NUMERICAL MODELING AND EXPERIMENTAL RESULTS OF HIGH CURRENTS DISMOUNTABLE CONTACTS

Ioan POPA
Ioan CAUTIL
Gheorghe MANOLEA
Florin OCOLEANU
University of Craiova
Electrical Apparatus Department
107 Decebal str., Craiova 200440, Romania
E-mail: ipopa@elth.ucv.ro

Dan FLORICAU
POLITEHNICA University of Bucharest
Faculty of Electrical Engineering
E-mail: df@conv.pub.ro
Serghie VLASE
Research Insitute ICMET, Craiova, Romania
Electrical Apparatus Laboratory
E-mail: vlase_serghie@yahoo.com

KEYWORDS

Numerical modeling, Coupled problems, Finite Volumes, Dismountable contacts.

ABSTRACT

The paper presents an electro-thermal numerical model which can be used for the modelling and optimization of high currents dismountable contacts for dc current. The model is obtained by coupling of the electrokinetic field problem with the thermal field problem. The coupling is carried out by the source term of the differential equation which describes the thermal field. The model allows the calculation of the space distribution of the electric quantities (electric potential, the gradient of potential and the current density) and of the thermal quantities (the temperature, the temperature gradient, the Joule losses and heat flow). A heating larger than that of the current lead appears in the contact zone, caused by the contact resistance. The additional heating, caused by the contact resistance, is simulated by an additional source injected on the surface of contact. Using the model, one can determine the optimal geometry of dismountable contact for an imposed limiting value of the temperature

INTRODUCTION

The optimization of the dismountable contacts (Figure 1) for high currents (500 – 4000 A), used in the design of electrical equipment in metal envelope, is possible by solving a coupled electrical and thermal problem. The dismountable contact of a system of bus bars has a non-uniform distribution of current density (Figure 2) on the cross-section of the current leads. The non-uniform distribution of the current density implies a non-uniform distribution of source term in the thermal conduction equation.

The distribution of the electric quantities can be obtained by solving of Laplace equation for electric potential. The solution of this equation depends on the temperature through electric conductivity. In its turn the electric conductivity influences the source term in the thermal conduction equation and thus the value and the distribution of the temperature of electrical contact.

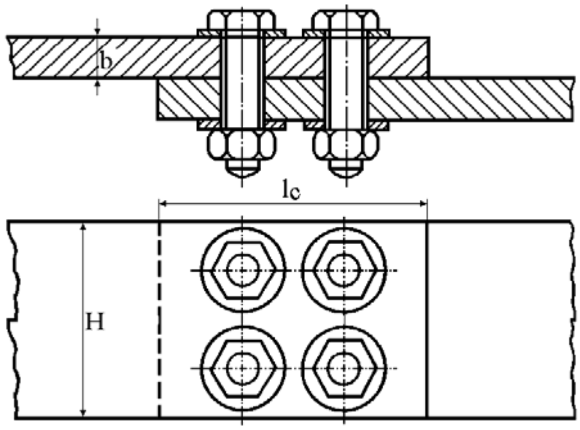

Figure 1: Typical Dismountable Contacts

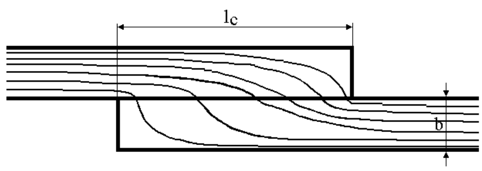

Figure 2: Current density distribution

Obtaining the correct distributions for the electric quantities (potential, intensity of the electric field, current density and losses by Joule effect) and thermic (the temperature, the gradient of temperature, density of the heat flow, the convection flow on the contact surface, etc) is possible by the coupling of the two problems, electric and thermal. The numerical model allows the calculation of the constriction resistance (caused by the variation of the cross section of the current lead).

MATHEMATICAL MODEL

The mathematical model used for obtaining the numerical model has two components, the electrical model and the thermal model, coupled by the electric conductivity, which varies according to the temperature, and the source term.

