NUMERIČKO RJEŠAVANJE RASPODJELE ELEKTROMAGNETSKOG I TEMPERATURNOG POLJA ZRAČNOG TRANSFORMATORA

NUMERICAL SOLUTION FOR THE DISTRIBUTION OF THE ELECTROMAGNETIC AND THERMAL FIELDS OF AN AIR-CORE TRANSFORMER

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U radu je prikazano numeričko rješavanje raspodjele elektromagnetskog i temperaturnog polja zračnog transformatora, metodom konačnih elemenata. Raspodjela magnetskog polja određena je za magnetsko-dinamičko stacionarno stanje i magnetsku jezgru s nelinearnom karakteristikom. Predstavljeni model omogućava uspostavljanje kriterija za optimiranje rada transformatora pod različitim uvjetima opterećenja, okoliša, pa i u slučajevima kvara. Na ovaj način transformator može raditi maksimalnim kapacitetom, dok su istodobno opasnosti od kvarova zbog pregrijavanja svedene na najmanju moguću mjeru.

The article presents a numerical solution for the distribution of the electromagnetic and thermal fields of an air-core transformer using the finite element method. The distribution of the magnetic field is determined for the dynamic steady state and magnetic nonlinear core characteristics. The model presented facilitates the establishment of criteria for optimizing transformer operation under various load conditions, environments as well as in the case of failures. Thus, the transformer can operate at maximum capacity while, at the same time, the probability of faults due to overheating is reduced to a minimum.

Ključne riječi: elektromagnetsko polje; numerički proračun; temperaturno polje; zračni transformator

Key words: air-core transformer; electromagnetic field; numerical calculation; thermal field

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1 UVOD

Predviđanje i određivanje elektromagnetskih i termičkih pojava u sastavnim metalnim dijelovima transformatora vrlo je važan korak u procesu projektiranja uređaja. Kvarovi transformatora uvijek uzrokuju nepovratna unutarnja oštećenja. Osnovni kriterij koji ograničava mogućnost opterećenja transformatora i njegov životni vijek djelimično je određen sposobnošću transformatora da disipira toplinu, generiranu u svojoj unutrašnjosti u okolni prostor.

Stoga je od velike važnosti predviđanje termičkog ponašanja transformatora tijekom normalnog opterećenja. Kreiranje modela transformatora vrlo je važno za proces monitoringa rada transformatora. Za numeričko rješavanje raspodjele elektromagnetskog i temperaturnog polja korišten je laboratorijski zračni transformator. Rezultati dobiveni numeričkim proračunom u idućem poglavlju uspoređeni su s rezultatima dobivenim u laboratorijskim mjerenjima.

Podaci o transformatoru su:

- tip DP/0-9896,
- nominalna snaga 2,4 kVA,
- nominalni napon, namot visokog napona (VN) 500 V,
- nominalni napon, namot niskog napona (NN) 380 V,
- frekvencija 50 Hz,
- nominalna primarna struja 3 A,
- nominalna sekundarna struja 3,6 A,

2 MATEMATIČKI MODEL MAGNETSKOG I TOPLINSKOG POLJA

Izvori elektromagnetskog i toplinskog polja su struje koje teku kroz namote transformatora, odnosno Jouleovi gubici koji nastaju kao posljedica protjecanja struja kroz vodiče, tj. namote transformatora.

Elektromagnetsko polje je određeno jednadžbama:

1 INTRODUCTION

The prediction and determination of electromagnetic and thermal phenomena in the metal parts of transformers are very important steps in the process of designing equipment. Transformer faults always cause internal damage. The basic criterion that limits transformer loading and its lifetime is partially determined by the ability of the transformer to dissipate internally generated heat into the surrounding area.

Therefore, it is of great importance to predict the thermal behavior of a transformer under normal load. Creating a transformer model is very important for the process of monitoring transformer operation. Laboratory air-core transformer data were used for the numerical determination of the distribution of the electromagnetic and temperature fields. The results obtained from the numerical calculation in the next chapter have been compared to the results obtained from laboratory measurements.

The transformer data are as follows:

- type DP/0-9896,
- nominal power 2,4 kVA
- nominal voltage, high voltage winding (HV) 500 V
- nominal voltage, low voltage winding (LV) 380 V
- frequency 50 Hz
- nominal primary current 3 A
- nominal secondary current 3,6 A

2 MATHEMATICAL MODEL OF ELECTROMAGNETIC AND THERMAL FIELDS

The sources of electromagnetic and thermal fields are currents that flow through transformer windings, i.e. joule losses that occur in consequence of the current flowing through conductors, i.e. transformer windings.

An electromagnetic field is determined by the following equation:

$$\nabla \times \boldsymbol{H} = \sigma\ (T)\boldsymbol{E} \tag{1a}$$

$$\nabla \times \boldsymbol{H} = \sigma\ (T)\boldsymbol{E} \tag{1b}$$

$$\nabla \cdot \left\lfloor\ \mu\ (H,T)\boldsymbol{H} \right\rfloor = 0 \tag{1c}$$

$$\nabla \times \boldsymbol{E} = -\frac{\partial \left[\ \mu\ (H,T)\boldsymbol{H} \right]}{\partial t} \tag{1d}$$

Ukupna gustoća struje određena je jednadžbom:

Total current density is determined by the following equation:

$$\boldsymbol{J}_{\mathrm{uk}} = \boldsymbol{J}_{\mathrm{iz}} + \sigma\left(T\right)\frac{\mathrm{d}\boldsymbol{A}}{\mathrm{d}T} = \sigma\left(T\right)\left(\boldsymbol{E}_{\mathrm{iz}} + \frac{\partial \boldsymbol{A}}{\partial t}\right) \tag{2}$$

Toplinsko polje je opisano jednadžbom:

A thermal field is described by the following equation:

$$\nabla\left(\lambda\nabla T\right) - \rho c\frac{\partial T}{\partial t} + q_{\mathrm{v}} = 0 \tag{3}$$

i predstavlja diferencijalnu jednadžbu nestacionarnog prijenosa topline, u kojoj je:

- T - tražena funkcija raspodjele temperature u prostoru i vremenu [K],
- c - specifični toplinski kapacitet [J/kg·K],
- ρ - specifična gustoća materijala [kg/m^3],
- λ - koeficijent vođenja topline [W/m·K],
- q_{v} - toplinska izdašnost eventualnog izvora topline u promatranoj točki,
- t - vrijeme [s],

pri čemu su to funkcije prostora i temperature.

