INVESTIGATION OF STEADY-STATE ASYMMETRIC MODES OF THREE-LEGS TRANSFORMER WITH EXTENDED TRIANGLE CONNECTION

INVESTIGAREA MODURILOR ASIMMETRICE STAŢIONARE A TRANSFORMATORULUI CU TREI COLOANE CU CONEXIUNE TRIUNGI EXTINS

Valeriu BOSNEAGA[1], Victor SUSLOV.[2]

Abstract. *The original investigation of steady-state asymmetric modes of 4 winding three-phase three legs conversion transformer with extended delta connection was made. The mathematical model in the MATLAB package was used. It takes into account the electromagnetic coupling of the windings, located on different legs. As initial data rated power and voltages of the windings, pair short circuit voltages, power losses in no-load and short-circuit modes, no-load current, and similar data for the zero sequence parameters were used. As it was demonstrated the presence of extended delta changes the transformer behavior, so that the magnetic flux didn't exit from magnetic core into the surrounding space.*

Keywords: 4-winding three-phase three-leg transformer, delta extended windings connection

Rezumat: *Au fost investigate modurile asimetrice staţionare a transformatorului de conversie trifazat cu trei coloane cu 4 înfăşurări cu conexiune delta extinsă. A fost folosit modelul matematic* elaborat anterior în pachetul *MATLAB. Se ţine cont de cuplarea electromagnetică a înfăşurărilor, situate pe diferite coloane. Ca date iniţiale au fost utilizate puterea şi tensiunile nominale ale înfăşurărilor, tensiunile de scurtcircuit a perechilor de infăşurări, pierderile de putere în modurile fără sarcină şi de scurtcircuit, curentul fără sarcină şi date similare pentru parametrii secvenţei zero. S-a demonstrat că prezenţa* conexiunii în *delta extinsă modifică comportamentul transformatorului, astfel încât fluxul magnetic să nu iasă în aer.*

[1]Dr., e-mail:valeriu.bosneaga@gmail.com,
[2]Eng., e-mail:svictorm46@gmail.com,
Power Engineering Institute, Academy of sciences, Moldova rep.,

Cuvinte cheie: transformator trifazat cu 4 înfăşurări, conexiunea înfăşurărilor în delta cu laturi extinse

1. Introduction

Asymmetric operating modes of three-phase power converter transformers can occur during their operation at short circuits on windings terminals or during damage of rectifying devices, as well as at no-load modes of operation during the failure of some phases of power supply network. In such modes, on secondary windings voltage distortion occurs, which leads to disturbance in the operation of adjacent consumers. Particularly dangerous is increasing of voltage. Actual standards determine the acceptable indices of currents and voltages asymmetry in networks at consumers. To verify that they will correspond to actual indicators, it is necessary to calculate asymmetric modes. In addition, dangerous for the transformer modes may arise with increasing of currents and voltages of the windings in comparison with rated values. This, as it is known, can lead to additional losses in transformer and its overheating. Sometimes asymmetric modes arise due to several different sources of asymmetry, which are quite difficult to calculate using the method of symmetrical components. For example, this could be the combination of two simultaneous damages - a break in one of the phases of supply voltage and a short circuit in the load.

Despite the presence of a significant number of works (here we give only [1-4]) devoted to modelling of three-phase three legs transformers with four or more windings, they mainly describe various general theoretical approaches to constructing mathematical models with respect to the solved there problems, which usually does not include a detailed study of asymmetric modes. In addition, there are no examples of calculations of specific asymmetric modes, the results of which could be verified by other methods, which would allow their comparative analysis. The aim of this work is to conduct studies of asymmetric modes on the basis of extended previous model for the case of four-winding converter transformer with specific windings connection diagram, namely a triangle with extended sides, which, will fill this gap. Among the works with various aspects of multi-winding transformer modelling ([5-15] are some of them we have found), there are no studies devoted to asymmetric modes of three-leg three-phase transformers with more than three windings, especially including windings connection into triangle with extended sides.

Used mathematical model of a multi-winding transformer is based on pair short-circuit impedances of windings and rated parameters of transformer, and is described for the single-phase case in [16]. In [17], the results of the study of asymmetric modes for a three-winding three-phase three legs transformer with windings connections in star/delta were previously presented. The present work is its further development for the case of 4 windings, besides it use more complex connections diagram, common for converter transformers, containing triangle with extended sides (see [18, 19]).

