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Reevaluation of IEEE and IEC Substation Design, Operations, and Maintenance Standards Considering Increased Fault Currents

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ABSTRACT

The ever-increasing demand for utility substations to pass higher and higher levels of throughput power has the consequence of driving up levels of short circuit (SC) currents from 63 kA to as high as 100 kA. Knowing whether substation bus structures and electrical equipment are capable of safely passing these higher levels of currents is a pressing need of substation personnel responsible for design, operation, and maintenance of station assets. This report presents results of a preliminary study to assess the adequacy of Institute of Electrical and Electronics Engineers (IEEE) and International Electrotechnical Commission (IEC) standards and guides in predicting potential negative impacts of high SC currents on substation design, operations, and maintenance and to provide practical guidance for mitigating their damaging effects.

Keywords
Fault currents
Substation design
Substation operation and maintenance
Short circuit force
Power transformers
Switchgear
Bus structures

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1
INTRODUCTION

With the introduction of distributed generation (DG) to the utility industry, the power throughput requirements of substations have risen dramatically. As a consequence, the levels of short-circuit (SC) currents in substation equipment have also increased, reaching levels as high as 100 kA. A 2011 EPRI technical update [1] reevaluated the guidelines of IEEE Std. 605-1998 [2] and IEEE Std. 605-2008 [3] for calculating the mechanical forces on substation rigid bus work in light of higher SC current levels. The report proposed a simple, dynamic, SC force calculation method as an alternative to the overly conservative, static analysis of the Standards.

Following this reevaluation of IEEE Std. 605 on the topic of rigid bus SC force calculation, EPRI posed the question as to whether there were any other aspects of increasing fault current levels in substation equipment that are not adequately addressed in existing standards. This report presents the results of a study conducted to provide initial answers to that question. The objective was to identify other aspects of increased SC currents in substation equipment that are not adequately addressed in the Standards. The scope of the study was expanded to include all IEEE/IEC standards and guides associated with substation **design**, **operations** and **maintenance**.

The approach involved surveying the open literature to identify the

1. Types of substation equipment negatively impacted by high SC current,
2. Negative effects of high SC currents on the equipment, and
3. IEEE and IEC standards pertaining to the design, operation, and maintenance of those types of equipment.

A potential shortfall in the standards was declared if, for each type of substation equipment, guidelines for mitigating the negative effects of high SC currents on the equipment during station design, operation or maintenance are not provided, or improved analytical techniques are available. EPRI's Fault Current Management (FCM) Handbook [4] was a central resource in understanding the negative effects of high SC currents, and identifying those "best practices" for the mitigation of SC current effects that are not currently issued via IEEE/IEC standards.

Section 2 of this report discusses the negative effects of high SC currents on substation equipment. From this discussion, the following types of equipment were included in the study:

1. Bus structures (e.g., bus conductors, insulators, supports, couplings, foundations, etc.),
2. Transformers (e.g., power transformers),
3. Switchgear (e.g., circuit breakers, disconnectors, etc.).

Section 3 identifies the IEEE/IEC standards and guides evaluated in this study for each of the three equipment types above. It also presents the results of the investigation concerning the adequacy of existing IEEE/IEC standards to deal with the negative effects of high SC current.

2
NEGATIVE EFFECTS OF HIGH SC CURRENTS ON SUBSTATION EQUIPMENT

Bus Structures

The flow of SC currents in substation bus work during electrical faults generates electromagnetic (EM) forces on the substation bus structure that can result in mechanical damage to rigid bus conductors, insulators, couplings, and foundations. The effects on insulators could be cracks, fractures, or breakage. Greater damage could result if a second fault occurs before the damage caused by the first one is repaired. The action of auto-reclosers, therefore, becomes of particular interest at that point [4].

The magnitude of SC forces applied to bus support structures during fault events is a function of fault current level, conductor spacing, and type of SC (e.g., single phase- vs. three phase line-to-line fault), fault duration, and the protection system's use of auto-reclosure. Current substation design practices [5] account for the threat of SC current forces on bus structure by employing the methodology of IEEE Std. 605 to predict (in the case of a rigid bus design) the

1. Maximum, static SC force and stress on the bus conductor, to determine if its yield strength will be exceeded,
2. Maximum span of the bus, for a given vertical deflection limit,
3. Cantilever force and bending moment on the insulators, to establish the maximum required insulator rating (i.e., max. bending moment capacity),
4. Insulator bending moment, as a result of conductor thermal expansion/contraction,
5. SC load, taken in combination with structural loading due to environmental factors (i.e., wind, ice, earthquake, etc.), and

The reevaluation of IEEE Std. 605's rigid bus calculation by EPRI [6] addressed the conservatism of the SC force prediction in the Standard and proposed a simple, more realistic alternative methodology which considers the dynamic response of the bus structure to the SC forcing function.

