Eddy Currents inside Pipeline buried beneath HV Overhead Power Transmission System

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Abstract— **Conductive pipes for liquids and gas transportation are frequently buried in the ground, in vicinity of a high voltage three-phase overhead electric power delivery system. The heating of the pipe, due to eddy currents, is of crucial importance.**

In this paper investigation of heating effect is performed at a real problem. First of all it was determined which voltage level power transmission system produces the most significant eddy currents. After that a model of real zinc coated steel pipe was positioned in vicinity of electric system. For nominal currents in electric power delivery system, external magnetic field and eddy currents were calculated, together with power of heating losses inside the pipe's wall.

All calculations were performed numerically, applying COMSOL Multiphysics 3.5a computer program, for the worst pipe position and minimal height of power delivery conductors from the ground, at eight different frequencies, up to 450 Hz. The calculation results, magnetic field distribution, induced current distribution and frequency dependent heating power, are given graphically.

All calculated results show that, for investigated type of power delivery system, currents induced in the pipe's walls are negligible, except in case when the pipe is extremely closed to the power delivery system, which cannot happen in practice.

Keywords—Time varying magnetic field; current induced in pipe's wall; eddy currents losses

I. INTRODUCTION

Metal, conductive pipes for liquids or gas transportation are always placed at previously determined corridors, on the ground surface, above the ground surface or buried into the ground, on the depth defined by appropriate standards. In all those situations it might occur that pipe transportation system approaches or crosses the corridor of electric power transmission or distribution system. Time varying magnetic field, produced by time varying currents in electric system conductors, induces eddy currents in pipe's wall. As any current, those currents are followed by Joules losses and pipe heating, which may provoke even an accident if some inflammable materials are transporting.

For that reason it is very important to be well acquainted with impact of any electric system on neighboring system containing conductive elements.

Time varying magnetic field and eddy currents calculations for some of electrical transmission and distribution systems were performed and presented in [1] and [2], while its influence on all neighboring conductive elements was shown in [3].

Before the main calculations of magnetic flux density vector and eddy current distribution take place, it has to be predicted the electrical system voltage level which produces highest eddy currents. Considering line ending transformers' power, nominal currents inside the system's conductors is defined and magnetic field can be determined. Taking into account minimal standardized conductors' heights above the ground as well, it was concluded that the most critical situation can occur at 400kV transmission system. In this case magnetic field on the ground surface has maximal values, producing maximal induced electromotive forces and maximal current induced in the pipe's wall.

In order to determine and present an impact of overhead high voltage electrical power transmission system on conductive pipe, a real problem, with standardized zinc coated steel pipe, buried in the ground was investigated. The geometry of calculated problem is presented in Fig. 1.

All calculations will be performed for the worst pipe position related to the electric system; the pipe is buried on 1m depth, parallel to the electric system, exactly below the central conductor and for phase arrangement 0-4-8.

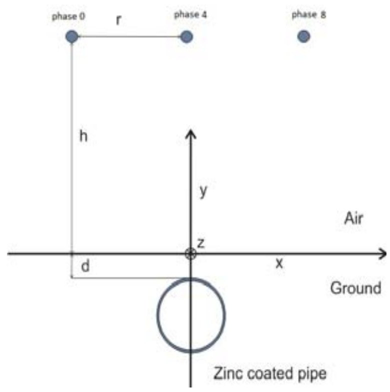

Figure 1. Geometry of investigated problem.

II. Theoretical Approach

Supposing that all currents inside three-phase system conductors are harmonic and that the entire system is linear, complex analysis can be applied. Actually, steel pipe is not linear material, but it can be taken as linear, with relative permeability much higher than 1, not dependent on magnitude of complex magnetic flux density vector. As a matter of fact it can be expected that magnetic field inside the pipe's wall has very low magnitude and for this reason the pipe's permeability can be treated as initial static or initial dynamic, but constant value.

