Digital model for assessing strength of busbars and busbar supports located in a switchgear under the influence of electrodynamic force

A V Korzhov1, A O Chertiavsky1, M A Dziuba1,3, D V Putenikhin2 and A I Kamynin3

1 South Ural State University, Lenina av., 76, Chelyabinsk, Russia
2 Chelyabinsk Electric Equipment Plant, Profsoyuznaya st., 78A/building 1, floor 2, office 3, Moscow, Russia

3 E-mail: dziubama@susu.ru

Abstract. Short circuit current impact tests of busbar arrangements in switchgears are very expensive. There are publicized studies that propose the assessment of the impact using simple geometric constructions, but that approach fails to deliver good results. In this article, we propose a finite element method for analysis of mechanical movements in the context of short circuit current impact over the sinusoidal current period. The proposed method allows us to research different designs of switchgears without conducting full-scale tests. We can determine the parts of the model that will shift into unacceptable positions under the influence of short circuit current and promptly make changes to the model.

1. Introduction

There is recorded evidence of mechanical rupture of busbar supports in cells of 10kV switchgears during the short circuit mode. The cell should be designed to sustain mechanical impact of electrodynamic force of short circuit current of up to 130 kA. As a rule, in order to test the electrodynamic withstand there is a need to conduct expensive full-scale tests. In the article we will discuss the application of digital twins for assessment of mechanical action.

Ampere force \( \vec{dF} \) that arises during the interaction of two current conductor elements is defined by a following equation [1]:

\[
d\vec{F} = I d\vec{l} \times \vec{B}
\]

\[
d\vec{B} = \frac{\mu_0}{4\pi} \frac{I [\vec{r} \times d\vec{r}]}{r^3} = \frac{1}{10^7} \frac{[\vec{r} \times d\vec{r}]}{r^3}
\]

where \( I \) – current; \( B \) – magnetic flux density; \( r \) – vector, describing the position of one conductor element in relation to the other.

In literature sources we can find simplified analytic equations for assessment of mechanical action [2, 3]. These equations do not allow for full picture of the mechanical action, particularly, in relation to structures with difficult geometric busbar arrangement intrinsic to compact cells of modern switchgears. A number of studies have been conducted in the area of joint electric, magnetic, thermal and mechanical...
interaction of switchgear busbars under the influence of short circuit currents [4, 5]. An analysis was carried out using a finite element model approach that allows for joint modeling of interaction between different physical factors. In these scientific works it is established that the type of the busbar support base plays an important role in the displacement of the conductor under the influence of short circuit currents [6-8]. Nevertheless, in the aforementioned studies the system under study consisted of busbars arranged on a single plane.

2. Methodology and the idea behind calculations

A system of arbitrarily set conductors can be split into elements. At each point in time the force that acts upon every selected element of the system can be calculated as a vector sum of forces that influences all other elements. The dependency of currents on time in each conductor may be arbitrary, even nonperiodical.

This approach eliminates the need to use additional assumptions: simplified geometry, correction coefficients for calculating finite length of conductors, assumptions in regards to the strictly periodic character of currents and forces created by them. Along with equations, that describe the mechanical dynamics of the conductor system, we get a full description that helps us to calculate the tension in conductors and supports – in the context of arbitrary configuration of conductors and use of arbitrary current change program, including conductors in a nonlinear arrangement (taking into account elastic-plastic behavior of materials and the possibility of a one-way connection – supports, etc.).

The numerical implementation of the aforementioned ideas was done using ANSYS (software for breaking a structure into finite elements) A set of tasks was completed on the topic of dynamic behavior of mechanical systems under the influence of specified forces.

To calculate electrodynamic forces, we wrote a special macro for ANSYS using APDL. The function of the macro: the macro allows for calculation of the current in each element (at each point in time of the set interval) and for calculation of forces of all other elements acting upon each element. The following assumptions were used for the macro:

- Uniform current distribution across the conductor cross section;
- Small movement of elements of the system (big movements that may lead to short circuiting are unacceptable) – initial distance between conductors can be used to calculate the electrodynamic forces;
- Supports (insulators, current transformer contacts) are absolutely rigid and will not collapse.

3. Implementation of the idea using a particular design

For illustrative purposes we chose to calculate electrodynamic forces in conductors in the cells of SCG 2-15 with a main circuit current rating of 3150 A. The finite element model of the busbar is presented in figure 1. In the figure 2 you can see the location of supports (large characters with the designation of positions - 1.1, 1.2, etc.) and the location of points where separate copper busbar strips are connected to each other (but no to the support) using bolts – small characters that do not have a special designation of positions.

Sinusoidal current with frequency of 50 Hz and amplitude of 50kA was used as actuation; current phases in 3 busbars have been shifted 120° in relation to one another (description of current dependency on time in a written macro was implemented using a formula, so adding an aperiodic component is not a problem). The currents flow from the lower ends (figures 1, 2) to the upper ends of busbars; horizontal parts in the upper left corner are free from currents (the circuit can be easily changed: left parts can be connected and the current will be distributed evenly between left and right parts).
The data on density and elastic modulus is similar to each other, and the yield stress data (deformation diagram) is very different - apparently, it depends on the technology. The use of a linear elastic material model - without plastic deformation - gives an overestimated load on insulators, but an underestimated estimate of busbar movements. Therefore, a linear elastic material model (with sufficiently reliable reference data) is enough to assess the strength of insulators (with an error within a safety margin), and to evaluate the busbar movements - the results of mechanical tests are needed on samples cut from busbars, made using standard technology.

