required.

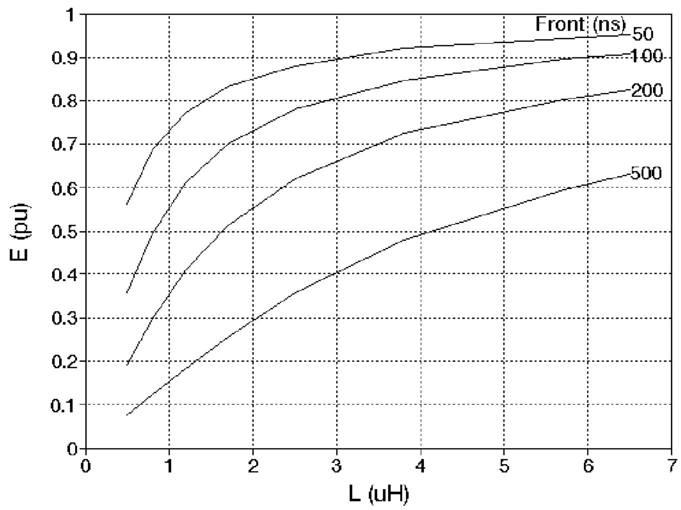

Figure 9—Capacitor reduction of surge at motor, sub-microsecond peak; cable surge impedance = 13 ohms

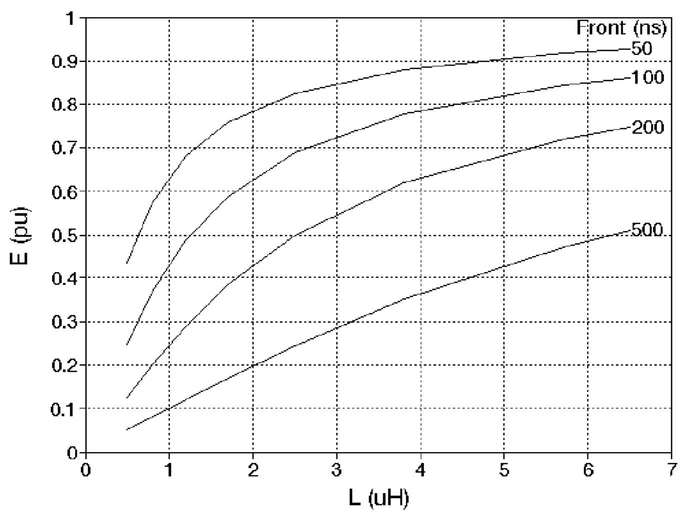

Figure 10—Capacitor reduction of surge at motor, sub-microsecond peak; cable surge impedance = 20 ohms

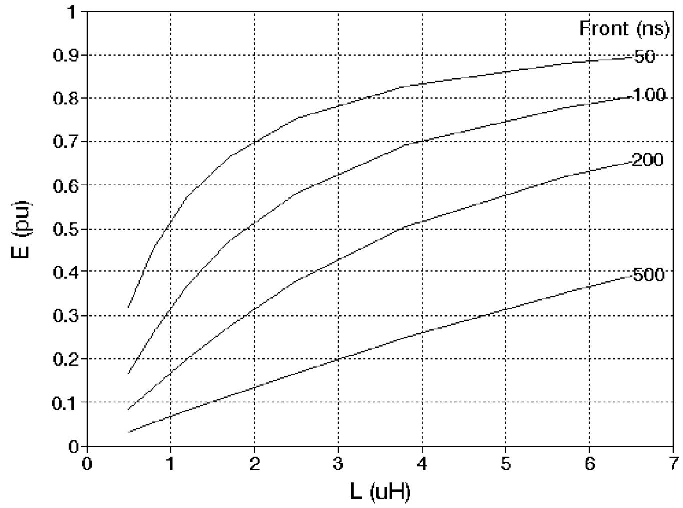

Figure 11—Capacitor reduction of surge at motor, sub-microsecond peak; cable surge impedance = 30 ohms

