EARTH SURFACE POTENTIALS AND GPR OF SUBSTATION GROUNDING

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ABSTRACT

In this paper simplified approaches for the earth surface potentials and GPR of substation grounding are presented in case of uniform or non-uniform soil. The equalization of current density and then decreasing of GPR is achieved. The image method is suggested to calculate the GPR and the earth surface potentials with accurate results for the grids buried in uniform or non-uniform soil structure. The voltage profiles have been designed in 3D to make the selection of suitable earthing system easier. The grounding system earth surface potential under transient condition is investigated

INTRODUCTION

There are two main design goals to be achieved by any substation grounding system under normal as well as fault conditions .These goals are:

i-To provide means to dissipate electric currents into the earth without exceeding any operating and equipment limits.

ii-To assure that a person in the vicinity of grounded facilities is not exposed to the danger of critical electric shock. Studying the effect of voltage distribution is an important parameter to design the grounding system of substations to ensure the safety of people above the substation ground. This can be achieved by equalizing the potential distribution of the ground surface and reducing step and touch potentials [1]. The safety of persons is affected by the ground potential rise (GPR) of grounded structures during electric power faults. So, in order to limit these voltages to safe values, it is necessary to design a right grounding system that effectively connects all metallic structures of the substations to ensure the safety criteria for both human and substations taking into account the economical purposes. However, the unequally spaced grid can make current density which is emanating from grid conductors more uniform, and therefore remarkably decrease potential gradients on the earth's surface [1-4]. Then, the maximum touch voltage for this grid will reach its lowest values and thus the safety conditions for human above the substation earth surface will be ensured.

UNEQUALLY SPACES GRIDS DESIGN PROCEDURES

Unequally Spaced Grounding Grids Procedure

If the conductor spacing is divided by k segments, the length of the ith segment, L_{ik} can be expressed in percent of the total length of the conductor L [5, 6]:

$$S_{ik} = \frac{L_{ik}}{L} \times 100\% . \qquad (1)$$

$$S_{ik} = b_1 e^{-b2i} + b_3 . \qquad (2)$$

The coefficients b1, b2 and b3 are dependent on number of segments of the conductor [6].

Optimal Compression Ratio (OCR)

The optimal design of grounding systems for substations is to suitably arrange the conductors of grounding systems to equalize the short circuit current distribution and the potential gradient of ground surface and at the same time to keep the maximum touch voltages within the safe limit; this would ensure making all grounding conductors sufficiently utilized so certified as a safe and economic design method. The conductor compression ratio "C" is related to the grid dimensions and the maximum conductor separation d_{max} which occurs toward the center of the grid and is given by [7]:

$$d_{\max} = \frac{L(1-C)}{1+C-2C^{(N/2+1)}} \quad \text{N even} \qquad (3)$$

$$d_{\max} = \frac{L(1-C)}{2(1-C^{(N-1)/2})} \quad \text{N odd} \qquad (4)$$

where N is the desired number of conductors perpendicular to given n grid axis of length L .In unequally spaced grid when the conductors are arranged according to an exponent , the span from the center could be calculated according to equation: [7 and 8]

$$d_i = d_{\max} C^i . \qquad (5)$$

For the optimal design of grounding system, the optimal compression ratio could be determined, which is defined as the compression ratio, where the touch voltage reaches its minimum if the grounding grid is designed under this compression ratio [7]. An empirical expression is obtained to calculate OCR as follows [8, 9]:

$$\text{OCR}=a_0+a_1\exp(0.0001h)+a_2\exp(bh) \qquad (6)$$

Where

$$b=-0.3503-9.6311\exp(-0.03666L). \qquad (7)$$

$$a_0=a_{01}+a_{02}k+a_{03}k^2. \qquad (8)$$

$$a_1=a_{11}+a_{12}k+a_{13}k^2. \qquad (9)$$

$$a_2=a_{21}+a_{22}k. \qquad (10)$$

K is number of segments of the conductor in any direction. The relationship between a_0, a_1... and L is cleared in table I [9].

Table I

The Relation between the Coefficients and Grid Length

Coefficients	L≤100 m	100 m≤L≤175 m	175 m≤L≤250 m	L>250 m
a01	0.44	0.38	-0.51	0.32
a02	-77.43	-50.65	-33.18	-15.44
a03	15.63	13.88	18.49	13.42
a11	0.033	0.19	1.15	0.38
a12	76.9	50.21	32.82	15.16
a13	-15.56	-13.83	-18.44	-13.38
a21	-0.067	-0.037	-0.029	-0.022
a22	0.5	0.41	0.34	0.26

EFFECT OF CONDUCTORS' DISTRIBUTIONS ON VOLTAGE PROFILE IN CASE OF GRIDS BURIED IN UNIFORM SOIL

Using Unequally Spaced Grounding Grids Procedure

To be used for the second order headings.