Proceedings 23rd European Conference on Modelling and Simulation ©ECMS Javier Otamendi, Andrzej Bargiela, José Luis Montes, Luis Miguel Doncel Pedrera (Editors)
ISBN: 978-0-9553018-8-9 / ISBN: 978-0-9553018-9-6 (CD)

Electrical Model

The electrical model is governed by a 2D model described by the Laplace equation for the electric potential

$$\frac{\partial}{\partial x}\left(\sigma(T)\frac{\partial V}{\partial x}\right)+\frac{\partial}{\partial y}\left(\sigma(T)\frac{\partial V}{\partial y}\right)=0 \quad (1)$$

where electric conductivity and thus the electrical resistance vary according to the temperature as

$$\rho(T)=\rho_{20}\left(1+\alpha_R(T-20)\right) \quad (2)$$

Knowing the electric potential, one can obtain the intensity of the electric field $\vec{E}=-\mathrm{grad}\,V$ and the current density $\vec{J}=\sigma\vec{E}$ (law of electric conduction).

The Joule losses (by the unit of volume) which represents the source term in the thermal conduction equation are calculated by the following relation

$$S(T)=\vec{J}\cdot\vec{E}=\rho(T)J^2=\sigma(T)E^2. \quad (3)$$

Thermal Model

The thermal model is governed by the thermal conduction equation in steady state

$$\frac{\partial}{\partial x}\left(\lambda(T)\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda(T)\frac{\partial T}{\partial y}\right)+S=0 \quad (4)$$

where λ - the thermal conductivity which is considered constant in the temperature range of the current lead (bellow $200\ ^{\mathrm{o}}\mathrm{C}$).

DOMAIN OF ANALYSIS AND BOUNDARY CONDITIONS

One considers a simplified analysis domain which is presented in Figure 3 and Figure 4 where one neglects the existence of the fastening bolts.

The boundary conditions of the electrical model are presented in Figure 3. In the general case, one knows the current I carrying the current lead and which determines a voltage drop V_1-V_2 . In this model, one initializes a voltage drop for which one calculates the current which corresponds to it (at each iteration) and then in a iteration loop one modifies the voltage drop to obtain the desired value of the current.

The current which passes any section of the current lead is calculated by the following relation

$$I=\int_S(\vec{J}\cdot\vec{n})\mathrm{d}S \quad (5)$$

where $\vec{n}$ - the normal at S which is the cross-section of the current lead.

The two assembled bars are considered sufficiently long to set, on the boundaries AB and CD (Figure 4) the boundary conditions of Neumann homogeneous type. If the length of segments AE and FD (375 mm) of Figure 4 is long enough the temperature distribution is uniform and consequently the temperature gradient is almost zero and the axial thermal flow is also zero.

On the other borders, one sets boundary conditions of the convection type, with a global heat exchange coefficient h (by convection and radiation, $h=14.5$ Wm^{-2} K^{-1}, increased by a coefficient that takes into acount the heat transfer through the side surfaces) to the environment having the temperature T_∞ (Popa et al. 2006a).

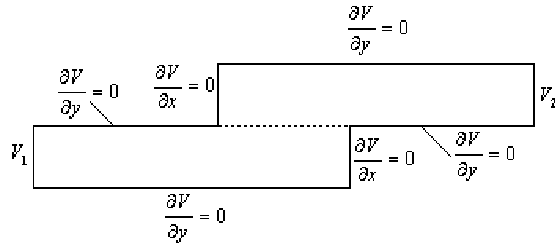

Figure 3: Analysis Domain and Boundary Conditions for Electrical Model.

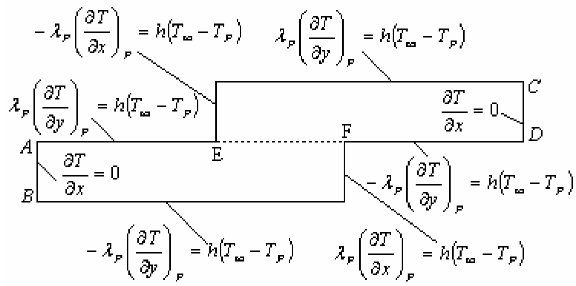

Figure 4: Analysis Domain and Boundary Conditions for Thermal Model
(AE = FD = 0.375 m, EF = 0.1 m).