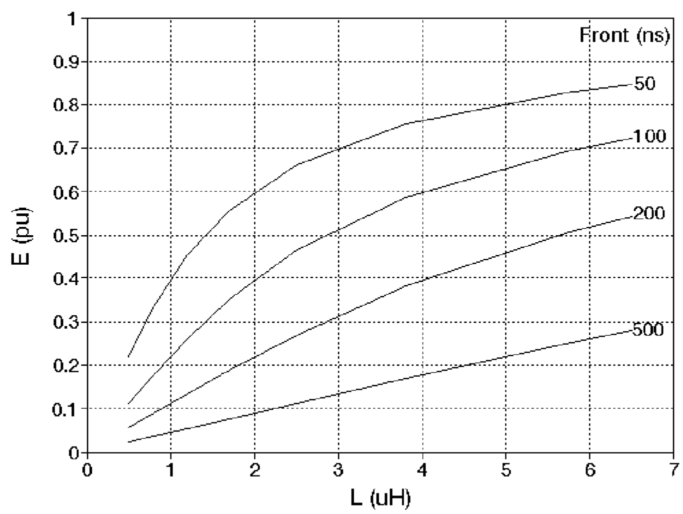

Figure 12—Capacitor reduction of surge at motor, sub-microsecond peak; cable surge impedance = 45 ohms

Annex A

(normative)

Formulas for calculators or personal computers

A.1 Surge Level, cables with no phase-to-phase coupling

Formulas have been derived for motor terminal voltage V_m of the equivalent circuit, Figure 6. First consider the simpler case where phase-to-phase coupling in the motor supply cable is ignored, either because each phase is individually shielded, or unshielded single phase conductors are well separated in a cable tray. The formulas are given in terms of the prestrike voltage $V_{p,}$ which has maximum values of 1.0, 2.41, and 2.82 pu for the first, second and third pole to close [B21]. Three separate formulas are given for V_m, depending on the location of shield grounding—[Equation (A.1), Equation (A.5), and Equation (A.6)].

a) Phases separated with no shield, or shielded and bonded to ground at both ends, V_m in per unit is

$$V_m = \frac{\dfrac{V_p 2 R_m Z_c}{R_m + Z_c}}{R_s + Z_c} \qquad \text{(A.1)}$$

An empirical formula [Equation (A.2)] for the motor loading resistance R_m from Dick, et al, [B22] is

$$R_m = 200(kV)^{0.32}(kHP)^{-0.64} \qquad (\Omega) \qquad \text{(A.2)}$$

Note that the motor voltage is in units of kilovolts and power rating is in thousands of horsepower.

The surge impedance Z_c for a shielded single phase cable is

$$Z_c = \frac{60}{\sqrt{\varepsilon_r}}\sqrt{\left(\ln\left(\frac{r_2}{r_1}\right)\right)} \qquad (\Omega) \qquad \text{(A.3)}$$

Here ε_r is the relative permittivity of the dielectric. Representative values of ε_r are: 2.3 for XLPE; 3.0 for EPR, and 3 to 10 for butyl rubber (typically 4.5, depending on the fillers used).

The term r_1 is the phase conductor radius. Strictly, r_1 is the geometric mean of the conductor radius considering inductive and capacitive effects separately. At low frequencies with current flowing uniformly through the bulk of the conductor, the inductive radius is GMR_{1C}, the geometric mean radius of a phase conductor, which is smaller than the physical radius of the conductor. On the other hand, the capacitive radius may be larger than the conductor radius when semi-conductive layers are present over the conductor insulation. However, for one microsecond or shorter surge fronts, the inductive radius is practically equal to the conductor physical radius. Semi-conductive layers are thin. With sufficient accuracy, r_1 may be taken as the physical radius of the conductor. Similarly, r_2 is the dielectric outer radius, the inside radius of any metallic sheath.

The equivalent resistance R_s of the supply and other load cables taken in parallel is usually well approximated by Z_c / n where n is the number of these cables, all of which are assumed to have the same impedance [B22].

