Use of mathematical models

for design review of new under construction transformers and evaluating the condition of existing transformers in operation

Leonid Kontorovych – Translab Ukraine/ZTZ services Int, USA
Volodymyr Prykhodko – ZTZ Services Int, USA

The article examines problems of mathematical models use while complex design inspecting of high-voltage power transformers for 10-750 kV. The aim of the investigation performed is condition assessment of the transformer components upon electrical, thermal and mechanical stresses in different modes of transformer operation (operational mode, testing and emergency modes.)

Scope of the necessary works at transformer inspection can vary in the wide range in dependence on a specific task, inspection purpose, stage of the transformer design and operation.

Investigation of the transformer mathematical models is based on calculation of the electric, magnetic, heat and hydraulic fields using finite elements method, as well as on calculation of established and transient processes in equivalent multi-element equivalent circuits. Set of methodic materials, mathematical models, software and hardware developed and used for the above-mentioned tasks is named “TRANSLAB system”. This article gives examples of TRANSLAB system software use for calculation of specific parameters that characterize the high-voltage transformer operation:

- modeling low-frequency transient processes inside the transformer at short-circuits at the substation;
- modeling high-frequency transient processes inside the transformer at lightning impulse influence at the substation;
- modeling the transformer insulation tests with AC applied voltage;
- modeling magnetic fields, losses and local overheatings in ferromagnetic and conductive transformer elements;
- modeling the heat-mass transfer processes for calculation of the windings hot spot temperature.

1. Subject of inspection

This article describes mathematical models for design review of the high-voltage GSU, autotransformers and reactors up to 1150 kV voltage and rated power up to 1000 MVA.

During the transformer complex inspection using tests, measurements and calculations, different parameters of its reliable operation are determined. These parameters depend not only on material condition or stresses, but also on the design of the transformer main elements. Software and hardware tools that we use permit investigating the following main elements of design:

1.1 Core
1.2 Windings.
1.3 Insulation.
1.4 Clamping rings, magnetic shunts, conductive shields.
1.5 Cooling system.

2. Aim of inspection

The aim of the transformer inspection using mathematical models is the condition assessment of transformer elements under electrical, thermal and mechanical stresses in different modes of the transformer operation (on-line mode, testing mode and malfunction).

Such condition assessment of the transformer elements is carried out at:

- development of transformer design or modernization of the existing design to provide reliability of the transformer operation;
- diagnostics of the transformer condition in case of its emergency switching to clear up the failure cause and assessment of the probable influence of the stress on the transformer components;
- diagnostics of the transformer condition in operation in order to analyze probable defects, determine transformer residual life in operation;
- at ordering a new transformer with purpose of coordination of a new transformer technical characteristics with equipment installed at the substation (circuit breakers, surge arrestors, capacitors banks, reactors and other equipment).

3. Scope and methods of transformers investigation using mathematical models

Scope of the necessary works while the transformer investigating can vary in wide range in dependence of a specific task, investigation purpose, stage of designing or transformer operation. To perform this work, first of all the transformer mathematical models are developed and investigated. Then analysis of mathematical modeling results should be performed and the design “weak points” are detected. If necessary, then a measurement program or recommendations on the probably defects elimination are developed.

While drawing up mathematical models we use detailed enough description of the transformer elements (core, windings, insulation), description of the material features, affecting voltages in different modes, load description. Initial data of the transformer design are determined upon the manufacturer documentation and standards requirements. For description of the rest equipment that affect on the transformers function (surge arrestors, circuit breakers, overhead lines, etc.), their technical specs and substation wirings are sufficient to perform the model.

Transformer mathematical models investigation is based on calculation of the electrical, magnetic and thermal fields by the finite element method, as well as on calculation of the steady-state and transient processes in multi-element equivalent circuit.

Transformer equivalent circuits, which contain ohmic resistances, self-inductance and leakage inductances of coil groups of windings and non-linear magnetic resistances of the core zones (core, yokes, angles), are used for calculation of established and transient procedures at short-circuits, emergency and regular switching of the transformer.

They are so named low-frequency (50 Hz-500 Hz) multi-element (10-50 elements) transformer equivalent circuits.

Transformer equivalent circuits that, besides the above-mentioned inductances and resistances, contain capacitances of separate insulating gaps are used for calculation of transient modes at affect of the lightning or switching impulses on the transformer. They are so named high-frequency (500Hz-5MHz) multi-element (100-1000 elements) transformer equivalent circuits.

Transformer equivalent circuits that contain non-linear hydraulic resistances, heat source and non-linear heat resistances are used for calculation of the transformer oil motion and heat processes in windings, core and cooling system. They are so named thermal and hydraulic multi-element equivalent circuits.

Calculations of the electric, magnetic, thermal and hydraulic fields according to different methods are used on the first stages for determination of the parameters of the above-mentioned multi-element equivalent circuits. Then, using finite elements method, a specified calculation of the local electric, thermal and mechanical influences to the transformer design separate nodes is performed.

Determination of admissible values of these influences is realized under corresponding standards or upon results of special (carried out before) experimental investigations.

Ratios of corresponding admissible values to the affecting values determine the transformer electrical, mechanical and thermal safety margins are one of the main factors for the transformer operation reliability.