Lay-out

To illustrate the effect of equally and unequally grid conductor distribution on the earth surface potentials above the grid, a square grid of 105x 105 m^2 with number of meshes equal 64 equally and unequally spaces parallel conductors in each direction is taken as an example as given in figure 1. Current emanating from the grid into the soil is I=10KA. By applying image technique [8, 9], the potential differences in volts and as a percentage of GPR for all grid modules .The obtained results are tabulated in table II when the soil resistivity was 100 ohm .meter

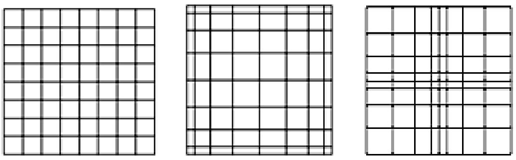

Fig. 1 An example for grid module of N=64 with equally, unequally spaced having denser conductors at the edges and the middle respectively.

From the obtained results, it's concluded that as increasing of equally spacing parallel grid conductors included in the same area, the GPR for the grid decreases and the earth surface potentials for grid increases, and then the potential difference between each two conductors will decrease and the voltage profile will be more uniform. Figures 2, 3 and 4 represent the three dimensions earth surface potentials above the mentioned grid in all conductors' distribution cases for every one meter in both x and y direction**.** Regarding to grid conductors' distribution with unequally spaces, the percentages of the potential differences between center and corner conductors for this grid whatever number of conductors are around 26 %, 37% and 15% in cases of equally spaces, unequally spaces having denser conductors at the middle and edges respectively. So, and as a conclusion, the conductor distribution with unequally spaces having denser conductors at the edges provides the most efficient design because it satisfies the lowest GPR and the lowest potential differences between center and corner conductors comparing with the results that occurred in other cases of conductors' distribution included with the same area, thus the voltage distribution will be more uniform.

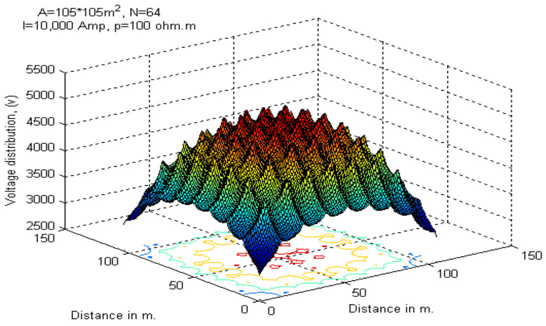

Fig.2. Voltage profile along all grid conductors in case of equally spaced grid. Number of meshes =64

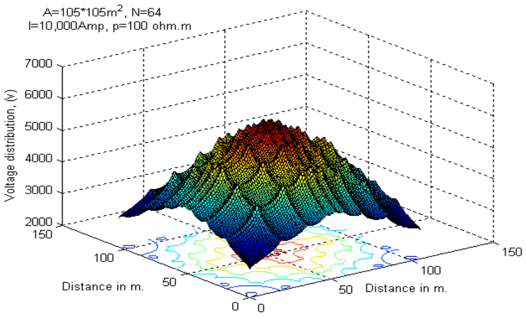

Fig.3. Voltage profile along all grid conductors in case of unequally spaced grid having denser conductors at the middle. Number of meshes =64

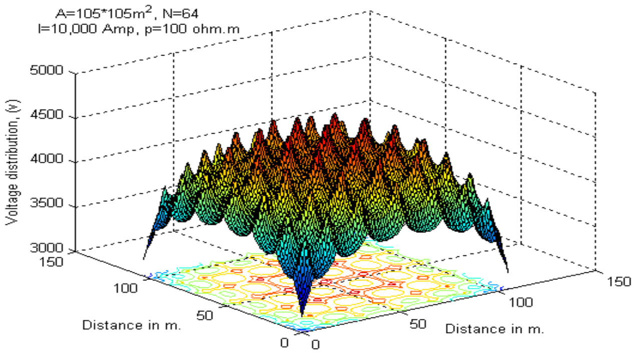

Fig.4.Voltage profile along all grid conductors in case of unequally spaced grid having denser conductors at the edges. Number of meshes = 64.

