Digital-Driven Design: Simulation-Based Approaches for Medium Voltage Switchgear Short-Circuit Performance

Aniket Shirode [1] , Amar kini [1], Pawel Bajerski [2] and Jakub Rozwod [2]
[1]North American Technology Center, Electrification Distribution Solutions, ABB Inc, Mebane, USA
[1]aniket.shirode@us.abb.com, [1]Amar.kini@us.abb.com
[2]Corporate Technology Center, Electrification business, ABB Sp.z.o.o, Krakow, Poland
[2]Pawel.bajerski@pl.abb.com, [2]jakub.rozwod@pl.abb.com

***Abstract*— This paper provides a detailed overview of best practices in the design of medium-voltage electrical switchgear, with a particular emphasis on short-circuit performance. The study explores theoretical approaches to short-circuit calculations and compares test methodologies prescribed by various standards like IEC/IEEE. A key focus is placed on the increasing relevance of advanced simulation techniques in today's digital landscape. Things to consider while using Tools such as finite element analysis (FEA) and electromagnetic transient programs (EMTP) are examined for their ability to model and analyze short-circuit behavior with high precision. By integrating conventional design methods with modern simulation technologies, the paper aims to identify optimal strategies that enhance the robustness and efficiency of switchgear systems. These insights are valuable not only for engineers and designers but also for end-users, helping them understand the significance of simulation-based validation in the digital era.**

***Index Terms* - Electromagnetic, finite element analysis, industry standards, Lorentz forces, medium voltage switchgear, short circuit performance, simulations techniques.**

I. Introduction

Medium-voltage (MV) switchgear, typically rated between 1 kV and 52 kV, is a critical component of electrical power distribution systems. Its primary functions are to control, protect, and isolate electrical equipment under both normal and fault conditions. Among the most severe stresses encountered by switchgear are those caused by short-circuit faults, which can subject the equipment to extreme thermal and mechanical forces within milliseconds. If the switchgear fails under these conditions, the consequences can include equipment destruction, extended outages, and severe safety hazards for operating personnel.

Short-circuit testing is therefore a critical design type test for medium-voltage (MV) switchgear, ensuring its capability to withstand these stresses and safely interrupt fault currents under extreme conditions. This testing verifies that copper conductors and insulation supports are adequately dimensioned and constructed to meet the specified short-circuit current ratings and withstand the required fault duration.

However, short-circuit testing requires significant time and financial investment. It involves manufacturing a full-scale product, performing destructive laboratory tests, and validating the design under actual fault conditions. Therefore, it is essential to first verify the design through theoretical calculations and simulations to increase confidence and ensure successful physical testing.

This paper examines global standard requirements and introduces both theoretical and digitally driven simulation approaches for design verification. It emphasizes the use of advanced simulations covering static and dynamic analyses to ensure accurate and reliable validation of medium-voltage switchgear designs.

II. Standards Requirements for Short Circuit Design Verification

Proper testing according to global standards like IEEE [13,14] or IEC [15] ensures that:
Mechanical strength of busbars, supports, and enclosures prevent deformation or rupture.
Thermal stability avoids excessive temperature rise that could degrade insulation or cause fire.
Dielectric integrity remains intact after fault clearance, ensuring continued safe operation.

International standards [13,14] require verification of momentary peak withstand current, short time withstand current, and duration, typically 2 s, under symmetrical fault conditions These tests confirm the assembly's ability to endure electrodynamic forces and thermal stress without permanent damage.

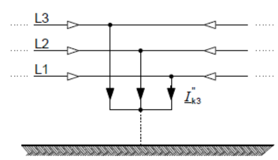
979-8-3315-8138-1

Post-test dielectric checks are required to confirm insulation integrity. Contact resistance measurements through the bus system must be performed before and after testing to ensure that bus joints maintain proper electrical connection even after a short circuit fault condition.

Compliance with these standards ensures that switchgear assemblies maintain operational reliability and personnel safety even under worse-case fault conditions. It also validates the effectiveness of interlocks, shutters, and grounding provisions. Ultimately, short-circuit testing is indispensable for minimizing downtime, preventing catastrophic failures, and meeting the stringent reliability requirements of modern power systems.