IEC 865-1 [7] provides two alternative methodologies ("simplified" and "detailed") for calculating SC forces in bus structures. EPRI's earlier study [6] compared the accuracy of these methodologies and three other approaches proposed in the literature, with measured data. The study concluded that a method developed by Attri and Edgar [8] produced the best results.

There are no IEEE standards/guidelines specifically addressing the design of substation foundations. IEEE Std. 691 [9] provides a relevant discussion on the design of transmission structure foundations. A practical resource for designing substation foundations is Pacific Gas and Electric (PG&E) company's Substation Design Criteria Memorandum (DCM) [10]. The short circuit force loading on the foundation of a steel structure under design is combined with other "transient" loads (e.g., wind, ice, seismic and operating load), according to Allowable Stress Design (ASD) or Load Factor/Strength Design (LRFD) load combination equations.

ASCE's *Substation Structure Design Guide* [10] provides details on designing the anchorage for bus structures, but requirements on the design of the foundation itself are typically taken from the American Concrete Institute (ACI) 318 - *Building Code Requirements for Structural Concrete* [12], and ASCE 7- *Minimum Design Loads for Buildings and Other Structures* [13].

Finally, the thermal effects of high SC currents include expansion of bus conductors, and excessive heating of cables and conductors in substation electrical equipment. IEEE Std. 605 provides guidance on bus thermal expansion, but does not address the conductor/cable heating issue. IEC 865-1 gives guidance in both areas. However, the FCM Handbook (Section 2.3.1) adds the recommendations that

1. The National Electrical Code (NEC) (NFPA 2005) [14] is considered when evaluating cable protection systems
2. The manufacturer-published I^2t limits of the cable damage curve for a particular cable's insulation type be adhered to
3. In the case of increased fault current levels, protective relay settings are changed to protect the cables, or the cables be resized as necessary

Power Transformers

Short circuits can cause currents up to 10 times or more than usual resulting in electromagnetic forces 100 times or more than usual. These large forces are typically present only for a relatively short period of time (i.e. several electrical cycles) but the response of the transformer winding and its structural elements to the forces is usually considered as a first order approximation to be instantaneous. The forces in a transformer are typically divided into two categories: radial and axial. The authors of [15] indicate that electromagnetic forces favor the minimization of the magnetic energy density such that radial forces cause inner and outer windings to pull inwards and push outwards and axial forces to compress the windings. Axial forces create stress on the key spacers, the pressure rings and clamps, the tie bars as well as conductor axial bending and tilting. Radial forces create hoop stress, which can lead to buckling or permanent deformation of winding. Radial forces also cause radial bending stress when the windings have inner radial supports [16]. The Fault Management Guidebook [4] provides detailed descriptions about the phenomena related to the various aspects of short circuit mechanical forces for both shell type and core type transformers. It also points out SC forces may lead to two categories of failure:

1. Bending of conductors past their elastic limit but without an internal fault
2. Buckling of conductor leading to insulation damage, which leads to an internal fault such as a turn-to-turn or turn-to-ground fault

Short circuit currents also cause heating in windings that can lead to significant winding temperature rises (i.e. on the order of 100 to 200 °C) depending on the magnitude of symmetrical current and the duration of the short circuit.

In accordance with the negative effects mentioned in the previous paragraph, the standards describe two key short circuit withstand capabilities of transformers: mechanical strength and thermal limit. Neither the IEEE nor the IEC standards associated with the requirements and testing of transformers and series-connected reactors [17-22] provide any formulas or recommendations for the calculation of any of short circuit related mechanical forces, although [22] indicates an intention to do so in future versions.

The authors of [23] report that 28% of transformers in a wide range of power and voltage failed during initial access (i.e. initial SC testing) over a 13 year period. The authors conclude that SC testing is a critical part of the design process as evidenced by the reported initial access failure rate. Interestingly, not all of the standards indicate that the mechanical strength has to be verified by testing or even what to use if not short circuit testing. IEC 60076-5 [22] states that a transformer's ability to withstand the dynamic effects of short circuit can be verified either by testing or by a design review. The second category is required to be validated by comparison of the design and SC testing to a similar transformer according to the criteria of "similar transformer" as listed in Annex A of [22]. The authors of [23] also call into question the utility of a having a design review in place of SC testing. They cite [24], which found that 1/3 of all transformers that failed in service underwent a design review only. IEEE Std. C57.12.00 [17] requires SC testing for smaller transformer designs (i.e. 500 kVA and smaller) when it should always be feasible (i.e. within test facility limitations). For larger transformers, SC testing is considered as 'other' testing that can be required if specified by the purchaser. IEEE Std. C57.12.01 [18] considers SC testing as 'other' testing for all transformer power ratings. Both [17] and [18] do not seem to give an alternative to SC testing if the purchaser does not require it or if it is not feasible for the testing labs. With regards to validating the SC thermal limit of a transformer or reactor, the standards state that the thermal withstand capability shall be verified by calculation.