Noteworthy from the table, and to confirm the previous conclusion, that the increasing of unequally grid conductors having denser conductors at the grid middle increases the GPR for this grid. Figures 5 illustrates the earth surface potentials and touch voltage along the center conductor of the mentioned grid modules in different cases of conductors' distribution. From the figures, and for all grid modules conductors, it is cleared that the maximum touch voltage along the center conductor reaches its lowest value in case of unequally spaced grid having denser conductors at the edges.

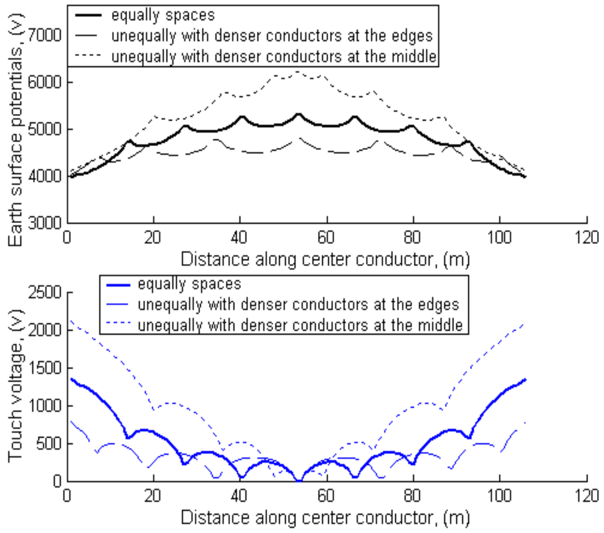

Fig.5. Earth surface potentials and touch voltages over the center conductor for mentioned grid having N=64

Effect of Unequally Conductor Distribution on Earth Surface Potential by Using Optimal Compression Ratio (OCR)

To illustrate the effect of unequally conductors' distribution by using OCR on the earth surface potentials and touch voltage profiles for the grid buried in uniform soil and to satisfy the optimal grounding grid design, the grid module of (A=105 x 105 m^2, N=8 x 8) as an example, buried in a uniform soil of 100 ohm. m resistivity, the earth surface potentials and touch voltages are calculated along the center conductor for this grid under different cases of compression ratios by applying equations (3) to (5) as presented in the Fig. 6. By the analysis of calculated data represented in the figures, it is stated that the maximum touch voltage along the center conductor reaches its lowest value when the compression ratio for this grid reaches 0.538, it means and as a conclusion, at the optimal compression ratio is obtained by applying equations (6) to (10), the best arrangement of grounding conductor span is achieved, so the minimum touch voltage and thus, the optimal design for grounding grid are satisfied. This result is influenced if compared with the different cases of conductors' distribution mentioned in the previous section for the same grid module of (A=105 x 105 m^2, N=8 x 8).

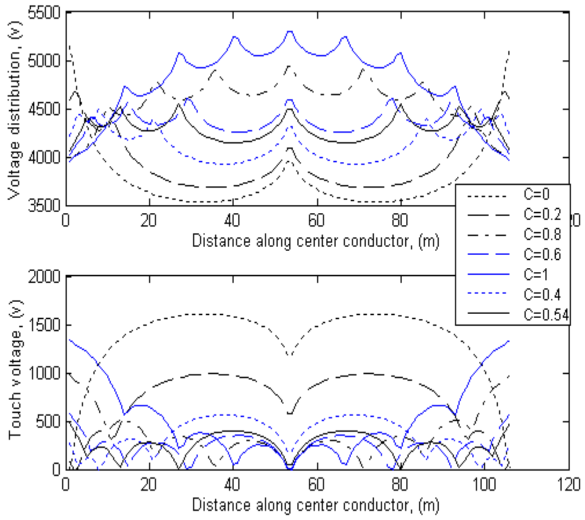

Fig.6. Earth surface potentials and touch voltages over the center conductor for mentioned grid having different cases of compression ratios.