The ground bus provides a low-impedance path for fault current to earth, protecting personnel and equipment. If undersized or poorly designed, it can overheat or fail, leading to dangerous touch voltages and arc flash hazards. Short circuit testing of the ground bus verifies its ability to withstand short-time and peak currents without mechanical or thermal failure, thereby maintaining safety and compliance.

The sample medium voltage switchgear structure and general setup for a three-phase short circuit test are presented in Figure 1.



a) Medium voltage switchgear

b) Three-phase short circuit

Figure 1. General symmetrical three-phase short circuit [6]

Figure 2. schematically illustrates the general configuration of a three-phase test circuit used to perform short-time current testing on switchgear.

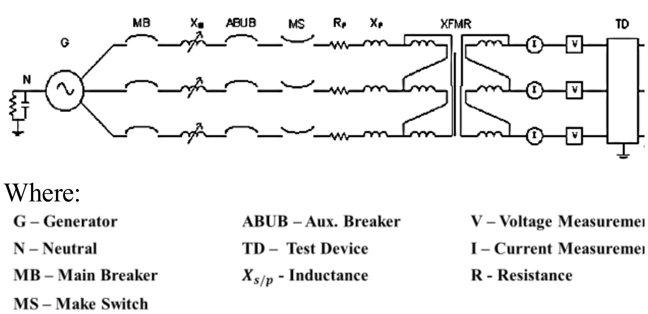


Figure 2. Three-phase short-circuit current test diagram

The typical waveform of short-circuit current generated far from the source (generator) is presented in Fig.3 defined time current behavior for the real test is applied in the numerical simulations for transient calculations, where the other two phases are shifted according to the symmetrical three-phase system current modelling. The decay time is given directly by specific standard and system voltage rating.

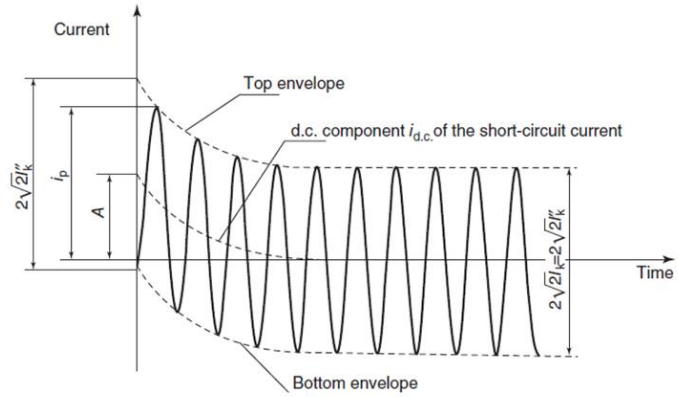


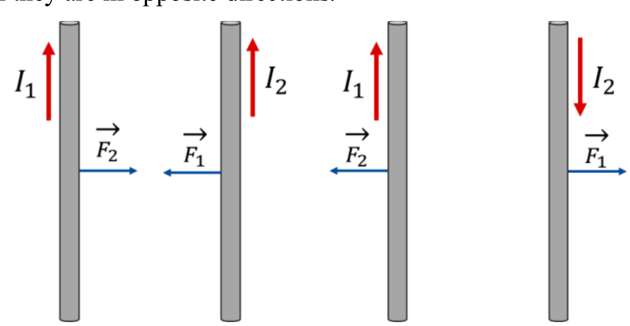
Figure 3. Time-current behavior of the short circuit current [1], [16], I''_k – initial symmetrical short-circuit current; i_p – peak short-circuit current; i_{dc} – decay d.c. aperiodic component, A – initial value of d.c. aperiodic component

The aforementioned requirements for a correctly built setup for short-time current (STC) tests are applied to predict structural behavior in numerical simulations.

III. Theoretical Approach

A theoretical approach based on electromagnetic principles and current distribution is critical before physical testing. By calculating peak momentary forces and evaluating stresses under short time withstand conditions, designers can optimize conductor spacing, bracing, and support systems to ensure compliance with IEEE and IEC standards, reduce design iterations, and improve the likelihood of successful type testing.