Razmjena topline između površina vodiča, jezgre, ulja i okolnog zraka dana je jednadžbom:

and represents the differential equation of non-steady state heat transfer, in which:

- T - the sought function of temperature distribution in space and time [K]
- c - the specific heat capacity [J/kg·K]
- ρ - the specific material density [kg/m^3]
- λ - the coefficient of thermal conductivity [W/m·K]
- q_{v} - heat generation of the eventual heat source at the observed point [J]
- t - time [s],

where the above are functions of space and temperature.

Heat exchange among the surfaces of the conductor, core, oil and ambient air are given in the following equation:

$$-\lambda\frac{\partial T}{\partial t} = \alpha\left(T_{\mathrm{p}} - T_{\mathrm{f}}\right) \tag{4}$$

Za rješavanje diferencijalnih jednadžbi kod zadanih početnih i graničnih uvjeta korištena je metoda konačnih elemenata (MKE). MKE je aproksimativni postupak. Primjenom ove metode problem rješavanja parcijalne diferencijalne jednadžbe prijelaza topline svodi se na rješavanje sustava simultanih linearnih jednadžbi. Područje unutar kojeg se rješava problem dijeli se na konačan broj elemenata. Kao rješenje dobivaju se temperature u čvorištima elemenata, dok se temperature unutar elemenata aproksimiraju pomoću vrijednosti u čvorištima elemenata.

For the solution of differential equations with the given initial and final conditions, the finite element method (FEM) was used. FEM is an approximate procedure. By applying this method, the problem of solving the partial differential equation of heat transfer is reduced to the solution of a system of simultaneous linear equations. The region within which the problem is solved is divided into a finite number of elements. The temperatures of the element nodes are obtained as solutions, while the temperatures within the elements are approximated using the values of the element nodes.

3 MODEL ZRAČNOG TRANSFORMATORA

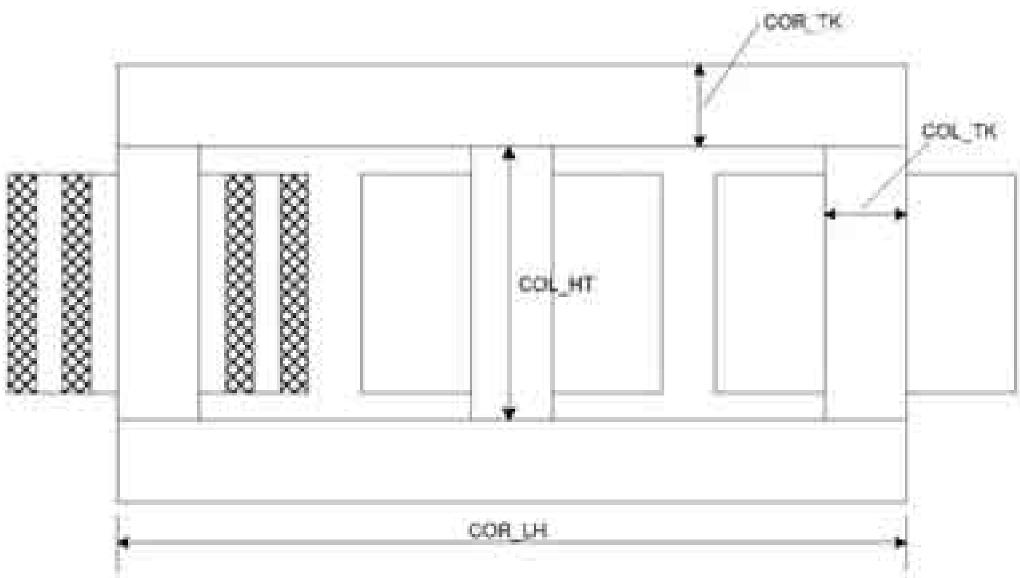
Za proračun elektromagnetskog i temperaturnog polja trofaznog zračnog energetskog transformatora metodom konačnih elemenata korišten je programski paket FLUX2D.

Proračun temperaturnog polja vršen je u poprečnom presjeku transformatora u dvije

3 AIR-CORE TRANSFORMER MODEL

For the calculation of the electromagnetic and thermal fields of a three-phase air-core power transformer using the finite element method, the software program FLUX2D was employed.

Two-dimensional calculation of the thermal field in the cross section of the transformer was performed.



Slika 1 – Geometrija transformatora
Figure 1 – Transformer geometry

dimenzije. Cilj je bio dobiti model trofaznog zračnog energetskog transformatora koji bi što vjernije prikazao zagrijavanja i rapodjelu temperatura, koje se javljaju pri radu transformatora.

Da bi se moglo izvršiti modeliranje termičkih procesa transformatora potrebno je primijeniti složeni matematički model koji opisuje spregnuta elektromagnetska i temperaturna polja. Pokazani model zračnog transformatora napravljen je s ciljem dobivanja informacije o stanju transformatora.

Na slici 1 prikazana je geometrija analiziranog transformatora. U tablici 1 dani su podaci o geometriji korištenog zračnog transformatora.

The goal was to obtain a model of a three-phase air-core power transformer that would describe the heating and temperature distribution which occur during transformer operation as accurately as possible.

In order to model the thermal processes of a transformer, it is necessary to apply a complex mathematical model that describes coupled electromagnetic and thermal fields.
The model of the air-core transformer presented was devised with the goal of obtaining information on the state of the transformer.

In Figure 1, the geometry of the analyzed transformer is presented. In Table 1, data are presented on the geometry of the air-core transformer used.