NUMERICAL ALGORITHM

The numerical model is obtained by the discretization of the differential equations (1) and (4) by using the finite volumes method (Popa 2002). The coupled model is of alternate type (Meunier 2002) where the equations are solved separately and coupling is realized by the transfer of the data of one problem to the other. The two problems (electric and thermal) are integrated in the same source code and thus use the same mesh. The numerical algorithm is shown in Figure 5. The criterion of convergence of the coupled model was selected the value of the current, through the current lead, calculated using the relation (5). One used a mesh having 3787 nodes (with $\Delta x=\Delta y=1.66$ mm). The imposed percent relative error, for electrical and thermal models, was 10^{-7} and for coupled model was 10^{-5}. The convergence of the coupled model is very fast ($4\div 6$

iterations). If the error is reduced then the number of iterations increases but this is not necessary. The desired value of the current in contact is adjusted by varying the voltage drop on contact. The number of iterations for the electrical and thermal models decreases sharply with the stabilization of current.

The numerical validation of the model was made using a simplified analysis domain with a current lead with variable cross-section (Popa et al. 2006a), (Popa et al. 2006b). The numerical validation of the results of this simplified model was made by using the software QuickField Professional for the electrical and thermal models. One can see a very good agreement between our results and the results obtained using the QuickField software.

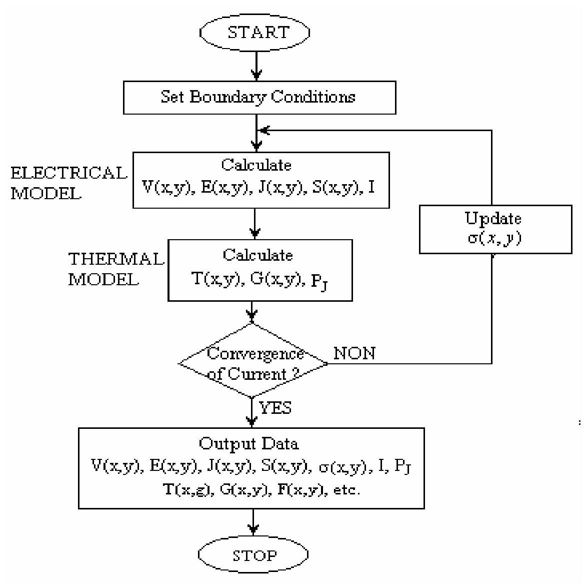

Figure 5: Simplified Diagram of Numerical Algorithm.

NUMERICAL RESULTS AND EXPERIMENTAL VALIDATION

The Figures 6, 7, 8, 9 and 10 present some numerical results. The dimensions of the analysis domain are those of Figure 4. The principal difficulty, in modelling and simulation the temperature distribution of a dismountable contact, is to take into account the resistance of contact (especially disturbance resistance). The contact resistance model is presented in the next paragraph. The optimization of the contact design supposes to determine the value of dimension l_c such that the maximum temperature, in the contact region, remains lower than the acceptable limiting value allowed by standards.

For the case presented ($l_c = 100$ mm and $I = 620$ A) the calculated losses by Joule effect with constriction resistance are 28.89 W, while calculated Joule losses without constriction resistance are 24.91 W. Varying overlapping length of the bars l_c (see Figure 1) the maximum contact temperature has a linear dependence with l_c (Popa et al. 2006b).

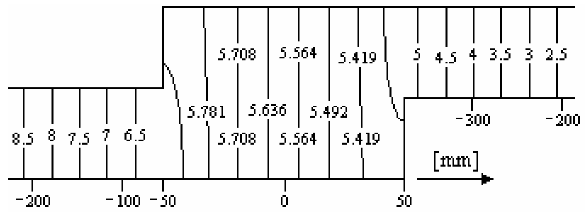

Figure 6: Potential Distribution in the Contact Region (in mV).

