INFOTEH-JAHORINA Vol. 16, March 2017.

Influence of Proximity Effect on Distribution of Electrical Current in Conductors of System for Deicing of River Sluices

Željko V. Despotović
University of Belgrade, Mihajlo Pupin Institute
Belgrade, Serbia
zeljko.despotovic@pupin.rs

Mladen V. Terzić
University of Belgrade, School of Electrical Engineering
Belgrade, Serbia
terzic@etf.rs

Abstract— **In practice, a lot of different techniques are used in deicing system of radial gate on the river sluice. One conventional method that is widely used is electrical heating. The electrical heating is performed with busbar electrical conductors which are incorporated in the sill of the radial gate. The very large electrical current (2÷20kA), at voltage 10÷15Vrms, 50Hz, which flows through conductors, heats the ice which is deposited on the sill. Because of large value of alternating current and proximity of conductors, uneven distribution of current density in cross section of conductors is obtained. In this paper, the distribution of electrical current for different configurations and interconnections between conductors are analyzed using Finite Element Method Magnetics (FEMM). In the analysis, a real disposition of the conductors is adopted, with Scott transformer connection (3x380V/2x12V, 50Hz) as an external power supply , which resembles the real heating system of sluice Stajićevo (Public Water Management Company "Vode Vojvodine", Novi Sad).**

Key words - Deicing system, radial gate, river sluice, heating, proximity effect, busbars, current density, FEMM

I. INTRODUCTION

Hydraulic structures, or water gates, barrages, sluices, navigation lock, roller gate, etc., which are used in civil and military purposes for control of water level in the rivers and watercourses, usually have a radial gate which can rotate about fixed axes and in that way control the amount of water in the upstream and downstream of watercourse. In many applications the radial gate is widely used in canal check structures to control canal flows and water levels [1].

In Fig.1 the disposition of a typical river sluice having the radial gate construction is shown. The radial gate is lifted by means of drive chains, mounted on the both sides of the gate and which are rolled up by an electric motor located at the command house. The radial gate is coated with rubber sealing from the outside which actually insures that flange during its movement actually glide over the sill of sluice. Very often this sill is called *radial gate sill*. Special electrical heaters that provide protection of sill and radial gate from icing and stacking together are usually inserted in this sill area. This is so called deicing function. The basic hydro-mechanical parameters of radial gate are: *PH*-pinion height, H_d - downstream depth and H_u -upstream depth and they are also given on Fig. 1. Problem with moving of the flange arises in ice days or months, when the ice accumulates on the flange or (and) the sill of sluice. Also, as detailed described in [2], the ice related problems at hydraulic structures are severe during winter months. Exposed mechanically operated systems, such as radial gates, may be frozen and become inoperable.

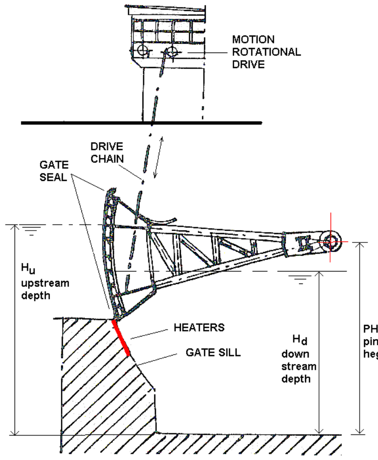


Figure 1. The typical disposition of radial gate structure with embedded heater panels

The weight of ice on the structures that need to be moved may become excessive, so that the lifting system and drive chain become overloaded. The ice loads can also cause structural damage. The ice buildup on sluice pier walls can obstruct the movement of the components of the sluice gate. Ice accumulation on water intakes, or hydropower plant, reduces the capacity of the water which has to pass through the intake, leading to water shortages or reduced power production. If the intake becomes completely blocked, it can cause structural damage. The ice buildup on walkways poses a safety hazard to personnel. All of these ice problems involve ice formation or adhesion to critical surfaces on hydraulic structures [2]-[4].