Tablica 1 – Podaci o geometriji transformatora
Table 1 – Data on the transformer geometry

Parametar / Parameter	Opis / Description	Veličina / Value [mm]
COL_HT	Visina stupa / Leg height	145
COR_TK	Debljina gornjeg i donjeg dijela jezgre / Top and bottom yolk thickness	50
COL_TK	Debljina stupa / Leg thickness	30
COR_LH	Dužina jezgre / Core leg	250
INS_TK	Debljina izolacije / Insulation thickness	7
C1_TK	Debljina namota 1 / Thickness of Winding 1	7,5
C2_TK	Debljina namota 2 / Thickness of Winding 2	7,5
COIL_HT	Visina namota / Winding height	145
R_INT	Unutrašnji promjer domena proračuna / Internal diameter of the calculation domains	2 000
R_EXT	Vanjski promjer domena proračuna / External diameter of the calculation domains	2 300

Ovaj model pruža važne informacije koje karakteriziraju termičke procese važne za prognozu, simuliranje i analiziranje rada transformatora.

Inače, fenomeni koji se događaju u električnim uređajima opisani su diferencijalnim jednadžbama:

– Maxwellovim jednadžbama,
– toplinskim jednadžbama,
– zakonitostima o ponašanju materijala.

Do jednostavnog rješenja ovih jednadžbi nije moguće doći zbog poteškoća koje su posljedica kompleksnosti jednadžaba i velikog broja proračuna koji se moraju izvršiti. Zbog toga, moduli fizikalne aplikacije koje nudi FLUX2D dopuštaju rješenje bilo kojeg zadanog problema, opisanog jednadžbom i hipotezama.

Tako se npr. transformator može proučavati na dva načina:

– kao magnetski problem (ako se žele odrediti Jouleovi gubitci) i
– kao električni problem (ako se želi znati vjerojatnost ispada transformatora).

Stoga ga je nužno analizirati posebno s magnetodinamičkom aplikacijom, a posebno s elektrostatičkom aplikacijom.

Problemi magnetske prirode mogu se analizirati sa sljedećim fizikalnim aplikacijama:

– magnetostatičkom,
– magnetodinamičkom,
– elektrodinamičkom,
– aplikacijom za tranzijentna stanja u magnetizmu,
– aplikacijom za proučavanje uređaja s pokretnim dijelovima koji se kreću translatorno ili rotacijski,
– aplikacijom koja se odnosi na supervodičke pojave,
– aplikacijom koja uzima u obzir i vanjske električne krugove,
– aksiperiodičnom aplikacijom.

Problemi termičke prirode mogu se rješavati primjenom aplikacije za:

– stacionarna termička stanja,
– tranzijentna termička stanja,
– megnetotermičke probleme,
– elektrotermičke probleme,
– dielektrotermičke probleme.

Elektromagnetsko polje je proračunato korištenjem magnetodinamičkog modela. Pro-

This model provides important information that characterizes the thermal processes necessary for the prediction, simulation and analysis of transformer operation.

The phenomena that occur in electrical equipment are described by the following differential equations:

– Maxwell's equations,
– thermal equations, and
– material behavior laws.

It is not possible to arrive at simpler solutions to these equations due to the complexity of the equations and the large number of calculations that must be performed. Therefore, the physical application models offered by FLUX2D facilitate solutions to any given problem, described by an equation and hypotheses.

Thus, for example, a transformer may be studied in two ways:

– as a magnetic problem, in order to determine Joule losses, and
– as an electrical problem, (in order to determine the probability of transformer failure.

Therefore, the transformer must be separately analyzed by a magnetodynamic application and an electrostatic application.

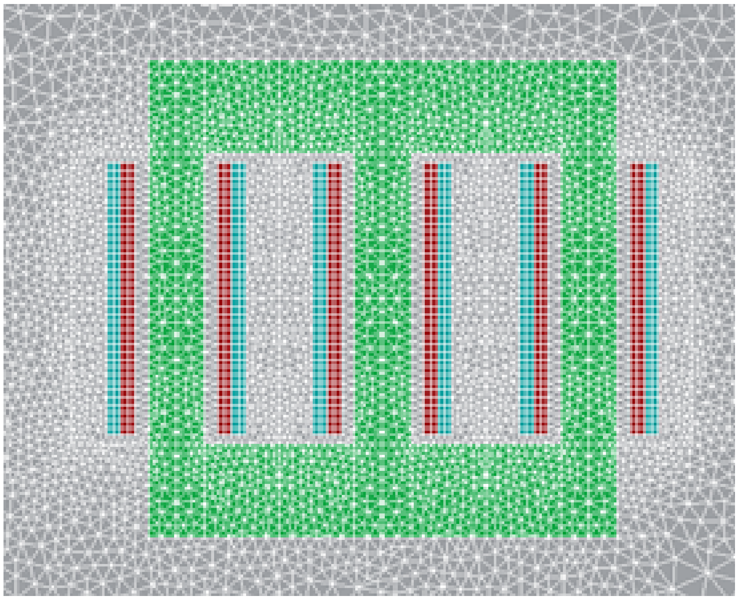
Problems of a magnetic nature may be analyzed using the following physical applications:

– magnetostatic,
– magnetodynamic,
– electrodynamic,
– an application for transient magnetic states,
– an application for studying equipment with parts that move translationally or rotationally,
– an application that refers to superconductive phenomena,
– an application that also takes external electrical circuits into account, and
– an axiperiodic application.

Problems of a thermal nature can be solved using applications for the following:

– steady thermal states,
– transient thermal states,
– magnetothermal problems,
– electrothermal problems, and
– dielectric thermal problems.

An electromagnetic field is calculated using a magnetodynamic model. By studying the



Slika 2 – Mreža konačnih elemenata
Figure 2 – Network of finite elements

matranim termičkim problemom također se definira područje proračuna kojem pripada. U analiziranom slučaju to je područje tranzijentno termičkog proračuna.

Transformator koji je u ovom radu analiziran sadrži magnetske materijale s nelinearnom permeabilnosti u željeznoj jezgri.

Kreirani model transformatora sadrži 34 729 čvornih točaka i 16 495 trokutastih elemenata (slike 2 i 3).

Kvaliteta mreže opisana je sljedećim podacima:

– broj elemenata dobre kvalitete: 99,01 %,
– broj elemenata osrednje kvalitete: 0,97 %,
– broj elemenata lošije kvalitete: 0,02 %.

thermal problem, the corresponding area of calculation is also defined. In the case analyzed, this is the area of a transient thermal calculation.

The iron core of the transformer analyzed in this article consists of magnetic materials with nonlinear permeability.

The transformer model created consists of 34 729 nodal points and 16 495 triangular elements (Figures 2 and 3).

