ЕЛЕКТРОТЕХНІКА

UDC 629.76.620.17
DOI https://doi.org/10.32838/TNU-2663-5941/2020.3-1/07

Chemerys V.T.
V.I. Vernadsky Taurida National University

ANALYSIS OF SOME DESIGN SOLUTIONS OF ELECTROMAGNETIC SCREENS FOR COMPENSATION OF THE LEAKAGE FLUX IN THE ROTATING COMPRESSION GENERATOR OF PULSED CURRENT[1]

The electromechanical generator of pulsed current which operational principle is based on the magnetic flux compression is the specific kind of electrical machine whose design and development needs a modern scientific approach. The high efficiency of generator application is possible at condition that the big swing of internal inductance variation of machine is provided in its design at the rotation of rotor. Mainly it can be reached owing to reduction of minimal inductance of machine in the phase of the magnetic flux compression. The electromagnetic shielding of the flux leakage in the slots of electromechanical pulsed generator with a compression of magnetic field is under consideration in this paper. Two design solutions of shields have been tested in the static experimental model of generator active zone part. The first variant of screen consists of two copper plates with insulation cover which are installed along the inner walls of slot. The second variant of screen consists of two copper plates of the same width as slot has. One of this plates is situated at the bottom of slot and other plate is situated at the neck of slot, and such a pair of plates has a connection between their edges by the copper crosspieces out of the space of slot. The new design of winding keeper is proposed for the increase of the total inductance swing. The group of slots which belong to the each pole division of winding are placed in the conducting block which in turn is places in the wide slot of magnetic core. This solution allows to reduce a magnetoconductivity for the flux directed across the slots. The principle of magnetic shielding operation has been demonstrated with application of numerical simulation of pulsed magnetic field passage across the screen, software COMSOL v. 3.5 has been used for this purpose. Some results of shielding simulation are reported, and problems of development and simulation of the screens for the flux leakage compensation have been discussed.

Key words: *compression generator, flux leakage, copper shields, implementation in model, testing of model, problems of numerical simulation.*

Introduction. The compression generator of pulsed current [1] is under consideration of many authors during a long time as the prospective source of the multiple pulses of high energy suitable for the experimental physical installations and technological applications. In the simplest view such generator which was proposed in [1] has the identical windings distributed in slots of stator and rotor which are connected in series due to the sliding contact realized with the brushes and contact rings. The ratio of maximal and minimal inductances of generator, or the total inductance swing, is the main design and operational parameter of compression generator [2]. Respectively, two phases of generator operation are the most important for analysis: a stage of the field excitation when the inductance of machine is maximal, and a stage of the field compression when the inductance of machine is minimal. In the normal mode of operation the steel of generator core in unsaturated that is why the maximal inductance can be changed only by the variation of the winding data. The minimal inductance is desirable to be minimal; beside of the winding data it depends on the steel saturation in the stage of compression and on the field distribution in the slots and teeth's zone. The reduction of the minimal inductance of generator means an improvement of the energy and current amplification, increase of the output energy and provides a possibility to match a generator with low-inductance load. One of the methods for the minimal inductance reduction is a using of the electromagnetic shields coupled with the magnetic fluxes of leakage in the phase of the field compression. Among the known propositions there was idea to put the windings of stator and rotor in the conduct-

[1] The author has a pleasant possibility to thank all colleagues and assistants especially engineer O.M. Shatz whose help was so important at the fulfillment of experiments on physical model.

ing tubes (published by P. Vasyukevitch [3]). It was a radical way but difficult for the practical performance in design. In addition it is necessary to remember that the shield must not form the short-connected contour for the main magnetic flux of machine. The success in the using of electromagnetic screens for the reduction of generator inductance in the phase of the field compression is related with the creation of shields coupled only with the flux of leakage but not with the main flux of machine. Some propositions on the creation of such shields have been considered in this paper.

The paper contains some data of testing of the special experimental model which was created for the electromagnetic shields study at alternating current instead of pulsed current and in statics without rotating parts. Some conclusions of this study are used for the following discussion from the point of view of their implementation into the real design of the compression generator.