Complex of methodological materials, mathematical models, software and hardware developed and used for solving of the above-mentioned tasks obtained denomination “TRANSLAB system” (transformer laboratory).

4. Cases of the transformer design review using mathematical models

Further one can find examples of using software of TRANSLAB system for calculation of specific indexes, which characterize reliability of high-voltage transformer operation.

4.1 Modeling of transient processes inside the transformer at short-circuits at substation.

At one of substations 500 kV during performance of routine repair, a two-phase and then three-phase short-circuit of the unit consisting of 3 single-phase autotransformers 500/220 kV, 167MVA occurred. Autotransformers were tripped. There were no external visual defects revealed.

It was necessary to determine if the mechanical stability of windings strength of these autotransformers meets the standards and to compare standard requirements with real situation at the failure at substation.

Modeling was carried out using computer program SIMULINK of MATLAB system . At this, while modeling autotransformers, an original low-frequency multi-element equivalent circuit from TRANSLAB system was used. Standard transformer model in MATLAB software does not permit taking into account the autotransformer internal design.

Basing on studying the substation circuit, autotransformer detailed documentation and passport data for other equipment, there was developed a mathematical model for analysis of transient procedures (Figure 2), calculated currents (Figure 3) and voltages (Figure 4) in autotransformer windings.

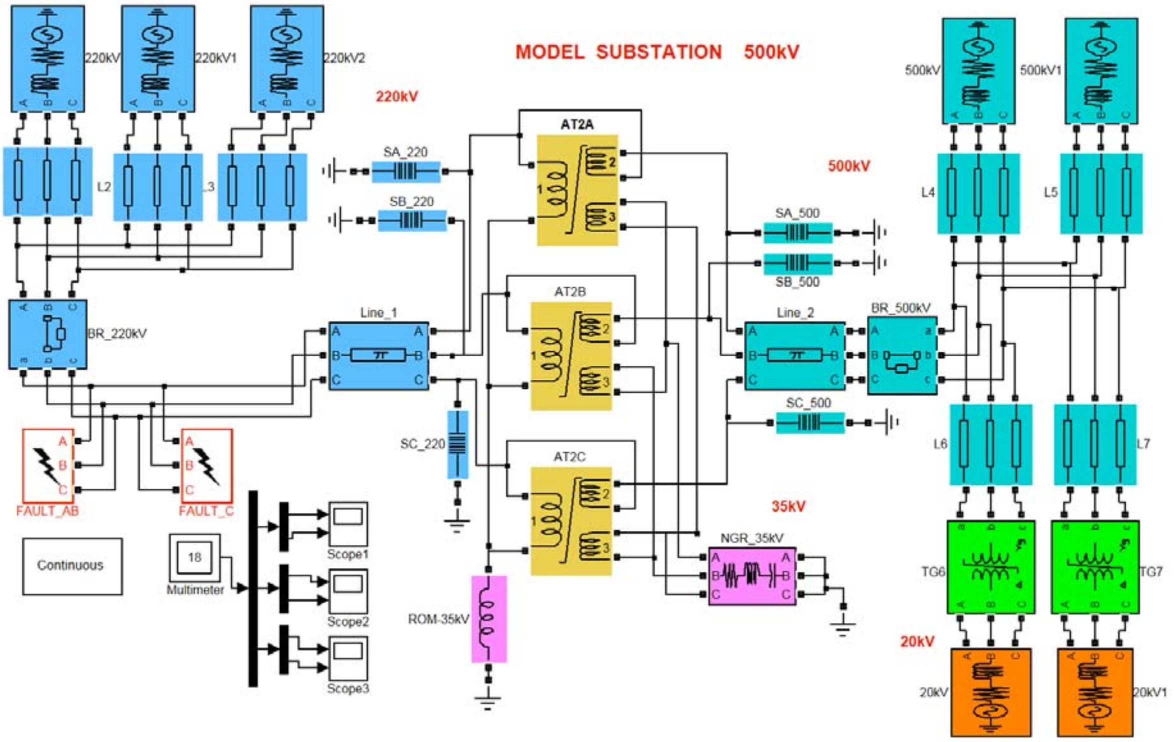

Figure 2. Mathematical model for calculating currents and voltages in AT2 unit of 167MVA-500/220/35 kV autotransformers at short-circuits

Figure 2 presents:

- 220 kV equipment units (220 kV generators, lines with distributed parameters L1-L3, switch BR_220, arresters SA, SB,SC, line with concentrated parameters Line_1) – blue color on Figure 2;
- units of similar equipment for 500 kV (dark green color);
- inspected autotransformers AT2, phases A, B, C (yellow color);
- generator transformers TG6 , TG7 (light green color);
- 20 kV generators (red color);
- reactor in neutrals of Common Winding (CW) of autotransformer
- measuring bus-bars and virtual oscillographs, on which currents and voltages oscillograms from all other model units are displayed (white units with black frame);
- units for modeling short-circuits in corresponding lines (the first unit – two-phase, and the second one – three-phase short-circuit), white units with red frame.