The quality of the network is described by the following data:

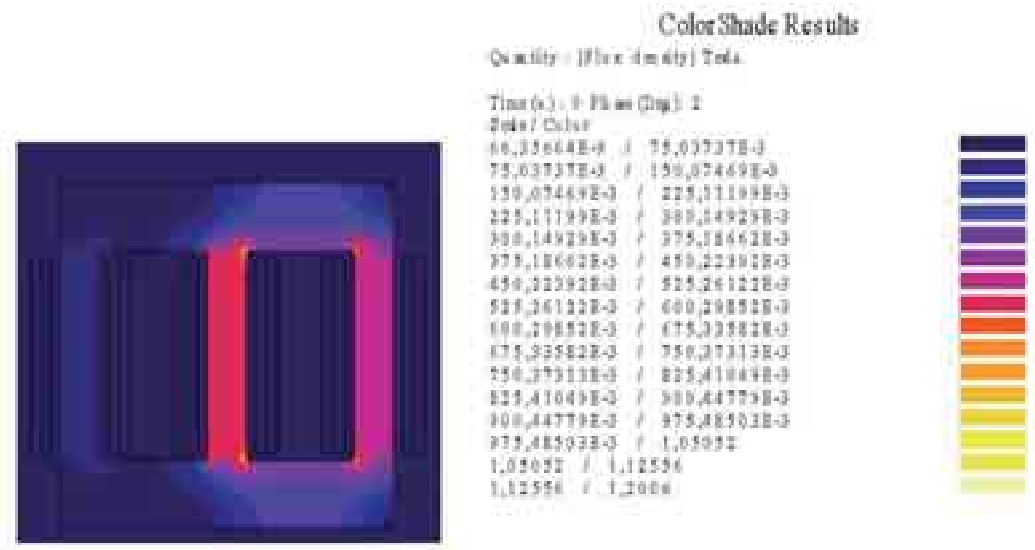
– the number of good quality elements: 99,01 %,
– the number of medium quality elements: 0,97 %, and
– the number of poor quality elements: 0,02 %.

00:09:46	126 sec.	1812 1st order lineic elements created
00:09:47	126 sec.	Display of 71 faces....
00:09:48	128 sec.	Finished updating display
00:09:48	128 sec.	Generating 2nd order elements is runnin
00:09:49	128 sec.	End generating 2nd order elements

Total number of nodes ⟶ 34 729

Number of elements not evaluated	: 0 %
Number of good quality elements	: 99,01 %
Number of medium quality elements	: 0,97 %
Number of poor quality elements	: 0,02 %
Number of bed quality elements	: 0 %

Slika 3 – Podaci o kvaliteti mreže konačnih elemenata
Figure 3 – Data on the quality of the network of finite elements



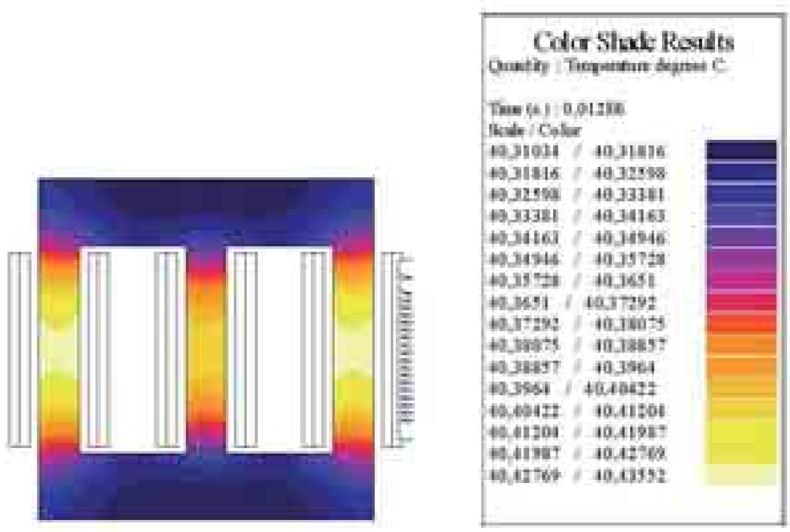
Slika 4 – Magnetska indukcija (fazni kut 0 stupnjeva)
Figure 4 – Magnetic induction (phase angle 0 degrees)

4 NUMERIČKI PRORAČUN ELEKTROMAGNETNOG I TEMPERATURNOG POLJA ZRAČNOG TRANSFORMATORA

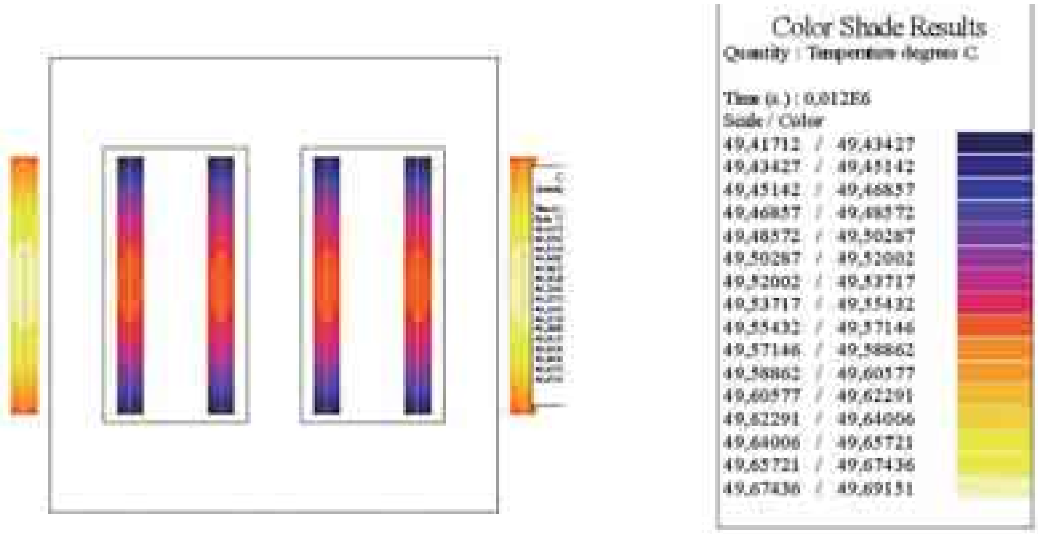
Numerički proračun vršen je na sljedeći način: izvori elektromagnetnog i temperaturnog polja struje su koje teku kroz namote transformatora, odnosno Jouleovi gubitci koji nastaju kao posljedica protjecanja struja kroz vodiče, tj. namote transformatora.