Experimental model and its testing. The linear model of teeth's zone has been manufactured for the experimental checking of electromagnetic screen as the method of the leakage inductance reduction at the phase of the magnetic flux compression. This model can be considered as the piece of the active zone of typical compression generator with identical windings of stator and rotor [1]. The sketch of model is given in the Fig. 1 and general view of model is presented in the Fig. 2 and Fig. 3. It consists of two linear magnetic cores with slots; the usual transformer steel has been used for production of cores. The dimensions of each core in plane are 495 x 160 mm. The teeth's zone occupies a full length of each core and has 18 slots of width 13 mm and height 70 mm. Each core has 4 concentric multi-turn copper wire coils (w = 10) mounted with a pole division τ = 208 mm which covers 8 teeth's steps. The coil of each slot is subdivided on 18 sections (2x9), two along the width of slot and 9 along the height of slot. The model in the open state is shown in the Fig. 2 and in the working position in the Fig. 3. The terminals of each section have been led to the commutation panel. The corresponding sections of the upper core as well as of the lower core have been connected in the groups following the number position inside of slot. So the upper core and lower core had 18 coil groups each one, 4 sections in each group. It was possible to connect all groups in parallel or in series, the last was preferable.

The 400 Hz alternator driven from industrial net 50 Hz has been used for the current supply. A direct measurement of current and voltage of each group of coils have been realized for the following inductance

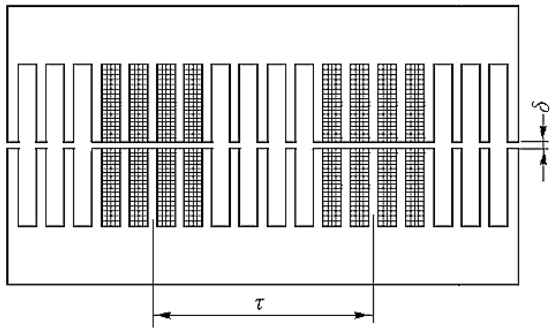

Figure 1. The Sketch of the experimental model of the active zone part

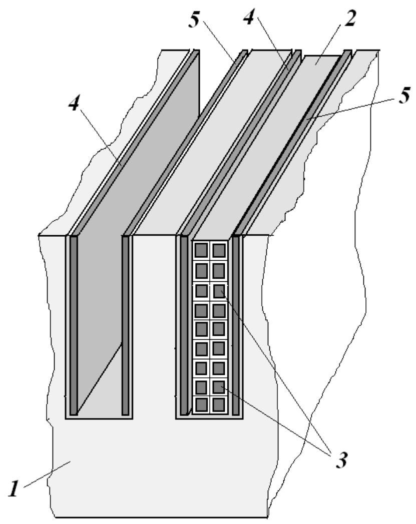

Figure 2. Using of the Shield 1 in the model (*1* is the ferromagnetic core, *2* is the winding package, *3* is the sections of winding, *4* is the copper plate at left side of slot, *5* is the copper plate at the right side of slot)

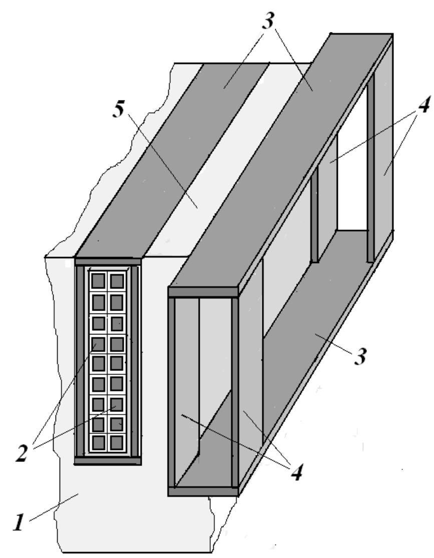

Figure 3. Using of the Shield 2 in the model (*1* is the ferromagnetic core, *2* are sections of winding, *3* are the copper plates, *4* are the conducting brattices). The brattices at the left side of pictures are omitted

calculation. Beside of the coils the possibility has been scheduled in the model to install the special electromagnetic shields in the form of the copper plates *4*, *5* (Fig. 2) 1.5 mm thickness contiguous to the sides of tooth inside of each slot (Shield 1) or in the form of the conducting frame *3–4* (Fig, 3, Shield 2). In the working position the air gap between cores was $\delta = 5$ mm. At the coupling connection of the both cores windings it was possible to simulate the excitation mode of the compression generator. The reverse of current in the windings of one core enabled to get a mode similar to the field compression mode in the compression generator. The parallel connection of coil groups was of the most interest because it was very close to simulation of the current distribution in the solid conductor when it would occupy the full cross section of slot.