Fig.7 illustrates the relationship between the maximum touch voltages over center conductor for the mentioned unequally spaced grid as a function of conductor compression ratio. Remarkable, this relationship usually has an obvious "U" shape. Colored graphical representations for earth surface potentials above the mentioned grid in different cases of compression ratio for every one meter in both x and y direction are saved in 3D contours plots as shown in figures 8 to 12. Figures 13, 14 and 15 give the voltage distribution 1n 3 D in case of unequally spaced grid having denser conductors at the middle, in case of equally spaced and in case of unequally spaced grid having denser conductors at the edges **respectively.**

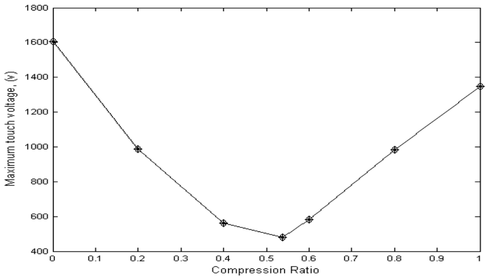

Fig.7. Maximum touches voltage over center conductor for mentioned grid as a function of conductor compression ratio.

VOLTAGE PROFILE OF GRIDS BURIED IN DOUBLE LAYER SOIL

To illustrate the effect of changing the first layer depth of double layer soil structure with variation of the upper and lower soil resistivities on the voltage profile, 2D graphically representation for earth surface potentials is plotted as in figure 16 along the center conductor for a 105 x 105 m^2 grid area with 9 equally spaces conductors in each direction buried in non-uniform soil having specifications that given in table II. The current emanating for all cases is 10,000 Amp.

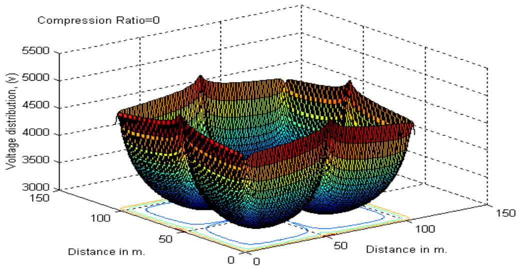

Fig.8. Earth surface potentials over all grid conductors for grid of (A=105 x 105 m^2, N=8 x 8) in case of C=0.

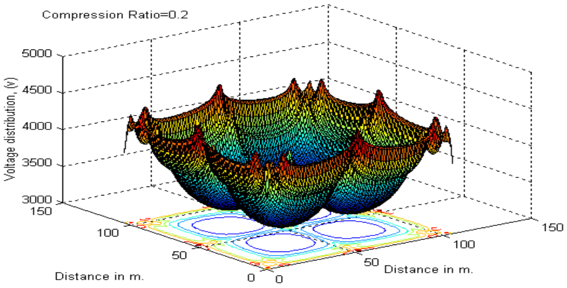

Fig.9. Earth surface potentials over all grid conductors for grid of (A=105 x 105 m^2, N=8 x 8) in case of C=0.2.

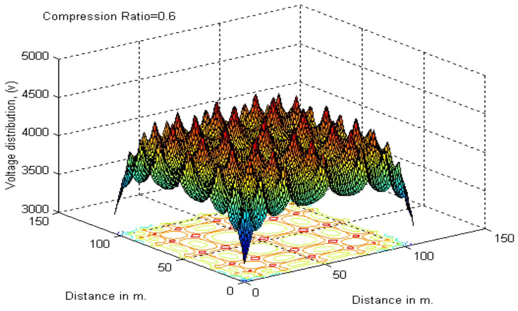

Fig.10. Earth surface potentials over all grid conductors for grid of (A=105 x 105 m^2, N=8 x 8) in case of C=0.6.

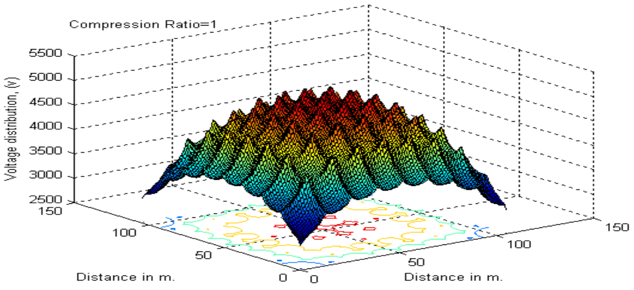

Fig.11. Earth surface potentials over all grid conductors for grid of (A=105 x 105 m^2, N=8 x 8) in case of C=1.

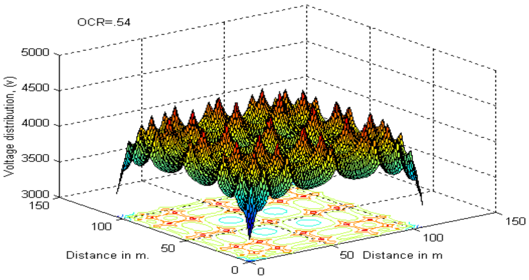

Fig.12. Earth surface potentials over all grid conductors for grid of (A=105 x 105 m^2, N=8 x 8) in case of C=0.54.