4 NUMERICAL CALCULATION OF THE ELECTROMAGNETIC AND THERMAL FIELDS OF THE AIR-CORE TRANSFORMER

The numerical calculation is performed as follows: The sources of the electromagnetic and thermal fields are the currents that flow through the transformer windings, i.e. Joule losses that occur due to current flow through conductors, i.e. transformer windings.



Slika 5 – Raspodjela temperature u jezgri trofaznog zračnog transformatora nakon 12 000 sekundi
Figure 5 – Temperature distribution in the core of the three-phase air-core transformer after 12 000 seconds



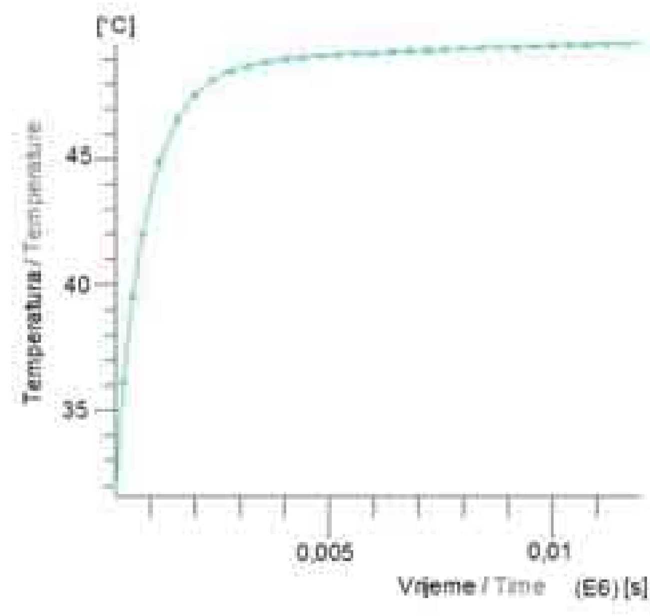
Slika 6 – Raspodjela temperature u namotima trofaznog zračnog transformatora nakon 12 000 sekundi
Figure 6 – Temperature distribution in the windings of the three-phase air-core transformer after 12 000 seconds

Rezultati raspodjele magnetskog i temperaturnog polja u poprečnom presjeku trofaznog zračnog transformatora prikazani su na slikama 4, 5 i 6.

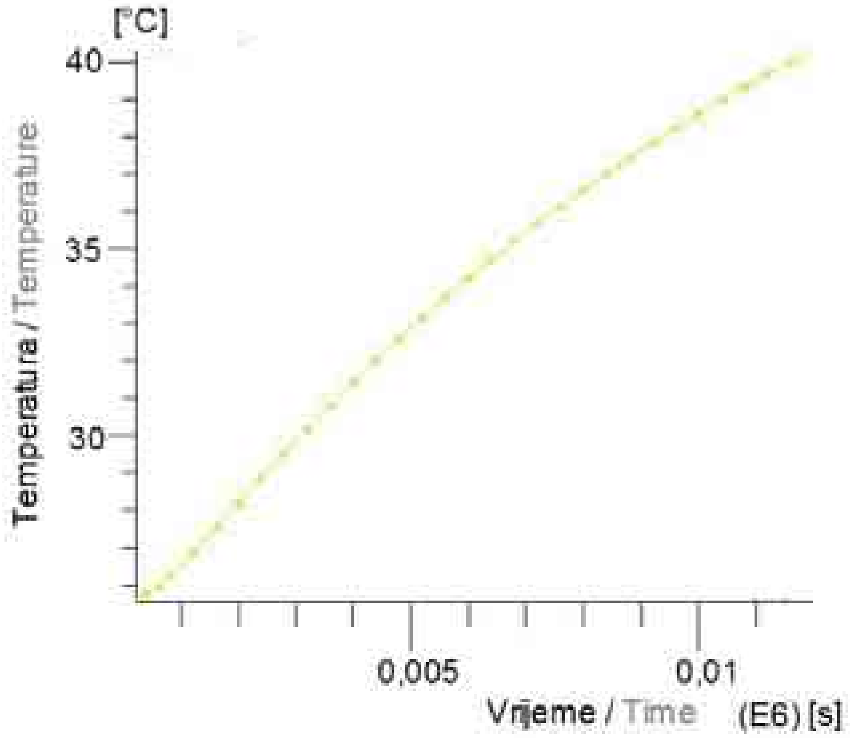
Na slici 5 prikazana je raspodjela temperature u jezgri trofaznog zračnog transformatora, za vremensko razdoblje od 12 000 sekundi nakon priključenja transformatora na mrežu.

The results of the distribution of the magnetic and thermal fields in the cross-sectional area of the three-phase air-core transformer are presented in Figures 4, 5 and 6.

In Figure 5, the temperature distribution in the core of the three-phase air-core transformer for the time period of 12 000 seconds after the connection of the transformer to the network is presented.



Slika 7 – Temperatura u točki na sredini namota čije su koordinate (-146,524, -1,254), nakon 12 000 sekundi
Figure 7 – Temperature at a point in the center of the winding (coordinates: -146,524, -1,254), after 12 000 seconds



Slika 8 – Temperatura u točki na sredini jezgra čije su koordinate (1,568, 128,012), nakon 12 000 sekundi
Figure 8 – Temperature at a point in the center of the core, (coordinates: -1,568, 128,012), after 12 000 seconds

Na slici 6 je prikazana raspodjela temperature u namotima trofaznog zračnog transformatora, za vremensko razdoblje od 12 000 sekundi.

Na slikama 7 i 8 prikazani su dijagrami promjene temperature u vremenu od 12 000 s u točki u centru namota i jezgri.

