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Analysis of the impact of the OHEW under full load and fault current

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Abstract
Electrical Safety as a result of induced voltage is gaining more attention in the area of HV utilities. This paper discusses the Electrical safety in a pipeline running parallel to a HV transmission line, and the methods of calculating the mutual impedance between the HV and pipeline. In addition, it also introduces a method of calculating the induced voltage in the pipeline and its mitigation process**.**

Keywords: AC interference, OHEW, Soil resistivity, HV safety.

1. Introduction
AC interference between HV line and pipeline has been studied for many years; many countries generated their own standards and nominated the maximum allowable induced voltage in pipeline running parallel to the HV line. The most commonly used equations to measure the induced voltage are Westinghouse and Carson equations. The induced voltage in a pipe line could reach a limit which will jeopardize the safety of people. AC study for pipeline is a mandatory during the design of new pipeline running parallel to a HV transmission line. The study must be carried on the induced voltage under full load operations and fault current levels.
The existing of the coupling between over head HV wire and any metallic object, through the induced voltage, will raise the electrical safety concerns among designers and workers. After the AC analysis and the possible existence of induced voltage the mitigation can take several directions, it could be an amendment to the direction of HV line, an installation of an earth grid around the pipeline or some sort of insulation sections along the line.

2. Soil resistivity
One of the main elements in the study of the induced voltage as a result of HV lines is the determination of soil resistivity of the surrounding area for the proposed pipeline, There are many ways to measure the soil resistivity, below is the most commonly used methods:

2.1 Wenner method
Wenner method consists of four electrodes, two are used for current injection and two for potential measurement, figure 1 shows the Wenner method [1]. The soil resistivity formula associated with Wenner method is shown in equation 1:

$$\rho = 2\pi aR \tag{1}$$

where a is the probe spacing in meters, R is the resistance measured in Ohms.

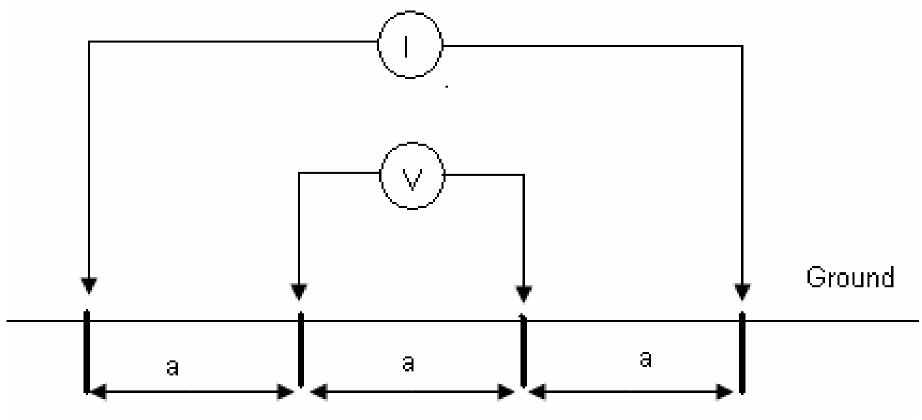

Figure 1. Wenner four probe arrangement

Wenner array is the least efficient from labor perspective. It requires four people to perform the task in a short time. On the other hand it is the best method when it comes to ration of received voltage per unit of transmitted current.

2.2 Schlumberger array

This method is more economical than the Wenner array when it comes to the man power required to perform the task. The outer electrode can be moved four or five time for each movement of the inner electrode. Figure 2 shows the arrangement for the Schlumberger Array. When contact resistance is a problem the reciprocity theorem can be applied to the Schlumberger array, this method is known as the Inverse Schlumberger Array. This method provides safer working environment for the tester under high current supply and also reduces the heavier cable that can be needed during the test. The soil resistivity can be calculated using equation 2 [1]:

$$\rho = \frac{\pi L^2 R}{2l} \tag{2}$$

where L is the distance the centre from the outer probe, *l* distance to the centre from the inner probe.