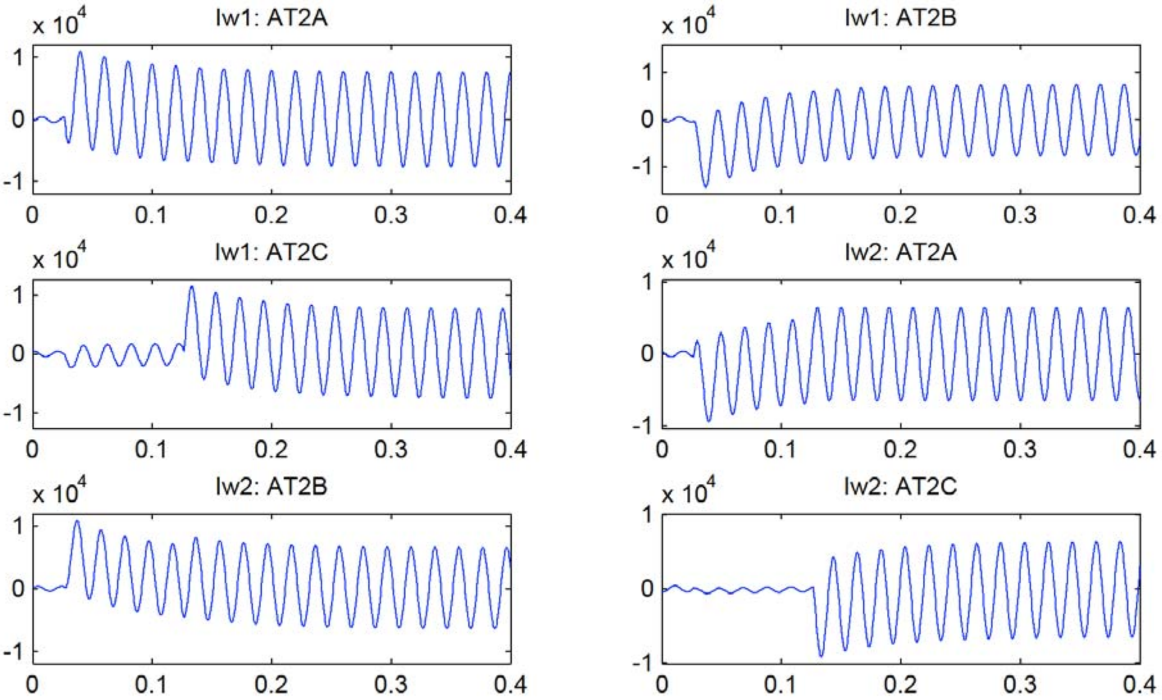

Figure 3   Currents (I) in windings (w1) and (w2), horizontal axis - time (sec.), Vertical axis - currents (A), autotransformers 167MVA-500/220/35 kV of AT2 unit, phases A, B, C.

