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Electromagnetic Interference Caused by Iraqi 400kV Transmission Lines on Buried Oil Pipelines

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Abstract

The electromagnetic interference caused by power transmission lines to oil and gas buried pipelines is under investigation for many years. Especially during fault conditions, large currents and voltages are induced on the pipelines that may pose danger to working personnel or may accelerate the corrosion of the pipeline's metal. In this research, the Joule effect of eddy currents induced in the oil buried pipelines due to the magnetic fields produced by nearby 400kV transmission lines in the South of Iraq have been computed. A computational model based on 2D finite element approach to calculate the heat generation rate. The influence of different earth resistivities for homogeneous earth model during steady state and fault conditions is analyzed. A mitigation system using mitigation wires has been simulated to reduce induced eddy current heating effects to the safety limit.

Keywords: Electromagnetic interference, finite element method, pipelines, eddy current.

التداخلات الكهرومغناطيسية المتسببة بواسطة خطوط نقل الطاقة العراقية 400 kV على خطوط انابيب النفط المدفونة

الخلاصة

تخضع التداخلات الكهرومغناطيسية المتولدة من خطوط نقل الطاقة على خطوط انابيب النفط والغاز والممتدة تحت الارض للبحث منذ عدة سنوات. خصوصا اثناء ظروف الاعطال حيث تتسبب هذه التداخلات في توليد تيارات وفولتيات كبيرة مستحثة على خطوط الانابيب التي قد تشكل خطر لتشغيل العاملين او قد تعجل من تآكل معدن خط الأنابيب. سيتم في هذا البحث حساب الأثر الحراري للتيارات الدوامية المحتثة بسبب المجالات المغناطيسية المتولدة من خطوط نقل الطاقة ذات 400Vk في جنوب العراق على خطوط انابيب النفط القريبة والممتدة تحت الارض. لقد استخدم نموذج حسابي مستند على نظرية العنصر المحدود ثنائي البعد في حساب المعدل الحراري المتولد. تم تحليل تأثير مختلف المقاومات النوعية لنموذج متجانس للارض اثناء الظروف العادية وفي حالة وجود عطل.وهذا يتطلب القيام بأجراءات وقائية للحد والتقليل من تأثيرات الأثر الحراري للتيارات الدوامية المحتثة بما يتوافق مع حدود الامان.

1. Introduction

AC interference in a pipeline sharing a corridor with a power line consists of an inductive component and a conductive component. Inductive interference, which is occurred by the magnetic field generated by the power line, is present during both normal load conditions and fault conditions on the power line. Conductive interference arises when a power line structure injects a large magnitude current into the earth during a single-phase to-ground fault and the pipeline is located near the faulted structure.

Initially, the attempts to develop a suitable calculation method for this interference were based on the

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Carson's relations [1] or similar improved ones [2]. With the advances computer technology, more sophisticated models were adopted, leading to more accurate methods of calculation [3], that may be used to solve complex problems. A general guide on the subject was issued later by CIGRE [4], while CEOCOR [5] published a report focusing on the AC corrosion of pipelines due to the influence of power lines. More recently, a hybrid method utilizing the finite element method and circuit theory was introduced [6].

This paper deals with the finite element based optimal design of a real situation encountered in the Iraq 400kV transmission system is presented. The paper gives valuable information about the interaction between three phase power transmission lines and a buried oil pipeline sharing a complex right-of-way. Previous published works and reports have a lack of comprehensive study on the effect of induced eddy currents on the coating pipeline. So This work is also an attempt to provide precise knowledge about heat by means of Joule effect of eddy currents induced on pipeline.

2. Case Study

The system under investigation is shared by the NSRP – KAZG 400 kV transmission line between Nassiriyah and Khor AL-Zuber power plants in the South of Iraq and a nearby oil pipeline, operated by the South oil Company. Where oil pipeline is running parallel with power transmission line for about 30 km and it is separated by 250 m, a typical system shown in Figure 1 has been modeled and studied in this work.

The NSRP – KAZG transmission line is a single circuit, with 2-bundle conductors per phase, mounted in horizontal configuration on a lattice steel structure. Tables (1 and 2) [7], list the physical characteristics of the transmission line phase conductors as well as ground wire conductors such as sectional area, overall diameter.

The pipeline under study is buried so that its center is 1 m below the Earth’s surface. Table (3) lists the characteristics for the buried pipeline such as radius, wall thickness, length, coating thickness.

Concerning the material properties, the earth is assumed to be homogeneous with a varying soil resistivity corresponding to sandstone, sandy, clay or a combination of these. Furthermore different separation distance d from the centerline to the pipeline is used throughout the study.

3. Formulation of the Problem

The formulation and the calculation method for the electromagnetic interference on a pipeline is based on finite element method. The required input data for the method are the geometrical configurations of power lines and pipeline, the physical characteristics of the conductors, the earth and the pipeline and loading of the power lines.

A system of N infinitely long conductors, carrying rms currents I_i , $i=1,2,\ldots,N$, over imperfect earth is considered. Taking into account that the cross section of the system under investigation, as shown in Figure 1, lies on the x - y plane. The following system of equations describes the linear 2-D electromagnetic diffusion problem for the z -direction components $\overline{A}_z$ of the magnetic vector potential (MVP) and $\overline{J}_z$ of the total current density vector [8] are:

$$\frac{1}{\mu_o \mu_r}\left[\frac{\partial^2 \overline{A}_z}{\partial x^2}+\frac{\partial^2 \overline{A}_z}{\partial y^2}\right]-j\omega\sigma\overline{A}_z+\overline{J}_{sz}=0 \qquad (1a)$$

$$-j\omega\sigma\overline{A}_z+\overline{J}_{sz}=\overline{J}_{sz} \qquad (1b)$$

$$\iint_{Si}\overline{J}_z dS=\overline{I}_i, i=1,2,...,N \qquad (1c)$$

Where
σ the conductivity
μ_o the permeability of vacuum;
μ_r the relative permeability;
ω the angular frequency;
$\overline{J}_{sz}$ the *z*- direction component of the uniformly distributed source current density;
$\overline{I}_i$ the rms value current flowing through conductor.