It was natural that re-distribution of current to the top of the slots took place at the frequency of current 400 Hz in comparison with 50 Hz. This fact jointly with shield presence had a direct influence on the total inductance swing $k_L = L_{\max}/L_{\min}$, here the maximal inductance $L_{\max}$ is defined at the excitation mode and the minimal inductance $L_{\min}$ is defined at the compression mode. Two different designs of the slot shields have been tested in the model under consideration. The first of them (Shield 1) used the copper plates *4* and *5* mounted along the sides of the slot (Fig. 2). The second of them (Shield 2) presented the copper frame made of two plates *3* (one on the bottom of slot and another on the top of slot, instead of usual gore) connected one with another by the external brattices *4* as it is shown in the Fig. 3. During the experiments the one or another type (Shield 1 or Shield 2) has been installed by similar way into all slots occupied by winding. The data for the building of curves *1, 2* in the Fig. 6 were measured with installed Shield 1 (Fig. 4).

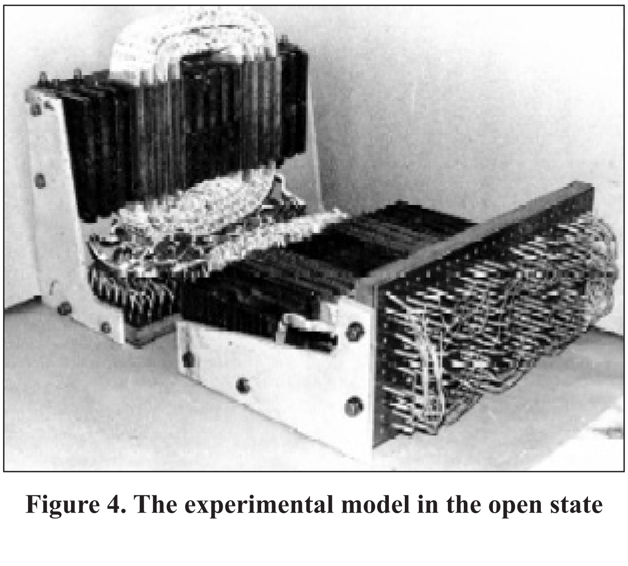

Figure 4. The experimental model in the open state

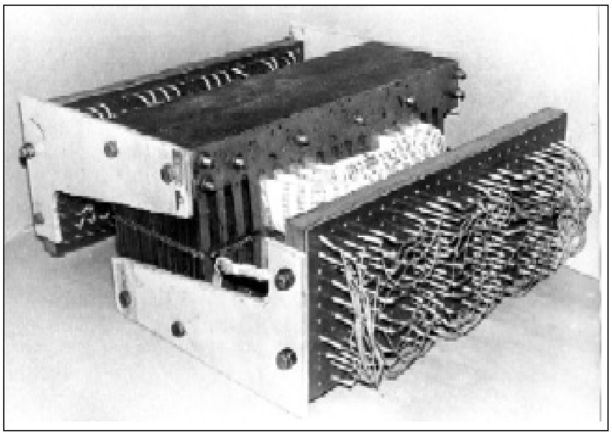

Figure 5. The experimental model in the working position

Table 1

Measurement of the Winding Parameters at 400 Hz

Measured parameter	Without shielding	Shield 1, Fig. 2	Shield 2, Fig. 3
$L_{\max}$, mH	74.3	60.7	67.8
$L_{\min}$, mH	6 .75	3.2	4.0
$R^{eff}_{\max}$, Ohms	9.26	27.5	10.6
$R^{eff}_{\min}$, Ohms	0.94	2.06	2.18
$k_L = L_{\max}/L_{\min}$	11.01	18.97	16.95

At the current frequency 50 Hz the current distribution along the sections at the mode of compression (curve *1* in the Fig. 6) has not a big difference in comparison with distribution in the mode of the field excitation (curve *2* in the Fig. 6), what says about the low efficiency of shields application at low frequency of current. The current in the sections of coils which have the smaller steps of slot deposition along the teeth practically had no difference with respect to the sections of coils which have more steps along the teeth (we imply the step deposition more or less than τ). At the presence of Shield 1 the ratio of measured values of inductance was equal to $k_L = L_{\max} / L_{\min} = 13.2$ ($L_{\max} = 78.3$ mH, $L_{\min} = 5.93$ mH).

