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Updated equation to compute the soil voltage contour under fault condition

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Abstract
The neighboring rates between high voltage substation and residential buildings are amplified due to populations increase. Under fault or system malfunction, earth potential rise could reach an unsafe condition. This earth potential rise extends to the surrounding soil and known as the soil voltage. To guarantee safety acquiescence of the new system, earthing system design is required. Earthing system offers a safe working atmosphere for employees and people transitory by during a fault or malfunction of a power system. The soil voltage due to high voltage EPR plays important roles when it comes to step and touch voltage computation. In this paper, a new equation is studied to compute the soil voltage at distance x from the fault location. Numerous field tests is included to verify the proposed method.

Keywords: Earth grid; High voltage substation; EPR Contour, Soil voltage.

1. Introduction
The neighbouring rates among the high voltage (HV) infrastructure and residential are rapidly inclining due to the growing population. This neighboring forces the obligation of a satisfactory earthing system to guarantee safety compliance of the HV infrastructure. Under fault situation, the earth potential rise (EPR) can grasp unsafe limits that may leads to human and property damage. The EPR is directly related to the substation earth grid resistance [1, 2]. The earth grid computation is directly related to the soil resistivity of the area [3-5]. The step and touch voltages are directly related to the soil voltage at the feet of the personnel [6].
When personal touching the pole, the person is standing at X distance away from the pole, as shown in Figure 1, the touch voltage is the different between the hand and feet potential, as the EPR dive toward the zero value with distance, the larger the X distance the higher is the touch voltage.
Many researchers address the soil voltage at distance X from the EPR [6-8]. The works is based on single electrode earth grid and on the estimation of the equivalent radius of the semi hemisphere which represent the single electrode. This method becomes complicated when it comes to complex earth grid.
The efforts in this paper work on establishing an equation to compute the soil voltage at distance X for single electrode and complex electrodes gird. Numerous field tests are included to verify the proposed method.

2. Theoretical study
Under fault condition, the earth potential rise extends to the surrounding soil area. The work in [7] shows the contour of the EPR around a transmission pole. Transmission poles are formed of conductive

materials, concrete or steel poles. Therefore, touch voltage to the pole becomes an issue under fault condition. The touch voltage is the difference between the pole EPR and the soil voltage at the feet of the person standing 1 or 1.5meters away from the pole. According to [8], the relative value of the potential at a distance X from the center of the circular flat earthing electrode, with diameter D is given in equation (1).

$$V(x) = \frac{2}{\pi} EPR \times Arc\sin\left(\frac{D}{2x}\right) \tag{1}$$

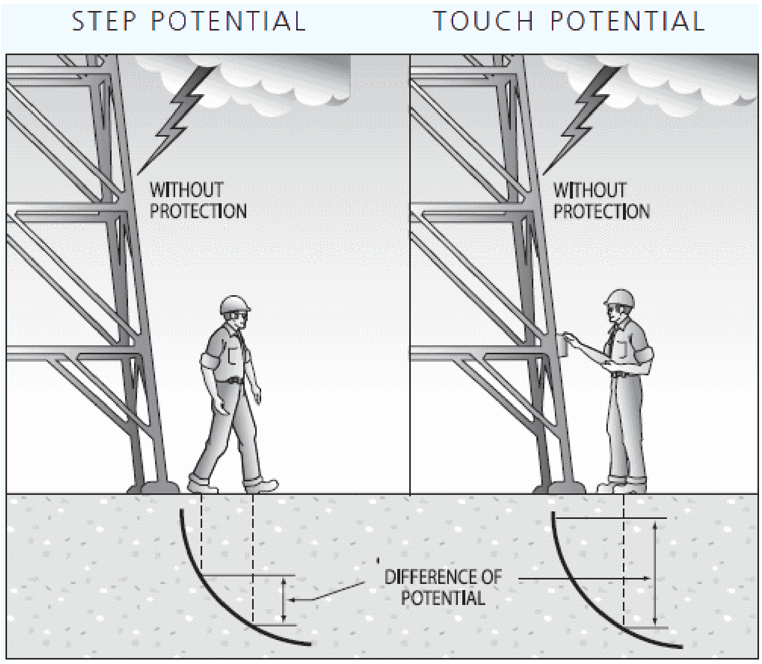

Figure 1. Step and touch voltage

Another approach to compute the soil voltage at distance X is presented in equation (2) [9].