It is shown in [9] that the finite element formulation of (1) leads to a matrix equation. Using the solution of this matrix equation, the MVP values in every node of the discretization domain, as well as the *N* unknown source current densities of the *N* current-carrying conductors, are calculated. Therefore, for a random element, the eddy-current density $\overline{J}^e_{ez}$ is calculated using the relation

$$\overline{J}^e_{ez}(x,y)=-j\omega\sigma\overline{A}^e_z(x,y) \qquad (2a)$$

and the total element current density $\overline{J}^e_z$ which is the sum of the conductor-*i* source current density $\overline{J}_{szi}$ and of the element eddy current density $\overline{J}^e_{ez}$ of (2a), is obtained by

$$\overline{J}^e_z(x,y)=\overline{J}^e_{ez}(x,y)+\overline{J}_{szi} \qquad (2b)$$

Integrating (2b) over a conductor cross section, the total current flowing through this conductor is obtained.

Assuming a zero Dirichlet boundary far away from the system that encloses all the currents flowing in the system, a square with l0km side is set as the total solution domain for the problem. A local error estimator, based on the discontinuity of the instantaneous tangential components of the magnetic field, has been chosen as in [10] for an iteratively adaptive mesh generation.

Joule heat is computed by elements using the vector potential method if the element has a nonzero resistivity and a nonzero current density. It is available as the output power loss. Power losses are caused by eddy currents induced by an oscillating leakage magnetic field.

The eddy current power loss (P_{le}) in a conductor with conductivity (σ) is calculated as:

$$P_{le}=\frac{1}{2\sigma}\int\left(J_{tr}{}^2+J_{ti}{}^2\right)dV \qquad (3)$$

where P_{le}= eddy current loss (W) for an axisymmetric model or (W/m) for a planar 2-D model
J_{tr} , J_{ti} = total current density real and imaginary components of total current density (A/m^2) and
V = Volume of conductor under consideration (m^3).

4. Simulation results and discussion

The case study has been modeled and simulated by using ANSYS software (Revision 11) to calculate the Joule effect of eddy currents induced in the concerned pipelines due to inductive interferences during both steady-state and transient conditions.

A. Steady-State Condition

The rights-of-way of 400KV NSRP – KAZG transmission system are modeled under worst-case steady-state conditions, with a maximum current of 2000 A per phase.

Analysis is presented to show the effect of changing soil resistivity (from 10Ωm to 1000Ωm), and the horizontal distance between overhead transmission line and the pipeline on the magnitude and distribution of magnetic flux density vector B in the pipeline as shown in Figures(2-4). It is clear that the non-uniformly distribution of the flux vectors appear where high field region at pipeline center. The maximum value of contrast increases with increasing the soil resistivity. Furthermore, the magnetic field in the metallic pipeline decreases with increasing the horizontal distance from centerline where the soil resistivity is assumed constant.

Further analysis is observed the effects of the inductive interference and the eddy currents induced in buried pipeline. Table 4 presents values of the eddy currents induced in the pipeline during worst case at steady state conditions, (no special mitigation is installed).

Comparing the results shown in Table 4, it can be concluded that the pipeline induced eddy currents increase with increasing the soil resistivity and decrease with increasing the separation distance d(m).

A subdomain of the metallic pipeline was affected by the Joule effect of eddy currents induced in this pipeline as shown in Figure 5.

The contours presented in Figure 5 show the details of non-uniformly distribution of Joules heat per unit length for different values of separation distance and soil resistivity.

B. Transient Condition

Single line-to-ground fault has been simulated at 10% intervals inside the zone of influence. The value of fault currents are taken as I_A= 2000A (assumed fault occurring at phase A) and $I_B = I_C = 0$A.

Magnetic flux density vector B in the pipeline during fault inside the zone of influence is shown in Figures (6-8) for various soil resistivity and separation distances. It is clear that magnitude of magnetic field is much higher as compared with normal operation.

Table 5 shows the eddy currents induced in buried pipeline in case of phase to ground fault; it can be observed that the pipeline induced eddy currents increase with increasing soil resistivity. From this table it is noticed also that pipeline induced eddy current decreases rapidly up to 1km after a maximum value at 100m when the fault at phase A (the nearest conductor to the pipeline). Figure 9 shows maximum Joule effect of induced eddy currents is obtained at the midpoint of the zone of metallic pipeline.

Based on the modeling results, the maximum allowable Joules heat per unit length exceed the maximum safe limits at transient conditions in high soil resistivity and therefore mitigation is required according to the Iraqi South Oil Company (refer to the IEC Standard) and IEEE Std 844-2000 [11].

5. Mitigation of Electromagnetic Interference Effects

Methods for mitigation the electromagnetic interference in the design stage are avoiding longer parallel running of the pipeline and the power transmission lines. Various techniques have been developed to mitigate induced currents on buried pipelines, such as lumped grounding, cancellation wire, insulating joints. The most popular and cost effective mitigation technique of mitigation induced currents on pipelines is a gradient control wire. A gradient wire is a wire that is placed in the ground next to the pipeline and it is connected to the pipeline at certain intervals [12]. Figure 1(c) shows a typical gradient control wire installation.

In the case of transient state analysis of the pipeline in this research, there is one high level of induced eddy current and its joule heat effect (at distance d 100m) that exceeds the values allowed by the standard [11]. Modeling shows that these values can be mitigated by increasing the distance between the pipeline and the power transmission line as much as possible. Further modeling showed that the proposed installations of gradient control wires successfully mitigated these values. Table 6 show the modeling results for the case study after installing the proposed gradient control wires. It is clear that the eddy current Joule heat effect (at soil resistivity 1000Ω.m) have been reduced to 112.03W/m, which is far below the safe Joule heat limit (150W/m).

6. Conclusions

This research covered the basis of electromagnetic field interference theory, and it illustrated an actual comprehensive local case-study. Thus, it is modeled, evaluated, and analyzed using a well-known software program.

The study revealed that the maximum induced eddy currents on buried pipeline during the steady state condition is within the standard limit. However, the resulting induced eddy currents and its joule heat effects during the short circuit condition exceed the safety limits within international standards such as IEC standard and IEEE Std 844-2000.