The results of measurement in the mode of the field compression at the current frequency 400 Hz are given in the Table I. The effective resistance of winding R^{eff} takes into account not only the own Ohmic resistance of wire but also the insertion resistance stipulated by the energy losses in the steel and in the conductors of shield due to induced current. It is seen in the Table I that the Shield 1 provides the most value of the ratio k_L but at the same time it gives the most contribution into the effective resistance of the winding. The Shield 2 which does not cover the side surface of teeth inside of slot provides less value of ratio k_L but it has also less level of the energy loss caused by induced current.

As the frequency of current was increased to 400 Hz, the distribution of current along the sections was changed (Fig. 7). In the mode of the field excitation, i.e. at the coupling connection of the winding in upper core and lower core, a current distribution along the sections of slot windings is shown in the Fig. 7 (curve *1*). and outer sections (curve *3* in the Fig. 7). At the reverse of current in one core winding what means a using of the model mode close to the compression mode the great difference is seen with respect to excitation mode.

The curve *1* in the Fig. 6 shows that at absence of Shelds' installation the current at frequency 400 Hz in the compression mode is located mainly in the parallel sections of windings which lies near the top of the slot, . thus a ratio of current in the top section to the current in the bottom section is 7.7. In spite of this factor the prevailing value of flux across the slot is coupled with sections of winding located close enough to the bottom of slot what is explaned as result of steel presence in the bottom of slots. The application of the Shields leads to re-distribution of flux into the area close to the top of slot. Whereas the current reduces in the top sections of slot the flux leakage becomes coupled with the all parallel sectons of winding more uniformly. The use of Shield 1 gives an increase of k_L since 11.01 up to 18.97 (in 1.72 times) due to reduction of $L_{\min}$ value (data of Table I). The best result has been obtained at the combined screen (Shield 1 + Shield 2), when the measured inductances were: $L_{\max}$ = 58.47 mH, $L_{\min}$ = 2.67 mH, with resulting ratio k_L = 21.6.

Discussion of the experimental results. The current measurement in the sections of winding and calculation of the total inductance swing k_L in the model displays the influence of the electromagnetic shielding of slots both on the maximal inductance and on the minimal inductance (each of them has a reduction). Making the leakage inductance reduced the shields at the same time insert the additional active resistance into the coils circuit as the result of energy loss due to induced current in the shields. The Shield 1 which covers the sides of slot is effective enough for the leakage flux diminishing but at the same time it inserts more active resistance to the circuit. The Shield 2 in the form of the conducting frame realizes the compromise: it provides a big enough diminishing of the leakage inductance and not so big inserted active resistance. Along with increase of the current frequency the efficiency of electromagnetic shields grows. In the model under consideration the minimal inductance of winding with Shield 1 at 400 Hz less in 1.85 times than at 50 Hz. The best results can be obtained at the combination of the Shield 1 with Shield 2. The full efficiency of the slots shielding in the real compression generator must be evaluated using the join criterion $\omega L_{\min} / R^{eff}$ where ω is the angular frequency of rotor rotation. This criterion is based on the comparison of the characteristic time of energy dissipation with a time of electromagnetic energy generation during a pulse.

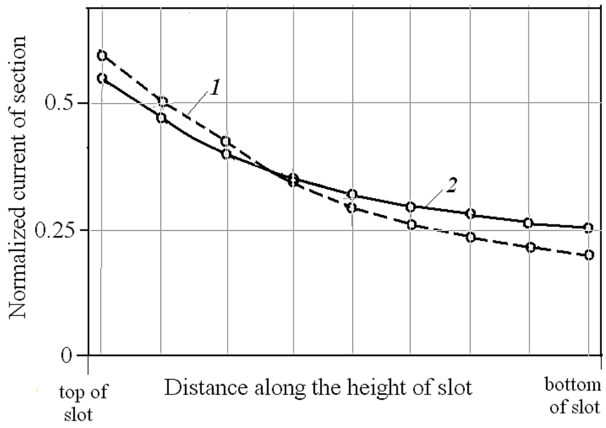

Figure 6. Distribution of current in the section of winding at the frequency 50 Hz (1 is the mode of compression; 2 is the mode of excitation at coupling connection of both windings). The basic value of current is equal to 1 A