$$V(x) = EPR \frac{r_e}{x + r_e} \tag{2}$$

where r_e is the radius of the equivalent hemispherical electrode in meters

Based on the author published works in [6], figure 2 shows the percentage of the maximum touch voltages based on equation (1) and (2). For person standing up to 1.5meters from the pole, the maximum possible touch voltage cannot exceed the 45% of the pole EPR.

2.1 New soil voltage equation

The following analysis is used to establish the soil voltage at distance X from the EPR as per this paper. The resistance of a cylindrical electrode in respect of a point at distance X can be found using equation (3) [10]:

$$R_{respect-to-x} = \int_{r}^{x} \frac{\rho}{S_{electrode}} dr \tag{3}$$

Equation (4) represents the surface of a cylindrical electrode with a semi hemisphere end:

$$S_{electrode} = 2\pi r l + 2\pi r^2 \tag{4}$$

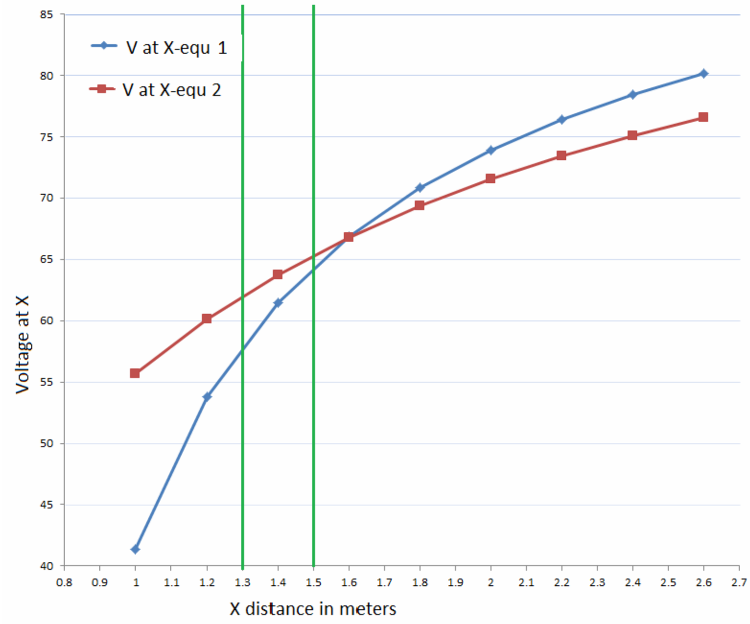

Figure 2. Voltages % at distance X against EPR as per equation 1 and 2

Equation (3) can be rearranged as shown in equation (5):

$$R_{respect-to-x} = \int_{r}^{x} \frac{\rho}{2\pi r l + 2\pi r^{2}} dr \tag{5}$$

Please note when X is infinite, equation (5) represents the true resistance of the electrode. Equation (6) represents the analysis of equation (5):

$$R_{respect-to-x} = \frac{\rho}{2\pi L}\left[Ln\left(\frac{x}{x+l}\right) + Ln\left(\frac{r+l}{r}\right)\right] \tag{6}$$

Using the EPR and the voltage at distance "X", equation (7) represents the resistance in respect to distance "X":

$$R_{respect-to-x} = \frac{EPR_{E} - V_{x}}{I} \tag{7}$$

where I is the current that generate EPR_E
Equation (8) is generated by analysing equations (6) and (7):

$$V_{x} = EPR_{E}\left|\left(\frac{Ln(A)}{Ln(B)}\right)\right| \tag{8}$$

where the terms A and B are defined in equations (9) and (10):

$$A = \frac{x}{x+l} \tag{9}$$

$$B = \frac{r+l}{r} \tag{10}$$

Equation 8 represents the new equation to compute the soil voltage at distance x under EPR condition. Figure 3 shows the simulation of equations (2) and (8) for a single electrode with EPR of 1 volt. The simulation is completed for a 4.8meter electrode with 14mm diameter. It should be noted, the results in Figure 3 show that equation (8) represents a more conservative approach when it comes to touch voltage.