The surge impedance for unshielded phase conductors well-separated in a tray is given in Equation (A.4).

$$Z_c = \frac{60}{\sqrt{\varepsilon_r}} \ln\left[\frac{h}{r_1} + \sqrt{\left[\left(\frac{h}{r_1}\right)^2 - 1\right]}\right] \qquad (\Omega) \tag{A.4}$$

Here h is the height of the conductor center above the tray. This assumes a homogeneous dielectric, which is actually partly plastic and partly air. To make it homogeneous, the plastic is replaced by a layer of air with the same capacitance, that is $1/\varepsilon_r$ as thick as the actual plastic, with h reduced accordingly. However, the correction is needed only for the capacitive part of Z_c and not for the inductive part. This is handled by taking Z_c as the geometric mean of two evaluations of Equation (A.4), one with and one without the correction applied. In each case, ε_r is taken as unity since an air dielectric is assumed.

b) Each phase shielded and bonded to ground at only the motor end, V_m, in per unit is

$$V_m = \frac{\frac{V_p 2 R_m Z_c}{R_m + Z_c}}{R_s + Z_c + Z_e} \tag{A.5}$$

The external impedance of the shielded cable Z_e can be calculated from Equation (A.4) using the radius of the shield for r_1. For equivalent shielding effect of non-shielded cables in metallic conduit bonded only at the motor end, Z_e is the surge impedance between the conduit and some equivalent ground plane. Use the outside radius of the conduit for r_1 in Equation (A.4) The equivalent ground plane is generally the closest adjacent conductor that is electrically continuous; for example, reinforced concrete, building steel, pipes or other trays.

The above V_m is called the “initial” surge. After several travel times of this external component, the shield reaches ground potential at the supply end and V_m increases towards a final level found by setting Z_e to zero. This final level is the “total” surge.

c) Each phase shielded and bonded to ground at only the supply end, V_m, in per unit is

$$V_m = \frac{\frac{V_p 2 R_m Z_c}{R_m + Z_c}}{(R_s + Z_c + Z_e)(R_s + Z_c)} \tag{A.6}$$

The parameters are the same as in item b) above and the “total” component is found by setting Z_e to zero.

A.2 Surge time constants

The motor surge rise time for the above “initial” component is estimated from the sum of several individual time constants. This approximates the convolution that is rigorously needed when calculating the cumulative effect of cascaded time constants. The time constant due to metalclad switchgear bus and breaker inductance is

$$\tau_s = \frac{L_s}{R_s + Z_c} \qquad (\mathrm{s}) \tag{A.7}$$

Here the supply bus and breaker have an equivalent phase inductance L_s which is typically $(1 + 0.02\,n)$ μH where n is the number of other cables [B22]. This is based on phase-to-phase components associated with second or third pole closing, which will make the calculated time constant slightly fast for first pole closing. For a motor breaker near the end of the supply switchgear, L_s is increased to $(1 + 0.05\,n)$ μH.

The time constant τ_m due to motor load capacitance is:

$$\tau_m = \frac{R_m Z_c}{R_m + Z_c} C_m \qquad \text{(s)} \tag{A.8}$$

Capacitance C_m of the motor is the power frequency capacitance of a coil in one slot, times the number of winding parallels [B22]. A delta-connected motor connection further doubles the capacitance. This coil capacitance can be found from the three phase winding capacitance divided by the number of coils. If this information is unavailable, use the empirical relationship that capacitance in picofarads is approximately equal to motor horsepower rating [B22].

The approximate time constant τ_c due to motor cable losses from [B22] is:

$$\tau_c = 75\sqrt{(\alpha_c + \alpha_d + \alpha_s)} \qquad \text{(s)} \tag{A.9}$$

The attenuation factor α_c is due to conductor skin effect, α_d dielectric loss and as semi-conductive layer loss. These losses are evaluated at 1 MHz in units of dB per meter as follows, and are then multiplied by the cable length, meters. Estimate skin effect loss α_c at this frequency using Equation (A.10).

$$\alpha_c = \frac{K_m}{Z_c w} \qquad \text{(db/m)} \tag{A.10}$$

Where K_m is a conductor material parameter and w is the surface width (mm) over which current flows [B22]. Values of K_m for common materials are—1.1 for copper, 1.5 for aluminum, 3.9 for lead, and 30 for steel (assuming a relative permeability of 100). For unshielded cables consider only one phase conductor since Z_c in Equation (A.10) is per phase. For shielded cables, the attenuation should be taken as the sum of losses in one phase conductor and its shield.

Dielectric losses α_d for PILC cables at 1 MHz can be estimated as 0.050 dB/m, and for other cables as 0.060×10^{-3} dB/m.

For EPR or XLPE cables with semi-conductive layers, an additional semi-conductive loss effect, as, is about 0.2×10^{-3} dB/m.

