Russian practice on tests and confirmation of power transformers ability to withstand short circuits

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SUMMARY

Ability of transformers to withstand short circuits (SC) is one of the main factors determining the transformers reliability, which are the most expensive and responsible element of electrical networks. Despite significant progress in the field of technologies, design, materials used in recent years, transformer faults due to insufficient short-circuit strength still occurs.

The report presents the Russian experience in scope of testing and design confirmation of power transformers ability to withstand short circuits.

The report describes the practice of confirming the short-circuit strength, established in the current national regulations and applied to acceptance of power transformers supplied to the power facilities of the largest Russian power grid company – PJSC "FGC UES", who manages the transmission networks and substations with voltage classes 220 – 750 kV.

Brief data on the recent statistics for short-circuit tests and the most characteristic faults detected during the tests are given.

The issues of alternatives to direct SC tests of large power transformers are considered, namely:

- tests of winding models and other transformer elements (in cases if some elements of large power transformer did not pass the SC test and these elements can be reproduced by models);

- practice of the Russian Federation on evaluation of the transformer ability by comparison with a reference transformer (prototype) which has passed the short-circuit test successfully as well as requirements to prototypes and "pitfalls" of this evaluation;

- confirmation of SC strength by calculation.

The report also provides brief information on the ongoing research work intended to create a method for calculating the SC strength of large power transformers, carried out by order of PJSC "FGC UES".

KEYWORDS

power transformers, ability to withstand short circuits, short-circuit test, short-circuit strength, design confirmation

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1. Russian practice of confirmation of power transformer short-circuit strength

Ability of power transformers to withstand short-circuit currents is one of the main factors determining the reliability of transformers, which are the most expensive and responsible element of electrical networks. At the same time, short-circuit strength is the only one of the most important reliability parameters of transformer equipment, which according to the current world-wide practice is not subject to mandatory confirmation by routine or type tests. Despite significant progress in the field of technologies, design and materials achieved recent years, the accidents with power transformers due to insufficient short-circuit strength still occurs. The related harm is associated not only with significant economic losses, but also with the violation of energy supply, safety and often with significant environmental impacts.

According to the Russian national standard GOST R 52719-2007 [1] short-circuit test is a type test. Acceptance of power transformers in terms of short-circuit strength is carried out depending on capacity of the transformer by at least one of the following methods, which shall be specified in the normative documents for specific transformers or specified at the transformer-supply contract agreements:

- short-circuit test according to standard GOST 20243 [2];

- comparative calculation with a transformer of similar design (prototype), which has withstood short-circuit test;

- confirmation by calculation according to the manufacturer's method in case of large power transformers (allowed only for transformers with a capacity of higher than 40 MVA).

According to GOST R 52719 it is allowed to confirm the short-circuit strength on the basis of a comparison with a transformer of similar design (prototype), successfully passed SC test, if the conditions listed below are fulfilled:

- considered transformer and its prototype shall be manufactured by the same manufacturer and using the same technology processes;

- considered transformer shall have a short-circuit withstand power (rated power divided by short-circuit impedance) in the range from 50% to 100% to its prototype and shall have same designs of windings, magnetic system, yoke insulation and pressing systems;

- prototype shall have higher mechanical forces and loads (stresses, strains, axial forces on the supports), smaller safety margins of strength and stability according to the results of comparative calculation performed using manufacturer’s method.

In addition to SC tests the tests of ability to withstand load overcurrents are established for transformers used in power plants auxiliary supply. Transformers for auxiliary supply irrespective of power shall be tested to confirm not only ability to withstand short circuits but also and ability to withstand load overcurrents. For these transformers it is possible to replace the tests by calculation comparison with the successfully tested prototypes, but it is not permitted to accept only on the basis of the confirmation by calculation.

2. Russian experience in SC tests of transformers

In the former USSR in the 60-70s, accompanied by the development of new voltage classes (330, 500, 750 and 1150 kV) and increasing the capacity of transformers, there was an increased fault rate of power transformers due to insufficient short-circuit strength.