Based on the foregoing, it follows that the most critical part of the sluice and radial gate, when it comes to icing, is the gate sill. For this reason it is justified to embed the electrical heaters in flange and sill of gate, as shown in Fig.1. There are many techniques for deicing of the flange that are described in literature and implemented in practice [5]-[6]. Some of the widely used techniques are: conventional heaters, electrolysis, electro-expulsive and trash rack heater that are compared in

[3], and which relate to efficiency, performances and power (or energy) requirements. In this paper, heating of flange it is not considered but exclusively heating of gate sill with conventional heater panels composed with busbar system.

For conventional heater panel in riverine structures (immersed), the specific power requirement of 4.5÷6kW/m² [3] is sufficient for complete removal of ice from the structure. For example, if the dimensions of the heating field of the sill gate are 30m x 1.6m, required heating power is about 220÷300kW. It should be borne in mind, that the power of these heaters (which are immersed in water) must be obtained with a reduced AC voltage, typically 10÷15Vrms, 50Hz, for reasons of safety and protection against electric shock. Thus, for example, for a voltage of 12Vrms and for the power of 240kW is obtained that the value of electric current in the heaters is about 20kArms. It should be noted that the actual required electrical power is significantly lower (typically 20÷30kW) when the heating system is running on +2C°, since then the main goal is to prevent the formation of significant deposits of ice on the sill.

From the above mentioned reasons, the heaters must be implemented as a busbar, which is embedded in the sill of gate. The performance of the heating system is affected mainly by the effect of uneven current distribution in the busbar conductors because of their proximity and alternating current. This effect is related to the phenomena known as skin and proximity effects. These two effects cause the uneven distribution of current density in the cross section of each conductor and also between the conductors which results with the uneven heating of conductors in the system. This in turn causes the unequally melting of the ice which prolongs the time for the radial gate of sluice to become operable.

The aim of this paper is to show how the distribution of electrical currents in different configuration and interconnection of heater conductors influence the performance of the sill gate heating system. This is done through development of the mathematical model of electromagnetic phenomena and by solving it using finite element method (FEM). Using the results of FEM simulations, distribution of electrical current and power losses are shown for one typical heating system with the different interconnection of the busbar conductors. Power supply of the busbar system is modeled as the power Scott transformer, which is the same as in sluice Stajićevo (Public Water Management Company “Vode Vojvodine”, Novi Sad).

II. DESCRIPTION OF REALIZED HEATING SYSTEM

Electrical heating system is the first deicing technique that has been widely used and that’s why there are now many structures where it is implemented. Therefore, in this paper for the purpose of realistic analysis the one such real system of sluice *Stajićevo* (Public Water Management Company *“Vode Vojvodine”*, Novi Sad) is taken as an example. The place on the construction of the sluice, where the massive electrical conductors or heaters are inserted, is shown in Fig.2. They are placed in the lateral right and left sides of the structure wall, and also in the sill of the sluice.

The conductors in the side walls of the sluice construction are at relatively large distances, so that proximity effect is not significant. Also, these conductors have no influence on the distribution of current in the conductors that are inserted in the sill of the sluice. Significantly smaller distances between the heating conductors are in the sill of sluice. For these reasons the research in this paper is focused on the impacts of the proximity effect on the distribution of electrical current in the conductors which are inserted in the sill of sluice. Also, this paper discusses the layout and the mutual influence of these conductors.

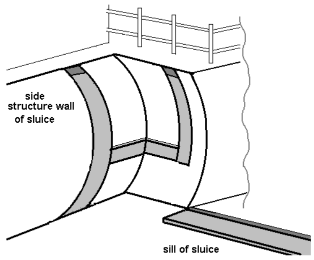


Figure 2. The typical disposition of electrical heaters on the side structure wall and the sill of sluice

A more detailed disposition of the arrangement of the heating conductors, i.e. high current rated busbars which are inserted in sill of sluice, is given in Fig.3.