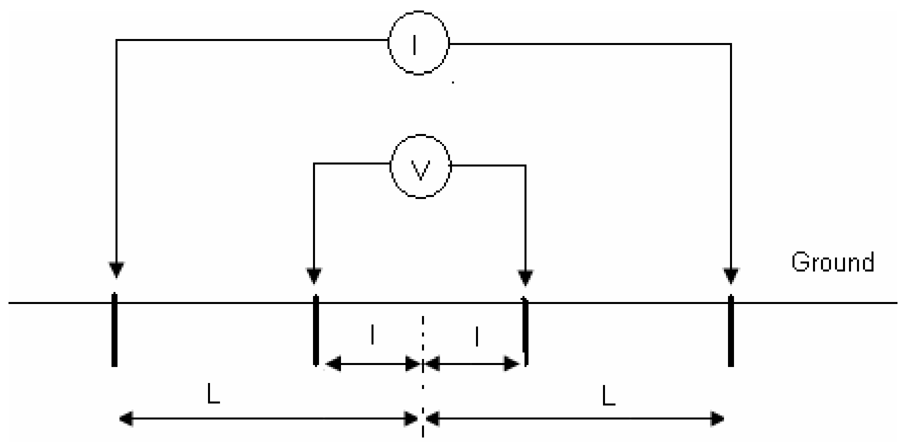

Figure 2. Schlumberger array layout

2.3 Driven rod method

This method is also called the three probe method or three pin method. This method is suitable the most for an area where the physical layout makes the usage of the previous two methods difficult, the soil resistivity under this method can be calculated using equation 3: [1].

$$\rho = \frac{2\pi dR}{\ln\left(\frac{8l}{d}\right)}. \tag{3}$$

where l is the length of driven rod in contact with earth in meters, d driven rod diameter in meters.

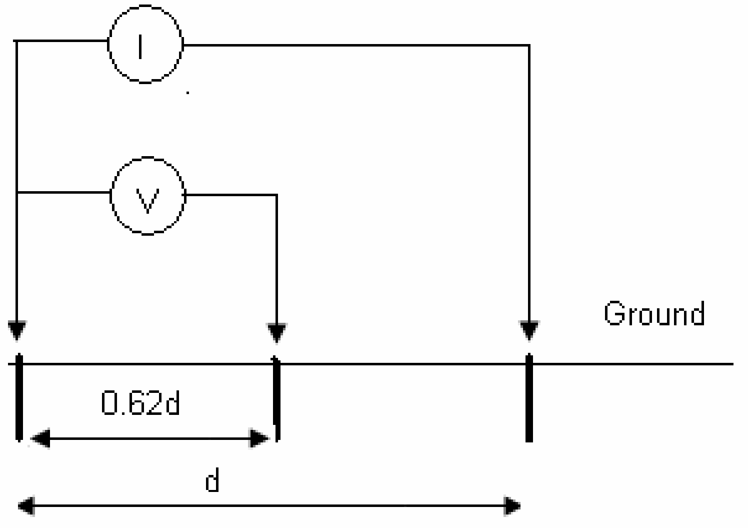

Figure 3. Driven rod test layout

3. Theoretical study

The flow of current in the phase conductor will create an electromagnetic field which is always sit at 90 degrees of the current vector, this magnetic field will induced a voltage on any metallic object laying parallel to the transmission line. The voltage induced in the pipe will depend on many variables such as: Carson's equations can be used to determine the impedance relation between the phase conductor and the pipe line. Figure 4 shows the layout of 3 phases HV power line and the pipe line without the existing of the OHEW.