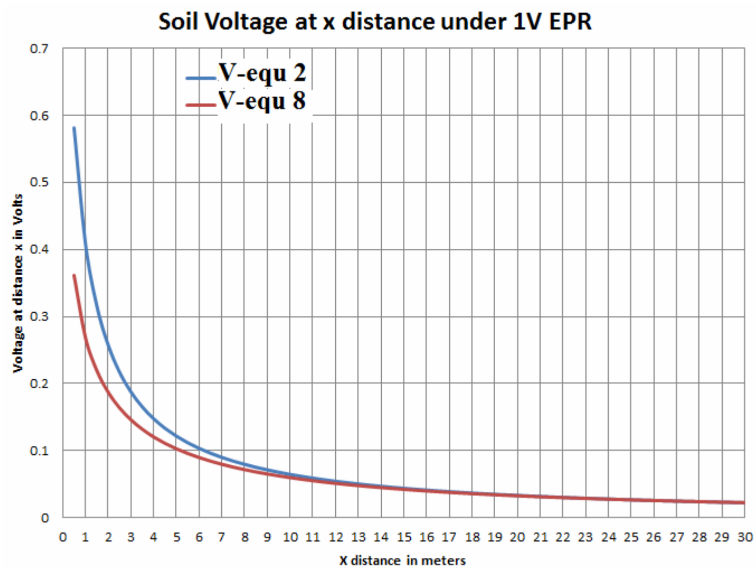

Figure 3. Soil voltage at distance x

3. Soil voltage field tests

The field tests were completed at UWS test ground as shown in Figure 3. The tests were completed on single electrode earth grid and on complex grid system as shown in Figures 4 and 5.

Figure 4. UWS field test area and the single electrode installation

As per this paper, there are two existing equations to compute the soil voltage due to existing EPR (equations (1) and (2)) and one proposed equation as per this paper analysis (equation (8)). The below works is to verify the validity of equation (8).

The first field test is completed on a single electrode. The installed electrode has the characteristics as shown in Figure 6, the equivalent radius of a full copper electrode is computed to be 1.6mm.

The field data is obtained by completing the tests at UWS ground and at another location which is located at Elizabeth Crescent in Kingswood NSW 2747. The test at Elizabeth is completed on an electrode length of 0.4meters. The computed and measured soil voltage is shown in Figure 7. The results show the accuracy of the proposed equation as per this paper. It should be noted that the soil resistivity at Elizabeth crescent for the depth of 0.5meters is homogenous