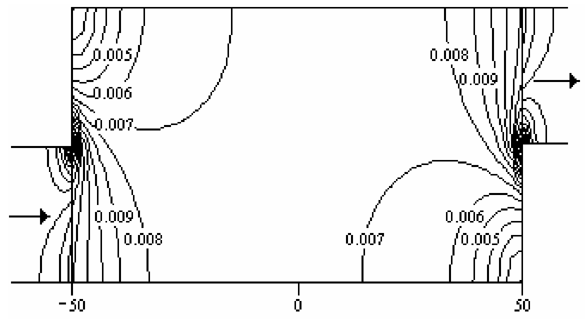

Figure 7: Electrical Field Distribution in the Contact Region (in V/m).

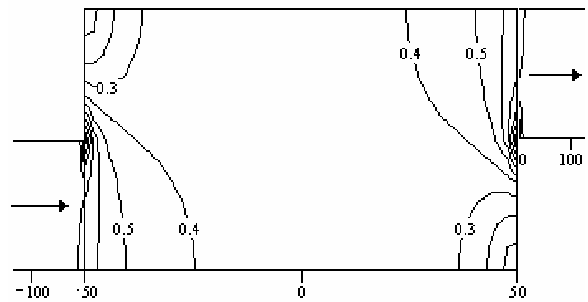

Figure 8: Current Density Distribution in the Contact Region (in A/mm^2).

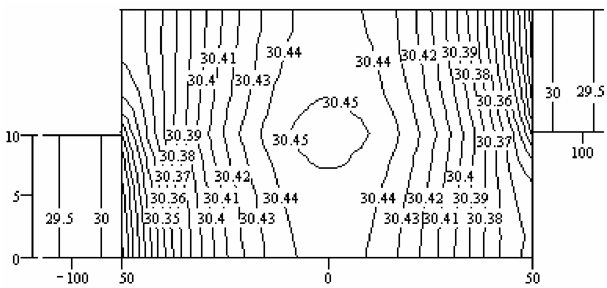

Figure 9: Temperature Distribution in the Contact Region (in ^{o}C).

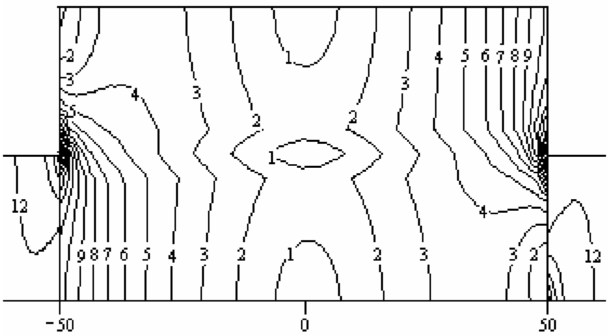

Figure 10: Gradient of Temperature in the Contact Region (in ^{o} C).

The experimental model and the measuring points are presented in Figure 11 (the measuring points are placed in the center of surface). The values measured in these points, using a digital thermometer with contact (Fluke 54 II) are shovn in Table 1. The numerical results for the thermal field, ilustrated in Figure 9, compared with the experimental results (see Table 1) show a good agreement. For exemple the error in the measurement point T_4 (in the center of the contact) is 2.13 %. The experimental data of Table 1 were measured for a tightening force of screws of $50\,\mathrm{N}$.

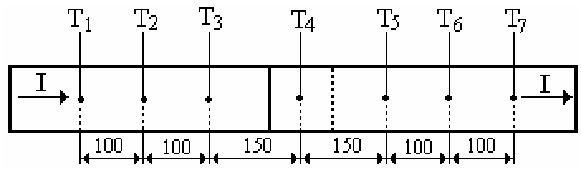

Figure 11: Points of Temperature Measurement.

Table 1: Experimental Results

Point	T_1	T_2	T_3	T_4	T_5	T_6	T_7
T [^{o}C]	29.3	29.3	29.4	29.8	29.4	29.3	29.3

For the considered contact geometry and the current of $I = 620\,\mathrm{A}$, the voltage drop measured between the limits AB and CD (see Figure 4) was $11.98\,\mathrm{mV}$, while the voltage drop controled to get the current imposed in the numerical model was $11.2\,\mathrm{mV}$.

The experimental results of Table 1 were obtained for the ambient temperature of 20.5 ^{o}C.