2. Calculation and investigation of asymmetric modes

As an example for the study of peculiarities of various asymmetric modes, we use the scheme, containing windings 1 and 2, connected in a triangle with extended sides (see Fig.1). The system of supply voltage is applied to the beginnings of the 1st windings of all phases. Two valve-side windings 3, 4 are connected respectively, in star and triangle, to which there are connected through rectifier devices (here, as a first approximation, they are not considered, all damages occurs at the terminals of the windings) two equal active loads, modelled by resistances, connected in stars with grounded neutrals. The load is here modelled by given active resistances; however, it could be also complex impedance. The dots indicate the beginnings of the windings, the letters A, B, C - windings of different phases, the indexes are the numbers of the windings. The rated linear voltage of the power supply for the main's windings is 10 kV; pair short-circuits voltages for all pairs of windings are conventionally assumed equal to 7% due to the lack of specific data for such transformer. However, if necessary, real values for a specific transformer could be set. The rated voltages of the windings to ensure a necessary phase shift angle of 15° between the vectors of the applied voltages and output voltages of the windings of the corresponding phase are taken equal to the following values: U_1 = 3 kV, U_2 = 5.18 kV, U_3 = 0.380 kV, U_4. = 0.660 kV. In addition, the open circuit current I_0 = 1.2% and the losses in the open circuit mode P_0 = 39 kW and the short circuit mode P_{sh} = 50 kW are set. Unfortunately, this is almost all information on the transformer parameters, which is usually provided by manufacturers. For the calculation, we also used approximate data for the parameters of the zero sequence, including windings pair short-circuit voltages, no load current and short circuit losses for the zero sequence mode. As a base for the analysis, here are presented the results of the symmetric mode calculation (at nominal load), used for comparison with the results for the asymmetric modes. For clarity and visualization, we will present the results of calculations in the form of vector diagrams (VD) for complex vectors of voltages and currents of the windings, which, in contrast to the tabular form allow analysing the results easily.

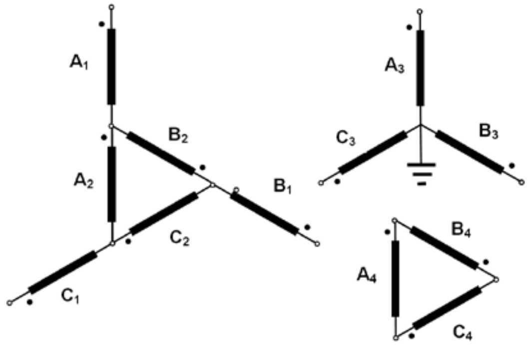

Figure 1 – Connection diagram of the 4-windings converter transformer.

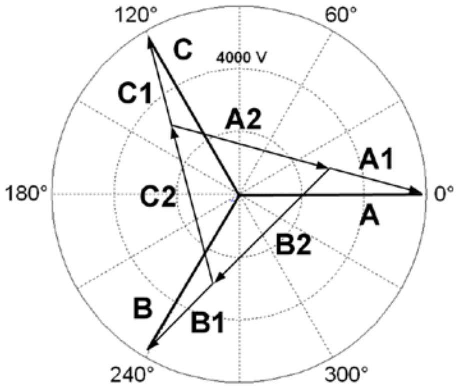

Figure 2 – VD of the voltages of main's windings (triangle with extended sides).

Thickened vectors show the voltage vectors of the supplying three-phase system A, B, C. It is seen that the voltages of all windings form a symmetrical system having the necessary phase shift between the supply and output voltages. Note that obtained in the calculation windings currents are also symmetrical. Further we will use the obtained values as a base for comparison with the corresponding values in asymmetric modes.

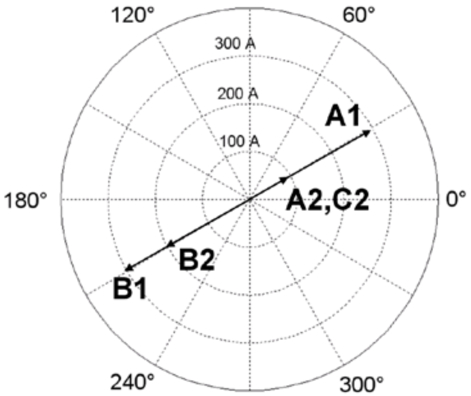

Figure 3 – The currents of the main's windings in the open-phase mode (break of phase C supply) with symmetrical load.

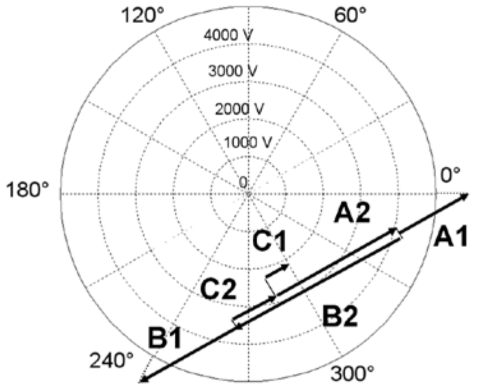

Figure 4 – The voltages of the mains windings in open-phase mode (break of phase C supply) and a symmetrical load.