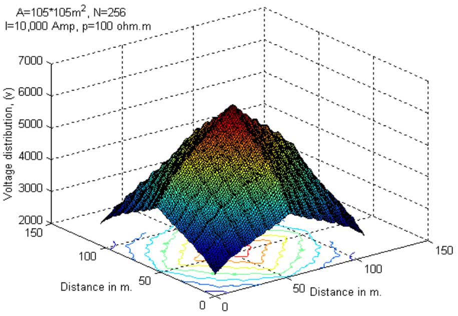

Fig. 13.Voltage profile along all grid conductors in case of unequally spaced grid having denser conductors at the middle.

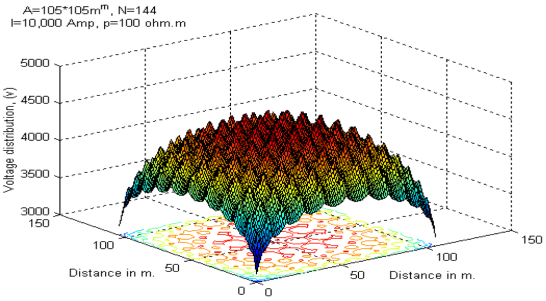

Fig. 14 Voltage profile along all grid conductors in case of equally spaced

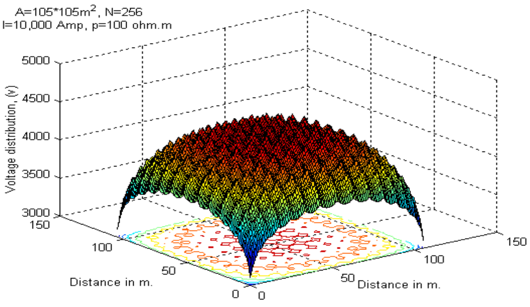

Fig.15. Voltage profile along all grid conductors in case of unequally spaced grid having denser conductors at the edges

Table II

Specifications of Mentioned Non Uniform Soil

ρ1	100	100	100	100	100
ρ2	100	40	40	250	250
H1	infinity	10	20	10	20

From the figure, it is cleared that the ground potential rise (GPR) for the grid buried in the high resistivity upper layer soil will be lower than that resulted above the grid if it is buried in the upper layer soil of low resistivity. Also, the GPR increases as the depth of the high resistivity upper layer soil increases and the opposite results in case of increasing the depth of the upper layer of low resistivity.

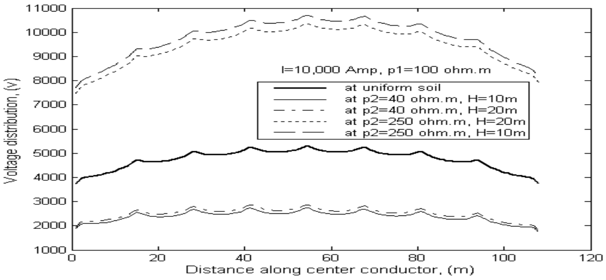

Fig.16. Earth surface potentials along center conductor for equally spaced grid (A= 105 x 105 m^2, N=8 x 8) with various soil structures.

To illustrate the effect of soil non-uniformity on the grounding grid system having different conductors' distribution by using OCR, the earth surface potentials and maximum touch voltages along center conductor for the mentioned grid of (A=105 x 105 m^2, N=8 x 8) buried in upper layer of double layer soil having are given in Fig.15. Fig. 17 clears that the compression ratio which determine the arrangement of grid conductors satisfies the lowest touch voltage for this grid according to the soil parameters in which grid is buried in. From the figure, it's concluded that in cases of (ρ1<ρ2), the compression ratio that satisfies the lowest maximum touch voltage will takes values less than the optimal compression ratio (OCR) determined by equation (6) for this grid. The results will be in the contrary of this in cases of (ρ1>ρ2). For the mentioned grid buried in double layer soil structures, in cases of (ρ1<ρ2) and since the maximum touch voltage reaches its lowest values at the compression ratio of 0.4, it means that the grid conductors will be denser at the edges and having widely conductor spans at the middle. The spaces between conductors will increase progressively from the periphery to the center and the middle spans will decrease gradually in cases of (ρ1>ρ2) where the maximum touch voltage reaches its lowest values at the compression ratio of 0.6.