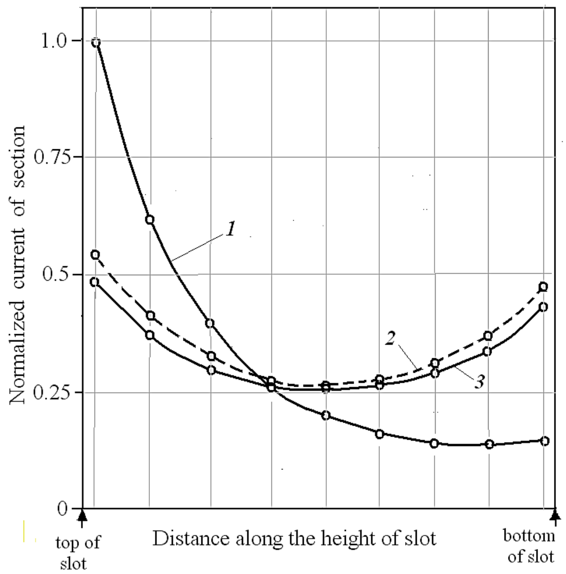

Figure 7. Distribution of current in the sections of winding at the frequency 400 Hz (1 is the mode of compression; 2 are the inner sections, mode of excitation; 3 are outer sections, mode of excitation). The basic current is equal to 1 A

Possible implementation of shields in generator design. The design of the Shield 1 is close to the proposed earlier in [4–6] in application to the shock generator stator. There was supposed in [4] to put the copper plates into the slit done in the center of each tooth. Such a position of screen reduces the common leakage of all slots but has no influence on the flux leakage of each slot separately. Shield 1 considered above has affect first on the individual flux leakage of the slot as well as on the collective flux. Its specific implementation in the generator design can be looking as the arrangement of winding in the one common wide slot done in the ferromagnetic core with inserted conducting block as the keeper of winding in several separate slots. This block-keeper at the same time is playing role of electromagnetic shield due to strong influence of the conducting material of block on the flux leakage in the mode of the flux compression. The sketch of such generator design is drawn in the Fig. 8. The left part of this figure has the marking of current directions corresponding to the mode of initial excitation of generator. The marking of currents in the right part of Fig. 8 corresponds to the mode of the flux compression after rotor turn on 180°. The picture of the magnetic field lines for this position of rotor presented in the Fig. 9. The purpose of the conducting blocks using is diluting of magnetic flux leakage in the space of slots and displacement of the flux into the air gap between rotor and stator with the corresponding improvement of the total inductance swing. A solution of this problem needs the careful analysis of electromagnetic field in the active zone of generator.

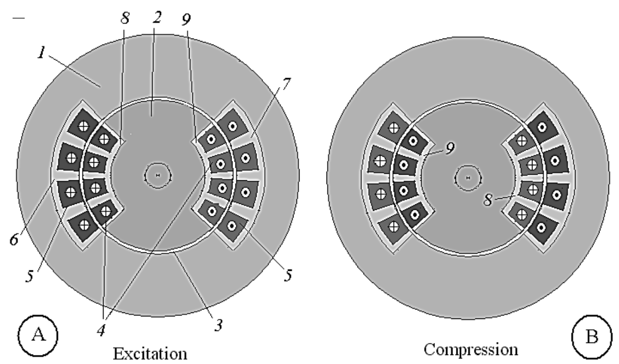

Figure 8. The cross section of the compression generator at two positions of rotor: A – for the excitation of the initial magnetic field, B – for the stage of the flux compression. Designations: *1* is the stator core, *2* is the rotor core, *3* is the air gap, *4* is the rotor winding, *5* is the stator winding, *6* and *7* are the block-keepers of stator winding, *8* and *9* are the block-keepers of rotor winding

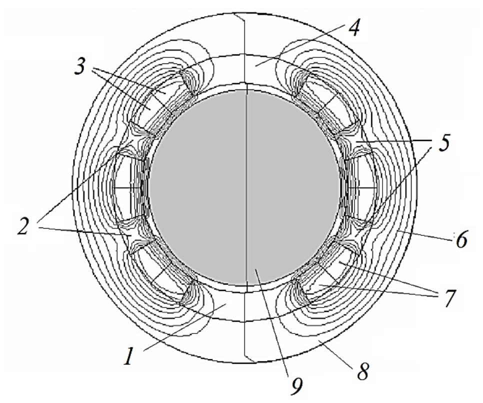

Figure 9. Cross section of magnetic system of generator with a picture of the field lines in the stage of the flux compression. Designations: *1* and *4* are the big teeth (poles) of stator core; *2* and *5* are the small teeth of statior; *3* and *7* are the winding conductors; *6* is the flux lines in the yoke; *8* is a yoke of stator; *9* is a rotor of generator. Details of rotor design are omitted