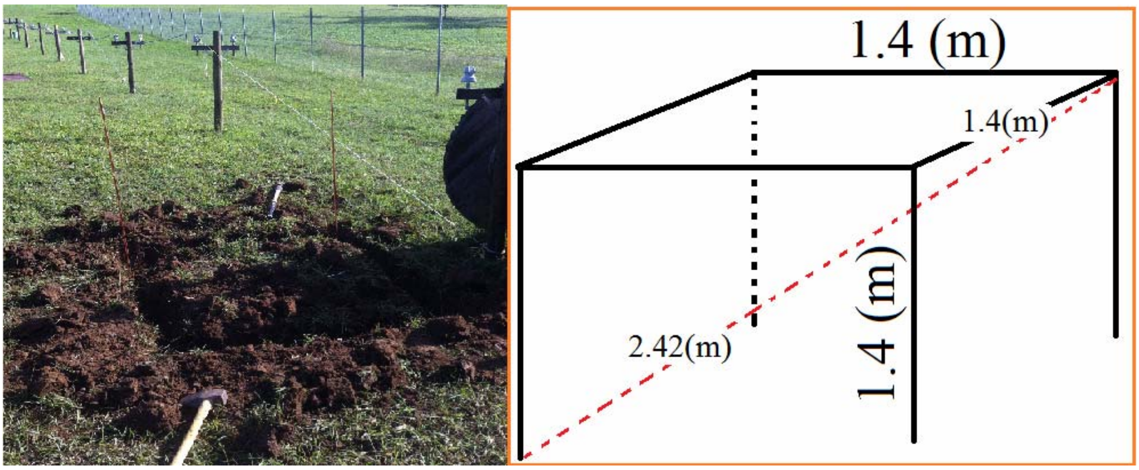

Figure 5. UWS complex earth grid field installation

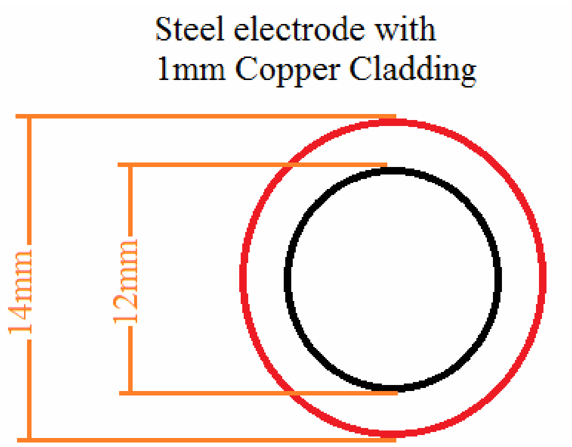

Figure 6. Steel electrode with 1mm copper cladding electrode

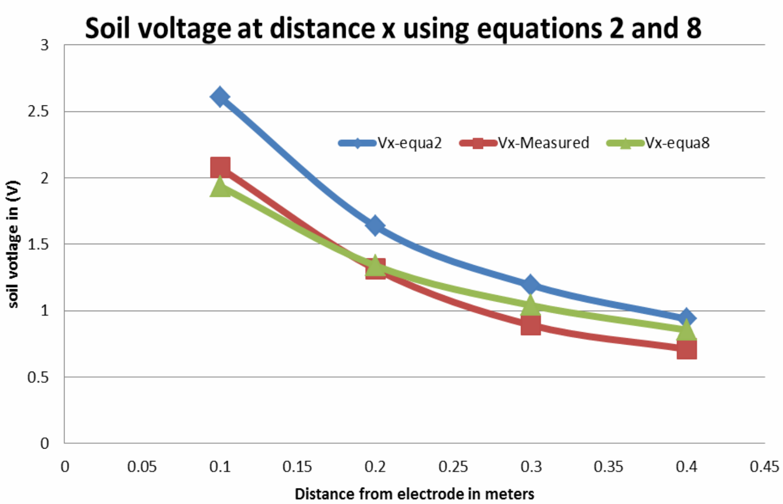

Figure7. Computation and measured data for Elizabeth street field test

Based on Figure 7, the use of equation 8 will yield lower error in comparison to equation 2 against the measured results. It should be noted that the soil resistivity structure at Elizabeth cresent was measured to be homogenous. The field works as shown below didn't find any deviation in the results when the soil resistivity structure is not homogenous. Figure 8 shows the layout of the installed electrode which covers different soil structure. When the surface soil resistivity is different to the first layer soil resistivity, the current in the electrode splits between both layers as shown in Figure 9. The field test shows that this current split will have no impact on the measurement and computation of the soil voltage.