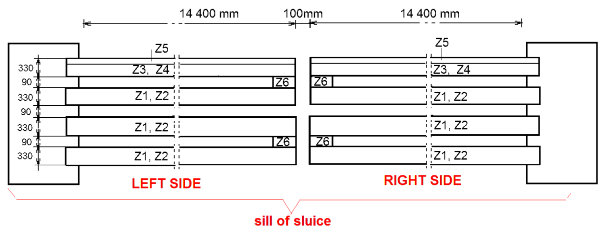


Figure 3. The detailed arrangement of busbars in the heating system on the left and the right side of the sill on the sluice Stajićevo

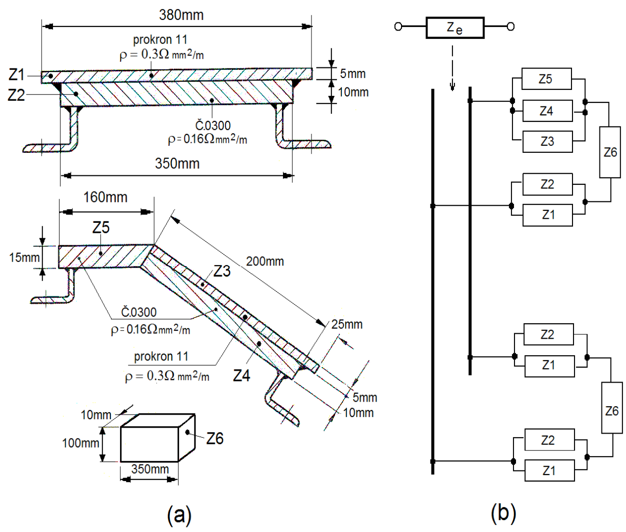


Figure 4. The detailed scope of busbars in the heating system of the sill on the sluice; (a) main dimensions of busbars, (b) equivalent electrical scheme of one half side of heating system of sill

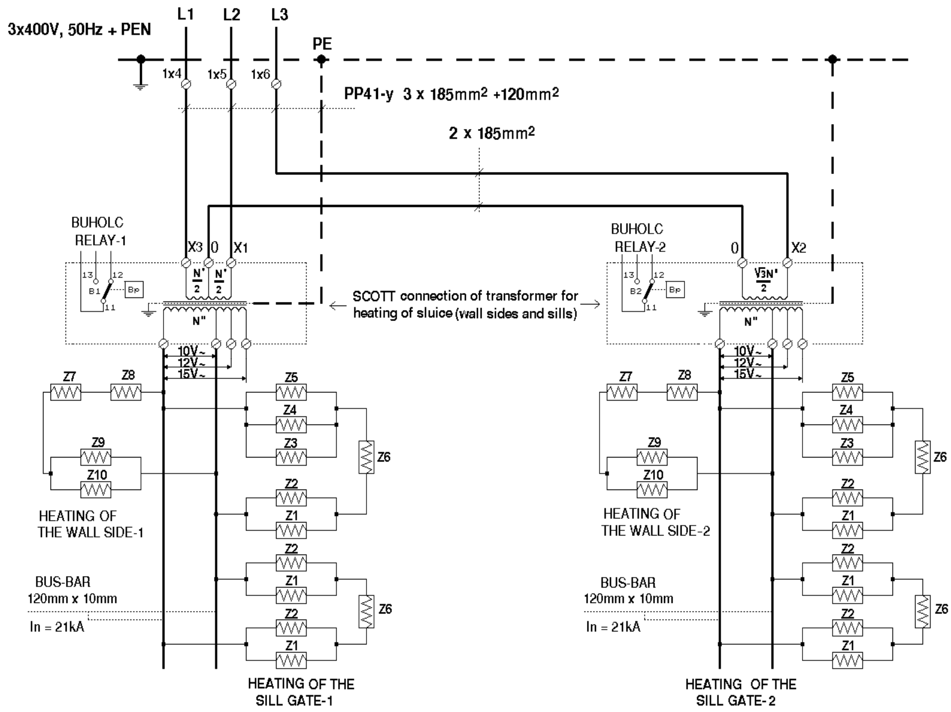


Figure 5. Electrical scheme of heating system of sluice Stajićevo

The heating system in the sill is symmetrical from the geometrical aspect and is divided in two parts. One part is on the left side and the other on the right side of sluice sill.

Detailed scope of the heating conductors and their electrical connections are shown in Fig.4. Detailed mechanical disposition of each conductor (busbar), cross section of each heating conductor Z_1-Z_6, and their geometric dimension are shown in Fig.4 (a). The equivalent electric scheme which corresponds to this arrangement is shown in Fig.4 (b).