Some results of simulation and their discussion. To evaluate the final efficiency of the electromagnetic shielding of any form including the proposed block-keepers the methods of mathematic simulation can be used. The numerical analysis of the transient field in the machine with a shielding of the slot leakage meets the troubles at the attempts to use the standard software for this purpose. The popular programs for the transient electromagnetic field simulation as the Comsol, Quick Field, Elcut don't allow to realize in 2d approximation the condition about the absence of the electromagnetic coupling between the slot shields and the main flux of machine. To realize this condition it is necessary to provide equality to zero for integral of the current density along the cross section of each slot's shield what means in fact a necessity to apply the quasi-3D simulation. The mentioned above programs imply that each induced current flowing perpendicular to the plane of problem is connected with itself at the infinity. It does not correspond to physical situation in the shield. Only the 3D simulation can satisfy the conditions of this problem. The numerical 2D analysis of the transient field with the induced current of shield perpendicular to the plane of task does not allow in any way to specify correctly the magnetic field distribution at Shields installed in the slots of winding. Nevertheless, it is possible to use the 2D simulation for demonstration of the principal peculiarities for Shield 1 and Shield 2. The boundary problems about the pulsed field excitation in the plane copper sheet similar to Shield 1 and in the copper frame of rectangular form likely to Shield 2 have been resolved using the combined model shown in the Fig. 10 which takes into account only the shield at omitted winding conductors.

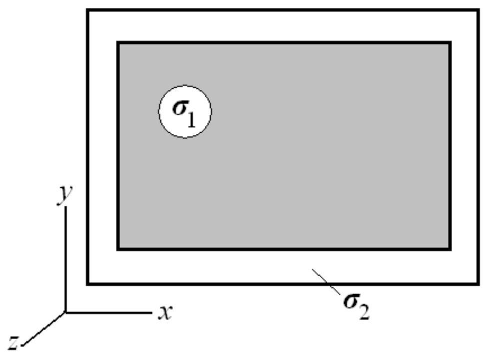

Figure 10. A simulation model for the study of the shields peculiariries

The plate of electrical conductivity σ_1 in the Fig. 10 serves as a model of Shield 1 with magnetic flux passage along the *z*-axis when the conductivity of the external frame $\sigma_2 = 0$. The boundary conditions specify the switch in of the magnetic induction B_z along the border contour of plate in the form of step function of time. The typical curves of the magnetic induction inside of non-dimensional time interval *T* = [0, 1] jointly with corresponding curves of induced current density are presented in the Fig. 11 for $\sigma_2 = 0$ = 0.5·10^8 S/m, $\sigma_2 = 0$, a time step between curves is equal to $0.1T_{max}$. For the simulation of the pulsed field at the presence only external frame it is necessary to put σ_2 = 0.5·10^8 S/m, $\sigma_1 = 0$. This situation is similar to using of Shield 2. The boundary and initial conditions can be specified here as the fast switch in of magnetic induction B_z pulse in the windows of frame. The results of simulation are shown in the Fig. 12. The specified values $\sigma_1 = \sigma_2 =$ 0.5·10^8 S/m can simulate a joint using of Shield 1 and Shield 2 at boundary condition given as the pulsed induction on the internal border of frame. Analysis of graphs in the Fig. 11, Fig. 12 leads to conclusion about ability of each kind of shield to cause a delay of the flux growth across the plane of shield. The plate similar to Shield 1 is able to have affect on the field distribution along the own surface while the frame similar to Shield 2 cannot change the field distribution in the own window. Evidently the better result for the flux screening can be obtained at the joint using of both kinds of shielding. The presence of bipolar currents in the Fig. 11, Fig.12 displays the essential and needed feature of both shields which consists of the equality to zero of total current in the cross section of the shield conductor. The residual magnetic flux in the end of the chosen control interval t/T_{max} in comparison with flux magnitude at $t = 0$ can be considered as the measure of the pulsed flux compensation by the screen.