The calculation starts from well known partial differential equation in complex domain involving complex magnetic vector potential [4], [5],

$$\Delta\underline{\vec{A}} - j\omega\mu\sigma\,\underline{\vec{A}} = -\mu\,\underline{\vec{J}}\,. \qquad (1)$$

In chosen Cartesian coordinate system, presented in Fig. 1, for imposed complex current density vector having only z component, the above equation can be written as,

$$\frac{\partial^2 \underline{A}_z}{\partial x^2} + \frac{\partial^2 \underline{A}_z}{\partial y^2} - j\omega\mu\sigma \underline{A}_z = -\mu \underline{J}_z\,. \qquad (2)$$

Z component of complex magnetic vector potential defines z component of complex induced electric field strength vector,

$$\underline{E}_{indz}(x,y) = -j\omega \underline{A}_z(x,y)\,, \qquad (3)$$

and z component of complex induced current density vector (complex eddy current density vector),

$$\underline{J}_z(x,y) = \sigma \underline{E}_{indz}(x,y)\,. \qquad (4)$$

Power of Joules' losses inside pipe's wall is defined per kilometer of the pipe's length and calculated as an integral over the pipe's wall cross section, S_{pwcs},

$$P_J' = \int_{Spwcs} \frac{\left|\underline{J}_z(x,y)\right|^2}{\sigma} dS\,. \qquad (5)$$

III. Model

As said in introduction, the most intensive eddy currents will appear in the pipes buried in vicinity of 400kV high voltage overhead transmission line. For that reason in this paper a real problem was investigated. Below a real power transmission line, with characteristics defined in [6], 1m below the earth surface, real zinc coated steel pipe, with Φ 1020mm (40″) and the wall thickness 8.2mm is buried, as shown in Fig. 1.

All calculations were carried out for minimal conductor's height allowed by Serbian standards; 7.5m (+40˚C or -5˚C plus due to weight of ice on conductors).

It should be mentioned that, according Serbian standard SRPS N.CO.105:1987, the conductive pipe cannot be placed so close to HV power delivery system, especially not beneath the system, parallel to the system conductors. Nevertheless, the problem presented in Fig. 1 was investigated, in order to become sure that higher values of heating losses could not appear in practice.

In all calculations, exploring the real case, the RMS modulus of complex current in each conductor of the symmetric three-phase power delivery system was supposed to be the nominal one, $|\underline{I}|$=430A for the power transformer's nominal power of 300MVA.

Several different pipe positions related to electric system were investigated, but only the worst pipe's position results, are presented in this paper.

Other relevant values, taken into consideration in entire calculations are as follows: The phase arrangement in electrical system is (0-4-8), the distance between the nearest conductor and pipe's surface is 8.5m, ground resistivity is 50Ωm and relative permeability of steel pipe is, μ_r=4000.

Moreover, in order to explore the behavior of the problem even in the case when higher current harmonics are present as well, the calculation was performed for eight chosen frequencies; 0.01Hz, 16⅔Hz, 50Hz, 100Hz, 150Hz, 250Hz, 350Hz and 450Hz.

All calculations were carried out applying COMSOL Multiphysics 3.5a computer program package [7], based on finite elements method.

IV. Obtained Results

The magnetic flux density distribution, produced by a HV overhead electric power transmission system, along y-axis, in a case of steel pipe buried in the ground, for the pipe positioned as presented in Fig. 1, at 50 Hz, is shown in Fig. 2.

The diagram shown in Fig. 2 has an expected shape. Due to low frequency and smaller influence of induced currents on magnetic field distribution, magnetic flux density vector magnitude is practically equal in the entire pipe's wall cross-section. From Fig. 2 it can be noticed that the magnitude is a little higher in the pipe's wall closer to ground surface, at y = -1m, compared to the part of pipe's wall the most distant from earth surface, y = -2m. Inside the pipe magnetic flux density vector magnitude is negligible, due to shielding effect of ferromagnetic pipe.

For the same model, magnetic flux density vector magnitude distribution at 450Hz is presented in Fig. 3.