The basis of electromagnetism phenomenon between two parallel conductors separated by a specific distance and in which current flows in congruent and opposite directions, is presented in Figure 4. The magnetic force generated is attractive if the currents are in the same direction and repulsive if they are in opposite directions.



a) b)

Figure 4. Current directions relation: a) Congruent direction, b) Opposite direction

The mathematical description of force relation between two conductors through which currents flow in congruent or opposite is presented by (1).

979-8-3315-8138-1

$$F = \frac{\mu_0}{2\pi} \cdot \frac{I_1 \cdot I_2}{R} \cdot l \quad (1)$$

Where, F - is the Lorentz force, μ_0 - magnetic constant, I_1, I_2 - current values, l - effective distance of the conductor (e.g., between two supports), R - distance between conductors [7]

The given basic rules of electromagnetic effects and consequently forces calculation are more described in [7 - 12].

The number of conductors in the current path, their cross-sectional area, and the spacing between supports are critical design factors determined by short-circuit ratings. Additionally, parameters such as material strength, busbar configuration, peak momentary and short time withstand currents, and thermal limits must be considered to ensure mechanical stability and compliance with standards. Multiple industry guides, standards and reference books in the field of electromagnetism provide detailed methodologies for these theoretical calculations, as outlined in the bibliography.

The next section introduces a modern digital simulation approach that provides deeper insight into the real behavior of switchgear assemblies under short-time fault conditions.

IV. Digital Simulation Approach

Theoretical calculations of electro-mechanical loads provide a solid foundation for initiating the design process of medium voltage switchgears, particularly in the context of Short-Time Current requirements. However, in more complex scenarios where a deeper understanding of system behavior is necessary, traditional analytical methods often fail to accurately capture the real response of the structure under the influence of electromagnetic loads. To address this limitation, the present study employs the Finite Element Method (FEM) to simulate the performance of medium voltage switchgear under STC conditions.

Digital simulation of short-time current (STC) using finite element analysis (FEA) requires performing the following calculations:

1) Electromagnetic simulation from which the magnetic forces are extracted.
2) Mechanical simulation in which the magnetic forces are applied to the structure.

For both electromagnetic and mechanical simulations, the approach may follow static or dynamic procedures.

1) The static approach is less computationally expensive as it assumes a constant level of current in the system. It can only generate results in one time point after achieving a state of force equilibrium condition. The approach is effective within the range of small deformations and when nonlinear material properties have only a minor influence on the results. Static approach does not capture inertia forces and consequently dynamic effects. Additionally, static analysis must be complemented by modal and buckling analyses to fully capture the behavior of the electromechanical system under Short-Time Current test conditions.
2) The dynamic (transient) approach enables us to simulate the effect of exact waveform of the short circuit occurring in the system. It considers the skin-effect and eddy currents. The transient analysis provides the means to capture non-linearities and inertia effects. Additionally, the theory of large deformations of the structure is correctly captured. The outcome of the transient analysis comes in the form of realistic animation showing exact movement of the conductors during the STC test.

The main purpose of electromagnetic simulation is to calculate magnetic field strength (H) and the flux density (B). Furthermore, the energy and the source current density (J) are displayed" [6]. Based on the primary results that the electromagnetic solver yields, it is possible to calculate magnetic forces in any given location, at any given time using the formula (2).

$$\vec{f} = \vec{J} \times \vec{B} - \frac{1}{2}\left|\left|\vec{H}\right|\right|^2 \nabla\mu \quad (2)$$

Where:

$\vec{J} \times \vec{B}$ – Lorentz force term, $-\frac{1}{2}\left|\left|\vec{H}\right|\right|^2 \nabla\mu$ – magnetic force due to the magnetic behavior of the material

A critical aspect of the electromagnetic simulation is the accurate definition of the excitation. For the short-circuit analysis of the medium-voltage switchgear, the excitation was modeled as a current flowing through the busbar system into the computational domain. The characteristics of this excitation can be derived using (3) [4]:

$$I_j = \sqrt{2} I_{rms}\left[\sin(\omega t + \varphi - \theta_j) - \sin(\varphi - \theta_j) \cdot e^{-t/\tau}\right] \quad (3)$$

Where:

I_j – short circuit current for the specific phase, I_{rms} – root mean square current, ω – angular frequency, φ – angle of fault initiation, θ_j – angle for the j-th phase, τ – dc time constant of the circuit.