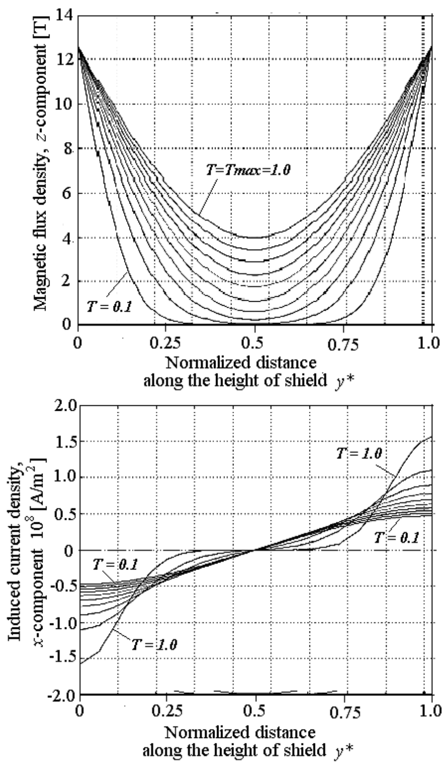

Figure 11. Results of simulation for the flux switch in across the conducting plate likely to Shield 1

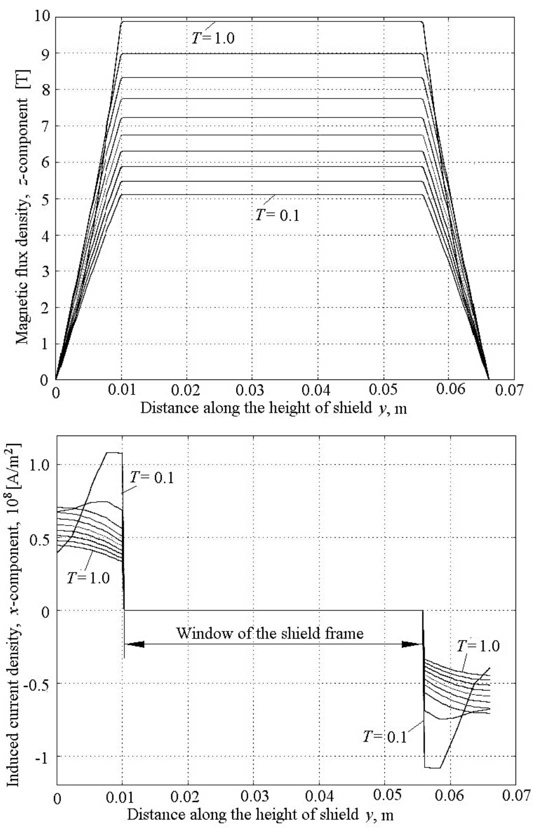

Figure 12. Results of simulation for the conducting frame likely to Shield 2 at the fast switch in of the flux in the window of frame

A simulation of the field in the considered combined model of Shields 1, 2 was performed in the software COMSOL v. 3.5. At the attempt to make a simulation the pulsed field in a real generator with a shielding conducting block we meet a limitedness of the 2D software for this problem solution. The reason for this troubles consists of a double polarity of induced currents in the block-keepers which play a role of electromagnetic shield. This fact can be taken into account in the 3D model or in the specialized (quasi-3D) 2D software. The presence of the short-connected contours coupled with the main flux of machine is inadmissible in generator because it is able to prevent the transfer of output energy into the load. That is why the 2D model built on the cross section of all conductors in the slots will not be adequate to the physical situation. A detail study of the problem about the flux leakage compensation in a real design of active zone of the compression generator at presence of electromagnetic shields makes urgent the 3D or quasi-3D program software. The analysis of field in such approach was realized in [7] using QuickField v. 6.2 (professional) software.

Conclusions. The ability of the flux leakage control in the slots by using of the conducting shields has been demonstrated in this work on the base of information received due to the testing of experimental model. The real role and specifics of the electromagnetic shields for a reduction of the minimal inductance of generator has been illustrated with a using of special numerical models. The simulation example in the frame of 2D approximation gives the clear arguments for need of the 3D simulation of magnetic field distribution in the problem of electromagnetic shielding or otherwise for development of specialized quasi-3D models in the frame of the existing 2D simulating programs taking into account the zero total induced current of shield during the transient electromagnetic process. For example, it is possible to realize in QuickField software what was shown in [7].