At the beginning let's consider the **first** simplest asymmetric mode, caused by a break in the supply voltage of phase C while maintaining a symmetrical load. In this case, obviously, the winding C1 current in the primary star will be zero. The currents of the remaining phases of the main's windings, obtained as a result of calculation, are shown in the vector diagram of Fig. 3. It can be seen that in the winding C2, located on the leg C (with supply winding C1 disrupted), there is a current, and the currents in the windings A2, C2, according to the circuit in Fig. 1., are the same due to the breakdown of phase C. In addition, it is observed that the sum of the currents in the nodes of the circuit according to the first Kirchhoff's law is equal to zero. For example, the sum of the vectors A1-A2+B2=0, taking into account the positive directions of the currents in the windings. It could be also seen from the VD that the sum of the currents in the triangle of main's windings A2 + B2 + C2 is zero, which indicates that there are no zero sequence currents in this mode, as it should be.

The VD of the currents of the valve-side windings have a similar appearance and therefore are not given here. Note that in the secondary triangle of the valve-side windings there are no zero sequence currents also. Further on fig. 4. VD of the voltages of the windings for the considered case of phase C breakdown is presented. In this mode, the line-to-line voltage is applied to the beginnings of the main's windings A1, B1. The vectors A2, B2, C2 forming the primary triangle (and all other voltages too) are practically directed along one straight line, therefore they are shown conditionally at a certain distance and are connected by thin solid lines that closes the triangle, which in this mode degenerates into straight line segment. In the vertex of the triangle, in accordance with the windings connection diagram on Fig. 1, the voltage vectors of the primary windings A1, B1, C1 are placed. Despite the supply failure of the phase C winding, the corresponding voltages are induced in the windings of this phase from the magnetic flux closing along this leg. Note that this is observed only in the three-legs design of the transformer core, in three single-phase units this, of course, will not happen. In addition, from the consideration of the VD of Fig. 4, it follows that the ends of the windings C1, C2, despite the disconnected supply of phase C, are at a significant potential relative to ground, equal to approximately half the phase voltage. As the calculation showed, the loads voltages are also significantly asymmetrical. Moreover, the VD of the voltage of the valve-side windings are similar to the VD of the voltages of the main's windings, and the voltages themselves are located along one straight line and are similar to those shown in Fig. 4.

The calculated relative fluxes (in p.u) in the legs of the magnetic circuit are shown in Fig. 5. The highest magnetic flux (as well as the highest voltages of the windings) is observed in the leg B, it is equal to the sum of the fluxes of the legs A and C and has the opposite direction. In this mode, as follows from Fig. 5, the sum of the fluxes of the legs is zero and the magnetic flux does not exit the magnetic core.

Next, let's consider the **second** asymmetric mode - a single-phase to earth

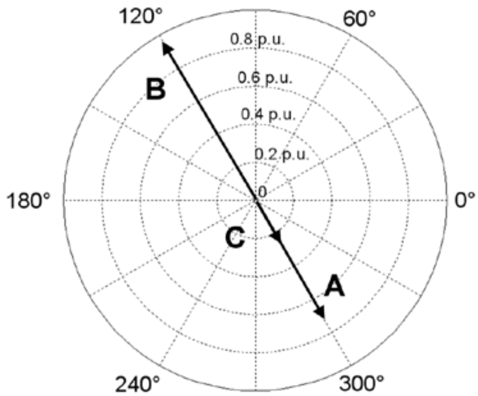

Figure 5 – Relative magnetic fluxes in the legs at phase C open and symmetrical load.

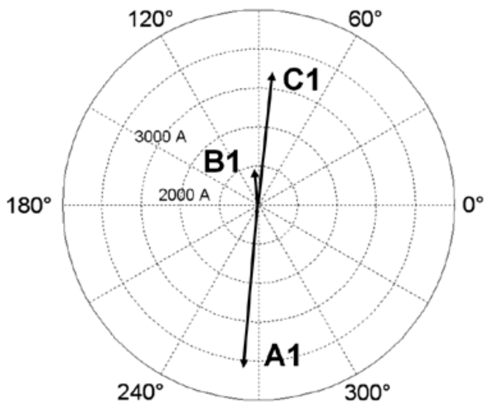

Figure 6 – Primary star currents.

short-circuit of beginning of valve-side winding A3 through the small resistance (10^3 times lower than the load resistances, connected to secondary windings). The corresponding VD for the currents of the main's windings 1, 2 are shown in Fig. 6,7.

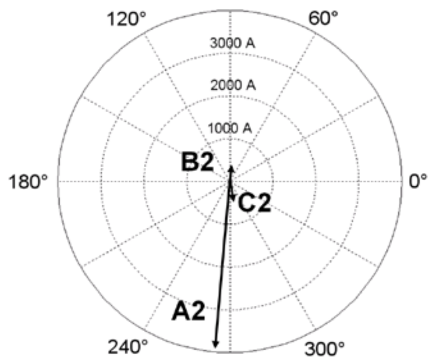

Figure 7 – The current vectors of the primary triangle of the main's windings 2.

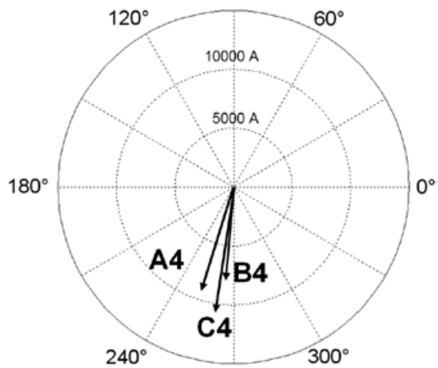

Figure 8 – The VD of currents in the triangle of the valve-side windings 4 at winding A3 short-circuited.