The majority of the numerical verification of electromechanical systems allow to simplify approach to static manner. It is based on simplifying current waveform to one analyzed point in time. Figure 5. presents the first period of the calculated short circuit waveform. The vertical line indicates the point in time at which the $I_1(t)$ reaches its maximum value, while the $I_2(t)$ and $I_3(t)$ half of that value. At this point the current's total energy reaches its maximum, posing the greatest risk to the structural integrity of the simulated model and thus it is most often chosen to base the simulation on. That makes the static approach a simplified way of transient analysis that is based on peak value of the current waveform.

979-8-3315-8138-1

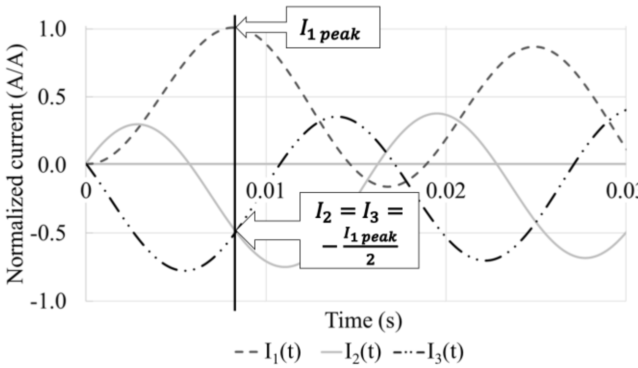


Figure 5. Short time current waveforms – comparison magnetostatic vs. time-domain

The following study of medium voltage switchgear is based on the transient approach. Thus, the complete waveform shown in Figure 6. could be used as an excitation signal, allowing the simulation to accurately reflect the time-dependent behavior of the physical phenomenon.

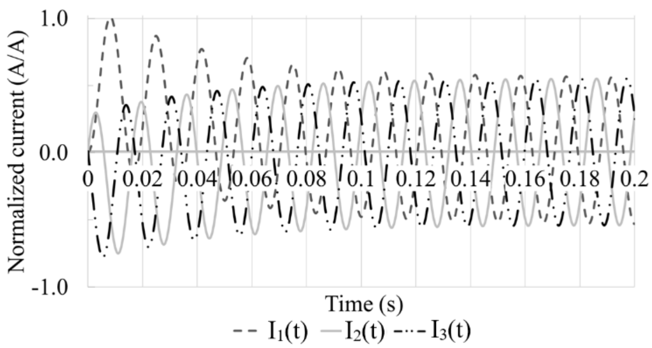


Figure 6. Complete waveform of three-phase short-time current as input to transient electromagnetic analysis.

The numerical model of the busbar system used for the electromagnetic simulation is illustrated in Figure 7. The snapshot was taken at simulation time equal to 8 ms, corresponding to the peak of the current signal $I_1(t)$ in the top busbar. At that time point, the highest electromagnetic load is observed, as indicated by the vectors representing Magnetic Force Density (N/m³).

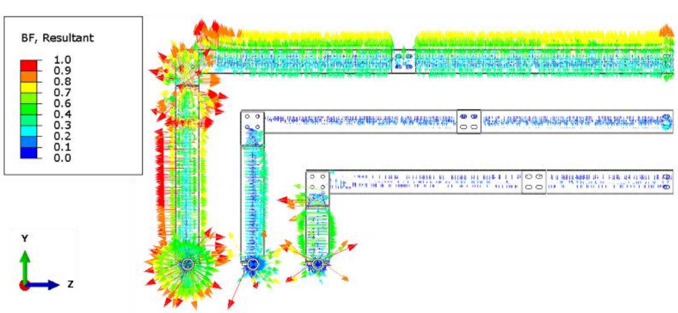


Figure 7. Magnetic Force Density vector field (N/m³) at 8 ms of transient electromagnetic simulation.

The time-dependent nature of the Short-Circuit Test is shown in Figure 8. , which presents the state of the magnetic forces at 11 ms of the electromagnetic simulation. At this stage, a noticeable shift in the force distribution is observed, with the bottom busbar experiencing high magnetic loading.