References:

1. Kuchinsky V.G., Larionov B.A. *Elektromashinnyi generator impulsov* [Electromechanical generator of pulses], USSR Auth. Sert. No. 934888, Cl. H 03 K 3/00. Data of publ. 15.03.1983, Bull. No.30. (Rus).
2. Druzhynin A.S., Kuchinsky V.G., Larionov B.A. Kompressionnye generatory' [Compression generators]. In the book: *Fizika I tehnika mozhchnyh impulsnyh system pod red. E.P.Velihova* [Physics and technology of pulsed power systems,edited by E.P.Velihov]. Moscow, Energoatomizdat Publ, 1986. P. 280–298. (Rus).
3. Vasyukevitch P.V. Koncentraciya magnitnogo potoka v elektromehanicheskom preobrazovatele [Concentration of magnetic flux in the electromechanical converter]. *Izvestiya Akademii Nauk SSSR "Energetika i transport"*. 1985. No. 4. P. 36–45 (Rus).
4. Sipailov G.A., Khor'kova V.Z. *Stator udarnogo generatora* [Stator of shock generator]. USSR Auth. Sert. No. 365768, Cl. H 02 K 1/16. Data of Publ. 08.01.1973. (Rus).
5. Baklin V.S. et.al. O dempfirovanii pazovogo rasseyaniya v obmotke statora udarnogo generatora [About damping of the slot leakage in the stator winding of shock generator]. *Elektrichestvo.* 1979. No. 8. P.71–73. (Rus).
6. Chemerys V.T. Field leakage study and possible ways of improving compression generator parameters. *2001 IEEE Pulsed Power and Plasma Sciemce Conference / Digest of technical paper*s. Las Vegas, 2001. P. 1516–1519.
7. Chemerys V.T., Borodiy I.A., Ocenka effektivnosti elektromagnitnyh ekranov dlya kompensacii potokov pazovogo rasseyaniya v impulsnom elektromashinnom generatore. *Visnyk NTU "KPI". Seriya: Electrichhi mashihy' ta elektromehanichne peretvorennya energiyi.* 2020. No. 3. P. 71–77. (Rus). doi: 10.20998/2409-9295.2020.3.12.

Чемерис В.Т. АНАЛІЗ ДЕЯКИХ КОНСТРУКЦІЙ ЕЛЕКТРОМАГНІТНИХ ЕКРАНІВ ДЛЯ КОМПЕНСАЦІЇ ПОТОКУ РОЗСІЮВАННЯ В ЕЛЕКТРОМАШИННИХ ГЕНЕРАТОРАХ ІМПУЛЬСНОГО СТРУМУ З КОМПРЕСІЄЮ МАГНІТНОГО ПОТОКУ

Електромашинний генератор імпульсного струму, принцип дії якого базується на компресії магнітного потоку, – це один з видів спеціальних електричних машин, конструювання й розвиток яких потребує сучасного наукового підходу. Висока ефективність практичного застосування такого генератора можлива за умови, що в його конструкції забезпечений високий перепад внутрішньої індуктивності машини під час обертання ротора. Головним чином цього можна досягнути шляхом зменшення мінімальної індуктивності машини у фазі компресії магнітного потоку. В цій статті розглядається електромагнітне екранування потоків пазового розсіювання в електромашинному генераторі з компресією магнітного потоку. На статичній експериментальній моделі частини активної зони генератора були досліджені два варіанти конструкції екрана. Перший варіант екрана передбачає встановлення мідних пластин, ізольованих тонким шаром діелектрика, вздовж бокових стінок пазів обмотки. Другий *варіант екрана передбачає встановлення в пазу двох електропровідних пластин шириною, що дорівнює ширині паза. Одна з них розміщується на дні паза, а друга – у відкритті паза, і вони на краях з'єднані між собою з допомогою мідних перемичок, розташованих за межами паза. Для збільшення перепаду індуктивності запропонована нова конструкція кріплення обмоток в пазу. Група пазів кожного полюсного ділення обмотки розташована в пазах, утворених в електропровідному блоці, який своєю чергою розміщений у розширеному пазу магнітопроводу. Це дає змогу значно зменшити магнітну провідність для потоку, орієнтованого поперек пазів. Робота також містить результати математичного моделювання екранів. Розглянуто, з якими труднощами пов'язані розроблення й моделювання екранів для компенсації потоку пазового розсіювання.*

Ключові слова: *компресійний генератор, потік розсіювання, мідні екрани, реалізація на моделі, випробування моделі, проблеми числового моделювання.*