High short circuit currents also have implications for the operation and maintenance of transformers. IEEE C37.91 [25] reports in Annex A that the mechanical effects of through-faults (i.e. insulation compression, insulation wear, friction-induced displacement) have gained increased recognition as a factor in transformer failures and that the damage from the effects is a function of magnitude and duration of each fault and the total number of faults. It also states that there should be different protection curves according to the application. Applications with infrequent faults should have a curve that considers the transformer's SC thermal limit whereas applications with frequent faults should have a curve that considers the transformer's SC mechanical withstand capability. It seems clear then that if fault current levels are increasing as described in [30], then the curves should be revisited periodically, perhaps as frequently as every five years.

Another issue that the standards do not seem to adequately address is the reenergiziation of transformers. The authors of [31-32] point that the stress of reenergizing a transformer can be significant (i.e. on par with short circuits) and that controlled energization can provide substantial cost savings. IEEE C37.91 [25] has a section on the reenergizing practice of transformers but it does not mention controlled switching. It is observed that the potential benefits of controlled energization could help to offset apparent negative trends such as the decreasing margin in short circuit withstand capability in transformers [30]. Note in [30] the authors argue that there is a margin in the design of short circuit withstand capability since there is a low rate of failure of transformers in service but the margin is expected to decrease with increasing fault current levels.

Switchgear

There are several different types of high voltage circuit breakers currently in use. They have in common to produce an electric arc between the (arcing) contacts at the instant of time the contacts separate from each other. The electric arc is supposed to extinguish at the earliest possible current zero crossing after contact separation. Thermal load, contact wear, and pressure

build-up increase with increasing arcing time and fault current level. Severe damage can occur to the circuit breaker and other components of the power system if the arc cannot be extinguished on time.

Besides the level of fault currents, the X/R ratio has also increased in recent years. This is in part due to the introduction of fault current reactors, which were added to the power system to reduce the level of fault currents. While they reduce the level of fault currents, they increase the reactance of the power system and therefore the X/R ratio. Higher X/R ratios are equivalent to increased DC time constants. This is of particular importance to circuit breakers. It can be shown [30] that the arcing time increases with X/R ratio due to changing current zero crossings. Longer arcing times substantially increase stress and wear to circuit breakers.

High voltage circuit breakers are tested for DC time constants of a certain value. Traditionally this was 45 ms (X/R = 17 for 60 Hz), which is still the preferred value today according to IEEE standard C37.09 [33]. If the X/R ratio of a particular power system is exceeding this value, the circuit breaker would need to be certified for an increased DC time constant. IEC standard 62271-100 [34] lists alternative time constants, which are dependent on the voltage level. These values reflect the tendency towards increased time constants.

Literature proposes an alternative solution to re-certifying circuit breakers for increased DC time constants: The use of a circuit breaker designed for a higher fault current level than the maximum fault current in the power system allows increased time constants without excessive wear or damage of the breaker CIGRE WG13.04-1997 [35]; CIGRE TB304-2006 [36].

Increased levels of short-line fault currents entail higher initial rate-of-rise of transient recovery voltage (TRV) across the breaker contacts. Extremely rapid rise of TRV can result in re-ignition or restrike, potentially leading to transients of very high magnitude. Capacitors can be placed in parallel to the circuit breaker to reduce the rate-of-rise of TRV.

Disconnectors can also get damaged by higher levels of fault currents. Higher levels of electro-dynamic force can lead to excessive deflection and potentially to permanent deformation. It is of utmost importance that the contacts remain closed during the fault. Otherwise arcing might occur and weld the contacts together. Peak current withstand tests are specified in IEC standard 62271-102 [37].