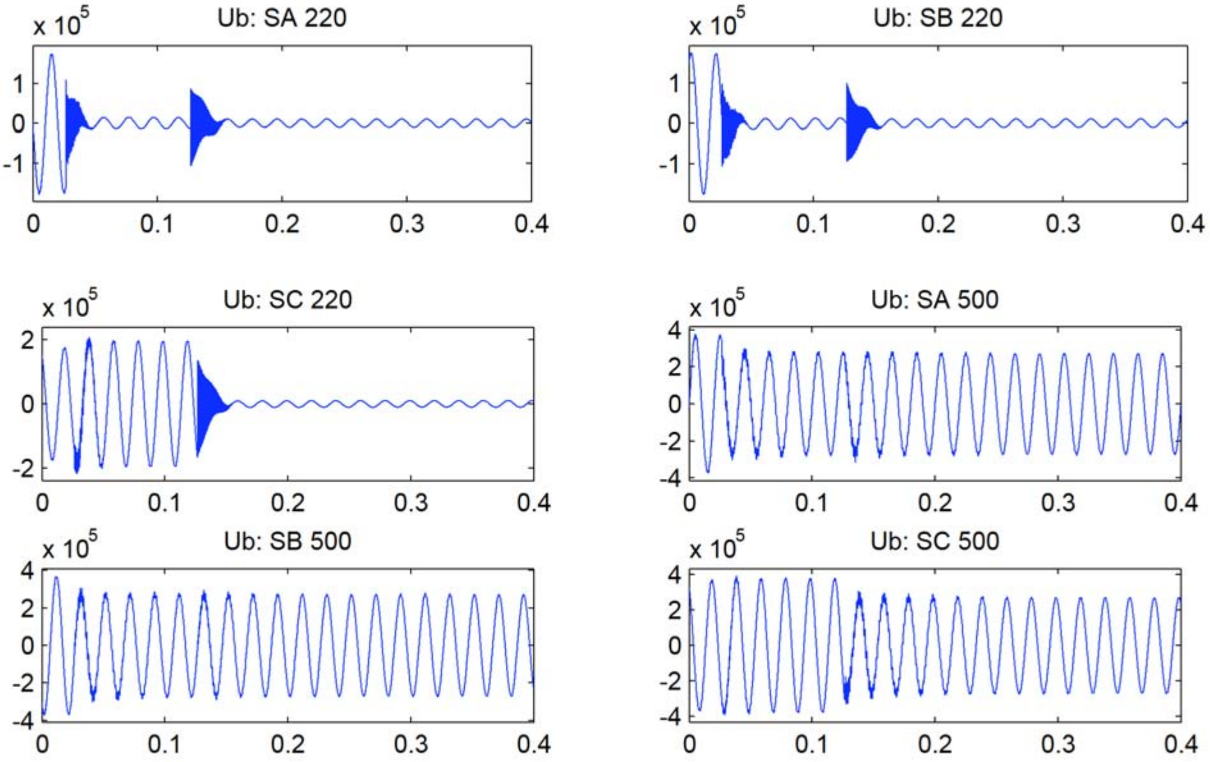

Figure 4 Voltages (U) on windings (w1) and (w2), horizontal axis – time (sec.), vertical axis – voltages (V), autotransformers 167MVA-500/220/35 kV of AT2 unit, phases A, B, C.

Calculations showed that at this failure the autotransformer of phase B was exposed to currents, which exceeded the admissible while designing values. Autotransformers of other phases were exposed to largest, but admissible effects (up to 905, phase C).

Using software of TRANSLAB system, for these currents the calculation of magnetic field and electrodynamic forces in autotransformer windings was performed. Then the indexes of the windings mechanical strength and stability were calculated. Analysis of these calculations results showed places of significant deformations in phase B windings, places of insignificant deformation in phase C and absence of deformation in phase A. Results of the mentioned autotransformers disassembling confirm these conclusions.

4.2 Modeling of transient processes inside the transformer at the affect of lightning impulses.

In compliance with international standards CEI/IEC 60076-3, high-voltage transformers insulation should support influence of lightning overvoltages. These overvoltages are distributed nonuniformly along insulating gaps and in the most of cases determine probability of insulation breakdown inside windings (longitudinal insulation), and sometimes insulation breakdown between the windings.

TRANSLAB system allows modeling transient processes at lightning impulses influence to the transformer (standard and non-standard forms). At this, temporal graphs of impulse voltages affecting on the insulating gaps are determined (Figures 5 and 6)

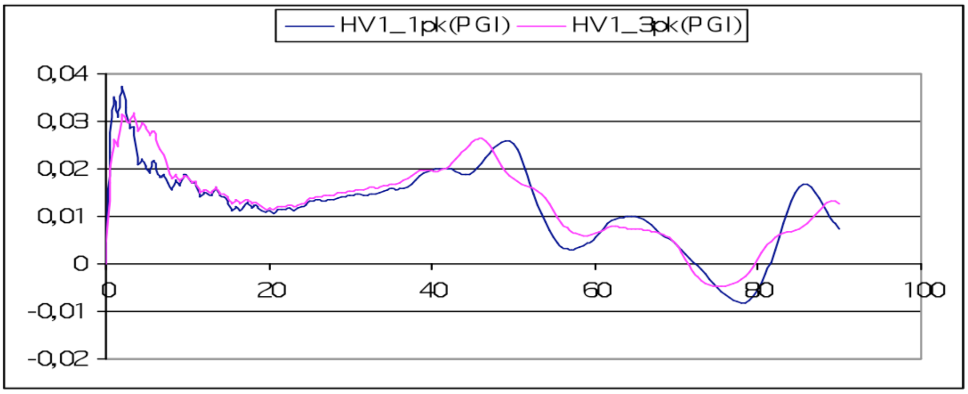

Figure 5. Graphs of voltages on two inter-coil channels of the highest-voltage HV1 winding of unit transformer 700MVA-420kV
Horizontal axis – time (mcsec.)
Vertical axis – voltage (part of Full Wave Impulse)

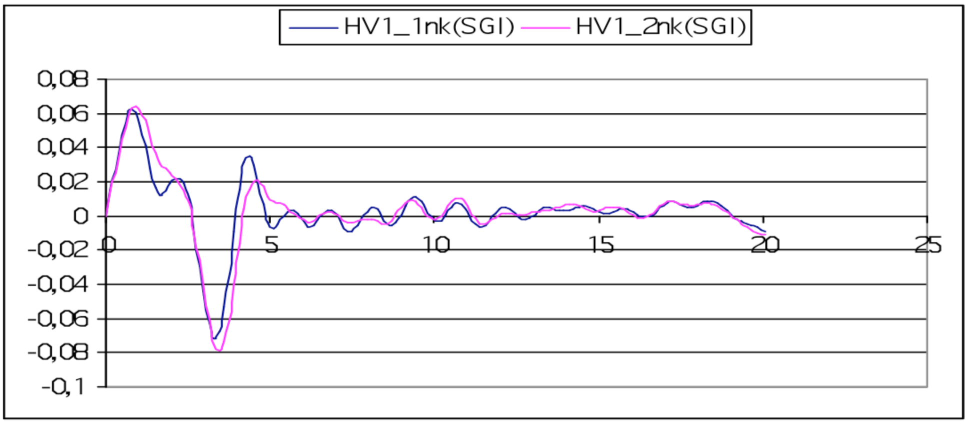

Figure 5. Graphs of voltages on two inter-coil channels of the highest-voltage HV1 winding of unit transformer 700MVA-420kV
Horizontal axis – time (mcsec.)
Vertical axis – voltage (part of Chopped Wave Impulse)

HV1 winding of 700MVA-420 kV transformer had combined design with twisted coils in input zone and continuous coils in the main zone. Input to the winding is located in the middle of its height. Figure 6 shows distribution of the voltage maximum values in all the channels between the coils of this winding bottom half, counting top-down.