A proposed mitigation system using gradient control wire has been simulated and it significantly reduced induced Joule heats on the pipeline to the standard's safe limits.

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Table (1) Physical Characteristic of Transmission Line Phase Conductors

Parameter	Data
Type	Twin ACSR
Number &radius of aluminum wires	54/1.7 No/mm
Number &radius of steel wires	7/1.7 No/mm
Total area	553.83 mm^2
Overall diameter	30.60 mm
Mass(without grease)	1852 Kg/km
Maximum tension	30570 N
Maximum sag	3.7 m
Minimum clearance	4.9 m
DC resistance at 20^o C	0.05896 Ω/Km

Table 2 Physical Characteristics of Transmission Line Ground Wire Conductors

Parameter	Data
Type	Dorking ACSR
Number &radius of steel wires	12/1.6 No/mm
Number &radius of aluminum wires	7/1.6 No/mm
Total area	152.8 mm^2
Overall diameter	16.00 mm
Mass(without grease)	717 Kg/km
Maximum tension	15200 N

Table (3) Oil Pipeline Characteristics

Parameter	Data
Service	South Oil Company
Pipe material	Carbon steel
Diameter	2033.98 mm
Wall thickness	17 mm
Length	340Km
Type of coating	Polyethylene tape
Coating thickness	0.89 mm
Outer radius	1016 mm
Inner radius	999.1 mm
$\sigma_{conductor}$	$5x10^6$ S/m
$\mu_{conductor}$	$250.0\mu_o$
$\rho_{coating}$	$5x10^7$ Ω.m
$\mu r_{coating}$	1
Maximum operating temperature	50^oC

Table (4) Pipeline eddy current (I_e) for various separation distances d and soil resistivity ρ under steady state operation

d(m)	ρ (Ω.m)		
	10	100	1000
	I_e(A)	I_e(A)	I_e(A)
100	212.6	217.1	221.65
500	3.75	9.11	13.42
1000	0.21	2.57	6.91

Table (5) Pipeline eddy current (I_e) for various separation distances d and soil resistivity ρ under transient conditions

d(m)	ρ (Ω.m)		
	10	100	1000
	I_e(A)	I_e(A)	I_e(A)
100	811.3	886	937.7
500	18.23	111.23	205.9
1000	2.06	37.11	126.3

Table (6) Effect of gradient mitigation wire on pipeline eddy current (I_e) and Joule heats at the separation distance d equal to 100m

ρ (Ω.m)	I_e(A)	P_{Loss}(W/m)
10	676.76	88.48
100	734.33	102.04
1000	773.73	112.03