Electrical scheme of power heating system and connection of the heaters, for sluice *Stajićevo*, are shown in Fig.5. As can be seen from this figure, the heaters are divided into four groups, two groups on the each side. Each group is supplied with AC voltage 10÷15Vrms, 50Hz (typically 12Vrms, 50Hz) that is taken from the secondary windings of the two transformers in Scott -T connection.

A Scott-T transformer (also called a Scott connection) is a type of circuit used to derive two-phase symmetrical power system from a symmetrical three-phase source or vice-versa. The Scott connection evenly distributes a balanced load between the phases of the source. The secondary windings of the two transformers are then connected to the two-phase circuit. The phase-to-neutral primary voltage is 90° out of phase with the phase-to-phase primary voltage, producing a two-phase voltage across the secondary windings [7]-[10].

III. FEMM MODEL OF BUSBAR SYSTEM

In order to perform comprehensive analysis of heating system on sluice *Stajićevo* and influence of the proximity and skin effect in conductors inserted in the sill, the Finite Element Analysis (FEA) are employed. The simulations were done in the software package FEMM, in which the calculation of the magnetic field is based on finite element method [11]-[14]. Model is built for the planar structure, i.e. cross-section of the conductors (busbars), which is fully justified, since the geometry is invariant along of the third dimension. The connection parts at the ends (Z_6, see Figs.3,4) between the busbars are neglected. To obtain the distribution of the electromagnetic field, 2D cross-section of the busbars system is divided into very small domains (finite elements) on which the equation for magnetic vector potential A is applied:

$$\nabla \times \left(\frac{1}{\mu(B)} \nabla \times A \right) = -\sigma \cdot A + J_{scr} - \sigma \cdot \nabla V \qquad (1)$$

Where are: ∇ - nabla operator, $\mu(B)$-magnetic permeability of materials, which depends on magnetic induction B (considering that the used materials are non-linear), J_{scr} - current density of electric source in the mesh element, σ- specific electric conductivity of used materials, ∇V - additional gradient of potential, which is constant across the whole cross section of conductive material (conductor), for a 2D problem.

The previous equation (1) is general and may be further simplified in the case of sinusoidal current source and the linear magnetic material.

The system of conductors (busbars) is powered by a controllable current source, whose value is adjusted so that the induced voltage at the ends of the busbars is equal to the nominal supply voltage. In addition, two sections of heating system are supplied from two power sources that are phase shifted by 90°. In this way, the real power supply from the secondary of Scott transformers is simulated, which resembles the real case [7]-[8].

The 2D geometry of busbars, which represents the simulation model, is shown in Fig. 6. The materials are modeled according to the data from the project design documentation of heating system in sluice *Stajiićevo* [15]. For carbon steel material the relative magnetic permeability is set to $\mu_{rcs} = 100$, while for the stainless steel is the value of $\mu_{rss} = 800$ is adopted [16]. As for the specific electrical resistance, the following values are taken: for carbon steel material $\rho_{ecs} = 0.16\Omega mm^2 / m$ and for stainless steel material $\rho_{ecs} = 0.3\Omega mm^2 / m$.

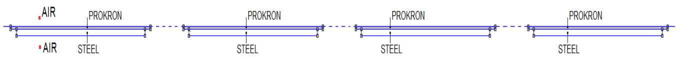


Figure 6. 2D Geometry of busbars in the sill of the sluice and assigned materials

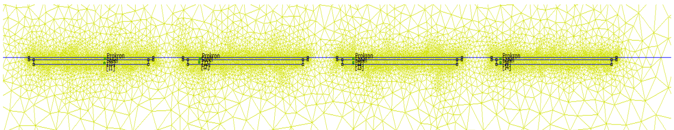


Figure 7. Generated finite element mesh for 2D geometry of busbars

Appearance of generated finite element mesh for 2D geometry is shown in Fig.7. As can be seen, finite element mesh is adapted for the geometry of the conductors, in order to model precisely the current distribution in them. Around the conductor system sufficiently large domain was adopted, so that its limitations do not significantly affect the distribution of the magnetic field, and thus the distribution of current density in the busbars. The boundary conditions at the edges of the surrounding domain of the bus system are modeled by the magnetic vector potential A, which is set to zero. The more convenient way of modeling the outside boundaries can be found in [13]. The boundary modeling which is adopted in this paper is taken because of it simplicity and still good modeling precision.