The shape of magnetic field distribution inside the ground, at 450Hz, shown in Fig. 3, differs from previous case. Magnetic flux density vector magnitude is much higher in the pipe's wall part closer to the earth surface. Higher frequency produces higher induced currents and its more significant impact on both magnetic field and eddy current distribution. Currents induced in the closer pipe's wall part produce magnetic field which decrease magnetic field in distant pipe's wall parts, acting as an electromagnetic shield.

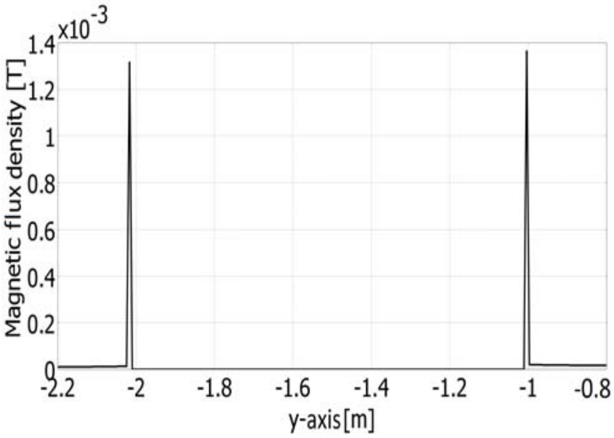

Figure 2. Magnetic flux density distribution along y-axis, at 50Hz.

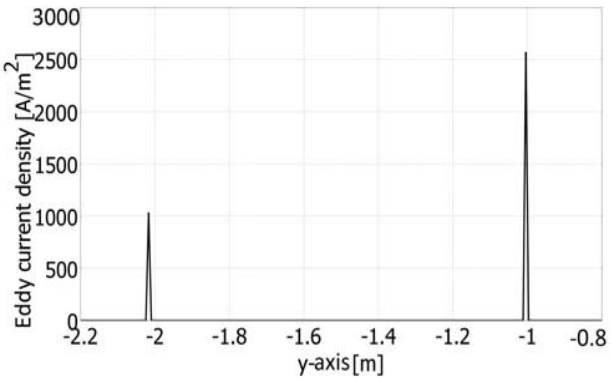

Figure 4. Induced currents density distribution along y-axis, at 50Hz.

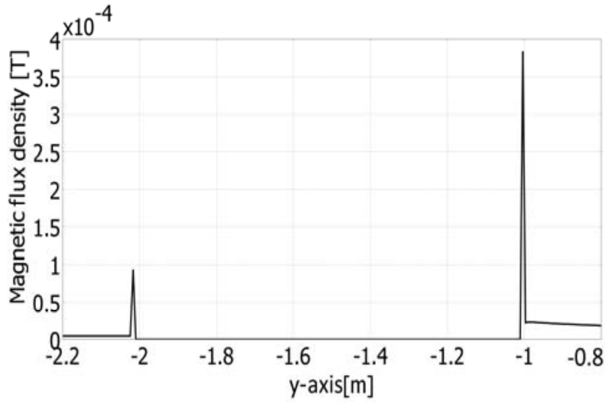

Figure 3. Magnetic flux density distribution along y-axis, at 450Hz.

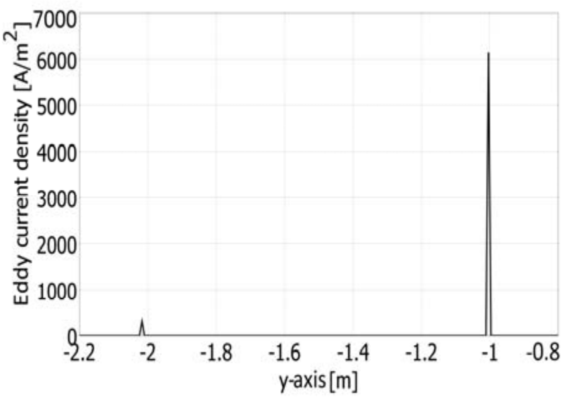

Figure 5. Induced currents density distribution along y-axis, at 450Hz.

Time varying magnetic field, produced by currents in electrical system conductors, provokes induced electromotive force, which cause the motion of free charges inside pipe's wall, forming induced currents (eddy currents).