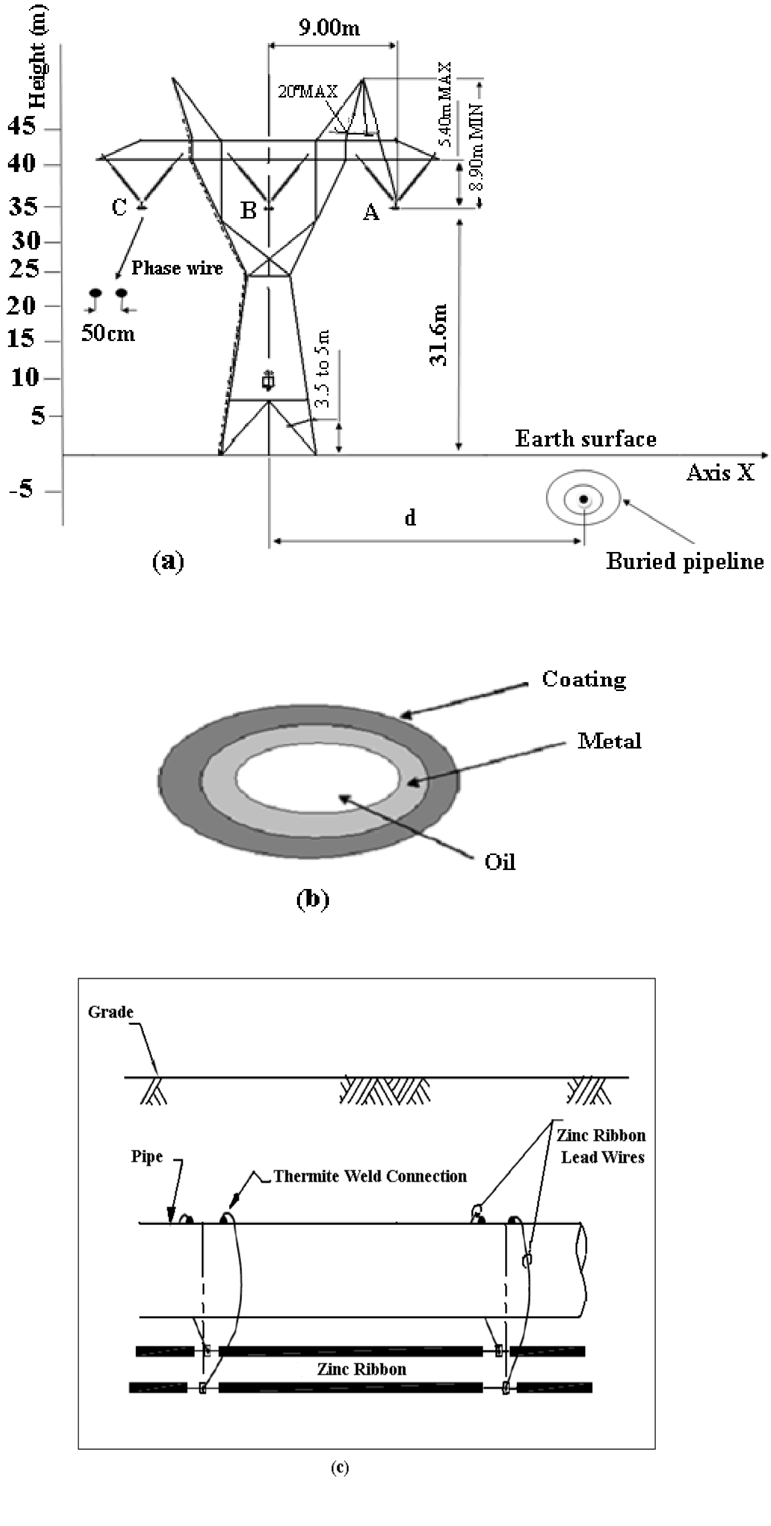
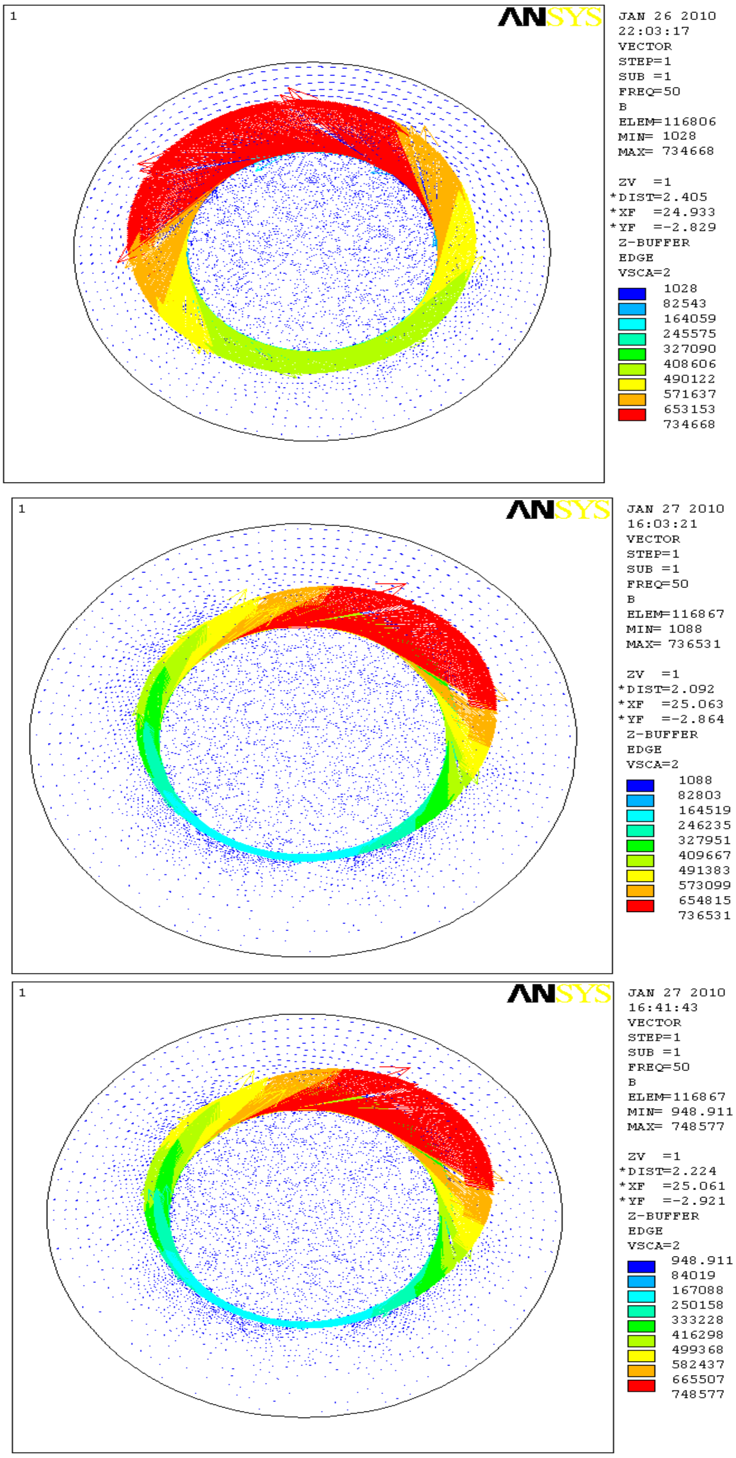


Figure (1) System under investigation a) Cross-section of the system (400 KV NSRP – KAZG Transmission Lines with the pipeline) b) Pipeline cross-section c) Typical gradient control wire installation