Affects of the standard test impulses Full Wave (PGI) и Chopped Wave (SGI) were modeled.

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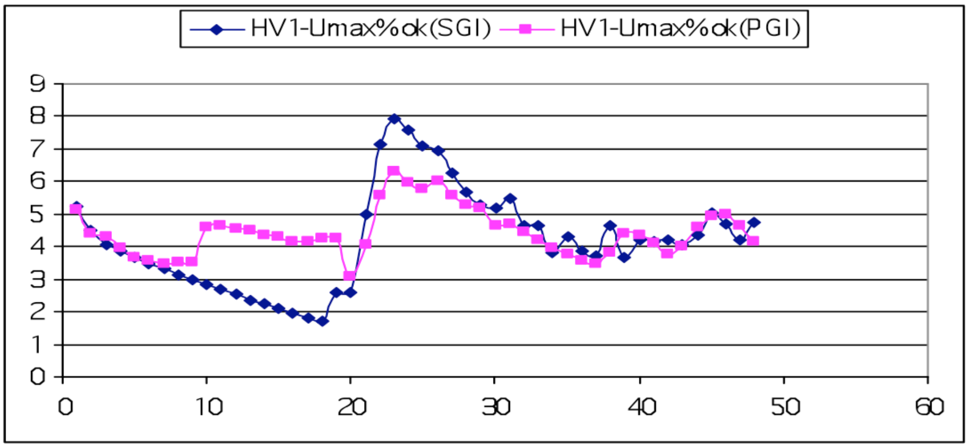

Figure 7. Maximum values of voltage Umax in HV1 winding inter-coil channels Horizontal axis – channels numbers, vertical axis – voltages (% of amplitude of the affecting impulse)

As may be seen from Figure 7 data, on the board between the interleaved and continuous coils (after channel 21), the voltage maximum values increase up to 6.3% occurs at Full Wave and 8% at Chopped Wave. Average duration of these impulse voltages varies from 1.5 mcsec. up to 40 mcsec.

Figure 8 shows distribution of electrical safety margin on inter-coil channels of HV1 winding. Safety margin is index of longitudinal insulation reliability and is determined as ratio of the voltage permissible values to the maximum affecting voltages U_{max}.

Permissible voltage values were obtained on the base of statistic processing of the test results. Permissible values of impulse voltages depend not only on geometric dimensions of the channels and insulation. They also depend on the average duration of the affecting impulse, condition and features of insulating materials in inter-coil channels.

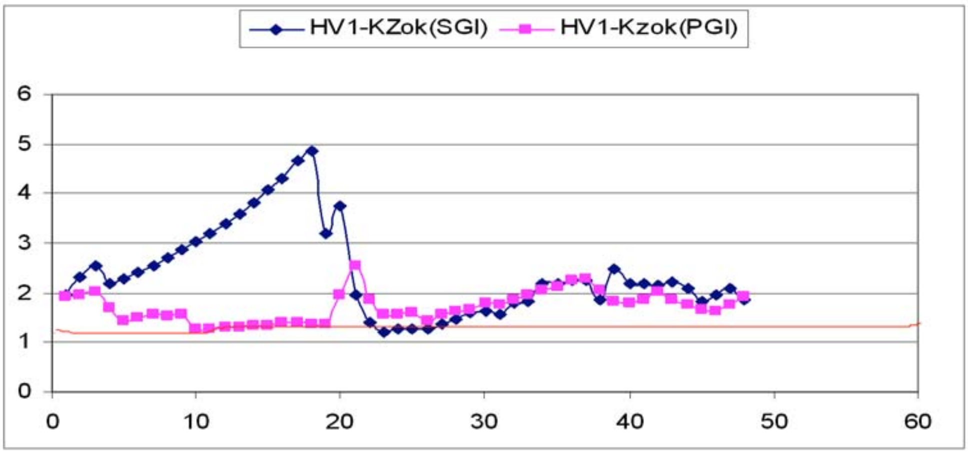

Figure 8 Electrical safety margins of short circuit on inter-coil channels of HV1 winding (horizontal axis – channels numbers, firm red line indicates normalized level of minimum admissible value of KZ).

As may be seen from Figure 8, on the board between the interleaved and continuous coils (after channel 21) the electrical safety margins have minimum values. On channel 23 at the affect of Chopped Wave (SGI) this safety margin is just lower that the normalized one for this type of design. Given calculations of impulse processes in the windings of 700MVA/420 kV allowed detecting the “weak” points in the design, clarifying the failure causes in HV1 winding bottom part (breakdown in the input zone was supposed), working out recommendations on increase of the windings electrical strength in the process of transformer repair.