In summary, the rise time of the *initial* component of the surge is taken to be the sum of the preceding time constants. If external splitting of the surge is present due to grounding only one end, the initial component is followed by the slower *total* component. This slower rise time should be at least two external travel times slower than the *initial* surge rise time. Typically, this adds 10 ns/m of motor cable length to the total rise time.

As an example of the use of these formulas, consider the previous example in the Table Look-Up procedure—a 500 HP, 4.2 kV motor supplied by a 100 m long, XLPE triplexed, shielded, 107 mm^2 (AWG 4/0) cable, shield bonded at both ends, 15 other source and load cables on the bus. From cable data sheets, the conductor radius is 6.1 mm, and shield radius 8.4 mm. For a coaxial shield, the cable surge impedance Z_c from Equation (A.3) is 13.885 Ω. With 15 source side cables, R_s is 13.89/15 or 0.9260 Ω. The motor equivalent resistance R_m from Equation (A.2) is 493.3 Ω. Using Equation (A.1), the surge level for third pole closing is 1.824 times the prestrike voltage of 2.82 pu, or 5.14 pu. This compares with 5.1 from the example at the end of the Table Look-Up procedure.

The source bus inductance is (1 + 0.02 × 15), or 1.3 μH [B22]. From Equation (A.7), this gives a time constant of 88 ns. Assume a motor capacitance of 500 pF, from the HP rating. From Equation (A.8), this gives a time constant of 7 ns. The cable attenuation in 100 m length due to conductor skin effect from Equation (A.10) is 100 × 1.1 /(13 × 6.1 × 2π) or 0.206 dB. Similarly for the shield it is 0.150 dB. Dielectric and semi-conductive losses total 0.026 dB. From Equation (A.9), the attenuation time constant is 47 ns. The sum of all time constants is 142 ns and this system has only an initial component since the shield is grounded at both ends.

A.3 Surge level, cables with phase-to-phase coupling

Phase-to-phase coupling in the motor cable can be significant for belted or triplexed constructions. The levels and time constants will vary for first, second or third pole closing. Here third pole closing has been assumed, although the results should be similar for second pole closing, since they both have only a small ground component. If used for first pole closing, the calculated levels may be higher and the rise times faster than the actual values.

The concept of line and ground components (modes) is used, which is similar to 60 Hz sequence theory. The ground mode impedance Z_{co} is found from Equation (A.4) by considering the phases to be paralleled and replaced by an equivalent conductor based on the geometric mean radius (GMR) method. Generally the three-conductor geometric mean radius, GMR_{3C}, is the cube root of (r_1 times phase-to-phase distance squared), where r_1 is the conductor physical radius for both inductive and capacitive calculations.

For belted cables covered by a shield, the ground mode impedance can be found from the geometric mean of two evaluations of Equation (A.3). For the inductive part, r_1 is the GMR_{3C} and r_2 is the GMR_{3C} plus the smallest distance between the phase conductors and the shield. For the capacitive part, r_1 is the GMR_{3C}, and r_2 is the GMR_{3C} plus the smallest distance between the phase conductors and the shield reduced by the ε_r factor. The Z_c of Equation (A.3) must be multiplied by 3 to give a “per phase” quantity.

For unshielded belted cables in a tray or conduit, the geometric mean of two evaluations of Equation (A.4) are used. For the inductive part, r_1 is the GMR_{3C}, and h is the GMR_{3C} plus the smallest distance between the phase conductors and the current return path. For the capacitive part, r_1 is the GMR_{3C}, and h is the GMR_{3C}, plus the smallest distance between the phase conductors and the tray reduced by the ε_r factor.

For more widely-spaced single phase cables, Z_{co} is found considering one phase and using the geometric mean of two evaluations of Equation (A.4). For the inductive part, r_1 is the conductor physical radius, and h is r_1 plus the smallest distance between a phase conductor and the current return path. For the capacitive part, r_1 is the same, and h is r_1 plus the smallest distance between the phase conductors and the tray reduced by the ε_r factor. Note this is already “per phase” and does not need multiplying by 3.