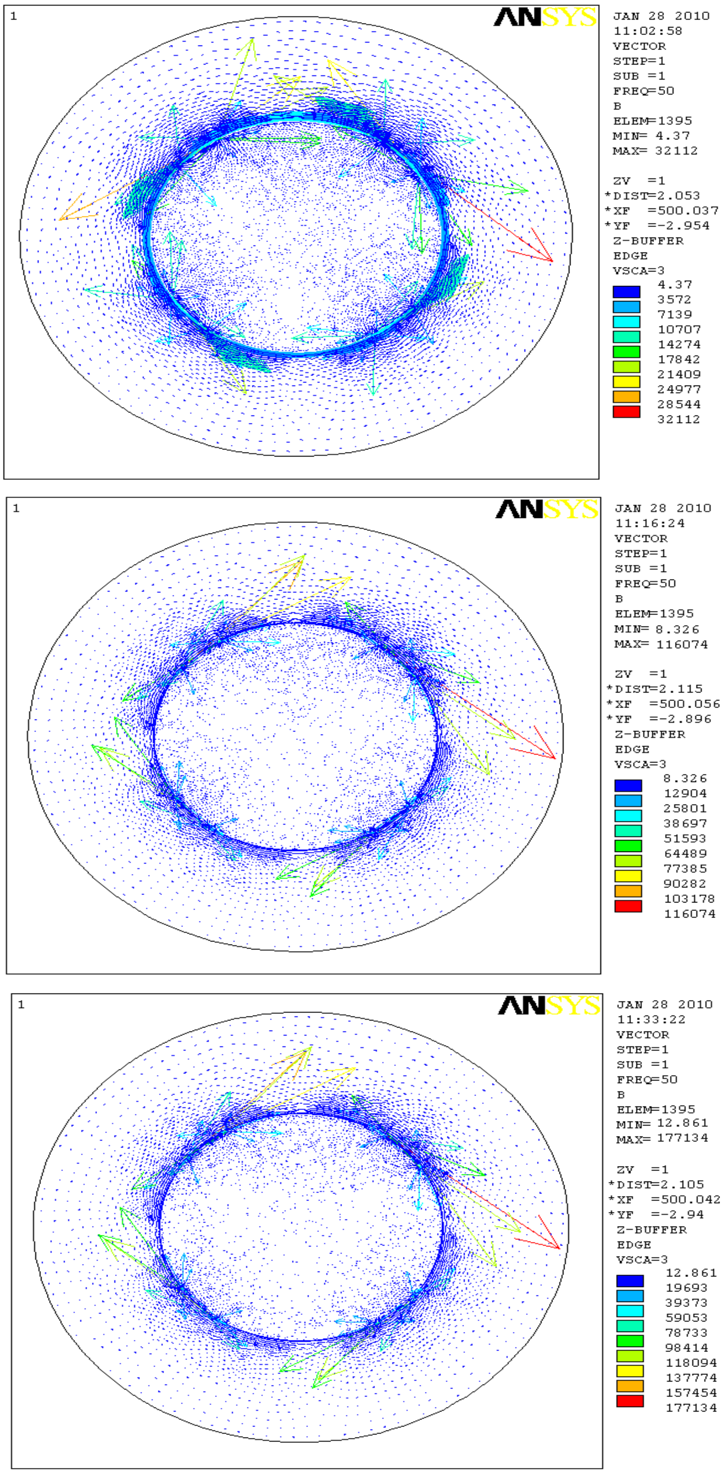


a) ρ = 10Ω.m

b) ρ = 100Ω.m

c) ρ = 1000Ω.m

Figure (2) Effect of various soil resistivities on induced magnetic field magnitude B (nT) in the oil pipeline under normal operation (Relative distance between Power line & Pipeline d= 100m)

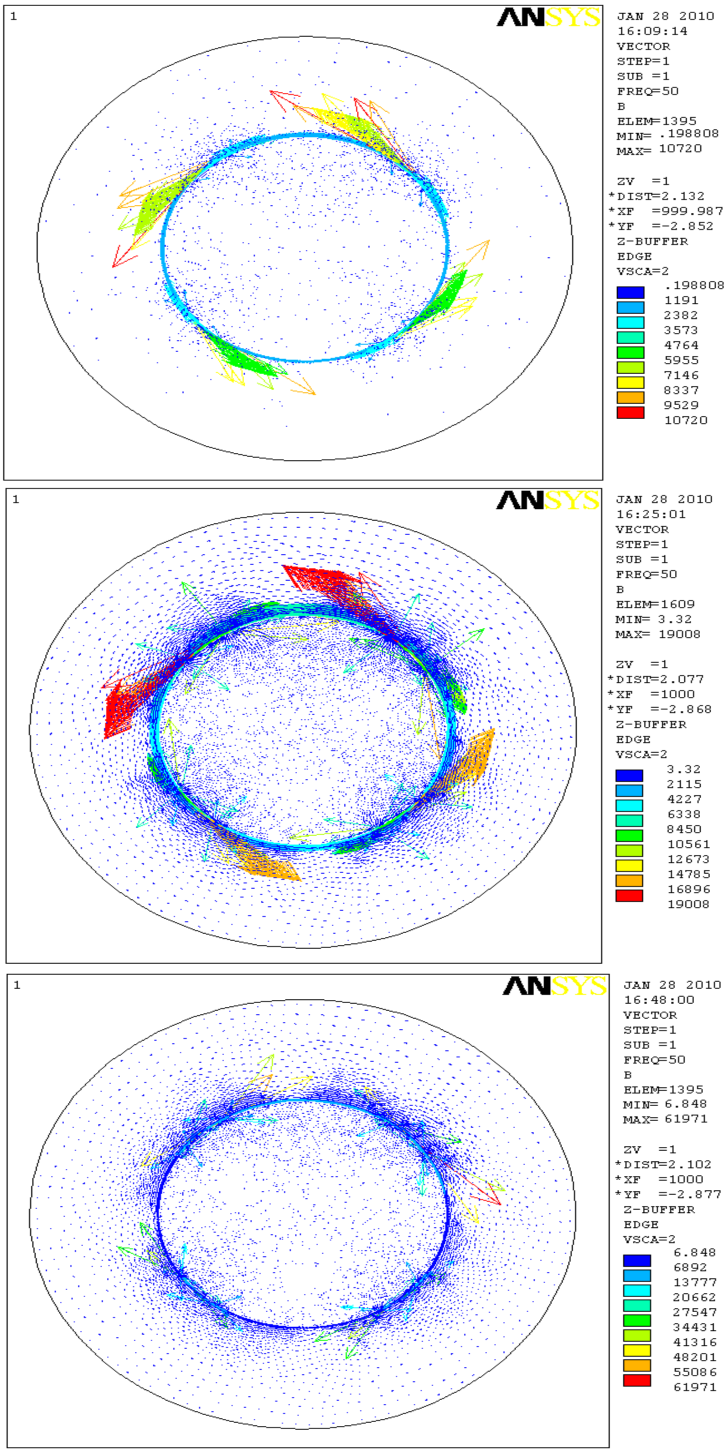


a) ρ = 10Ω.m

b) ρ = 100Ω.m

c) ρ =1000Ω.m

Figure (3) Effect of various soil resistivities on induced magnetic field magnitude B (nT) in the oil pipeline under normal operation (Relative distance between Power line & Pipeline d= 500m)