3
IMPLICATIONS FOR SUBSTATION STANDARDS

Bus Structures

The following standards/guides have been reviewed in light of the known mechanical and thermal effects that high short circuit currents can produce in substation bus structures:

Table 3-1
Summary of Bus Structure Standards/Guidelines Reviewed

Standard / Guide	Title	Remarks	Category
IEEE 605-1998 [2]	IEEE Guide for Design of Substation Rigid-Bus Structures	• Guidelines for calculating SC force on a rigid bus system following a static force analysis	D
IEEE 605-2008 [3]	IEEE Guide for Bus Design in Air Insulated Substations	• Guidelines for calculating SC force on rigid bus, and strain bus systems following a static force analysis	D
IEC 865-1 [7]	Short-circuit currents – Calculation of effects, Part 1: Definitions and calculation methods	• Guidelines for calculating SC force on rigid bus, and strain bus systems following a "simplified" and "detailed" analyses	D
IEEE 691- 2001 [9]	IEEE Guide for Transmission Structure Foundation Design and Testing	• Design guidelines for the foundations of transmission line structures	D

The results of this review imply that current IEEE standards for bus structure design

1. Over-estimate the magnitude of SC forces on rigid bus conductors, their insulator supports, and foundations resulting in overly conservative, and unduly costly, design outcomes.
2. IEC 865-1 provides a more realistic alternative to IEEE Std. 605 [3] when calculating SC force, but the methodology developed by Attri and Edgar described in [8] has the potential of providing even more accurate SC force predictions [1].
3. Are inadequate in helping substation designers to accurately assess the potential impact of increased short circuit currents on bus structure foundation designs, and
4. Are only partially adequate in assessing the thermal impact of increased short circuit currents on substation equipment. IEEE Std. 605 [3] provides guidance on bus thermal expansion, but does not address the conductor/cable heating issue. IEC 865-1 [7] gives guidance in both areas. However, the FCM Handbook (Section 2.3.1) adds the recommendations that
   a. The National Electrical Code (NEC) (NFPA 2005) [14] be considered when evaluating cable protection systems.
   b. The manufacturer-published I^2t limits of the cable damage curve for a particular cable's insulation type be adhered to, and
   c. In the case of increased fault current levels, protective relay settings be changed to protect the cables, or the cables be resized as necessary.

Transformers

The following standards/guides have been reviewed in light of the known mechanical and thermal effects that high short circuit currents can produce in substation power transformers:

Table 3-2
Summary of Transformer Standards/Guidelines Reviewed

Standard / Guide	Title	Remarks	Category
IEEE C57.12.00-2006 [17]	IEEE Standard for Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers	• Definition of transformer categories • Requirements on short circuit characteristic • Classification of testing for the transformer categories • Calculation of winding temperature during a short circuit • SC Acceptance criteria	D
IEEE C57.12.01-2005[18]	IEEE Standard General Requirements for Dry-Type Distribution and Power Transformers, Including Those with Solid-Cast and/or Resin Encapsulated Windings	• same as IEEE C57.12.00-2006	D
IEC 60076-1 [19]	Power Transformers. Part 1: General	• Specification of short circuit impedance • Measurement of short circuit impedance	D
IEEE C57.12.90-2006 [20]	IEEE Standard Test Code for Liquid-Immersed Distribution, Power, and Regulating Transformers	• SC test arrangements and requirements • SC test procedure • SC proof of satisfactory performance • Impedance voltage (i.e. short circuit impedance) test methods and calculations	D
IEC 60076-5 [22]	Power Transformers. Part 5: Ability to Withstand Short Circuit	• Definition of transformer categories • Requirements on short circuit characteristic • Calculation of winding temperature during a short circuit • SC acceptance criteria • Guidance on finding a “similar” transformer	D
IEEE C57.12.91-2001 [21]	IEEE Standard Test Code for Dry-Type Distribution and Power Transformers	• Same as IEEE C57.12.90-2006 • Failure detection techniques and analysis of test results	D

Table 3-2 (continued)
Summary of Transformer Standards/Guidelines Reviewed

Standard / Guide	Title	Remarks	Category
IEEE C.57.109-1993 [26]	IEEE Guide for Liquid-Immersed Transformer Through-Fault-Current Duration	• Definition of transformer categories • Short-time thermal load times • Short circuit duration limit curves	D, O
IEEE C57.59-2001 [27]	IEEE Guide for Dry-Type Transformer Through-Fault Current Duration	• Same as IEEE C57.12.109-1993	D, O
IEEE C37.91-2008 [25]	IEEE Guide for Protecting Power Transformers	• Reenergizing practice • Application notes to guides on transformer through-fault-duration	O
IEEE C57.106-2006 [28]	IEEE Guide for Acceptance and Maintenance of Insulating Oil in Equipment	• In the case of long duration faults, which lead to significant temperature rises, this standard provides information how gases dissolved in oil can be used as a tool to aid in detecting abnormal operating conditions in load tap changer (LTC)	M
IEEE C57.104-2008 [29]	IEEE Guide for the Interpretation of Gases Generated in Oil-Immersed Transformers	• In the case of long duration faults, which lead to significant temperature rises, this standard provides information how gases dissolved in oil can be used as a tool to aid in detecting abnormal operating conditions in transformer	M