As it could be seen from Fig. 6, in this mode (and in all considered below) the sum of the currents from the supply source (currents in the winding A1, B1, C1) is zero, since there is no way for the current to flow through the grounded neutral of the power source. Note, that the sum of the currents at the nodes, where the extensions of the sides are connected to the triangle, is again zero in accordance with the first Kirchhoff's law. At the same time, the sum of the currents flowing through the A2, B2, C2 windings of primary triangle (see Fig. 7) is not equal to zero, which indicates the presence of zero sequence current in the primary triangle of the main's windings. Let consider the values of the currents in the remaining windings. As the calculations showed, in the valve-side winding 3, connected in star, the big current flows in the short-circuited phase, in two "healthy" phases the current is even less than in the nominal symmetrical load mode. The sum of the currents flowing through the phases of the valve-side winding 3 is not equal to zero, which indicates the flow of the zero sequence current through the circuit formed by the star windings, the load and the grounded neutrals of the star windings and the load. The current pattern in the valve-side winding 4, connected in a triangle, is shown in Fig. 8. It could be seen that the sum of the currents flowing in the phase windings is also not equal to zero; this indicates the presence (as in both primary and secondary triangles and in the valve-side star) of zero sequence currents.

However, as the calculation showed, the presence of zero sequence currents in three windings in the considered mode does not lead to the appearance of a zero sequence magnetic flux outside the magnetic core. Figure 9 shows the VD of the relative values of magnetic fluxes in the legs. It could be seen that the fluxes are asymmetric, but balanced. Their sum is zero.

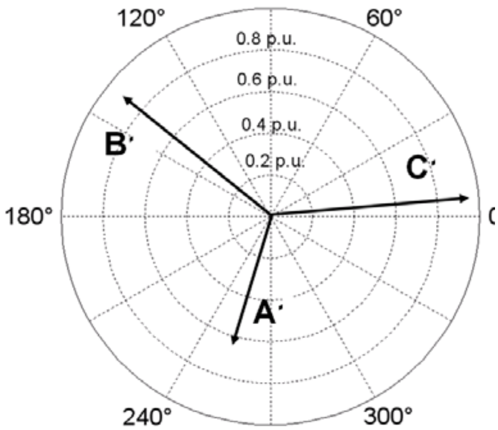

Figure 9 – VD of leg's magnetic fluxes.

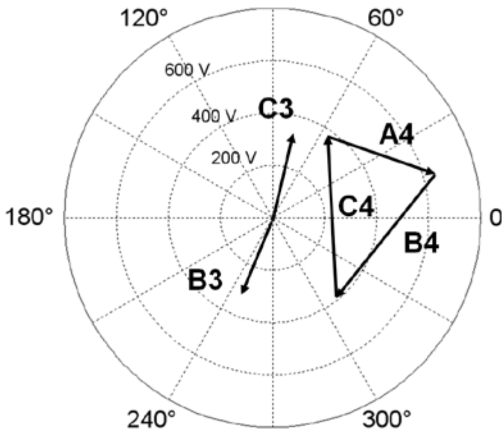

Figure 10 – Voltage of valve-side windings.

Given that the relative values of fluxes in the legs make up a balanced system, we can conclude that the zero sequence currents flowing in the primary and secondary triangles and in the "secondary" star create the magnetizing forces that compensate each other and do not allow the formation of zero sequence magnetic flux. The flux of a short-circuited phase leg A is less than in the other legs; the system is noticeably asymmetric. Thus, in the considered mode of single-phase short-circuit of the valve-side star connected winding, the magnetic flux does not exit into the surrounding space. As the calculation showed, in this mode the voltages of the main's windings visually remains close to symmetrical (therefore not shown), but the voltages of the secondary triangle (vectors A4, B4, C4 to the right of the star voltages) are somewhat distorted (see Fig.10). The voltage of the short-circuited winding A3 is small and therefore in Fig. 10 only the voltages of the "healthy" phases B3 and C3 are shown.

If in this mode disconnect the neutral grounding of the star winding 3, then the short circuit mode of winding A3 disappears, zero sequence currents disappear everywhere, the magnetic flux becomes symmetrical, the current in the short circuited phase A becomes several times smaller and is comparable with the nominal one. But instead in the star's neutral point a voltage appears, almost equal to the phase to ground one, and, accordingly, the voltages and currents in load “healthy” phases almost double.

Let us further consider the **third** asymmetric mode, caused by the disconnection of the load phase in the valve-side winding, connected in star. The currents of the main’s windings in this case certainly become asymmetrical; the corresponding VD is shown in Fig. 11. As before, it is obvious that the sum of the currents from the power supply (currents of windings A1, B1, C1) is zero, but the currents of the “primary” triangle (windings A2, B2, C2) contain a small zero-sequence current.