IV. Simulation Results

According to the disposition of the busbars in the heating system of sluice, which is shown in Figures 4 and 5, there are actually two cases of electrical connections (I, II) that are of interest for modeling, and they, were the basis for obtaining simulation results. Fig. 8 shows these two configurations of bus conductors with the associated power source of 12Vrms, 50Hz. Hereafter, these configurations are called busbar system I and II.

For the case of comparison of current distribution and losses, one more simulation is performed with the DC current supply.

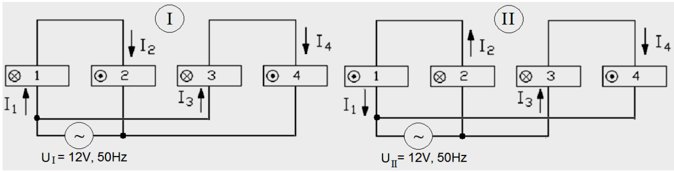


Figure 8. Two configurations (I,II) of the busbar system and AC power

The distribution of magnetic field of the busbar system (I) is given in Fig.9. For clarity of presentation the detailed current distribution in the same busbar system is given in the following.

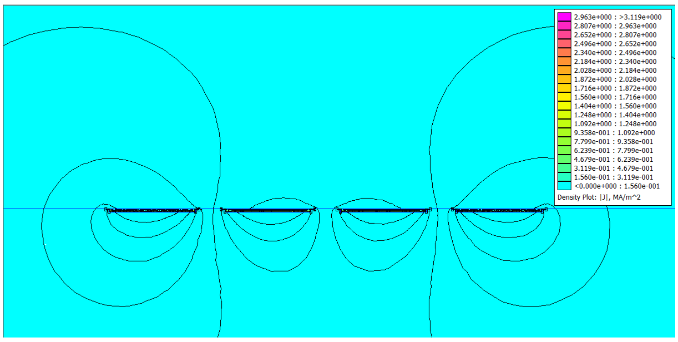
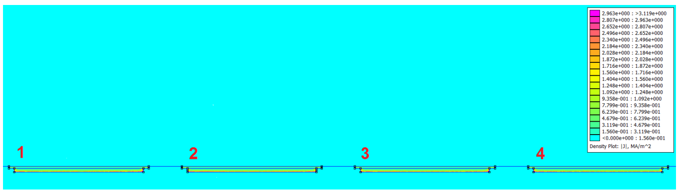
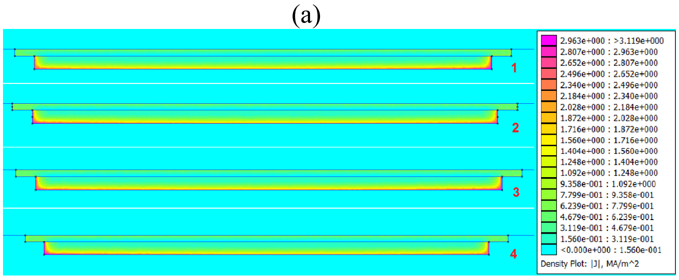


Figure 9. Distribution of magnetic field of busbar system I

The detailed distribution of the current density in the busbar system (I) is given in Fig.10. In Fig. 10 (a) current density distribution for the real disposition of the conductors is given. In order to show more clearly the current distribution in the individual conductors, each of them is enlarged and place on top of the other and presented in Fig. 10(b).



(a)



(b)

Figure 10. The electrical current distribution in busbar system I; (a) horizontal string, (b) detailed scope in vertical string

The distribution of magnetic field of busbar system (II) is given in Fig.11. For clarity of presentation the detailed current distribution in the same busbar system is given in the following.

The detailed distribution of the current density in the busbar system (I) is given in Fig.12. In Fig. 12 (a) current density distribution for the real disposition of the conductors is given. In order to show more clearly the current distribution in the individual conductors, each of them is enlarged and place on top of the other and presented in Fig. 12(b).