4.1 Laboratorijska mjerenja

S obzirom da se radi o zračnom transformatoru, mjerenja temperature mogla su se izvršiti termometrima. Kod ovih transformatora razlika između prosječne temperature namota i lokalnih temperatura nije velika. Mjerenje je izvršeno na najtoplijem pristupačnom mjestu namota. Temperatura vanjskog dijela željezne jezgre kod suhih transformatora također se može mjeriti termometrom. Kao temperatura rashladnog sredstva, u ovom slučaju mjerena je temperatura okolnog zraka, na udaljenosti 1m do 2 m od transformatora, i u polovici njegove visine. Termometri su bili zaklonjeni od strujanja i ižaravanja. Transformator je bio opterećen otpornikom otpornosti od $R_{opt} = 29\Omega$, simetrično u sve tri faze.

In Figure 6, the temperature distribution in the windings of the three-phase air-core transformer for the time period of 12 000 seconds is presented.

In Figures 7 and 8, charts are presented of the changes in temperature during a time period of 12 000 s at a point in the center of the winding and core.

4.1 Laboratory measurements

Since this concerns an air-core transformer, temperature measurements can be performed with a thermometer. For these transformers, the difference between the average winding temperature and the ambient temperature is not great. Measurement was performed at the hottest accessible spot of the winding. The temperature of the external part of the iron core for dry transformers may also be measured by a thermometer. The temperature of the cooling agent, in this case the temperature of the ambient air, was measured at a distance of 1 m to 2 m from the transformer, at half of its height. The thermometers were protected from air flow and radiation. The transformer was loaded with a resistive load, $R_{opt} = 29\Omega$, symmetrical in all three phases.

Fazni naponi primarnog i sekundarnog namota tijekom izvođenja eksperimenta bili su:

$U_{prim,f} = 176\ \text{V},$
$U_{sek,f} = 143\ \text{V}.$

Struje koje su protjecale kroz namote primara i sekundara bile su:

I_{prim}=2,8 A,

I_{sek}=3,6 A.

Izmjerena temperatura okoline na početku mjerenja je bila 25,5 °C, temperatura jezgre 22,2 °C, a temperatura namota 25,5 °C. Mjerenje je započelo u 11:35 sati, a očitavanje pokazivanja dviju sondi postavljenih na namot i jezgru vršeno je svakih deset minuta, sve dok temperatura namota nije postala stalna, tj. dok nije nastupilo stacionarno stanje. Mjerenje je trajalo 3 sata i 20 minuta.

Rezultati mjerenja dani su u tablici 2.

The phase voltages of the primary and secondary windings during the experiment were as follows:

$U_{prim,f} = 176\ \text{V},$
$U_{sek,f} = 143\ \text{V}.$

The currents that passed through the primary and secondary windings were as follows:

I_{prim}=2,8 A,

I_{sek}=3,6 A.

The measured ambient temperature at the beginning of measurement was 25,5° C, the core temperature was 22,2° C, and the winding temperature 25,5° C. Measurement began at 11:35 a.m. and readings of two probes placed on the winding and core were performed every ten minutes, until the temperature of the windings became constant, i.e. until steady state was reached. Measurement lasted for 3 hours and 20 minutes.

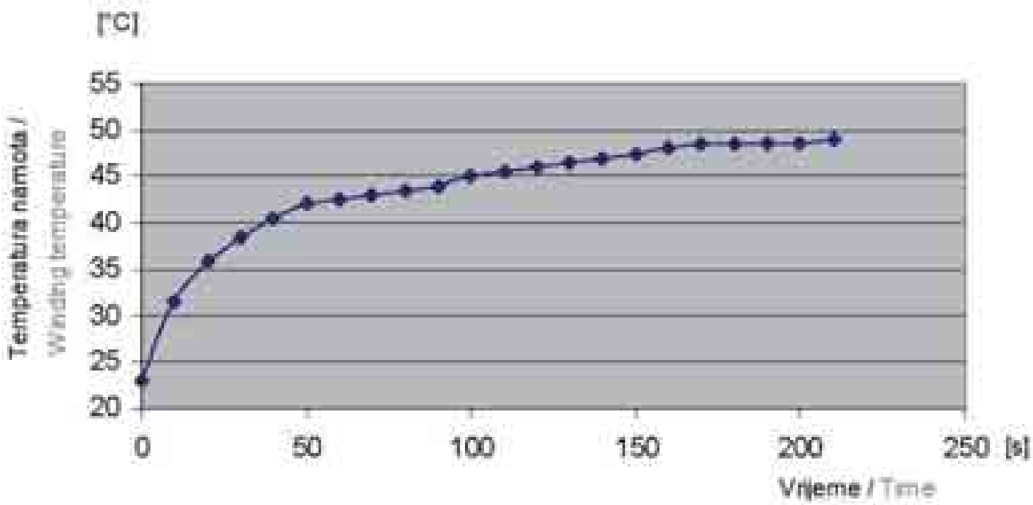
The results of the measurement are presented in Table 2.

Tablica 2 — Rezultati mjerenja temperatura jezgre i namota
Table 2 — The results of the measurements of the core and winding temperatures

Vrijeme mjerenja [sati] / Time of measurement	11:45	11:55	12:05	12:15	12:25	12:35	12:45	12:55	13:05
Temperatura jezgre / Core temperature [°C]	23	23,95	24,9	26,0	27,2	28,3	29,4	30,5	31,6
Temperatura namota / Winding temperature [°C]	31,5	36,0	38,5	40,5	42,0	42,5	43,0	43,5	44,0

Vrijeme mjerenja [sati] / Time of measurement	13:15	13:25	13:35	13:45	13:55	14:05	14:15	14:25	14:35
Temperatura jezgre / Core temperature [°C]	32,6	33,5	34,5	35,3	36,0	36,8	37,5	38,2	38,8
Temperatura namota / Winding temperature [°C]	45,0	45,5	46,0	46,5	47,0	47,5	48,0	48,5	48,5

Vrijeme mjerenja [sati] / Time of measurement	14:45	14:55	15:05
Temperatura jezgre / Core temperature [°C]	39,4	39,9	40,4
Temperatura namota / Winding temperature [°C]	48,5	48,5	49,0



Slika 9 – Promjena temperature namota u vremenu
Figure 9 – Changes in winding temperature over time

Tablični rezultati prikazani su na slikama 9 i 10, pomoću dijagrama.