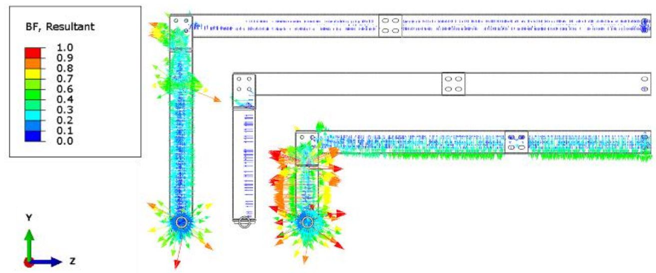


Figure 8. Change of Magnetic Force Density vector field (N/m³) at 11 ms of simulation.

The calculated forces are then fed into the mechanical solver. It can be done either in the form of concentrated forces acting on the numerical nodes at the structure, or as a distribution of force density in the volume element. The forces are interpreted and transformed internally by the mechanical solver and treated as an external load. The mechanical response of the entire structure is then calculated. The state of the medium voltage switchgear at the time equal to 70 ms of the STC simulation is shown in Figure 9 The presented displacement distribution of the busbar system reaches maximum at the marked measuring point in the picture.

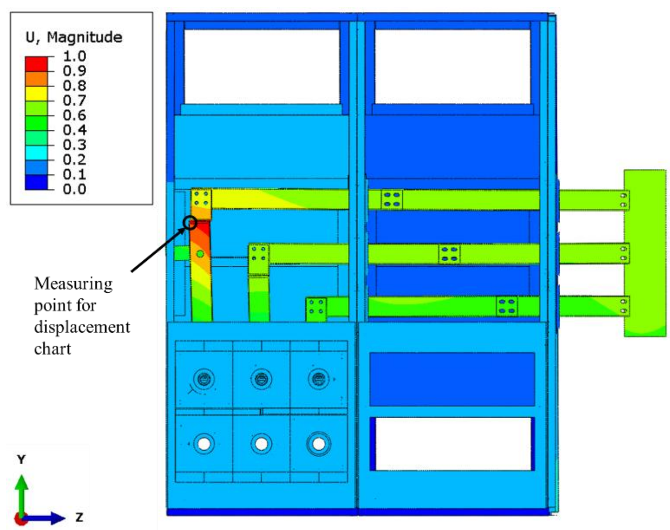


Figure 9. Displacement (-) distribution of busbars in switchgear system at time 70 ms

The time-dependent history of the node that expierences the greatest displacements is shown in Figure 10. The peak of the deformation occurs at 70 ms although the peak of current appeared at 8 ms. That discrepancy shows the importance of inertia effects and indicates the neccesity of performing modal analysis to check the risk of resonance in the system, which the static analysis can not capture.

979-8-3315-8138-1

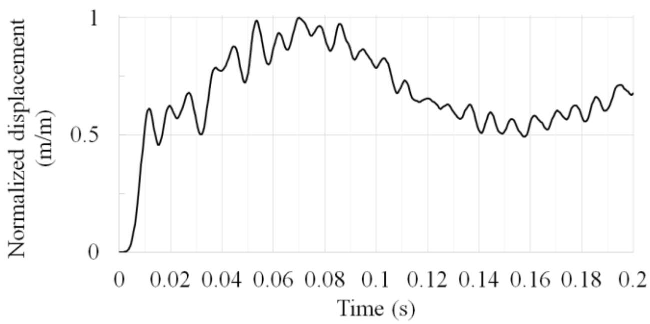


Figure 10. Displacemnt (-) chart of the selected node in switchgear model

Finite element method for electro-mechanical assesssment offers powerful capabilities for evaluating structural performance of switchgear systems. Figure 11 presents the utilization factor of Von Mises Stress distribution over the Switchgear enclosure and the busbar system at the specific time frame equal to 70 ms. The contuor plot shows the areas of stress concentration that could potentially lead to structural failure. By identyfing and redesigning weak points, the product becomes more reliable and safe. The output from the Finite Element Analysis may also include the reaction forces in anchor points, forces acting on bolted joints, weld assessment and overall look on the system safety under the influence of STC test.