The results of this review imply that current IEEE/IEC standards and guides related to substation power transformers do not adequately address the issues associated with the flow of high SC currents. The following conclusions are made:

1. IEC 60076-5 [22] allows verification of short circuit mechanical withstand capability by calculation and design considerations but does not provide any standardized means or recommendations to assess the mechanical forces.
2. The IEEE standards [17-18] provide flexibility in stating in that in some cases (see the subsection on Transformers in section 2) short circuit testing is not required unless the purchaser requests it. However, the standards do not provide an alternative.
3. The authors of [15] and [23] point out that verification of a transformer's short circuit mechanical withstand by design reviews as allowed for by [22] leads to a high rate of failure in the field.
4. The curves of [26-27] might need to be reviewed periodically in light of increasing fault current levels.
5. The standards related to the operation of transformers [25] do not mention the controlled reenergization of transformers, although researchers have shown there are significant potential benefits.

Switchgear

The following IEEE/IEC standards and guides have been reviewed in light of the known arcing and electrodynamic effects that high short circuit currents can produce in substation circuit breakers and disconnectors:

Table 3-3
Summary of Switchgear Standards/Guidelines Reviewed

Standard / Guide	Title	Remarks	Category
IEEE C37.06 [38]	Standard for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis – Preferred Ratings and Related Required Capabilities for Voltages Above 1000 V	• Preferred ratings for different classes of circuit breakers • Ratings for single line-to-ground short-line faults	D
IEEE C37.09 [33]	Standard Test Procedure for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis	• Distinction between design tests, production tests, and conformance tests • Short circuit current interrupting tests are defined in the design tests • How to obtain the most severe switching conditions	D
IEC 1633 [39]	Technical Report: High Voltage Alternating Current Circuit-Breakers – Guide for Short-Circuit and Switching Test Procedures for Metal-Enclosed and Dead Tank Circuit-Breakers	• Distinction between circuit breakers with a single pole in one enclosure and circuit breakers with three poles in one enclosure • Tests for short-circuit making and breaking (single pole in one enclosure), terminal fault tests (three poles in one enclosure), and short-line fault tests (both types)	D
IEC 62271-100 [34]	International Standard: Alternating-Current Circuit-Breakers	• Ratings for short-time withstand current, peak withstand current, duration of short circuit • Rated short-circuit breaking current • Details to both AC component and DC time constant of short-circuit current • Standard values of TRV related to the rated short-circuit breaking current and defines rated short-circuit making current • Suitable test circuits and test duties for short-circuit making and breaking tests • Guidance for the selection of circuit-breakers for service	D

Table 3-3 (continued)
Summary of Switchgear Standards/Guidelines Reviewed

Standard / Guide	Title	Remarks	Category
IEC 62271-102 [37]	International Standard: Alternating Current Disconnectors and Earthing Switches	• Ratings for short-time withstand current, peak withstand current, duration of short-circuit, and short-circuit making current • Type tests for short-time withstand current and peak withstand current tests • Test to prove the short-circuit making performance of earthing switches • Guide to the selection of disconnectors and earthing switches	D
IEC 62271-308 [40]	Technical Report: Guide for Asymmetrical Short-Circuit Breaking Test Duty T100a	• Test procedures for the demonstration of arcing dimes during three-phase and single-phase tests • Procedure for testing the breaking capability with DC component of short-circuit breaking current	D
IEEE C57.106 [28]	Guide for Acceptance and Maintenance of Insulating Oil in Equipment	• For oil circuit breakers, information how gases dissolved in oil can be used as a tool to aid in detecting and diagnosing faults and abnormal operating conditions in equipment	M

The results of this review imply that current IEEE/IEC standards and guides related to substation switchgear adequately address the issues associated with the flow of high SC currents. One interesting observation is that IEC Std. 62271-100 [34] and IEEE C39.07 [33] address increasing DC time constants (X/R ratios) in different ways [30]:

1. IEC Std. 62271-100 lists 120 ms for rated voltages below 52 kV, 60 ms for rated voltages between 72.5 kV and 410 kV, and 75 ms for voltages between 550 kV and 800 kV.
2. IEEE C39.07 lists a preferred value of 45 ms, which is the traditional DC time constant. However, IEEE also accepts any other value.

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