To solve the problem of short-circuit strength of power transformers, 7 test laboratories were established, in which a large number of transformers of almost all types with a capacity up to 666 MVA and voltage class up to 750 kV were tested. A lot of prototypes were tested which were used later for comparative calculations. The industry method of SC strength calculation was developed which was introduced at all transformer factories of the USSR. The measures taken made it possible to reduce significantly the fault rate due to insufficient short-circuit strength and improve the reliability of power transformers.

In recent decades, new transformer manufacturers have appeared in the Russian Federation, which did not have sufficient experience in SC tests of transformers. Factories having previously huge experience in testing began to apply new technologies, materials and technical solutions that had not previously been fully tested for short-circuit strength and which are not fully covered by calculation methods applied by factories.

In order to ensure the high reliability of transformers, the testing of power transformers, first of all, the most frequently used types, namely distribution transformers with capacity up to 4 MVA and power transformers with capacity of 6,3 – 40 MVA, was intensified. It was reflected in the new national standard GOST R 52719. For instance, in recent years, Russian factories have tested (along with large amount of distribution transformers) about 20 transformers (prototypes) of various types with a capacity of 6,3 – 40 MVA, of which 5 transformers (~25%) with capacity 25 and 40 MVA had been damaged during tests.

Transformer faults during the SC tests can be roughly grouped as follows:

1. Local mechanical deformations which do not change the integrity of the transformer design and do not affect its main function i.e. voltage transformation:

- local axial and radial bending of winding conductors;

- local loss of axial stability of winding conductors (tilting);

- local sliding down of the turns of regulation winding under the action of axial forces (telescoping);

- local loss of radial stability of windings (buckling);

- shift of winding leads under the action of tangential forces;

- twist of the windings (spiraling);

- displacement / deformation of the leads;

- local deformation of conductors and winding insulation in places of inhomogeneity (transpositions).

Deformations belonging to this group are poorly detected by traditional diagnostic methods. Transformers with such defects can remain in operation for a long time – as long as overload, overvoltage or electrodynamic effects during next short circuit will not lead to the development of local deformations and more severe damage.

The loss of winding clamping force, which has a significant impact on the electrodynamic stability of the transformer, can also be attributed to above mentioned group of hard-to-detect defects.

2. Extensive mechanical deformations without internal inter-turn and inter-disc short circuits:

- displacement of windings under the action of axial forces;
- extensive loss of radial stability of the windings (buckling).

These defects can be reliably detected by traditional diagnostic methods during the assessment of the transformer condition after observed short circuit.

3. Mechanical deformation of the windings, resulting in the destruction or weakening of the turn-to-turn or disc-to-disc insulation and subsequent internal short circuit, accompanied by severe winding damage.

3. Alternative to SC tests for large power transformers

3.1. Testing of winding models

One of the alternative ways to confirm the SC strength, which has been used in practice, is the test of physical models of individual elements of transformers. Since one of the most common transformers fault is the winding buckling and bending, we may primarily talk about testing models of transformer windings.

It is important to note that the SC tests of winding models cannot be considered as a complete replacement of the short-circuit tests of real power transformer. At the same time tests of winding models have found its application. Typical examples of its application are as follows:

- research tests in order to clarify the criteria used in the calculation methods applied for the design of large power transformers;
- design tests in order to check of different winding designs and to choose the optimal technical solutions and technology at the design stage;
- tests for confirmation of certain factors of SC strength of the transformer which earlier has not passed successfully SC tests only by one of the factors, for instance, related to winding SC strength (e.g., in case of local buckling of LV winding).

For the purpose of testing of winding full-scale models the test setup named LDU (light dynamic unit) have found its application. LDU are intended for SC tests of transformer winding physical models on radial and axial stability and strength, as well as for tests of mechanical strength of pressing system elements.

The LDU test setup is without the magnetic system and consists of permanent and variable parts (figure 1). The permanent part includes the auxiliary (exciting) winding (EW), top and bottom steel clamping plates, tie rods for clamping the top and bottom plates, the pressing ring of the EW winding along with clamping elements (blocks, clamping screws, supports, etc.), as well as the yoke insulation of EW winding and inter-winding insulation (cylinders). The variable part includes the winding under test (TW) with yoke insulation and clamping rings with clamping elements (blocks, clamping screws, etc.). The design of the variable part usually corresponds to the real transformer.