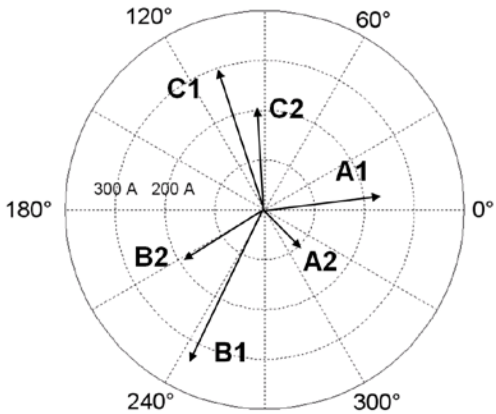

Figure 11– VD of currents in main’s windings 1 and 2, load phase break of winding 3.

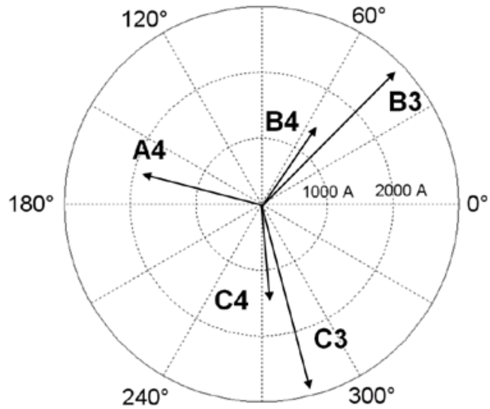

Figure 12–VD of currents in windings 3 and 4, load break in phase A of winding 3.

In Fig. 12 it is seen that the current in the A3 winding with load break is absent, while the sum of the currents in remaining phases is not equal to zero, which indicates the presence of zero sequence currents in the "secondary" star. Similarly, the currents in the valve-side windings A4, B4, C4, connected in a triangle, also contain zero sequence components. As a result, the magnetizing forces of the zero sequence currents arising in the primary and secondary triangles and in secondary star mutually compensate each other, at this the magnetic flux and voltages of all windings, as was shown by calculations, remain almost symmetrical.

If in this mode, the neutral of the valve-side winding 3 is additionally ungrounded, then similarly to the previous, the zero sequence currents disappear everywhere, potential appears on this neutral, and the relative magnetic fluxes became symmetrical. Lets consider the **forth** asymmetric mode - a double-phase short circuit (without earth) on a valve-side winding 3, connected in a star. The results of currents calculating in the main's windings for this mode are shown in Fig. 13,14.

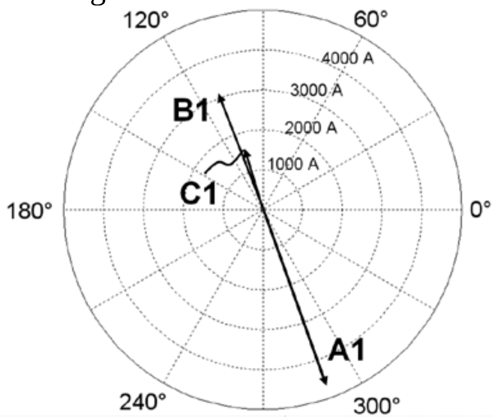

Figure 13 – VD of currents in main's windings 1 at double-phase short circuit of load in valve-side winding 3.

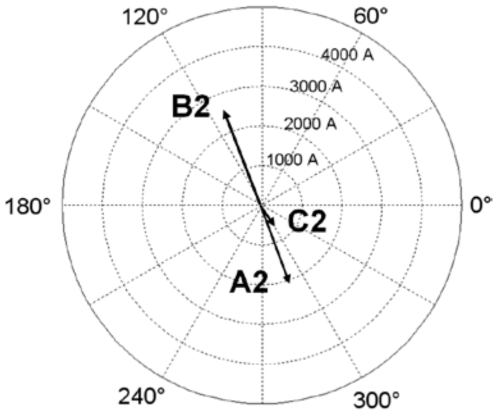

Figure 14 – VD of currents in windings 2 at double-phase short circuit of load in the valve-side winding 3.

As always earlier (see Fig. 6, 11), the sum of the primary currents is zero. The sum of the currents in the "primary" triangle A2, B2, C2 (as can be seen from Fig. 14 and was verified by calculation) is zero, the currents of the zero sequence, as it should be at such damage (see, for example, [20]), are not present. Note that the currents of all three phases are practically located on one straight line. The same is true for the currents of valve-side windings, connected in a star, so this VD is not shown. The currents of the valve-side triangle windings form an asymmetric system, but their sum is also equal to zero, so there is no zero sequence. As the calculations showed, the relative magnetic fluxes of the legs are asymmetric, but balanced, so the flux does not leave the magnetic core. The voltages of the main's windings are visually symmetrical, the voltages of the short-circuited phases of valve-side star windings 3, as it should be, coincides, and, besides, all three voltages are directed along one straight line. As the calculation showed, the voltages of the valve-side triangle windings are somewhat distorted.