Figure 12 shows the thermal image of the contact zone obtained with the thermal camera. One can observe the scews areas which is colder. The scews help to cool the contact region by enlarging the surface of thermal eschange with surrouding environment.

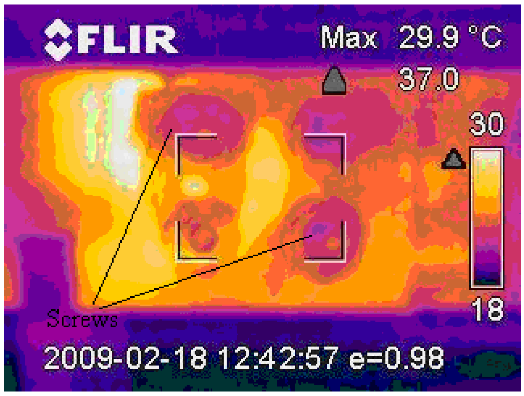

Figure 12: Thermal Image of the Contact Region

CONTACT RESISTANCE MODEL

The source term determined by the contact resistance is calculated by the following relation

$$S_c = \frac{R_c I^2}{(nc-1)\Delta x \Delta y\, H}, \qquad (6)$$

where Δx and Δy - the dimensions of the control volume, nc - the number of mesh points in the contact region (see Figure 13), H - the bus bar width (see Figure 1).

The contact resistance R_c is calculated with the following relation (Hortopan 1993)

$$R_c = \frac{\rho}{\pi a n} arctg \frac{\sqrt{d^2 - a^2}}{a} - 1.2 \frac{\rho \sqrt{d^2 - a^2}}{A_a} + \frac{R_{ss}}{n \pi a^2} \qquad (7)$$

where ρ - the electric resistivity, n - the number of contact points, A_a - the total area of contact (see Figure 14) and R_{ss} - the specific resistance of oxide film of contact point (in $\Omega\,\mathrm{m}^2$).

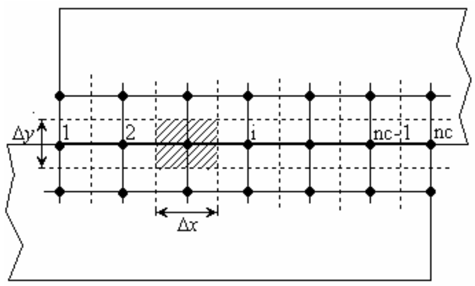

Figure 13: The Mesh in Contact Region

The radius of contact surface a is calculated from Holm's relation (Hortopan 1993)

$$a = \sqrt{\frac{F}{\pi n \xi H_d}}. \qquad (8)$$

where F - the tightening force, ξ - Prandtl coefficient,

H_d - material durity.

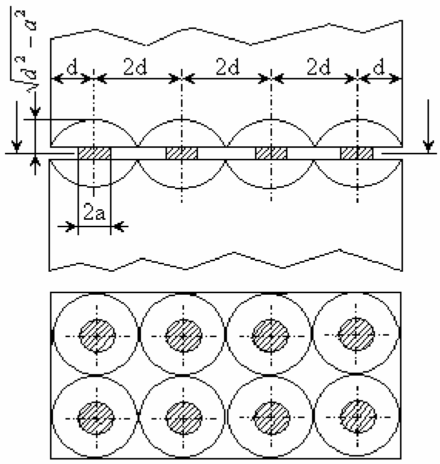

Figure 14: Physical Model of Contact Region

The relation (7) does not take into account the variation of contact resistance with temperature. To take it into account one can use the relation (Hortopan 1993)

$$R_c(T) = R_c(20)\left(1 + \frac{2}{3}\alpha_R (T - 20)\right) \qquad (9)$$

where α_R - the variation coefficient of electric resistivity with temperature, $R_c(20)$ - the contact resistance at $20\ ^{o}\mathrm{C}$.

The contact resistance model was implemented in numerical model of dismountable contact. For a constant value of the current ($I = 620\ \mathrm{A}$), varying the tightening force of the screws one can get the variation of the maximum temperature versus tightening force.