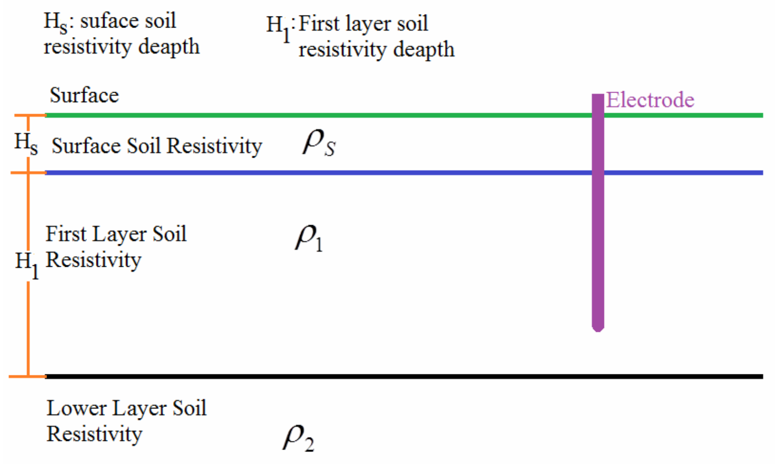

Figure 8. Electrode installed in non-homogenous soil

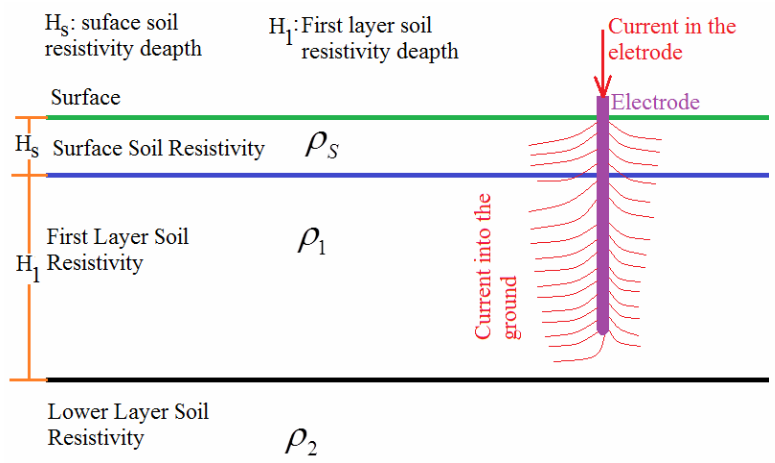

Figure 9. electrode current splits between both soil layers

At UWS field test, an electrode is installed in the middle of a track where crush rock and disturbed ground is installed. Figure 10 shows the computed soil resistivity of the area using the measured field data with the aid of engineering software. Figure 11 shows the computed results as per equations (2), (8) and the field tests results. The figure shows the advance accuracy of the developed equation over the existing one.

Further to the single electrode test works, the project completed the voltage soil measurements for the complex earth grid which is installed at UWS ground. The installed complex electrode grid is shown in Figure 5. Figure 12 represents the soil voltage simulation using equation 8 for an EPR of 1V. The figure shows that the soil voltage drops with distance which also supports the behavior of the EPR contour when assessing the step and touch voltages as illustrated in figure 1. The author works in [11] is used to compute the equivalent radius of the complex earth grid system.