Let consider the **fifth** damage, double-phase to ground short circuit of star load. In Fig. 16 is shown the VD of the currents of main's windings at this damage. As it could be seen from Fig. 16 the sum of the currents A1, B1, C1 from the source is still zero, and therefore there are no zero sequence currents in the windings of "primary star". But at the same time, the sum of the currents flowing through the windings A2, B2, C2 of "primary" triangle is obviously not zero; this indicates the presence of zero sequence currents in this triangle. Let consider the calculated currents in the remaining windings. As the calculation showed, in the damaged phases of the valve-side star winding 3 a large short-circuit currents flow, in the "healthy" phase the current is three times less than the rated current,

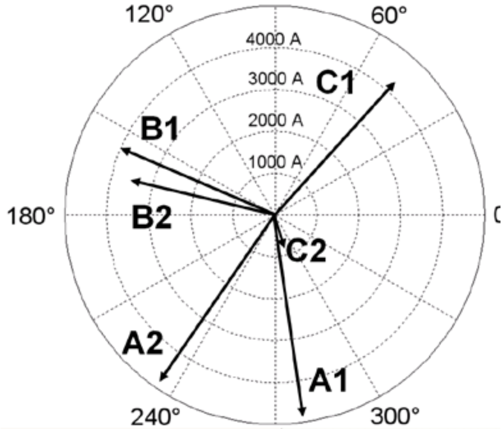

Figure 16 – VD of main's windings currents at double phase to ground fault at load of the valve-side star windings 3.

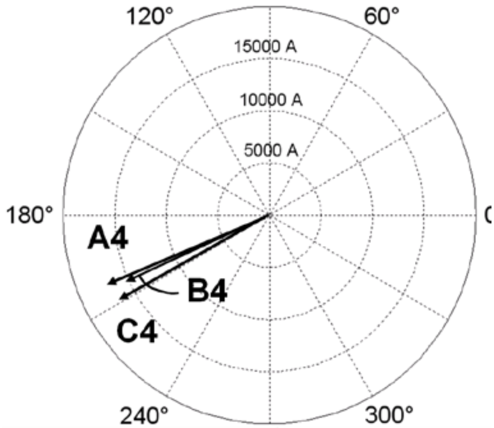

Figure 17 – VD of valve-side winding currents at double phase to ground short-circuit.

the sum of the star's currents is not zero, therefore, there is a zero-sequence current that flows through the grounded neutrals of the windings and load

(VD is not given for this case). Fig. 17 shows the VD of the valve-side triangle winding 4 currents. As it follows from Fig. 17, a zero sequence current flows in the triangle of the valve-side winding. Thus, for this damage, zero sequence currents are present in three windings - in the 2nd, 3rd, and 4th. However, as the calculation showed, the relative fluxes of the legs in this mode are almost symmetrical, although much smaller in magnitude than in the normal load mode. Thus, in this mode there are no unbalanced magnetizing forces from the zero sequence currents and, accordingly, the zero sequence magnetic fluxes.

Let consider the **sixth** damage: double-phase short circuit of load on the valve-side triangle. At this damage, the currents of the main's windings are mostly located along one straight line, so the VD is not very impressive and so not given here. However, all the previously noted patterns inherent to the currents of the primary star and triangle are observed. In valve-side windings, increased faults currents are observed in the triangle windings with short circuit. In this case, there are no zero sequence currents, so it should be during this damage. In Fig. 18 is shown the VD of relative magnetic fluxes, the system is distorted, the fluxes are less than normal values due to demagnetizing by fault currents.

The consideration of the **double phase short-circuit of phases A and C** with ground on the valve-side triangle winding showed that, as one would expect, this mode is similar to the previous one. It also has no zero sequence currents and magnetic flux.

In conclusion, let consider **seventh** mode that occurs at symmetrical load and the valve-side triangle windings open at one point, so as to stop the flow of zero sequence currents in it. In this case the zero sequence currents flow in both triangles, but their magnetizing forces compensate each other, and as a result, the magnetic flux remains balanced and symmetrical. In Fig. 19, 20 the VD of the currents in primary and secondary

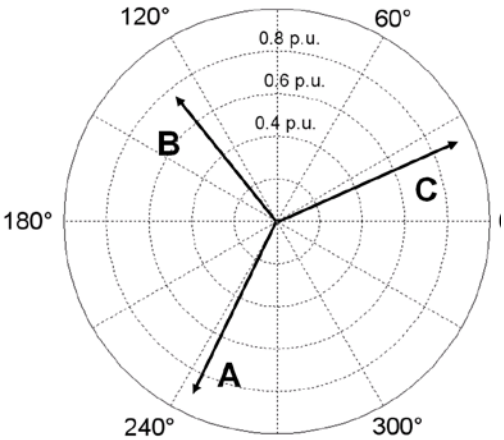

Figure 18–VD of relative magnetic fluxes at double phase short-circuits of phases A and C.