CONCLUSIONS

The created model can be used for the optimization of the current leads of high currents with variable cross-section, such as the dismountable contacts. The model allows the calculation of the constriction resistance of current lead, the constriction resistance of contact region and takes into account the specific resistance of oxide film of contact point which is an important component of the contact resistance.

Numerical model created allows evaluation of the maximum temperature in the contact area as a function of the tightening force of the dismountable contact.

An improvement of the model is possible taking into account the presence of the tightening screws and usage of the model of contact resistance moore precise as exemple the model given by Greenwood (Feng et al. 1998). The model is valid only for dc. In alternating current Equation (1) must be replaced by a magneto-dynamic equation.

REFERENCES

Popa, I. 2002. "*Modélisation numérique du transfert thermique. Méthode des volumes finis*", Edition Universitaria, Craiova,

Meunier, G. 2002. "*Electromagnétisme et problèmes couplés*", Hermes Science, Paris,

Popa, I., Cautil, I., and D. Floricau. 2006. "Modèle numérique électrothermique pour l'optimisation des contacts démontables de forts courants", *Annals of the University of Craiova – Electrical Engineering Series*, Year 30, Number 30, 330 - 333.

Popa, I., I. Cautil, D. Floricau. 2006. "Modeling and Optimization of High Currents Dismountable Contacts", *WSEAS Transaction on Power Systems,* Issue 9, Volume 1, 1641 - 1646.

Hortopan, Gh. 1993. *"Aparate electrice de comutaţie"* (in romanian), Editura Tehnică, Bucharest,

Schofy, S., J. Kindersberger, H Lobl. 2002. "Joint Resistance of Busbar-Joints with Randomly Rouggh Surfaces", *Procedings of 21th Conference on Electrical Contacts* (Zurich), 230 - 237.

Feng, Z., S.S. Babu, M.L. Santella, B.W. Riemer, J.E. Gould. 1998. "An Incrementally Coupled Electrical-Thermal-Mechanical Model for Resistance Spot Welding", *Procedings of 5th International Conference on Trends in Welding Research,* (Pine Mountain, GA, 1-5 June), 1 - 6.

ABOUT AUTHORS

IOAN POPA is a professor of Electrical Apparatus and Heat transfer modeling in electrical euipment at University of Craiova, Romania. He is an author of a few books and numerous articles on numerical modelling of the electric arc of high voltage breakers with SF_6 and nunerical modelling of heat transfer in electrical equipment. ipopa@elth.ucv.ro

IOAN CAUTIL is an associate professor in Computer Science at University of Craiova, Romania. He is an author of books and articles on Computer Programming and Control Systems Design and Simulation. His e-mail address is: icautil@elth.ucv.ro

GHEORGHE MANOLEA is a professor of Electrical drive and Basics of the creative research at University of Craiova, Romania, and head of the Center for Innovation and Technology Transfer CIIT Craiova.He is author of a books and numerous articles of electrical drive, control systems and technology transfer. His e-mail address is: ghmanolea@gmail.com

FLORIN OCOLEANU graduated by University of Craiova, Romania, with a degree in Electrical Engineering in 2005. He works at University of Craiova, Electrical Apparatus and Technologies Department. Since 2007 he is studying for the doctor degree at University of Craiova. His research area is connected with modeling, simulation and optimisation of electrical equipments. His e-mail address is: focoleanu@elth.ucv.ro

DAN FLORICĂU was born in Ilovat, Romania, in 1962. He received the B.SC. degree in Electrical Engineering from the University POLITEHNICA of Bucharest (UPB), Romania, in 1986 and the Ph.D. degree from UPB in 1996. Since 2001 he is full professor in static power converters. His research areas are multilevel converters, DPWM strategies for voltage source converters, PWM AC choppers, modeling and simulation of power electronics. He has published more than 100 publications in his research fields. His e-mail address is: dan.floricau@upb.ro.

SERGHIE VLASE is senior researcher in Medium Voltage Switchgear at Research, Development and Testing National Institute for Electrical Engineering of Craiova, Romania. He is author of papers in the field of Medium Voltage Switchgear. His e-mail address is: vlase_serghie@yahoo.com