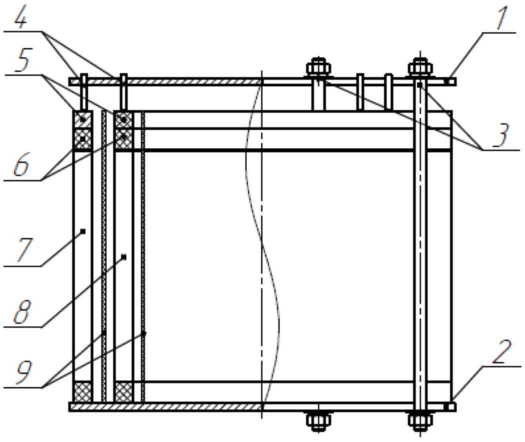

Figure 1 – LDU test setup

1 – top plate; 2 – bottom plate; 3 – tie rods; 4 – clamping screws;
5 – clamping rings; 6 – yoke insulation; 7 – exciting winding (EW);
8 – winding under test (TW); 9 – insulating cylinders.

Tests on the LDU installation are carried out in the short-circuit mode with power supply from SC generator. In the case of the external location of the EW winding the generator voltage is fed to the EW winding, while the TW winding is shorted through the current shunt. In the case of the internal location of the EW winding, the voltage is applied to the TW winding, while the EW winding is shorted through the current shunt. Test currents are selected taking into account the correction for differences in the distribution of the magnetic field without core.

3.2. Evaluation by comparative calculation with a transformer of similar design (prototype), which has withstood short-circuit test

The introduction of GOST R 52719 and standard technical requirements of PJSC “ROSSETI” and PJSC “FGC UES” [3] prompted domestic manufacturers to intensify work on short-circuit testing of transformers with a capacity up to 40 MVA, intended as well as for using this transformers (in case successful SC tests) as a prototype for comparative calculation with new transformers, provided the above mentioned conditions. As noted above, GOST R 52719 allows this method of confirmation.

According to the experience gained by manufacturers in terms of confirming the SC strength by comparative calculation with tested prototypes, it is not always easy to perform practically the above mentioned conditions for prototypes according to GOST R 52719, despite its seeming evidence and simplicity. In practice, this issue is more complicated, because in considered transformers which may be of lower capacity, the forces acting at short circuit can be smaller and for economic reasons, other design solutions can be applied in them compared to the tested prototype. This can lead to the differences in design of windings, clamping system and other elements. The main reasons limiting the possibility of spread of test results are the following (and this list is far from complete):

1) Different winding design (disc-type, layer-type, helical-type etc., for instance, due to different rated voltage of HV and/or LV windings).

2) Different number and placement of windings (e.g., the presence of stabilizing winding, location of regulating winding).

3) Different types of winding clamping system (e.g., common or separate clamping rings, materials, clamping screws or blocks etc.).

4) Forces and mechanical stresses in the considered transformer can be sometimes greater than in the prototype.

5) Different values of short circuit impedance and short-circuit capacity.

Thus, actually tested transformers, as a rule, cannot always be complete prototypes for all possible variants even for transformer with almost the same rated power. This fact should be kept in mind during selection of proper candidate for prototype to be tested.

3.3. Confirmation of SC strength by calculation

A feature of the Russian practice related to the confirmation of power transformer SC strength by calculation is that vast majority of the transformers with capacity higher than 40 MVA, entering Russian market (domestic-made and imported) are subject to calculation according to the unified industry calculation method RD 16.431-88 [4]. This method was developed in the 70-80-ies of the last century at the expense of state funding on the basis of joint theoretical and experimental studies of scientific organizations, transformer plants and testing laboratories.