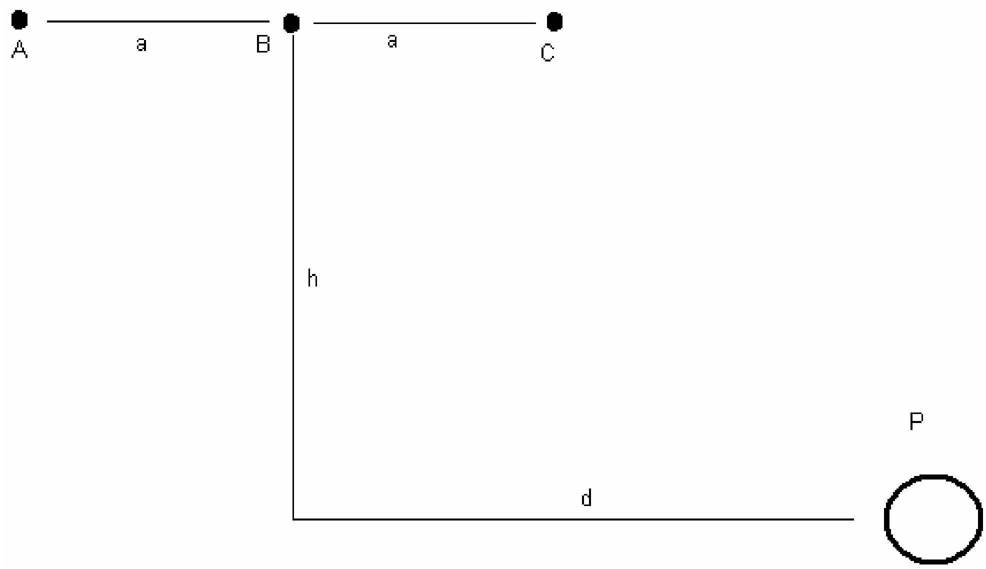

Figure 4. Layout HV transmission line and pipeline

The voltage induced in the pipe line due to the full load current flow in the transmission line can be found using equation 4 [2-3]:

$$V_p = I_A Z_{Ap} + I_B Z_{Bp} + I_C Z_{Cp} \tag{4}$$

where V_p is the voltage induced on the pipe, I_A, I_B & I_C are the full load phase current, Z_{Ap}, Z_{Bp} & Z_{Cp} are the mutual impedance between the phase conductor and the pipeline.

The mutual impedance can be found using equation 5:

$$Z_{Phase-pipe} = 9.88 \times 10^{-7} f + j28.938 \times 10^{-7} f \log_{10}\left(\frac{D_e}{D_{phase-pipe}}\right) \tag{5}$$

And $D_{phase-pipe}$ is the mean distance between the phase and the pipe, for example in Figure 4.

$D_{bp} = \sqrt{h^2 + d^2}$, and f is the frequency.

$$D_e = 658.4\sqrt{\frac{\rho}{f}} \tag{6}$$

The soil resistivity value can be found using equation 1 or 2 or 3 to calculate the value in ohms/m, then using equation 6 to determine D_e will make it easy to find the value of the mutual impedance for each phase in relation to the pipe.

3.1 Existing of the OHEW

The existing of the OHEW under the full load condition will increase the impact of the induced voltage on the pipeline; the OHEW will break the balance of the system and leads to higher induced voltage on the pipe line. Figure 5 shows the layout of the transmission like including the OHEW and the pipeline.

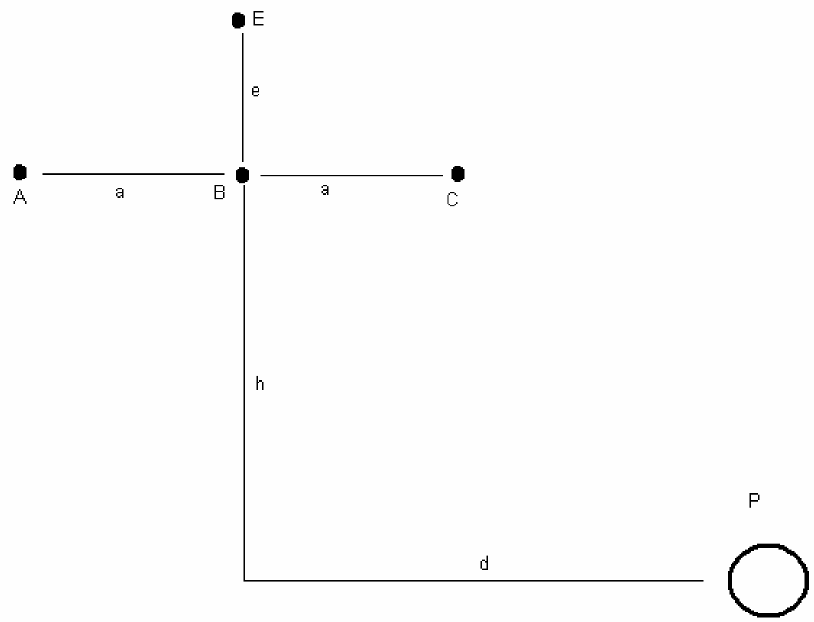

Figure 5. Layout of the transmission line with the OHEW and the pipeline

Equation 7 shows the relation between the induced voltage in the pipe and the phase conductors:

$$V_p = I_A Z_{AEp} + I_B Z_{BEp} + I_C Z_{CEp}. \quad (7)$$

where Z_{AEp}, Z_{BEp} & Z_{CEp} can be found using the following equation:

$$Z_{phase-E-p} = Z_{Phase-p} - \frac{Z_{Ep} Z_{phase-E}}{Z_E} \quad (8)$$

where $Z_{Phase-p}$, Z_{Ep} and $Z_{phase-E}$ can be determined using equation 5.and Z_E can be determined using equation 9:

$$Z_E = R_E + 9.88 \times 10^{-7} f + j28.938 \times 10^{-7} f \log_{10}\left(\frac{D_e}{R_{GM}}\right) \quad (9)$$

where R_{GM} is the geometric mean radius of the OHEW in m.

The existing of the OHEW will reduce the mutual impedance between the transmission line and the pipe but will change the angle of mutual impedance which leads to higher induced voltage on the tested pipeline.

4. Fault current

Under the fault condition the existence of the OHEW will reduce the impact of the induced voltage on the pipeline due to its shielding factor. Equation 5 can be used to calculate the mutual impedance between the phase and the pipeline, and the only changes will be to the mean distance $D_{phase-pipe}$ which can be found using equation 10.

$$D_{phase-pipe} = \sqrt[3]{D_{Ap} D_{Bp} D_{Cp}} \quad (10)$$

Equation 11 shows the induced voltage on the pipe under single line to ground fault stage with the absence of the OHEW:

$$V_p = I_{fault} Z_{phase-p} \quad (11)$$

Equation 12 shows the induced voltage under the existing of the OHEW:

$$V_p = I_{fault} \times K \times Z_{phase-p} \quad (12)$$

where K is the Shielding factor and can be determined using equation 13:

$$K = 1 - \frac{Z_{phase-earth} Z_{p-earth}}{Z_E Z_{Phase-P}} \quad (13)$$

Using different type of OHEW will lead to different Z_E which lead to different impact on the pipeline, by choosing an OHEW with its R_E is small and its R_{GM} is bigger, the shielding factor will have more impact on the induced voltage.

5. Case study

Figure 6 shows the arrangement of a HV transmission line near an existing pipeline, the OHEW studied are:

- Pluto 19/3.75 AAC with GMR at full load of 0.00676m and resistance of 0.168 Ohms/km
- Triton 37/3.75 AAC with GMR of 0.00982m and resistance of 0.0869 Ohms/km
- Leo 7/2.5 AAC with GMR of 0.00244m and resistance of 1.02 Ohms/km.

Full load current is 500A and the fault current is 4.8kA single phase to ground. The parallel distance is 10km. with clearance time of 0.5s the safe induce voltage is 50V.

5.1 Full load

First calculation will ignore the existing of the OHEW in the circuit to show the impact that the OHEW can have on the induced voltage under the full load current.
Using equation 5 gives:

$$Z_{Ap} = 0.04935 + j0.24454 = 0.2494\angle 78.5$$
$$Z_{Bp} = 0.04935 + j0.24790 = 0.252\angle 78.7$$
$$Z_{Cp} = 0.04935 + j0.25153 = 0.256\angle 78.8$$

Equation 4 gives, $V_p = 2.7\angle -128V / km$. For the 10km there is a 20.7V that is induced on both end of the pipe, this value is under the safe threshold.