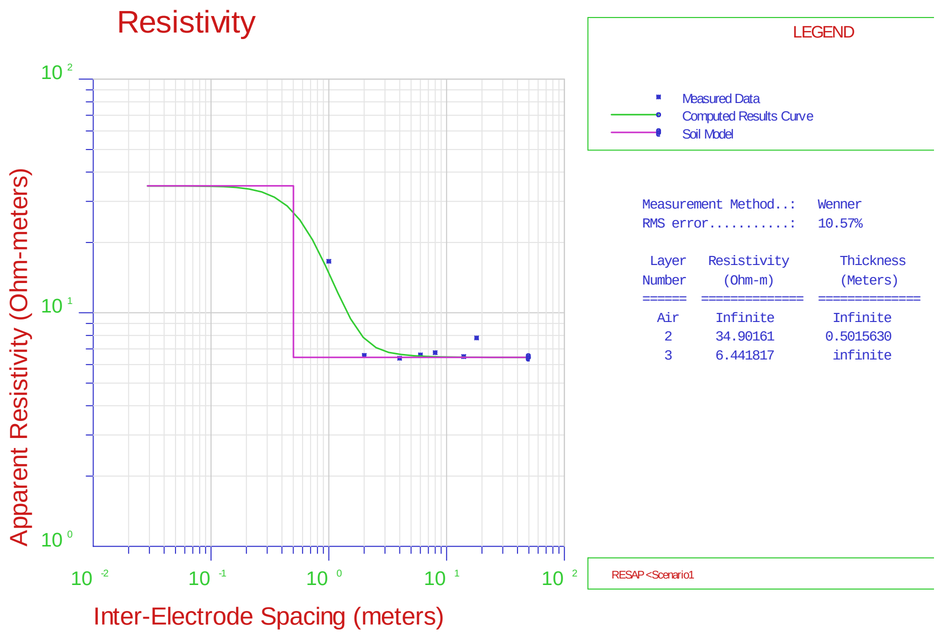

Figure 10. Soil Resisivity strucutre at the tested electrode at UWS

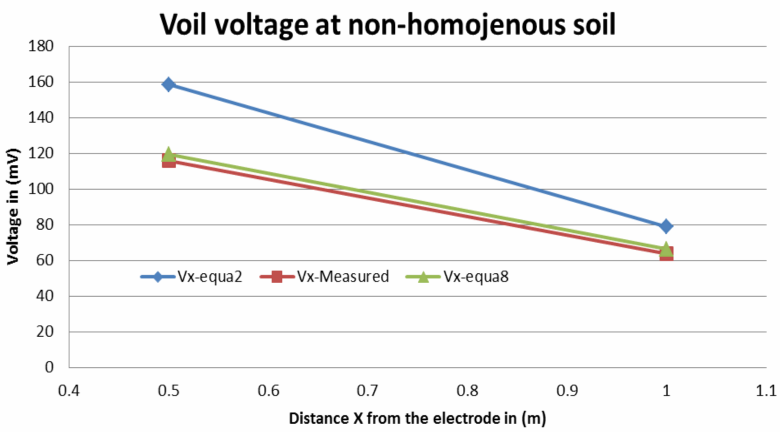

Figure 11. UWS field test to verify equation (8)

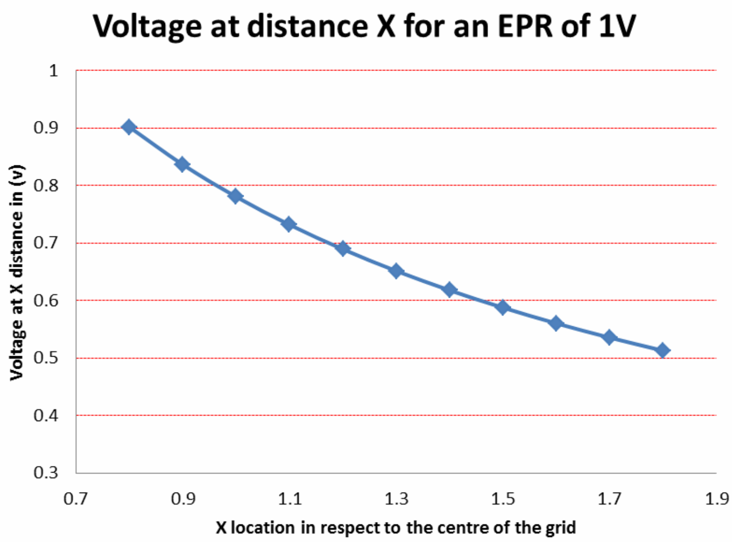

Figure 12. Voltage at distance X from the installed earth grid of EPR 1V

The field test followed the following steps to measure the voltage at distance X:
1. Locate the injection probe 24meters away from the grid. This represents 10 time the diagonal dimension of the grid
2. Measure the voltage using the potential probe
3. Measure the injected current for each measurements
4. Use the actual grid resistance which was previously measured to compute the EPR of the grid.
5. The voltage at distance X is computed by subtracting the voltage measured in step (2) from the grid EPR.

Figure 13 represents the test layout. The test results are shown in Figure 14.