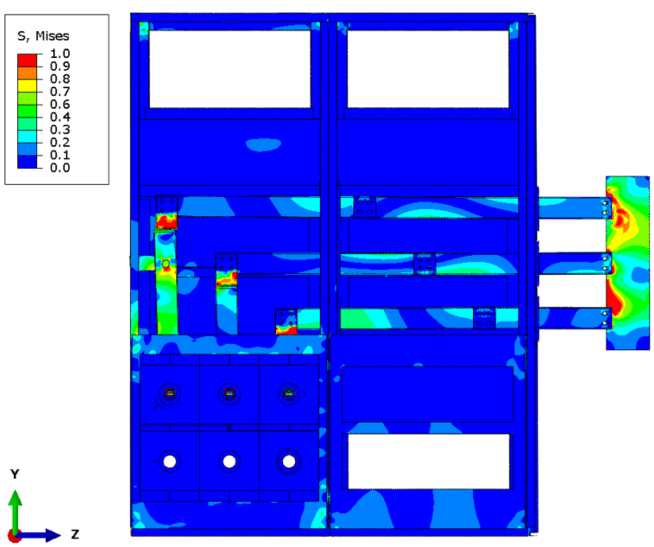


Figure 11. Utilization factor (-) for von Mises stress distribution on the Medium Voltage Switchgear at time frame 70 ms

Conclusions

Medium-voltage switchgear under Short-Time Current (STC) conditions demands precise evaluation to ensure safety and compliance. Traditional theoretical formulas while useful for Initial calculations fall short in capturing the complex electromechanical phenomena during fault events. This paper demonstrates how integrating advanced numerical techniques, particularly the Finite Element Method (FEM), provides a more comprehensive understanding of electromagnetic forces, stress distribution, and dynamic effects. Furthermore, a **dynamic simulation method** is introduced and explained with an example to predict the condition of switchgear at the end of the STC period. This approach has the potential to replace certain destructive physical tests, significantly reducing testing time and financial investment. By embedding FEM-based dynamic simulations into the design workflow, designers can proactively identify weaknesses, optimize structural integrity, and ensure compliance with international standards—ultimately enhancing reliability, safety, and cost-efficiency in medium-voltage switchgear development.

References

Books and Technical Reports:

[1] Ismail Kasikci, "Definitions: Methods of Calculations," in Short Circuits in Power Systems: A Practical Guide to IEC 60909-0 , Wiley, 2018, pp.1-22, doi: 10.1002/9783527803378.ch1.
[2] Ismail Kasikci, "Calculation of Short-Circuit Currents," in Short Circuits in Power Systems: A Practical Guide to IEC 60909-0 , Wiley, 2018, pp.147-159, doi: 10.1002/9783527803378.ch11.
[3] Ismail Kasikci, "Mechanical and Thermal Short-Circuit Strength," in Short Circuits in Power Systems: A Practical Guide to IEC 60909-0 , Wiley, 2018, pp.167-183, doi: 10.1002/9783527803378.ch13.
[4] B. de Metz-Noblat F. Dumas C. Poulain, "Calculation of short-circuit currents" Cahier Technique Schneider Electric n° 158 / p.3
[5] J. Jian-Ming. The finite element method in electromagnetics, Wiley & Sons, 2015
[6] ABB Switchgear manual, 12th edition, 2012.
[7] A. J. Flewitt, Electromagnetism for Engineers, Wiley, 2022, p. 37-50.
[8] CST Studio Suite 2025 documentation:
[9] Simulia/ Abaqus 2025 documentation:

Papers from Conference Proceedings (Published):

[10] Rozwod J. Bajerski P. "Multiphysics Simulations for Short-Time Current (STC) Tests of Electrical Power Equipment", NAFEMS, April 2024
[11] Smajic. J, How To – perform Electromagnetic Finite Element Analysis, NAFEMS, HT43, 2016
[12] Ellis. D, Tang. K, why do – perform Electromagnetic Finite Element Analysis? NAFEMS, HT39, 2009

Standards:

[13] IEEE.Standard for Metal Clad switchgear, IEEE Std C37.20.2 – 2022
[14] IEEE Standard for Metal Enclosed switchgear, IEEE Std C37.20.3 – 2023
[15] High-voltage switchgear and controlgear - Part 200: AC metal-enclosed switchgear and controlgear for rated voltages above 1 kV and up to and including 52 kV , IEC 62271-200: 2021
[16] IEC Short-circuit currents in three-phase a.c. systems – Part 0: Calculation of currents, IEC 60909-0 Edition 2.0 2016-01

979-8-3315-8138-1