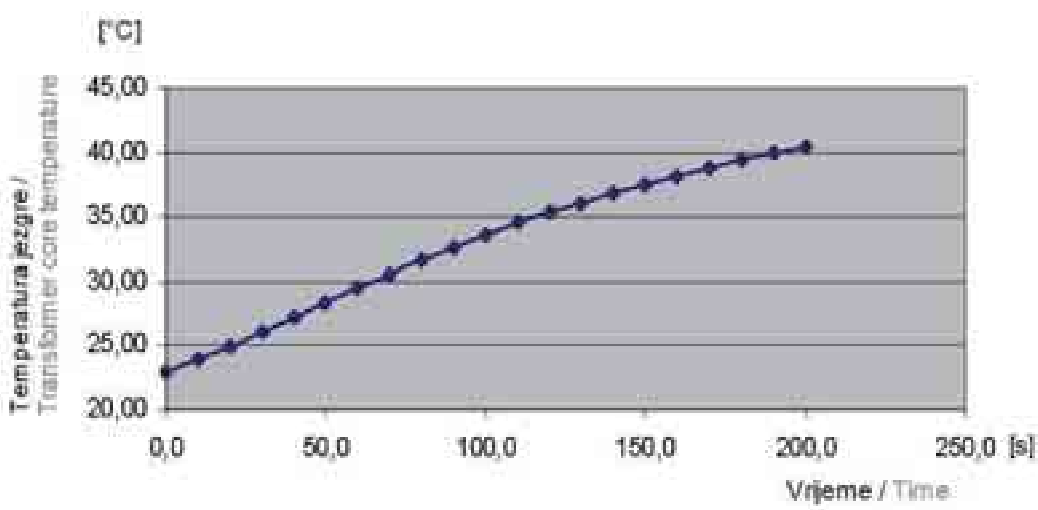
5 ZAKLJUČAK

Analizom dobivenih rezultata numeričkog proračuna: raspodjele magnetske indukcije, raspodjele silnica magnetskog polja, temperaturnog polja u poprečnom presjeku trofaznog zračnog transformatora, kao i dijagrama promjene temperature u pojedinim točkama u vremenskom razdoblju od 12 000 sekundi, može se zaključiti:

The results are presented in Figures 9 and 10.

5 CONCLUSION

Through analysis of the results obtained by numerical calculation, the distribution of magnetic induction, the distribution of magnetic field lines, the temperature field in the cross-sectional area of the three-phase air-core transformer, as well as the temperature change charts for individual points during a time period of 12 000 seconds, the following can be concluded:



Slika 10 – Promjena temperature jezgra u vremenu
Figure 10 – Changes in core temperature over time

– Na slici 4 prikazana je raspodjela magnetske indukcije u jezgri trofaznog zračnog transformatora. Srednja vrijednost magnetske indukcije dobivena iz rezultata numeričkog proračuna, a koji predstavljaju vrijednosti magnetne indukcije u srednjem stupu jezgre, iznosi približno 0,5 mT, što odgovara vrijednosti magnetske indukcije izmjerenoj pomoću Hall-ove sonde postavljene na mjesto između 2 stupa, a koja iznosi 0,46 mT.

– Na slici 5 prikazan je dijagram promjene temperature u određenim točkama (danim određenim koordinatama) jezgre. Za proračun je uzeta temperatura okoline od 25,5 °C, što odgovara temperaturi pri izvođenju laboratorijskog eksperimenta.

– Na slici 6 prikazana je raspodjela temperature u trofaznom zračnom energetskom transformatoru. Najtopliji su namoti, gdje temperature dosežu maksimalnu vrijednost od 49,69 °C. Prema rezultatima provedenog eksperimenta, maksimalna izmjerena vrijednost temperature namota iznosila je 49 °C. To znači da su vrijednosti dobivene eksperimentalnim i numeričkim putem približno iste.

– Pri ustaljenom radnom stanju zračnog transformatora mehanizam hlađenja je sljedeći: zrak dodiruje aktivne dijelove transformatora u kojima se proizvode gubitci čija je temperatura najviša. Zbog toga se dodirni zrak zagrijava, postaje lakši i ide naviše, na njegovo mjesto dolazi donji hladniji zrak i na taj način se ostvaruje prirodna cirkulacija zraka. Međutim, pri stacionarnom stanju (ustaljenom opterećenju, npr. nominalnom), temperature pojedinih dijelova transformatora u zavisnosti od njegove visine, nisu jednake. Najviše se zagrijavaju namoti, zatim magnetski krug pa okolni zrak.

– Kada se izvodi pokus zagrijavanja, pokus se prekida kada transformator dođe u stacionarno stanje, tj. kada mu je temperatura tolika da je toplina predana hlađenjem upravo jednaka razvijenoj toplini u istom vremenskom intervalu. Smatra se da je to stanje dosegnuto kad temperatura namota u zadnja dva sata ne poraste više od 1 °C. U numeričkom proračunu vrijeme trajanja proračuna je 12 000 sekundi, jer je to bilo dovoljno dugo

– In Figure 4, the distribution of the magnetic induction in the core of a three-phase air-core transformer is presented. The mean value of the magnetic induction obtained from the result of the numerical calculation, which represents the values of magnetic induction in the central leg of the core, amounts to approximately 0,5 mT, corresponding to the values of the magnetic induction measured using a Hall probe placed between two legs, which amount to 0,46 mT.

– In Figure 5, temperature changes of the core at specific points (with assigned specific coordinates) are presented. In the calculation, the ambient temperature of 25,5 °C was used, which corresponds to the temperature while the laboratory experiment was being conducted.

– In Figure 6, temperature distribution in the three-phase air-core power transformer is shown. The hottest spot of the windings reached a maximum temperature of 49,69° C. According to the results of the experiment, the maximum measured value of the winding temperature was 49 °C. This means that the values obtained experimentally and numerically are approximately the same.

– Under steady state conditions, the cooling mechanism of the air-core transformer is as follows: air comes into contact with the active parts of the transformer in which losses are generated and which have the highest temperatures. Therefore, the air in contact with the hot surface heats up, becomes lighter and rises upwards. It is replaced by colder lower air, thereby creating natural air circulation. However, during steady state conditions (steady load, e.g. nominal load), the temperatures of the individual parts of the transformer are not equal, depending upon their heights. The windings heat up the most, followed by the magnetic circuit and then the ambient air.