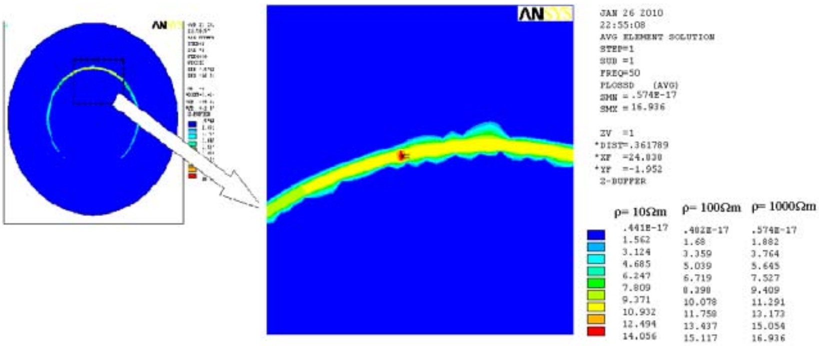


a) ρ = 10Ω.m

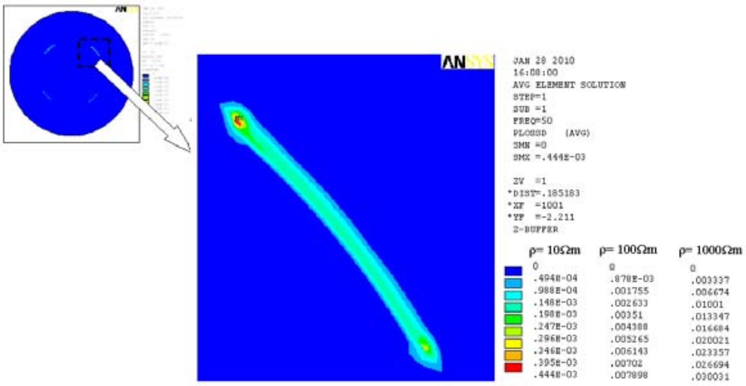
b) ρ = 100Ω.m

c) ρ = 1000Ω.m

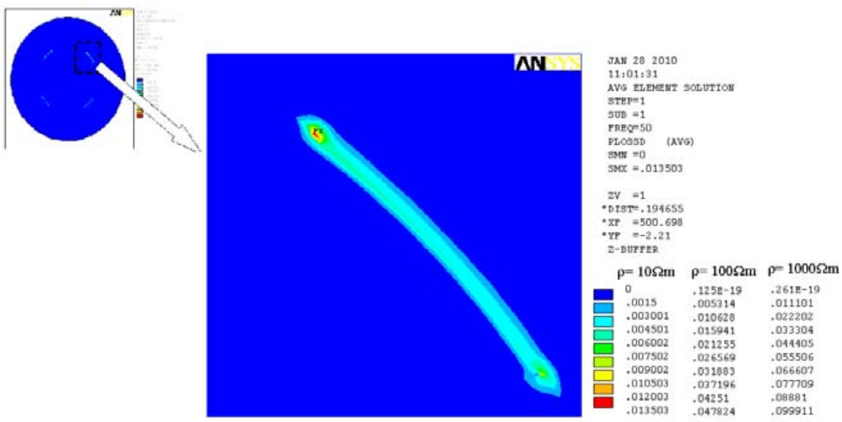
Figure (4) Effect of various soil resistivities on induced magnetic field magnitude B (nT) in the oil pipeline under normal operation (Relative distance between Power line & Pipeline d= 1000m)



a) Relative distance between Power line & Pipeline d= 100m

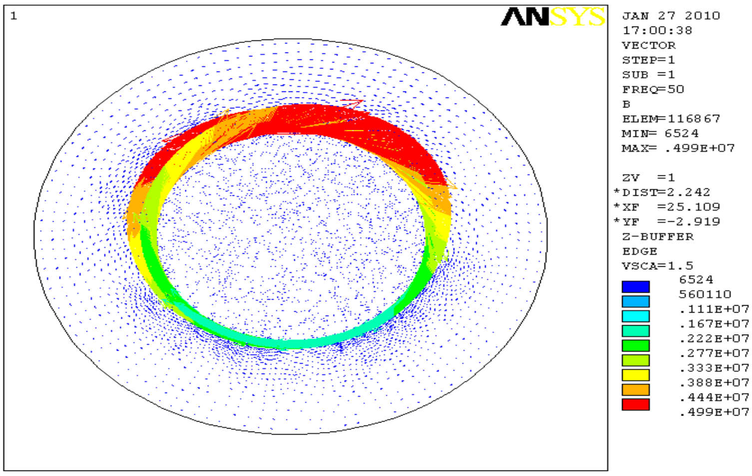


b) Relative distance between Power line & Pipeline d= 500m

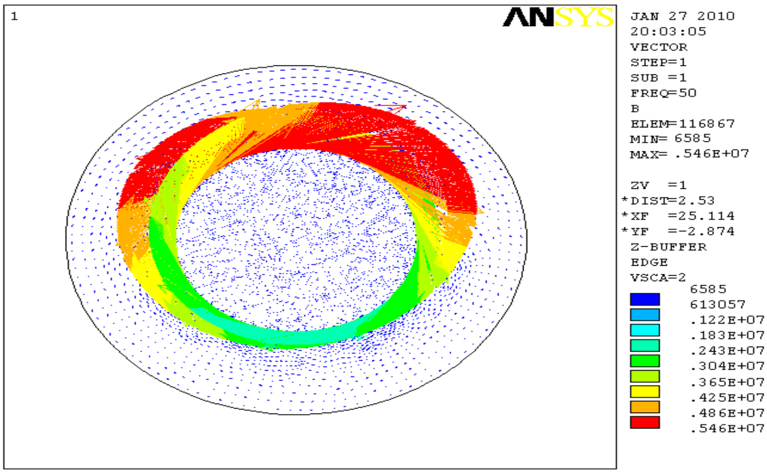


c) Relative distance between Power line & Pipeline d= 1000m

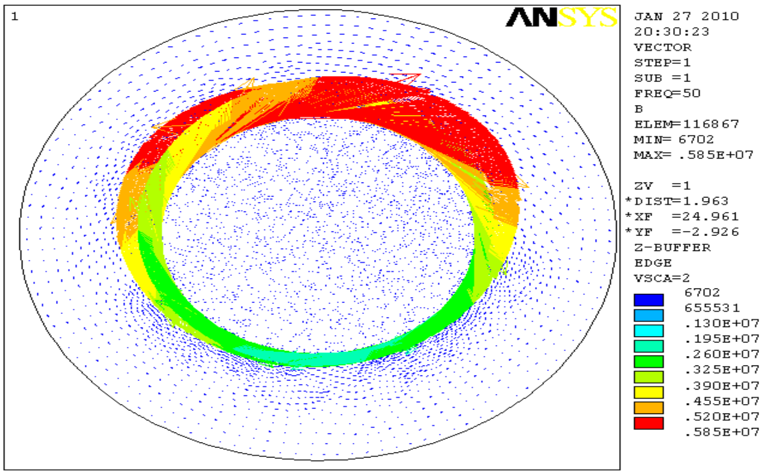
Figure (5) Zoomed effect of various soil resistivity and separation distance on the Joule heat (output as power loss per unit length W/m) of the pipeline under normal operation