4.3 Modeling of the transformer tests with alternating power-frequency voltage

For assessment of the insulation electrical strength at operational voltage at the manufacturer’s plant, the transformer test with power-frequency voltage for 50-60 Hz is carried out. In the most of cases, these tests determine reliability of major insulation (between different windings, insulation from the windings to the core and tank).

However, insulation breakdown has stochastic nature and can not appear during the tests. Besides, in operation conditions the transformer oil and insulation features can vary. So, to find the “weak” points in major insulation design and to assess the electrical strength, the mathematical models of different insulating gaps are used.

Voltage distribution along the winding turns in this case is uniform and depends on the windings design and connection circuit (established process). In the same time, the electrical field tension distribution on the separate areas of insulation is sharply irregular. This tension value can exceed the admissible values and lead to the partial discharges generation and further to the insulation breakdown.

Below one can see examples of modeling results of the electrical field affecting tensions in insulating gaps on the edge (Figure 9) and in the input zone (Figure 10) between HV and MV windings of 133MVA-330/220 kV autotransformer.

Figure 9 Picture of electrical field on the edge between the windings
Horizontal axis – radial dimensions, vertical axis – gap axial dimensions (mm)

Figure 10 Picture of electrical field between the windings in the zone of input coils
(input to the winding height middle),
Axes – radial and axial dimensions of gap (mm)

While modeling, the coil potential surfaces parts and facial capacitive rings (on Figures they were marked with white color), insulating cylinders, angle washers, yoke insulation, insulation on the coils and capacitive rings were taken into consideration. Insulation areas with different values of the electrical field tension module (kV/mm) were shown in color. From high values (red) to low values (blue).

As may be seen from Figure 9, the most dangerous place is zone near the capacitive ring face of HV winding. In case of incorrect choice of the radius of the ring curve and insulation design, appearance of partial discharges source and breakdown evolution are possible in this place. The most dangerous places in the area of the windings middle (Figure 10) are faces of the input coils.

In TRANSLAB system there are determined not only values of affecting tensions of the electrical field, but also their admissible values. We use two approaches. The first one (Figure 11) supposes determination of the field force line with maximum average tension upon the length. The second approach (Figure 12) supposes determining the volume, in which the tension value exceeds 90% from the maximum value (loaded volume).

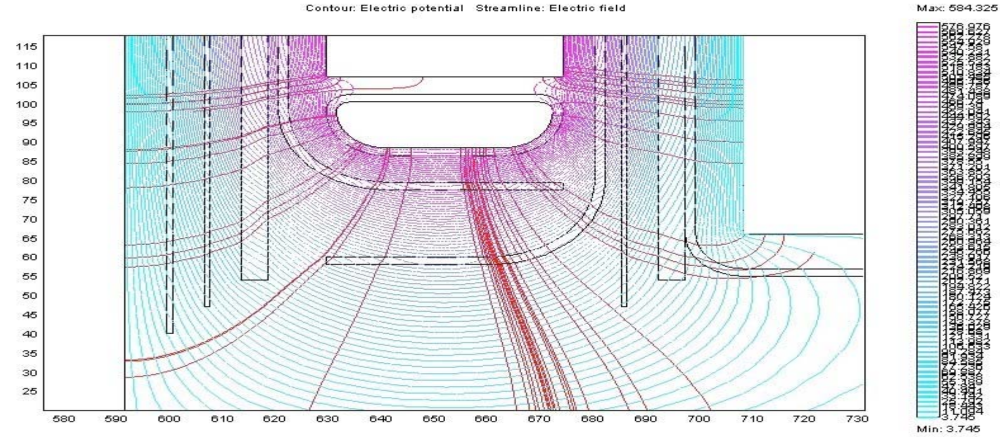

Figure 11. Force lines and equal potential lines in the winding yoke insulation

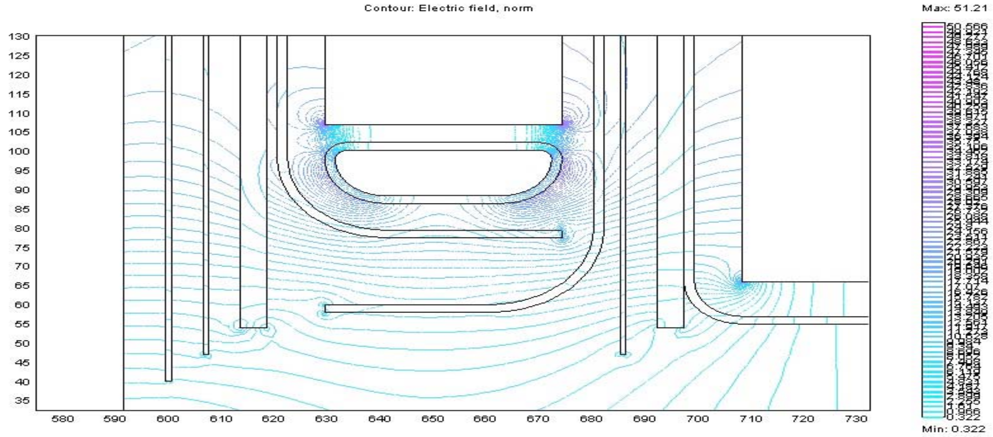

Figure 11. Lines of equal values of the electrical field tension module on the winding face in yoke insulation

Calculated values of the field tensions, force lines length and loaded volume for a specific transformer are compared with obtained before experimental admissible values. In such a way the electrical safety margin of insulating gaps at operational voltage is determined.