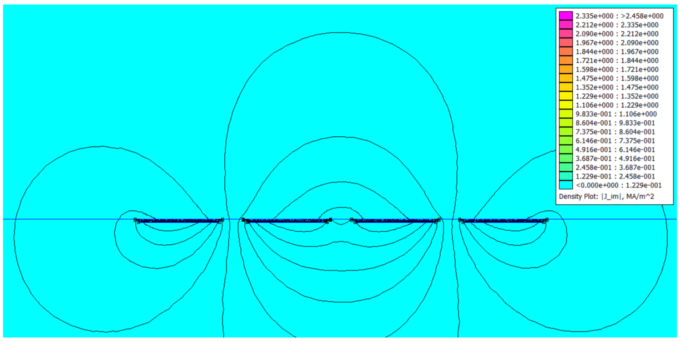
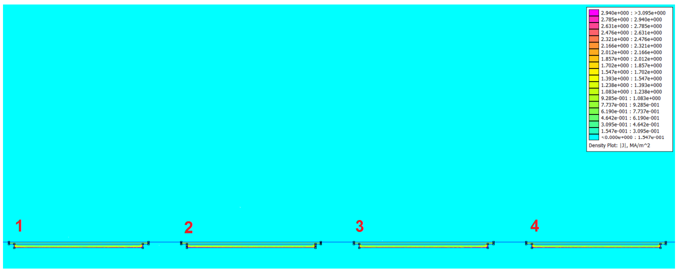
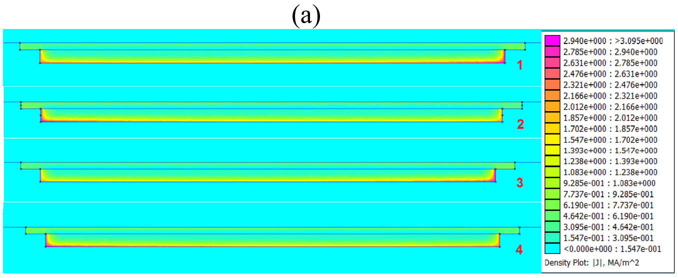


Figure 11. Distribution of magnetic field of busbar system II



(a)



(b)

Figure 12. The electrical current distribution in busbar system II; (a) horizontal string, (b) detailed scope in vertical string

The distribution of magnetic field of busbar system for DC power (12VDC) is given in Fig.13.

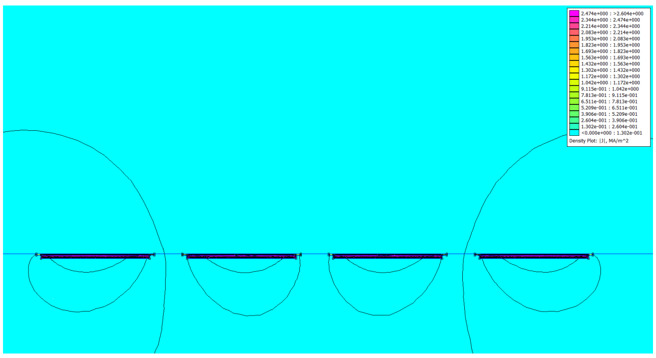
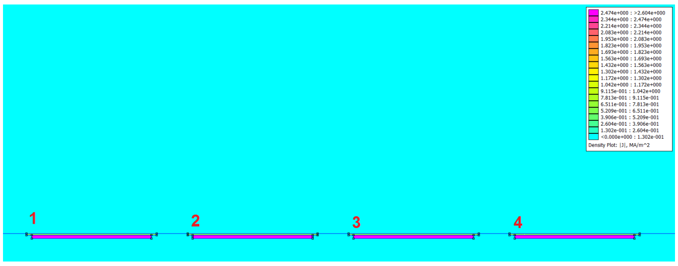


Figure 13. Distribution of magnetic field of busbar system for DC power

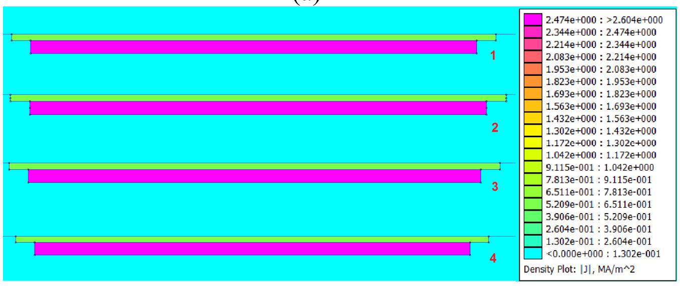
The detailed distribution of electrical current in the busbar system in case of DC power is given in Fig.14. In Fig. 14 (a) current density distribution for the real disposition of the conductors is given.