– While the heating experiment is being conducted, it is interrupted when the transformer reaches the steady state, i.e. when its temperature is so high that heat transferred by cooling is actually equal to the generated heat during the same time interval. It is believed that this state is reached when the winding temperature has not increased by more than 1° C during the preceding two hours. In the numerical calculation, the duration of the calculation is 12 000 seconds, because this is a time period long enough to include the steady state as well, i.e. the temperature of the transformer winding had become steady.

vremensko razdoblje da se njime obuhvati i stacionarno stanje, tj. temperatura namota transformatora je postala stalna.

Zagrijavanje transformatora, ako se zanemare prijelazne pojave između bakra (aluminija) i zraka, i ako se transformator promatra kao homogeno tijelo, u kojem se razvija toplina, odvija se po eksponencijalnoj funkciji. Mjereno zagrijavanje tijekom numeričkog proračuna, u zavisnosti od vremena, predstavljeno je na dijagramima, slike 7 i 8. Može se primijetiti da se najbrže zagrijavaju namoti i da najbrže postižu stacionarno stanje. Sporiji odziv na zagrijavanje ima jezgra, kojoj treba znatno duže vrijeme da uđe u stacionarno stanje.

Točnost rezultata dobivenih numeričkim proračunom potvrđena je rezultatima eksperimentalnih mjerenja, prikazanim na slikama 9 i 10. Usporedbm dijagrama prikazanih na slikama 7 i 8, koji su rezultat numeričkog proračuna i dijagrama prikazanih na slikama 9 i 10, koji su rezultat eksperimentalnih mjerenja, može se primijetiti da su približno jednaki, što ukazuje na opravdanost uvođenja i razvijanja ovakvih numeričkih proračuna za praktične probleme.

Postotna pogreška između mjerenih i proračunatih vrijednosti, za trofazni zračni transformator određena je na sljedeći način:

Temperature namota i jezgre dobivene numeričkim proračunom i mjerenjem, u stacionarnom stanju iznose:

$T_{n,np}$ = 49,69 ºC,
$T_{n,mj}$ = 49 ºC,
$T_{j,np}$ = 41 ºC,
$T_{j,mj}$ = 40,4 ºC

gdje je:
$T_{n,np}$ - temperatura namota dobivena numeričkim proračunom,
$T_{n,mj}$ - temperatura namota izmjerena,
$T_{j,np}$ - temperatura jezgre dobivena numeričkim proračunom,
$T_{j,mj}$ - temperatura jezgre izmjerena.

Apsolutna pogreška je:

$\Delta T_n = 49,69 - 49 = 0,69$ ºC
$\Delta T_j = 41,0 - 40,4 = 0,6$ ºC

gdje je:
T_n - temperatura namota,
T_j - temperatura jezgre.

The heating of the transformer occurs according to exponential function if transient phenomena are ignored between copper (aluminum) and the air, and if the transformer is viewed as a homogeneous body in which heat is generated. Temperature as a function of time is presented in Figures 7 and 8. It can be noted that the windings heat and reach steady state most rapidly. The core has a slower heating response, requiring a significantly longer period of time to reach steady state.

The precision of the results obtained by numerical calculation is confirmed by the results of experimental measurements, presented in Figures 9 and 10. By comparing the charts presented in Figures 7 and 8, which are the results of numerical calculations, and the charts presented in Figures 9 and 10, which are the results of experimental measurements, it can be noted that they are approximately identical, thereby providing justification for the introduction and development of such numerical calculations for practical purposes.

The percentage of error between the measured and calculated values for the three-phase air-core transformer is determined in the following manner:

The temperatures of the windings and core obtained by numerical calculation and measurement in steady state are as follows:

$T_{n,np}$ = 49,69 ºC,
$T_{n,mj}$ = 49 ºC,
$T_{j,np}$ = 41 ºC,
$T_{j,mj}$ = 40,4 ºC

where:

$T_{n,np}$ - winding temperature obtained by numerical calculation,
$T_{n,mj}$ - measured winding temperature,
$T_{j,np}$ - core temperature obtained by numerical calculation,
$T_{j,mj}$ - measured core temperature.

The absolute error is as follows:

$\Delta T_n = 49,69 - 49 = 0,69$ ºC
$\Delta T_j = 41,0 - 40,4 = 0,6$ ºC

where:
T_n - winding temperature,
T_j - core temperature.

Relativna – postotna pogreška je:

$$\partial T_{\mathrm{n}} = \frac{\Delta T_{\mathrm{n}}}{T_{\mathrm{mj}}} 100 = \frac{0,69}{49} 100 = 1,408\ \%,$$

$$\partial T_{\mathrm{j}} = \frac{\Delta T_{\mathrm{j}}}{T_{\mathrm{j}}} 100 = \frac{0,6}{40,4} 100 = 1,485\ \%,$$

gdje je:
T_{n} - temperatura namota,
T_{j} - temperatura jezgre,
T_{nj} - izmjerena temperatura.

Ovo je pogotovo praktično s ekonomske točke gledišta, budući da se na ovaj način, tj. primjenom adekvatnih programskih paketa (npr. FLUX2D, FLUX3D) može realizirati model bilo kojeg uređaja, pa i transformatora, i na taj način reducirati potreba za eksperimentalnim skupim mjerenjima i remontima.

The relative percentage error is as follows:

$$\partial T_{\mathrm{n}} = \frac{\Delta T_{\mathrm{n}}}{T_{\mathrm{mj}}} 100 = \frac{0,69}{49} 100 = 1,408\ \%,$$

$$\partial T_{\mathrm{j}} = \frac{\Delta T_{\mathrm{j}}}{T_{\mathrm{j}}} 100 = \frac{0,6}{40,4} 100 = 1,485\ \%,$$

where:
T_{n} - winding temperature,
T_{j} - core temperature,
T_{nj} - measured temperature.

This is particularly practical from the economic point of view since in this manner, i.e. by using suitable software programs (e.g. FLUX2D, FLUX3D) it is possible to devise a model of any device whatsoever, including a transformer, and in this way reduce the need for expensive experimental measurements and repairs.

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