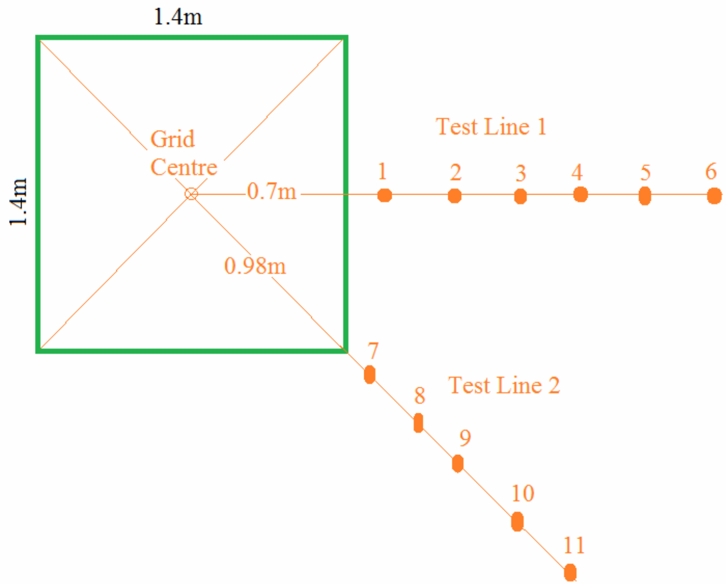

Figure13. Field test layout

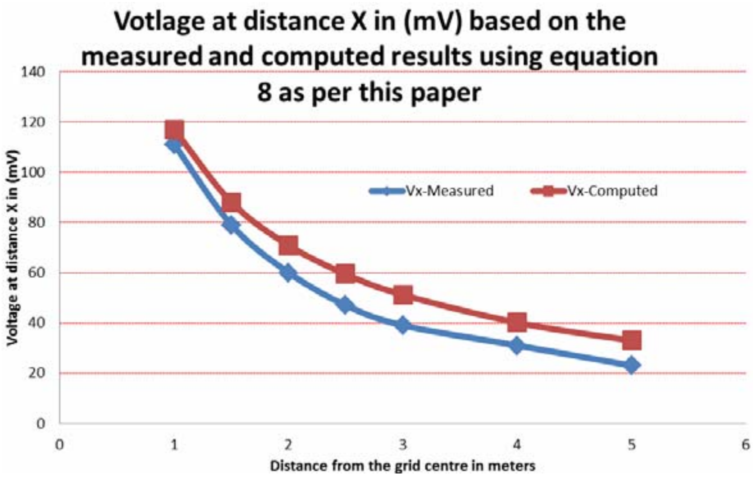

Figure 14. Voltage at distance X field test for line 1 as per Figure 12 layout and computed results

4. Soil voltage contour discussion

Under fault condition, the EPR of the faulted structure extends to the surrounding soil area. This EPR causes the step and touch voltages. The cited equations (1) and (2) do not yield accurate results as shown in the field test. The works in this paper establish the new equation (8) to compute the soil voltage contour. The field tests show the accuracy of the proposed methods over the existing ones. Furthermore, the work shows that the proposed equation is valid for homogenous and non-homogenous soil resistivity structure. In addition, the field's tests show that equation (8) along with the works in [11] yield accurate results when it comes to soil voltage computation for complex earth grid system.

The main benefits of this finding are:

- Accurate compute of the soil voltage contour
- Accurate computation of the touch voltage
- As shown in the next section, the soil voltage contour aid in accurate computation of the fault current distribution within the OHEW system

5. Conclusion

This paper highlights the relation between the soil voltage and the touch voltages. The work introduces the new equation to compute the soil voltage at distance x from the EPR. The field test shows the high accuracy reading of the new equation in regards to the existing ones. The novel findings of this paper add valuable information to the soil voltage computation which leads to higher accuracy computation when it comes to step and touch voltages.

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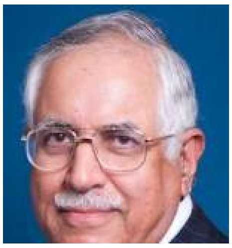

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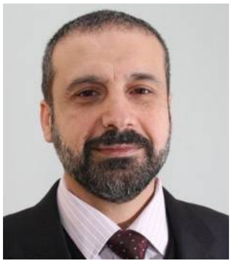

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