a) ρ = 10Ω.m

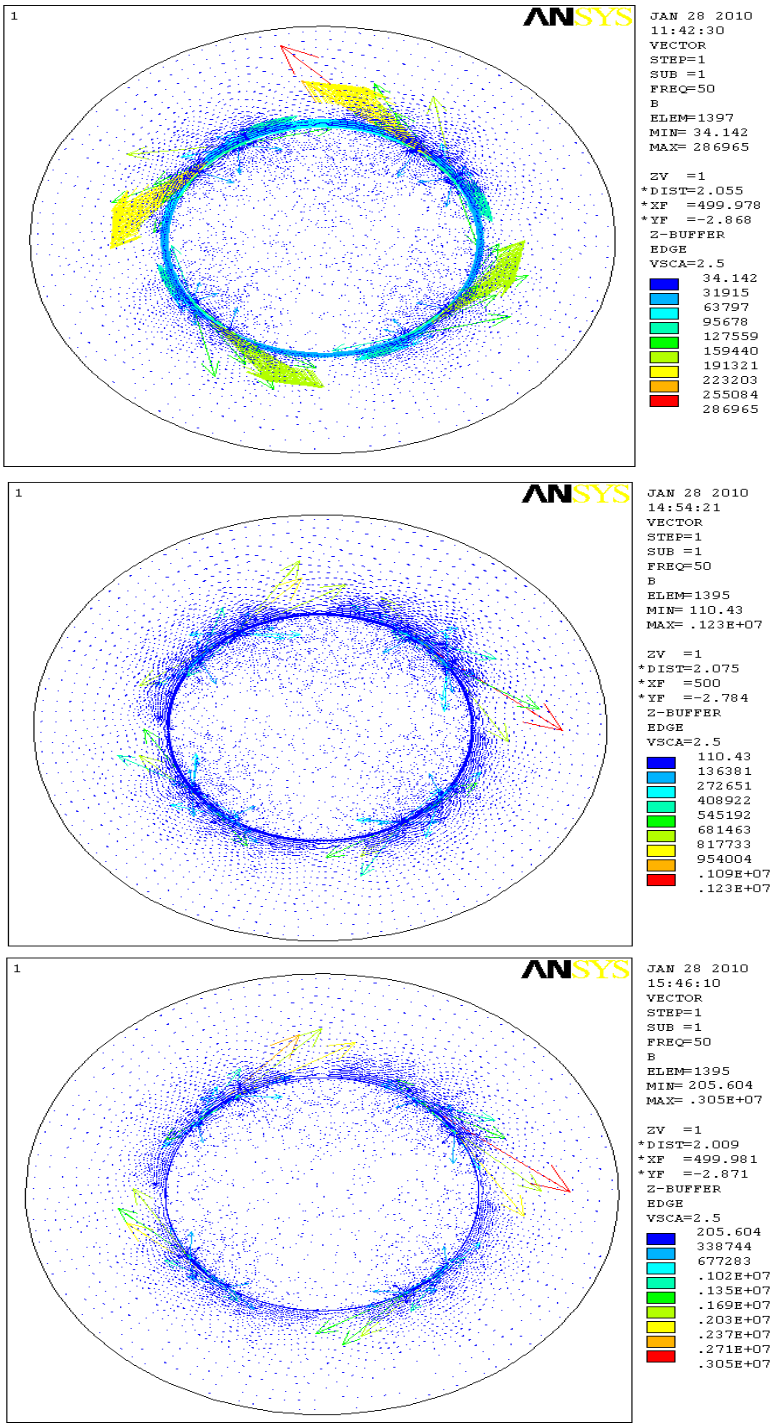


b) ρ =100Ω.m



c) ρ=1000Ω.m

Figure (6) Effect of various soil resistivities on induced magnetic field magnitude B (nT) in the oil pipeline under transient condition (Relative distance between Power line & Pipeline d= 100m)