The line mode impedance Z_{c+} per phase for a belted cable can be approximated by half the return impedance of any two phase conductors. For belted cables, the electric field can be assumed constrained to the plastic dielectric. Thus a single evaluation of Equation (A.4) is used with h being half the geometric mean distance (GMD) of the phase-to-phase spacing.

For Z_{c+} of triplexed or single phase cables the geometric mean of capacitive and inductive values are used. For the capacitance, the plastic dielectric should be replaced by an equivalent layer of air having the same capacitance, that being the actual thickness reduced by the factor $1/\varepsilon_r$. This altered value for the GMD is used only for the capacitive part of Z_c. The full spacing GMD is used for the inductive part of Z_c. Furthermore, for single phase unshielded cables, Z_{c+} is significantly affected by the presence of the ground planes considered in calculating Z_{co}. A correction for this effect is to take Z_{c+} as the shunt (parallel) combination of this evaluation of Equation (A.4) and Z_{co} [B22]. Table 6 provides typical values for these modal impedances.

Equation (A.11), Equation (A.12), and Equation (A.13) provide a means for including the effect of the ground mode in calculating the surge magnitude at the motor for cables with phase-to-phase coupling. In these equations Z_c, the equivalent phase impedance, has the value of Z_{c+}. Similarly, Z_n, the equivalent neutral impedance, has the value of $(Z_{co} - Z_{c+}) / 3$. See Table 6 for typical values of Z_{co} and Z_{c+}. R_s is the phase impedance of the supply system. The equivalent of R_s has the value of Z_c / n. R_n is the neutral impedance of the supply system. The equivalent of R_n has the value of Z_n / n. When the preceding modal equivalent values are used in Equation (A.11), Equation (A.12), and Equation (A.13), the surge level at the motor can be calculated for the following three configurations of shield bonding to ground. and neutral impedance:

a) Belted cable with single shield, both ends grounded, or no shield with phases in close proximity, V_m, in per unit is

$$V_m = \frac{(V_p 2R_m)(Z_c + 3Z_n)}{3(R_m + Z_c + 3Z_n)(R_s + Z_c + 3R_n)} + \frac{(V_p 4R_m Z_c)}{3(R_m + Z_c)(R_s + Z_c)} \tag{A.11}$$

b) Shield, tray or conduit grounded at motor end only, phases in close proximity. For the "initial component," V_m, in per unit is

$$V_m = \frac{(V_p 2R_m)(Z_c + 3Z_n)}{3(R_m + Z_c + 3Z_n)(R_s + Z_c + 3R_n + 3Z_e)} + \frac{(V_p 4R_m Z_c)}{3(R_m + Z_c)(R_s + Z_c)} \tag{A.12}$$

For the "total" component, set Z_e to zero.

c) Shield, tray or conduit grounded at supply end only, phases in close proximity. For the "initial" component, V_m, in per unit is

$$V_m = \frac{(V_p 2R_m)(Z_c + 3Z_n)}{3(R_m + Z_c + 3Z_n + 3Z_e)(R_s + Z_c + 3R_n)} + \frac{(V_p 4R_m Z_c)}{3(R_m + Z_c)(R_s + Z_c)} \tag{A.13}$$

For the "total" component, set Z_e to zero.

Line and ground modes generally have different time constants. However, for practical purposes on second and third pole closing, the ground mode rise time can be neglected, giving an error on the conservative side.

A.4 Summary of motor starting surge levels and surge rise times

Given a maximum prestrike voltage on third pole closing of 2.82 pu, the steep-fronted motor terminal surge can vary between 2 pu and 5 pu depending on the configuration. The highest surges are associated with small motors fed by shielded cables grounded at both ends with a large number of other loads present on the motor-starting bus. The most effective mitigation measure is to ground only the motor end of the shield.

The calculated surge rise time, using time constants, can range from 50 to 1500 ns depending on the configuration. The fastest rise times are associated with small wye-connected motors, short shielded XLPE or EPR cables, and narrow width switchgear (short bus length at the supply end).