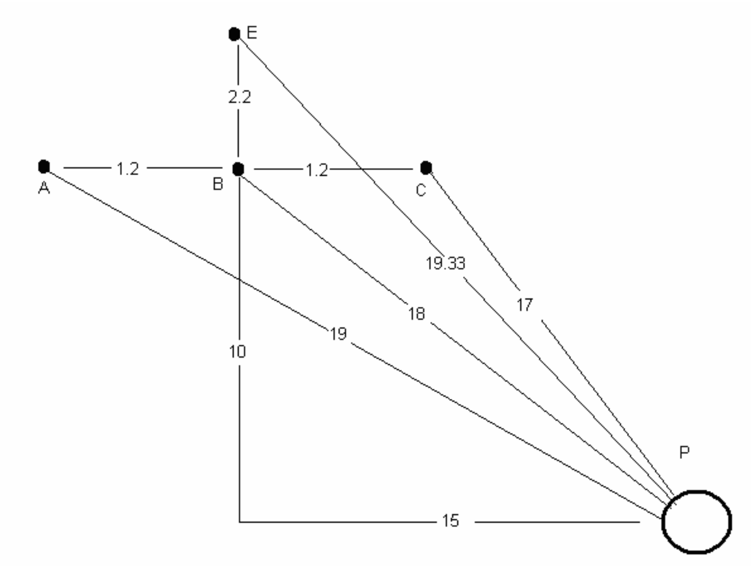

Figure 6. Layout of the study system

Under the existence of the OHEW, and using the nominated conductor for the earth wire, the following results have been calculated.

Pluto OHEW:

$$Z_{E-Pluto} = 0.77\angle 73.7$$
$$Z_{AEp} = 0.13\angle 70$$
$$Z_{BEp} = 0.13\angle 72.3$$
$$Z_{CEp} = 0.14\angle 71$$

Using equation 8, $V_p = 6.3\angle 33V / km$. For the 10km there is a 63V that is induced on both end of the pipe, this value is above the safe threshold.

Triton OHEW:

$Z_{E-Triton} = 0.73\angle 79.3$

$Z_{AEp} = 0.1212\angle 76.59$

$Z_{BEp} = 0.12126\angle 76.14$

$Z_{CEp} = 0.1239\angle 75.896$

Using equation 8, $V_p = 4.67.3\angle -6.772V / km$. For the 10km there is a 46.7V that is induced on both end of the pipe, this value is under the safe threshold.

Leo OHEW:

$Z_{E-Leo} = 1.34\angle 37$

$Z_{AEp} = 0.205\angle 65.1$

$Z_{BEp} = 0.207\angle 64.6$

$Z_{CEp} = 0.208\angle 64.86$

Using equation 8, $V_p = 3.93\angle 211.3V / km$. For the 10km there is a 39.3V that is induced on both end of the pipe, this value is under the safe threshold. Results shows that using OHEW with different characteristics will have different impact on the induced voltage in the pipe line.

5.2 Fault current

First case study is conducted by ignoring the impact of the earth wire during fault stage. Using equation 11 to determine the mean distance:

$$D_{phase-pipe} = \sqrt[3]{19 \times 18 \times 17} = 17.38$$

$$V_p = 4800 \times 0.254\angle 78 = 1219\angle 78$$

Taking into consideration the existing of the OHEW will introduce the shielding factor, below is the shielding factor for the nominated OHEW.

Pluto OHEW:

$K = 0.526\angle -7$

$V_p = 641.299\angle 71V / km$

Triton OHEW:

$K = 0.491\angle -3.1$

$V_p = 598.529\angle 75V / km$

Leo OHEW:

$K = 0.803\angle -13.6$

$V_p = 978.017\angle 65V / km$

There is a significant reduction in the induced voltage when using different OHEW. This reduction will make the mitigation approach to achieve required safe voltage easier. Figure 7 shows the induced voltage for different OHEW