Calculation of the electrical safety margin in the main insulating gaps at impulse and commutation affects is carried out in similar way. At this, calculation of the electrical field tensions, force lines length and loaded volume is performed for several momentary values of the coil potentials. The maximum values are chosen from the calculated momentary values, and their average duration is defined. Potentials time dependences are determined from calculation of the transient process, as mentioned in chapter 4.2. Admissible values are determined in dependence on parameters of corresponding insulating gaps, material features, type of impact and its average duration.

In such a way, TRANSLAB system allows assessing the safety margin of the design for conditions of the transformer designing and operation. In the first case, the voltages affecting on the transformer meet data of the approved standards, and material characteristics and design features meet conditions of the transformer assembling at manufacturer factory.

In the second case, material features change and the windings probable deformation are taken into consideration. The voltages affecting on the transformer consider characteristics and connection circuit of specific substation equipment. In the calculated minimum safety margin exceeds the normalized value, then with specified probability we can consider that insulation breakdown will not occur.

It is necessary to note that appearance of high-tension zone on the winding end while putting into the height middle is characteristic for tests at position of regulating taps switch in the modes “maximum” and “minimum”. In these modes, HV winding edge has potential of regulating winding. Tests of 133MVA-330/220 kV were carried out in the rated mode. In this mode the winding face had zero potential and did not have areas with the field increased tension. After several years of operation, when the autotransformer was operated in the mode “minimum“, it was switched-off according to data of dissolved-in-oil gasses chromatographic analysis.

While its disassembling, traces of the insulation failure on the capacitive ring face were detected. The calculations performed permitted showing that gassing cause are not the operation actions, but incorrect selection of the capacitive ring configuration (error of the transformer manufacturer).

4.4 Modeling of magnetic fields, losses and local overheatings in ferromagnetic and conductive elements of the design.

Local temperature excess of the design elements (yoke beams, magnetic shunts, conductive shields, tank walls) is often a cause of gasses generation and transformer emergency switch-off. So, during the transformer designing and failures analysis, it is needed to define the design elements temperature excess over the oil temperature in the tank.

In TRANSLAB system this task is solved in four stages.

On the first stage, similar to item 4.1, there is modeled transient or established processes in the windings and the currents distribution is determined. At this, the design and different circuits of windings connection, core and tank influence, specific load and transformer operation mode influence are taken into consideration.

On the second stage, upon the currents distribution the magnetic dissipation field in the windings area and design elements are modeled. Basing on the magnetic field picture, inductance and tension values of the magnetic field in the windings and on the design elements surface are calculated.

On the third stage there is calculated loss distribution in the design elements according to magnetic field tension values on their surface.

On the fourth stage the thermal field in the design elements at known from the previous stage distribution of the losses power (heat sources) is calculated.

On Figure 12 one can see a picture of the magnetic dissipation field of 700MVA/420 kV unit transformer.

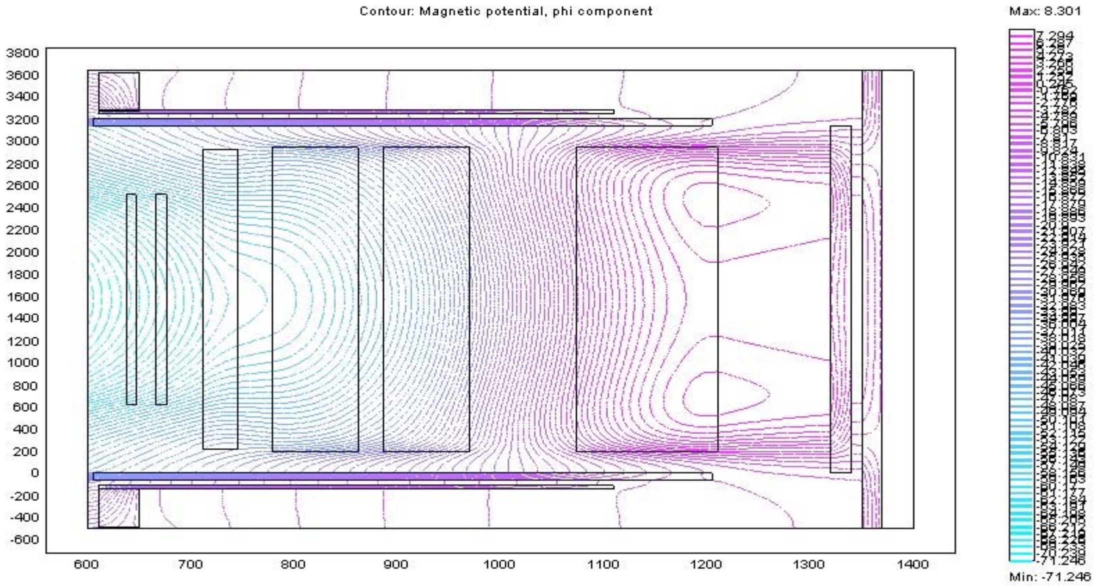

Figure 12. Distribution of magnetic dissipation flow lines

Windings and design elements location on the transformer core is as follows:

- two-layer regulating winding (two extreme left rectangles on Figure 12);
- HV winding the second CONCENTER (the third left rectangle);
- LV winding the second and first CONCENTERS (rectangles 4 and 5);
- HV winding the first CONCENTER (the sixth left rectangle);
- Copper conductive shield on the tank wall (the seventh left rectangle);
- Ferromagnetic conductive tank wall (construction steel, rectangle 8).
- ferromagnetic shunts manufactured of the transformer steel strips (rectangles on Figure 12 in the windings top and bottom close to their faces);
- ferromagnetic conductive horizontal caps of yoke beams manufactured of construction steel (rectangles next after shunts).
- Vertical caps of the yoke beams (in the top and bottom after horizontal caps).

On the picture of Figure 12 it is seen how the magnetic dissipation flow is distributed in the core window, how it penetrates into the shunts that have non-linear magnetic characteristics, how the magnetic flow penetrates into the shield and is replaced by eddy-current field. Maximum overheatings are generated in the places of magnetic flow concentration and poor heat release. On Figure 12 this place is between the shunt and horizontal cap of the yoke beam. In given transformer the ferromagnetic shunt let pass a significant part of the magnetic flow to the yoke beam, what lead to inadmissible local overheating, and then – to the transformer emergency switch-off.

4.5 Modeling of heat and mass transmission processes for calculation of maximum heated point inside the transformer windings.

Calculations of temperature distribution in the windings, tank and cooling system of the power high-voltage transformers are carried out in the process of designing and operation.
At designing, these calculation results significantly affect to selection of the design and cooling system and winding parameters. During operation, the heat calculation results are used at failures

analysis, selection of admissible loads and assessment of the transformer residual resource. In TRANSLAB system heat calculations are solved in three stages.

On the first stage, similarly to chapter 5.4, the distribution of the main and supplementary losses of the magnetic dissipation field along all the winding coils is calculated. Calculations are performed for several modes that correspond to different distribution of currents in the windings. Losses in the design elements, core and summary losses are calculated. All calculations on this stage are realized for basic (initial) values of temperature.

On the second stage, for each mode with established distribution of losses on the constructive parameters of windings, tank and cooling system there are formed equivalent multi-element and non-linear heat and hydraulic equivalent circuits. Established process calculation in these circuits is performed by iterative methods. At this, change of oil heat and physical features (viscosity, density, heat capacity) and losses of temperature are taken into consideration. Hydraulic and thermal circuits parameters are defined on this stage using analytical formulas.

These formulas use experimental dependences for coefficients of internal friction and heat-transfer factors in the cooling system, as well as in vertical and horizontal winding oil channels. As a results of these calculations, winding temperature average values are determined, losses values are specified, temperature average values and mass oil exhaust in the top, bottom and middle parts upon height of the windings, tank and coolers are defined.

On the third stage, basing on solution of differential equations system of heat and mass transfer, there are determined temperature and circulating oil flow rate distribution in the calculated areas of the windings and temperature of maximum heated points of the winding (Figures 13- 16).

Figure 13. Vector module of the oil flow rate in the winding channels without barriers

Figure 14. Vector module of the oil flow rate in the winding channels with barriers

Figure 15. Oil temperature and turns in the winding distribution without barriers

Figure 13. Oil temperature and turns in the winding distribution with barriers

Calculation of the system of heat and mass transfer non-linear differential equations at mixed (natural and forced) convection and oil laminar movement was carried out using finite-elements method and software MATLAB (produced by MathWork Inc.).

As an example, Figures 13- 16 show mathematical model calculation results of a group of 10 coils of low-voltage winding in 260MVA-230/16 kV transformer with cooling system M. Calculation was performed for two designs: at presence and absence insulating barriers in the winding vertical oil channels. Installation of such barriers in chess order upon the height permits regulating the oil motion direction not only for forced, but also for natural convection.

It is seen on Figure 13 that the oil moves under affect of the emersion forces only along the winding vertical channels. Having small dimensions (3 – 4 mm), the horizontal channels does not take part in the process of convective heat-exchange between the coil wires and oil. In case of installation of barriers below and above the coils group (Figure 14), the oil flow changes its movement direction, passing from the external vertical oil channel to the internal one. In this case the horizontal channels take part in convective heat-exchange and improve the winding cooling.

Temperatures distribution changes (Figures 15 and 16). Location and temperature of the maximum heated winding point is also changed. On Figure 16 the maximum temperature remained in the top coil, but shifted from the middle conductor closer to the face.

This coil face is washed by the heat oil (Figure 16), which moves with the higher velocity (Figure 15). It should be noted that the value and location of the maximum heated point is changed at changing the winding dimensions, number of coils between the barriers, ratio of horizontal and vertical channels resistance and increase of the oil exhaust in the input to the vertical channels. For given winding the maximum temperature decreased for 9.5 degrees Celsius at installation of the guide barriers. Windings cooling improvement increases reliability and operation resource of the transformer.