The method applies to core-type liquid-immersed transformers with an arbitrary arrangement of windings. The method implements the calculation of axial, radial and tangential forces and the corresponding mechanical stresses and strains for each disc (turn) of each core windings for all short-circuit modes given in the initial data, the calculation of strength and stability criteria, safety factors, as well as the values of the required clamping force for each individual winding and windings set.

The experience of almost 50 years of development and application of the method allowed significantly reduce the transformer failure rate due to insufficient SC strength. During this time, calculated studies of several hundred types of transformers of various manufacturers were carried out. Currently, main network operator companies accept transformers into operation only after assessing their SC strength using unified industry calculation method. The method showed a good coincidence of calculated and experimental data. As a rule, transformers having sufficient calculated design margins withstand successfully the SC tests and have no damages in operation due to short-circuit problems.

As far as the development of technologies for the transformer design and manufacture is never ending, the calculation method needs to be constantly updated by experimental data to account for new technologies and materials as they begin to be widely used. For the confirmation of SC strength by calculation, it is necessary to be sure that the applied calculation method adequately reflects all main factors affecting the strength of the transformers.

In the period 2018 – 2021, R&D Center of FGC UES and VEI (All-Russian Electrotechnical Institute), both of which has research and testing laboratories, carry out large-scale research and development work (R&D) by order of FGC UES aimed to develop further the industry-applicable method for calculating short-circuit strength of power transformers. All major Russian transformer manufacturers, who produce power transformers of voltage classes 110 kV and above, are participating in this R&D work. That will allow to take into account in the newly developed method the actual materials and technologies used by them as well as their experience in SC tests of power transformers. This work involves the design and manufacturing of special test setups and carrying out the tests of full-scale physical models of windings and elements of the clamping system of large power transformers in order to study the key factors that affect the SC strength (table 1). R&D also involves the SC tests of transformer prototypes prepared specially for R&D purposes.

Table 1 – Key factors influenced on transformer SC strength

Category	**Factor description**
1. Radial stability of windings (buckling)	1.1. Application of conductors with high proof stress. 1.2. Application of epoxy-bonded continuously-transposed conductors. 1.3. Application of epoxy-bonded twin and triple conductors. 1.4. Application of axial cooling duct (clackband). 1.5. Application of rigid cylinders (bakelite and glued pressboard) for inner compressed windings. 1.6. Influence of axial compression. 1.7. Influence of winding diameters, width and conductor dimensions. 1.8. Influence of technological and other factors.
2. Axial stability of windings (tilting)	2.1. Application of conductors with high proof stress. 2.2. Application of epoxy-bonded continuously-transposed conductors. 2.3. Application of epoxy-bonded twin and triple conductors. 2.4. Influence of winding diameters. 2.5. Influence of winding radial width. 2.6. Influence of number of radial spacers and its width. 2.7. Influence of radial duct height. 2.8. Influence of conductor dimensions. 2.9. Influence of dynamic behavior of axial forces. 2.10. Influence of technological and other factors.
3. Radial and axial strength of windings (bending)	3.1. Application of conductors with high proof stress. 3.2. Application of epoxy-bonded continuously-transposed conductors. 3.3. Application of axial cooling duct (clackbands). 3.4. Influence of winding temperature before short circuit.
4. Strength of clamping systems	4.1. Application of common clamping rings. 4.2. Application of clamping rings made from different materials. 4.3. Application of different clamping designs.

CONCLUSIONS

1. Short-circuit tests are the most complete way to confirm power transformers short-circuit strength. But due to its high cost and time consuming and technical limitations of test laboratories it is advisable to do this test in obligatory order as type test only in case of power transformers of mass series (i.e., distribution transformers) as well as most responsible transformers.

2. The comparative calculation of considered transformers and successfully tested prototypes is alternative to SC tests. Herewith it needs to be assumed that such spread of SC tests results cannot be made in all desired cases due to possible presence of design differences of considered transformer and its prototype. This fact should be kept in mind during selection of proper candidates for prototypes.

3. The development of short-circuit strength calculation method plays important role in reducing of number of transformers failed during SC tests and in increasing of transformer operational reliability. But this method should reflect modern state of transformer designs and manufacturing technologies and materials and thus need to be continuously updated.

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