A simple, but informative preliminary calculation is the calculation of the natural frequencies and oscillation modes of a busbar as a part of the mechanical system (excluding currents flowing through the busbars). This calculation allows us to determine the resonant frequencies and to evaluate the fulfillment of the detuning from resonance requirement - difference in the frequency of the exciting force (50 Hz, 100 Hz) from the natural frequency of the structure. The natural lower frequencies - about 8 Hz - correspond to oscillations of horizontal sections of busbars. These oscillations are not dangerous, since their frequencies are far from the frequency of the exciting force. At the same time, one of the natural frequencies — 53 Hz — is close to the excitation frequency.

4. Simulation results
In the figures shown below, you can see the results of calculation of electrodynamic forces and their effect on the structure of the aforementioned model.

The calculation was carried out using time steps. The step value is set at 0.001 sec (20 steps per current change) with the possibility of automatic reduction, if the calculating procedure encounters difficulties in terms of convergence of results. The duration of the interval under consideration is 0.2 sec; as seen in the results shown below, the duration is enough in order to stabilize the process and assess the maximum values of forces (to increase the duration - all one has to do is to increase CPU time).

The calculations showed that the most loaded insulators are number 2.4, 1.3 and 3.4 (see figure 2). It is difficult to pick the most loaded insulator due to the fact that all the aforementioned insulators differ in terms of relation of tension force N to lateral force Q: a higher amount of tension force is applied to the insulator 3.4, while on the other two insulators a higher amount of lateral force is applied.

The most loaded (in terms of mechanical force) transformer is located in the middle – points 2.A and 2.B (see figure 2). We note that the calculated values of lateral forces Q are lower than the mechanical flexural strength parameter set in the specifications for epoxy-compound insulators (75 and 95 kN). At the same time,
the calculations show that not only the mechanical flexural strength is applied to the insulators, but also the tension force \( N \) reaches a significant value.

In the absence of experimental data on the strength of insulators with combined load \((N, Q)\) such estimated can be obtained using a calculation that takes into consideration the insulator blueprints and data guaranteed resistance to bending. However, this calculation is another matter entirely.

The results of calculation of movements in the structure (using arbitrarily set elastic-plastic characteristics of busbar material) are shown in figure 3. It was supposed that the deformation diagram could be represented as a two-link broken line with a yield stress of 150 MPa, elastic modulus of \( 1.3 \times 10^5 \) MPa and local modulus of 200 MPa. Most movements occur in the part of structure where the natural frequency is close to the exciting force frequency. These oscillations lead to a rapid increase in movements which stops due to the strengthening of material under the influence of plastic deformation. The maximum movement value of 145 mm violates the proposition set in section 2 about the scarcity of movement (in the absence of the effect of movements on the calculated electrodynamic forces), and due to the arbitrarily set characteristics of the materials it cannot be considered precise. But it is certain that the area in question is dangerous.

5. Conclusion
The calculations allow us to assess possible effectiveness of measures aimed at improving the structure of the switchgear cells. Two busbar elements connected to each other (even without that point being attached to the body frame) increase the rigidity of the construction and lower movement (see figure 4).

The numerical implementation of the idea described in the article is conducted using ANSYS software which allows you to abandon expensive full-scale tests. Changes necessary to ensure dynamic stability are made at the design stage according to the calculation results, and expensive tests are carried out only once as confirming ones - according to certification requirements.

The calculation procedure allows you to analyze the effects of both periodic and current pulses - aperiodic asymmetric, specific of real emergency conditions in electrical networks.

References
[1] Malygin V M 2016 Magnetic interaction of conductors with currents: special characteristics of
Ampere’s formula and the Newton’s third law *Space and time* 3 86-92

[2] Krčum M, Zubcic M, Dlabač T 2019 Electromechanical analysis of the medium voltage earthing switch due to short-time and peak withstand current test *Energies* 12 3189

[3] Panteleevaa I V 2017 Peculiar features of electrodynamic withstand of the arbitrary rigid busbar arrangement *Current Sci. Res. in the Mod. World* 4 24 51-3

[4] Kadkhodaei G, Sheshyekani K and Hamzeh M 2016 Coupled electric magnetic-thermal-mechanical modeling of busbars under short-circuit condition *IET Gener. Transm. Distrib.* 10 955-63

[5] Kadkhodaei G, Sheshyekani K, Hamzeh M and Tavakoli D 2016 Multiphysics analysis of busbars with various arrangements under short-circuit condition *IET Electrical Systems in Transportation* 6(4) 237-45

[6] Abd-El-Aziz M M, Adly A A and Abou-El-Zahab E M 2004 Assessment of electromagnetic forces resulting from arbitrary geometrical busbar configurations *Int. Conf. on Electrical, Electronic and Computer Engineering* ICEEC04 pp 774-7

[7] Yusop F M, Jamil M K M, Ishak D et al 2011 Study on the electromagnetic force affected by short-circuit current in vertical and horizontal arrangement of busbar system *Proc. IEEE Int. Conf. on Electrical, Control and Computer Engineering* (Pahang, Malaysia) pp 196-200

[8] Yusop F M, Jamil M K M, Ishak D et al 2011 Investigation of electromagnetic force during short-circuit test in three-phase busbar system *IEEE Colloquium Humanities, Science and Engineering* (Penang) pp 340-4