In order to show more clearly the current distribution in the individual conductors, each of them is enlarged and place on top of the other and presented in Fig. 14(b).

It is noticeable that the distribution of the current density in the busbars is uniform in this case, which is caused by the absence of inductive resistance, since it is a DC power supply. In this case there is only active Ohmic resistance.



(a)



(b)

Figure 14. The electrical current distribution in busbar system for DC power; (a) horizontal string, (b) detailed scope in vertical string

Table I presents the distribution of power losses in individual conductors of the heating system for the cases I, II (AC power) and in the case of DC power.

TABLE I. PRESENTATION OF POWER LOSSES BY INDIVIDUAL CONDUCTORS AND A SUMMARY OF THE CASES: (I), (II) AND FOR DC POWER

Conductor (busbar)	Connection (I)	Connection (II)	DC power
1	*4716.258*	4069.09	60999
2	4677.956	*4112.11*	60999
3	4671.579	4108.37	61011
4	4704.611	4058.54	61011
Total Active Power (W)	**18770.4**	**16348.1**	**244020**

As can be seen from the given results, significantly lower losses are in the case of AC power. This is due to smaller current, which is the consequence of higher equivalent impedance (which has its active and reactive part in AC case) when compared to the case of DC power (in this case there is only the active Ohmic resistance).

When comparing busbar systems I and II, it can be seen that the active power losses are smaller in the case II.

Fig.15 gives presents graphically the active power losses for the cases I and II (AC power). It should be noted that given results present losses for one half of the sill of sluice and that the total power loss is twice as large for case of the whole heating system: 37.54kW for case (I) and 32.70kW for case (II).

For DC power the total power losses are about 488kW.

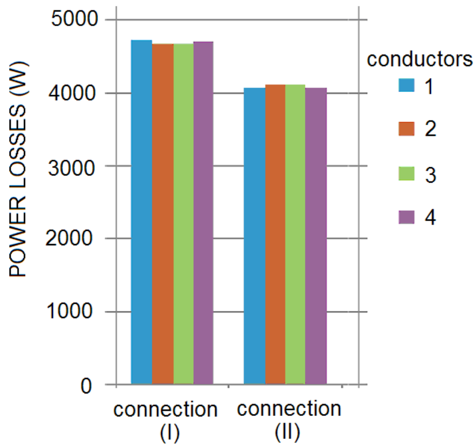


Figure 15. The detailed distribution of power losses in busbar system of sill heating for sluice Stajićevo; connections (I) and (II), and for each of conductors 1÷4.

V. Conclusions

This paper presents in detail the heating system of the sill of sluice *Stajićevo*. This system is of great importance, especially in the winter time when it comes to icing of radial gate and sill of the sluice.

In the paper, simulations of the distribution of magnetic field and electric current in the heating conductors (busbars) in FEMM software are performed, for three typical cases: two arrangements of busbars for AC power supply, and for DC power supply of the heating system.

The simulation results showed that significantly more active power is produced in conductors in the case of DC supply. DC power has an advantage in the event of deicing of great amount of ice that is already deposited on the sill of sluice, because it can develop a large amount of power.

AC power supply has significantly less power and it is useful in cases where it is of interest to prevent the deposition of large quantities of ice on the sill of sluice. In this case the activation of heating is carried out at temperatures slightly higher above 0°C. In this sense the AC power system proves to be more energy efficient and convenient for implementation.

By this paper, the authors made attempt to more accurately determine the distribution of electrical current and power losses in the conductors of the heating system by taking into account the pronounced proximity effect between the conductors as well as skin effect in the conductors themselves.

Acknowledgements

The investigation presented in this paper, has been carried out with the technical and financial supports of the *Serbian Ministry of Education and Science* - Project of technological development grant No: TR33022-“*Integrated system for flue gas cleansing and development of technologies for zero pollution power plants*”.

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