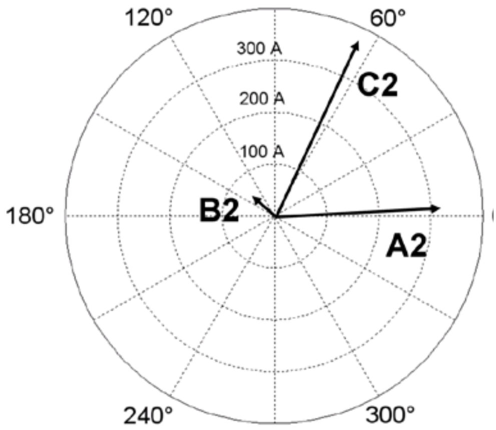

Figure 19–VD of currents in the primary triangle with secondary triangle open.

triangles are shown. The currents in the rest of the windings in this mode are almost symmetrical.

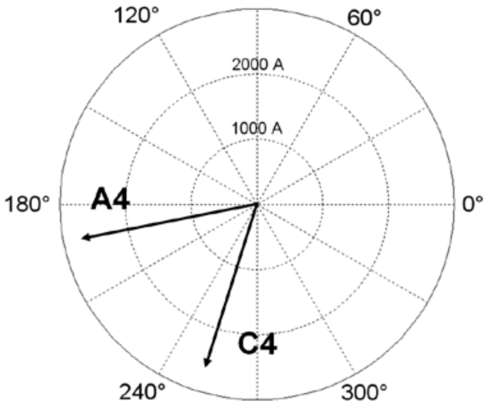

Figure 20 – VD of valve-side winding 4 currents at symmetrical load.

The sum of the currents is obviously not equal to zero.

It can be seen from Fig. 19 that zero sequence currents flow in the primary triangle. From Fig. 20 follows that the sum of the currents in the valve-side windings, connected in a triangle, is also not equal to zero. So, in both triangles we have zero sequence currents, and their magnetizing forces compensate each other. It should be noted at first glance a paradoxical phenomenon, which consists in the fact that in the secondary triangle, despite the fact that it is open, still there are zero sequence currents. The fact is that these currents are closed through the resistance of the connected loads and their grounded neutral. If the loads are removed, then the zero sequence currents also disappear. If, at symmetrical load and an still opened triangle, a single phase short circuit occurs in the star's load, an additional zero-sequence current will appear in the secondary star and the system of relative magnetic fluxes will become asymmetric, but will remain balanced, so that the flux will not go outside of the magnetic circuit. Thus, in both triangles there are zero sequence currents

3. Conclusions

1. Using the developed model of a four-winding three-legs transformer, calculations were carried out and the peculiarities of some of the most characteristic steady-state asymmetrical modes of conversion power transformer, containing a triangle with extended sides were studied. The open-phase mode and various types of short circuits, combined with the break of phase load are considered. Based on calculated modules and angles of the currents and voltages in the windings vector diagrams were constructed, which clearly reflect the magnitudes of currents and voltages. To explain the processes occurring during asymmetry vector diagrams of relative magnetic fluxes in the legs were used, which allows to understand the specifics of the occurring modes.

2. Available model allows to calculate practically any asymmetric modes, as caused by a single asymmetry (unbalanced load, different short circuits, etc.), so as complex one, with simultaneous combination of several

asymmetries or damages of various kinds, for example, a combination of short circuits and phase breaks. This model is a convenient tool that allows investigating the whole variety of asymmetric modes of four-winding three-leg transformers based on a unique approach. Something similar to the described model, allowing such calculations with the account of real parameters of transformers, in available free access publications was not found.

3. It is shown that with asymmetry in the presence of two or more windings, connected in triangles, mutually compensated zero sequence currents could occur in them, therefore the system of magnetic fluxes of the legs remains balanced, and the magnetic flux closes within the magnetic core and do not exit in the surrounding area.

R E F E R E N C E S

[1] *R.W.Erickson, D.Maksimovic.* «A multiple-winding magnetics model having directly measurable parameters”. PESC 98 Record. 29th Annual IEEE Power Electronics Specialists Conference (Cat. No.98CH36196) Year: 1998 | Volume: 2 | Conference Paper | Publisher: IEEE

[2] *A. Sapin, P. Allenbach, J.-J. Simond.* “Modelling of multiwinding phase-shifting transformers applications to DC and multi-level VSI supplies”. Swiss Federal Institute of Technology, Electrical Machines Laboratory (LME) CH-1015 Lausanne, Switzerland

[3] *A. Muñoz Carlos, Alberto Rojas.* “Four-Winding Transformer and Autotransformer Modeling For Load-Flow and Short-Circuit Analysis, Part I: Theory”. Universidad Nacional de Ingeniería, Lima, Perú COVIEM S.A., Lima, Perú, April, 2016. https://www.researchgate.net/publication/300005026.