Induced current density vector magnitude distribution inside pipe's wall, along y-axis, at 50 Hz, is shown in Fig. 4.

Similar to the magnetic field distribution, induced currents at 50Hz have smaller value and less significant effect on magnetic field distribution. Currents induced in pipe parts closer to the earth surface (y = - 1m) are stronger and produce magnetic field which decreases total magnetic field dipper in the ground. This effect can be noticed in Fig. 3, showing smaller magnetic flux density vector magnitude at y = - 2m and consequently smaller value of eddy currents.

Induced current density vector magnitude distribution at 450Hz is shown in Fig. 5.

Due to higher frequency and more significant shielding effect, smaller magnetic field in the pipe's parts dipper in the ground, which can be noticed in Fig. 3, produces almost negligible eddy currents in a pipe's wall parts at y = - 2m, presented in Fig. 5.

As said in introduction, part of electrical transmission system energy through induced electric field and induced currents in pipe's wall, will transform to thermal energy inside the pipe's wall. Considering thorough energy transmitting by electrical power delivery system, this loss of energy is negligible. Nevertheless, due to the thermal energy, pipe temperature may increase, which can be significant especially in the cases of inflammable material transportation inside the pipe. In that case, even a fire brake out or an explosion can occur.

For that reason the knowledge of Joules' losses power, defined by (5), is very important. As emphasized before, this power is determined per kilometer of pipe's length and its dependence on frequency is presented in Fig. 6.

At industrial frequency, f=50Hz, the Joules' losses power per kilometre of pipe's length are,

$$P'_{J\,50Hz} = 51W / km \,.$$

At the highest examined frequency, f=450Hz, the Joules' losses power per kilometre of pipe's length are,

$$P'_{J\,450Hz} = 131W / km \,.$$

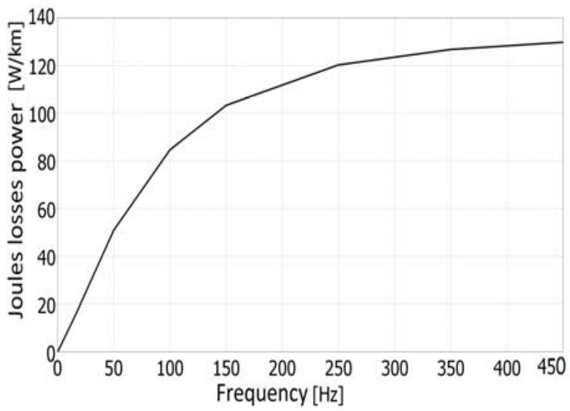

Figure 6. Frequency dependent eddy currents losses power inside pipe's wall, per kilometer.

Obviously, even in the worst case which can not appear in practice, Joules' losses power is insufficient to produce a significant heating of the fluid inside the pipe.

V. CONCLUSION

Prior to all calculations, the worst case had to be defined. Investigating magnetic field, produced by overhead high voltage three-phase power delivery systems, with nominal system currents, at the earth surface, the transmission system at 400kV was determined as the most significant one.

After that, we started with magnetic field calculations, in electrical system vicinity and eddy currents inside the buried zinc coated pipe's wall determination. Several different positions of electrical system and pipe were explored but in this paper only the worst case was presented. The entire calculation has been repeated for 8 different frequencies, up to 450Hz, in order to take into account possible presence of higher current harmonics.

The calculation results were as expected. Even in the worst case, which, according to existing standards, can not appear in practice, calculated Joules' losses power is not sufficient to provoke significant heating of the pipe, nor of fluid transporting inside the pipe.

Nevertheless Serbian standard, SRPS N.C0.105:1987, suggests that, if there is a need for crossing of two systems, the pipe system should be positioned orthogonal to the electrical system's conductors. In that case the currents induced in pipe's wall are minimal and the fluid heating is minimal as well.

The problem was successfully resolved applying COMSOL Multiphysics 3.5a computer package. For all calculations the AC/DC Module was applied, together with materials library data.

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