A.5 Other equivalent circuit values

A.5.1 L_S switchgear bus and other motor cables, [B22]

The short length of switchgear bus and breaker wiring is represented by the inductance L_S. In Dick, et al, [B22] typical 5 kV to 15 kV class circuit breaker cubicles were considered for supply bus equivalent inductance. The phase mode inductance of the breaker wiring was calculated for current flowing in the middle conductor with return in the outer two phases and the metal-clad structure. Based on a breaker near the center of a bus having an inductance of 0.1 μH to 0.2 μH per breaker, the equivalent bus inductance for 5 and 20 breaker sections is 0.05 μH to 0.1μH and 0.16 μH to 0.32 μH respectively. For breakers near the end of a bus, the corresponding inductances are 0.13 μH to 0.26 μH and 0.66 μH to 1.3 μH. Current transformer and breaker cubicle wiring is found to be 0.7 to 1.1 μH. This should be added to the previous breaker inductance figures. The overall source inductance L_S thus ranges from 0.75 μH to 2.4 μH.

The equivalent inductance of the switchgear bus, supply cables and cables supplying other motors, may be estimated by using Equation (A.14) and Equation (A.15), which are both empirical:

$$L_S = 1 + 0.02n \quad (\mu\text{H}) \quad \text{End breaker} \tag{A.14}$$

$$L_S = 1 + 0.05n \quad (\mu\text{H}) \quad \text{Center breaker} \tag{A.15}$$

where n is the total number of connected load and supply cables.

The preceding parameters are for phase mode propagation associated with second or third pole closing which produces the worst surges. For the first pole to close, the effective current return paths are further removed, possibly doubling the bus inductance to about 4μH and reducing the imposed surge.

A.5.2 R_m motor loading impedance, [B22]

Motor loading impedance can be represented by a parallel resistance and capacitance which may be measured, calculated from geometry, or empirically derived from nameplate data. The surge impedance of the motor is the actual frequency-dependent complex impedance. The load resistance R_m is a fixed shunt resistor, which together with an optional load capacitance C_m, approximates this surge impedance.

Several equations were developed in [B22] for the loading impedance constants. Equation (A.16) for R_m is an empirical relationship where T is turns per coil and P is the number of winding parallels per phase, including the effect of a delta connection (which doubles the parallels). The number 75 is a scaling factor introduced to best fit the motor data.

$$R_m = \frac{75T}{P} \quad (\Omega) \tag{A.16}$$

Equation (A.2) for R_m, from A.1, is an empirical relationship with motor nameplate ratings, where kV is motor rated voltage, and kHP is motor rated horsepower in thousands:

$$R_m = 200(kV)^{0.32}(kHP)^{-0.64} \quad (\Omega) \tag{A.2}$$

Equation (A.17) provides a means for calculating R_m when geometric and materials data are available for the motor winding:

$$R_m = \frac{N\sqrt{(750qdt\ln(d/r))}}{P\sqrt{rs}} \quad (\Omega) \tag{A.17}$$

where
d is the coil diamond length (coil slot to nose),
N is the turns per coil,
P is the number of parallel winding paths (including a delta connection),
q is the coil pitch,
r is the equivalent coil radius,
s is the slot length; and t is the groundwall insulation thickness.
(All dimensions are in meters.)

Equation (A.18) calculates the winding capacitance C_m using the parallel plate formula:

$$C_m = \frac{200Prs}{t} \quad \text{(Pf)} \qquad \text{(A.18)}$$

where

P is the number of parallel winding circuits including the effect of a delta connection,
s is the slot length and t is the insulation thickness (both in meters),
permittivity is assumed as 3.6,
r is the radius of a round conductor having the same circumference as the ground wall perimeter of the rectangular conductor.

Table A.1 presents the measured and calculated results for several motors of various sizes and ratings, using each of the preceding equations [B22].

Table A.1—Motor loading resistance (Ω) and capacitance (pF)

Motor rating		Measured		Calculated from equation			
(kV)	(HP)	(Ω)	(pF)	(A.16) (Ω)	(A.2) (Ω)	(A.17) (Ω)	(A.18) (pF)
6.6	11000	90	12800	110	80	120	9000
6.6	11000	100	5000	110	80	80	4500
4.1	5500	50	5500	—	100	—	—
4.1	1500	160	5000	—	240	—	—
4.1	400	800	700	—	550	—	—
4.1	3500	160	4500	—	140	—	—
4.1	5300	150	4000	150	110	90	3200
4.1	500	800	300	—	470	—	—
13.8	34000	90	3200	—	50	—	—
4.1	4000	110	8000	—	130	—	—

Annex B

(informative)

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