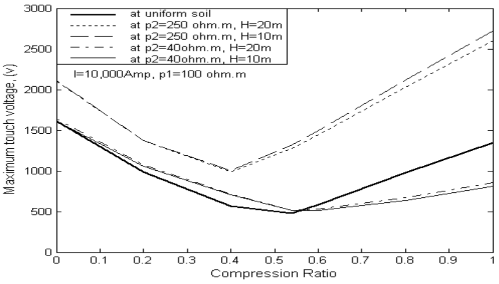

Fig.17. Maximum touch voltage over center conductor for mentioned grid buried in various soil structures as a function of compression ratio.

TRANSIENT SURFACE POTENTIAL OF GROUNDING GRID

The program ATP-EMTP is used to calculate the transient impedance and grid potential, the software widely used by power engineer for transient analysis [6]. Using the formula mentioned in [6, 7] to calculate the grid parameters.

$$R = \rho\left[\frac{1}{l} + \frac{1}{\sqrt{20A}}\left(1 + \frac{1}{1 + h\sqrt{20/A}}\right)\right]\Omega \qquad (11)$$

Where **R** is the resistance of the grid, ρ is the soil resistivity $\Omega.m$, **A** is the area of the grid, and ***l*** is the total length of the grid.

$$C = \frac{\varepsilon \cdot \rho \cdot 10^{-9}}{36\pi R}\ \Omega \qquad (12)$$

Where C is the capacitance of the grid, ε is the permittivity of soil.

$$L_1 = \frac{2l''}{3 \cdot 10^{-7}} \ln \frac{2l''}{r''}\ \text{H} \qquad (13)$$

Where $\mathbf{L_1}$: is the inductance of the main wire, ***l”*** is the length of the main wire, and ***r”*** is the main wire radius.

$$L_2 = \frac{2l'''}{3 \cdot 10^{-7}} \ln \frac{4l'''}{r'''}\ \text{H} \qquad (14)$$

Where $\mathbf{L_2}$ is the inductance of the grid conductors, ***l’”*** is the side length of the grid, and ***r’”*** is the grid wire radius. The injected current impulse at point A is $I(t) = 12000 \cdot (e^{-27000.t} - e^{-5600000.t})$, the peak value of the current impulse is about 12kA. [11]. Transmission line approach has been chosen to simulate the buried grounding system under lightning condition. Figs (18) and (19) present results of the transient impedance and ground potential rise at injection point as response to the fast lightning current impulse.

CONCLUSION

The following points are briefly analyzing the main conclusions of this paper:

- As increasing of equally spacing parallel grid conductors included in the same area, the GPR for the grid decreases and the minimum earth surface potentials for grid increases, and then the potential difference between each two conductors will decrease, so, the voltage profile will be more uniform.

- The conductors distribution with unequally spaces having denser conductors at the edges provides the most efficient design.
- As a conclusion, for grids buried in double layer soil, the compression ratio that satisfies the lowest touch voltage will differs according to soil parameters.
- Transient performance of grounding grids is complicated and its transient GPR and impedance contain oscillation affected by the values of the grid capacitance and inductance values rather than the grid resistance.

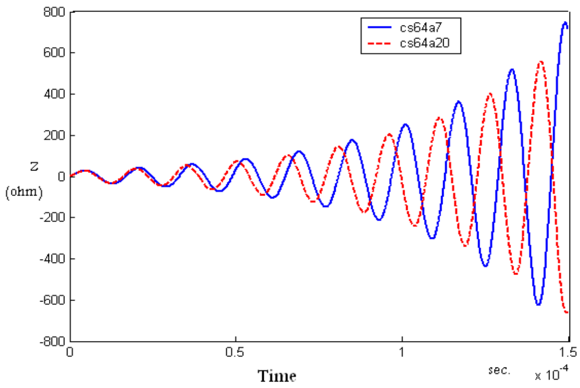

Fig. 18 Transient impedance

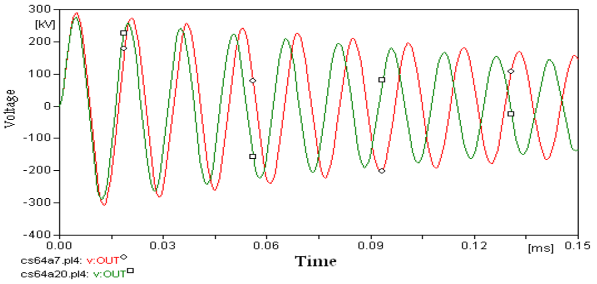

Fig. 19 Voltage wave form for G.P.R

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