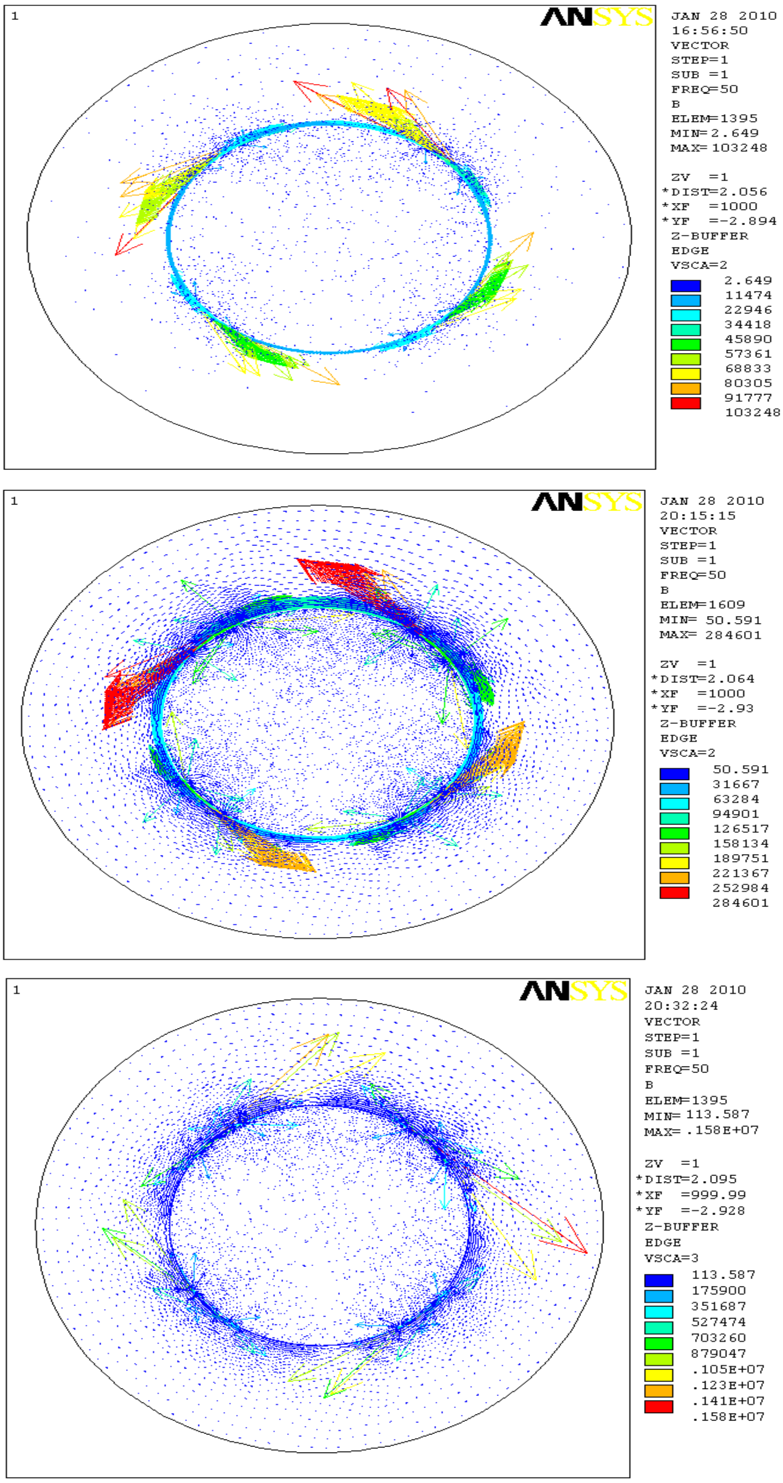


a) ρ = 10Ω.m

b) ρ =100Ω.m

c)ρ=1000Ω.m

Figure (7) Effect of various soil resistivities on induced magnetic field magnitude B (nT) in the oil pipeline under transient condition (Relative distance between Power line & Pipeline d= 500m)

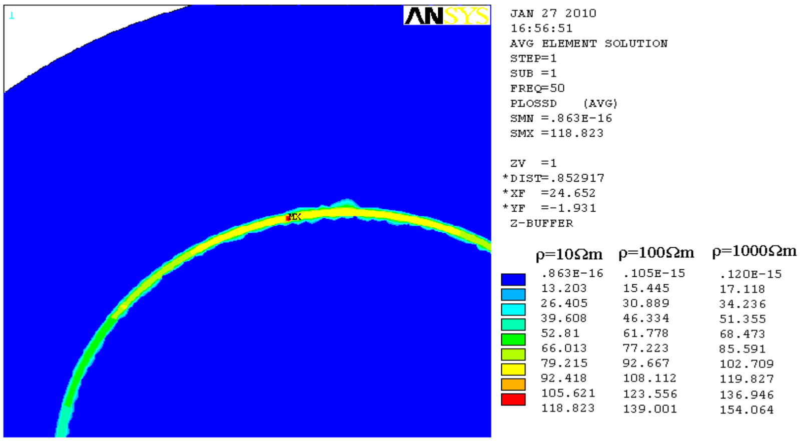


a) ρ = 10Ω.m

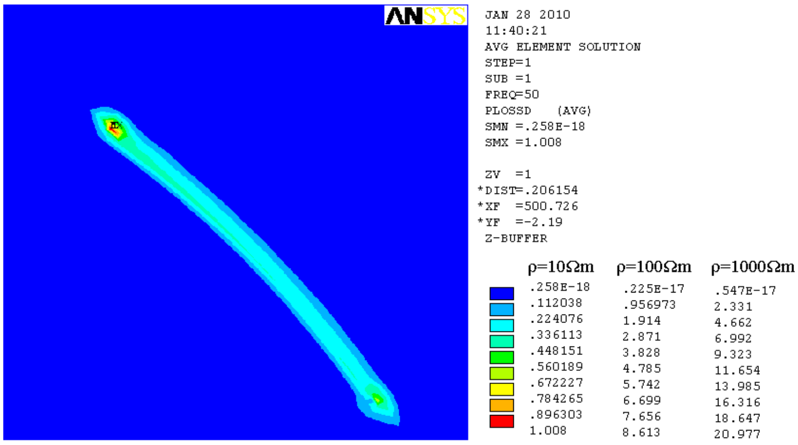
b) ρ =100Ω.m

c)ρ=1000Ω.m

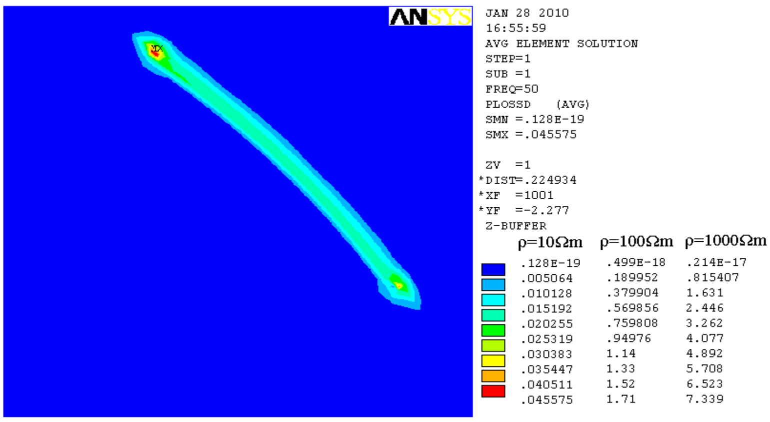
Figure (8) Effect of various soil resistivities on induced magnetic field magnitude B (nT) in the oil pipeline under transient condition (Relative distance between Power line & Pipeline d= 1000m)



(a) Relative distance between Power line & Pipeline d= 100m



(b) Relative distance between Power line & Pipeline d= 500m



(c) Relative distance between Power line & Pipeline d= 1000m

Figure (9) Zoomed effect of various soil resistivity and separation distance on the Joule heat (output as power loss per unit length W/m) of the pipeline under transient condition