[4] *C. Alvares-Marino, F. de Leon, X.M.Lopez Fernandes.* “Equivalent Circuit for the Leakage Inductance of Multiwinding Transformers: Unification of Terminal and Duality Models”. IEE Transaction On Power Delivery, vol. 27, NO 1, January 2012. pp. 353-361.

[5] *K. D. T. Ngo, A. Gangupomu.* (2003). “Improved method to extract the short-circuit parameters of the BECM”. IEEE Power Electronics Letters, 1(1), 17–18. doi:10.1109/lpel.2003.813479

[6] *V. A. Niemela.* “Leakage-impedance model for multiple-winding transformers”. 2000 IEEE 31st Annual Power Electronics Specialists Conference. Conference Proceedings (Cat. No.00CH37018). doi:10.1109/pesc.2000.878853

[7] *J. G. Hayes, N. O’Donovan, M. G. Egan.* “The extended T model of the multiwinding transformer”. 2004 IEEE 35th Annual Power Electronics Specialists Conference (IEEE Cat. No.04CH37551). doi:10.1109/pesc.2004.1355391

[8] *Casimiro Álvarez-Mariño, Francisco de León. Xosé M. López-Fernández.* “Equivalent Circuit for the Leakage Inductance of Multiwinding Transformers: Unification of Terminal and Duality Models”. IEEE TRANSACTIONS ON POWER DELIVERY, VOL. 27, NO. 1, JANUARY 2012, 353

[9] *J. El Hayek, T. J. Sobczyk.* (2005). “Equivalent circuit of multi-windings traction transformers including magnetizing currents”. 2005 International Conference on Electrical Machines and Systems. doi:10.1109/icems.2005.202857

[10] *M. P. Oommen, J. L. Kohler.* (1999). “Effect of three-winding transformer models on the analysis and protection of mine power systems”. IEEE Transactions on Industry Applications, 35(3), 670–674. doi:10.1109/28.767019

[11] *T.-H. Chen, M.-Y. Huang.* (1999). “Network modelling of 24-pulse rectifier transformers for rigorous simulation of rail transit power systems”. Electric Power Systems Research, 50(1), 23–33. doi:10.1016/s0378-7796(98)00096-0

[12] *F. De Leon, A. Semlyen.* (1992). “Efficient calculation of elementary parameters of transformers”. IEEE Transactions on Power Delivery, 7(1), 376–383. doi:10.1109/61.108931

[13] *M. Masoum, P. S. Moses, A. S. Masoum.* (2008). “Derating of Asymmetric Three-Phase Transformers Serving Unbalanced Nonlinear Loads”. IEEE Transactions on Power Delivery, 23(4), 2033–2041. doi:10.1109/tpwrd.2008.923057

[14] *L. Kasprzyk, Z.Stein, M.Zielińska.* “Basic equations for analysis of a three-phase three-winding transformer subjected to asymmetric load”. Computer Applications in Electrical Engineering, pp.161-169, Poznań University of Technology, Institute Of Electrical Engineering and Electronics. IEEE Poland Section, Volume 9, editor Ryszard Nawrowski, 2011.

[15] *Carl Mihael F. Odulio, Miguel T. Escoto.* “Multiple Winding Transformer Model for Power Supply Applications in Circuit Simulations”. Proceedings of the World Congress on Engineering, 2013, vol.II, July 3-5, London, U.K.

[16] *V.M. Suslov, V.A. Bosneaga.* “Method of Parameters Determination for Multi-Winding Transformer Equivalent Circuit in the Form of Multi-Beam Star”. Institutul de Energetica, “PROBLEMELE ENERGETICII REGIONALE”, 2 (37) 2018. URL http://journal.ie.asm.md/ro/contents/electronni-jurnal-237-2018 (last accessed October 23rd 2018) (In Russian).

[17] *V.M. Suslov, V.A. Bosneaga.* “Calculation and Investigation of Steady-State Asymmetric Modes of Three-Windings Three-Legs Power Transformer with Star/Star/Delta Windings Connection”. Institutul de Energetica, PROBLEMELE ENERGETICII REGIONALE 3(38) 2018, ELECTROENERGETICĂ. URL http://journal.ie.asm.md/assets/files/02_03_38_2018.pdf (last accessed May 15th 2019) (In Russian).

[18] *Ia.L. Fishler, P.N. Urmanov, L.M. Pestreava.* “Transformatornoie oborudovanie dlea preobrazovatelinih ustanovok”. [“Transformer Equipment for Conversion Installations”] . M.:Energoatomizdat, 1989, 320 pp. (In Russian).

[19] Mejgosudarstvenni standart GOST 16772-77. “Transformatori I reaktori preobrazovatelinie. Obschie tehnicheskie uslivia”. [“Interstate standard GOST 16772-77. Converter Transformers and Reactors. Common technical Requierements”]. IPK izdatelistvo standartov, Moscow, 32 pp. Table 4. (In Russian).
[20] *S.A. Ulianov*. “Elektromagnitnie perehodnie protsessi v electricheskih sistemah”. [“Electromagnetic transients processes in electrical systems”]. Moscow., «Energia», 1970. (In Russian).