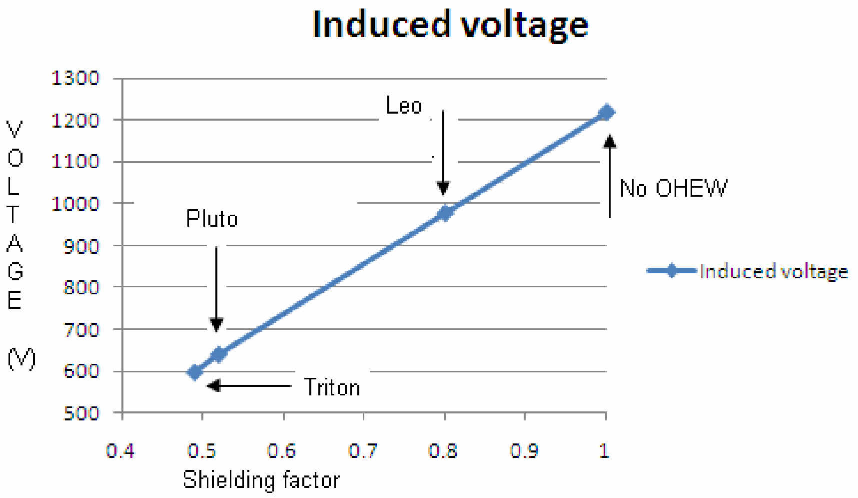

Figure 7. Induced voltage

6. Mitigation

The fault current stage is the worst case scenario. In this case, the mitigation techniques can be accomplished by installing two electrodes at each end of the pipe; this can reduce the high induced voltage. A full potential test must be carried out to determine the impedance of the pipe. However, if the pipe is still at design stage, the maximum impedance can be taken as 6.28 ohms according to the Australian standards AS/NZS 4853:2000. Figure 8 shows the layout of the proposed mitigation;

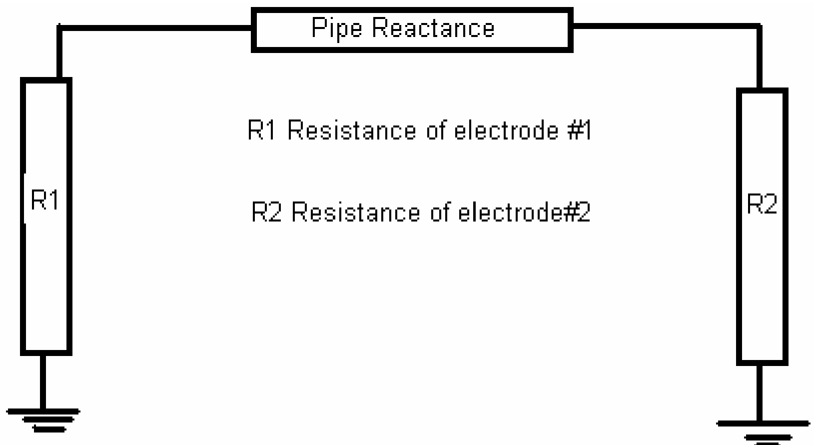

Figure 8. Pipe and electrode resistance circuit

$I = \frac{V}{Z_{Total}}$. Where V is the induced voltage and Z_{Total} is the total impedance in the circuit.

The pipe impedance is represented by it is reactance X, therefore the total impedance can be found using equation 14.

$$Z_{Total} = \sqrt{(R_1 + R_2)^2 + (X_{pipe})^2} \tag{14}$$

The electrode must be chosen to guarantee a drop voltage on the electrode less than 50V under the condition where 50V is the save touch voltage.

$V_{R1} = I \times R1$. Taken into consideration that the two electrodes are identical, therefore:

$$I = \frac{V}{\sqrt{(2R_1)^2 + (X_{pipe})^2}}. \tag{15}$$

Figure 9 shows the resistance value for the electrode and the drop voltage. in order to achieve a safe induce voltage it is required to install two electrodes at each end of the pipe with resistivity value less than 0.2 ohms if there is no OHEW.

Figure 10 shows the induced voltage in the electrode under the existing of the Triton OHEW. In order to achieve a safe induce voltage it is required to install two electrodes at each end of the pipe or resistivity value less than 0.5 ohms if there is Triton OHEW installed.

7. Conclusions

The existing of the OHEW could have positive and negative impact on the circuit; under full load situation the existing of the OHEW will increase the induced voltage. However under fault current the existence of the shielding factor for the OHEW will reduce the induced voltage and make mitigation work easier and cheaper. If the fault current stage has been eliminated by installing a fault current limiter there is no need for the OHEW in the system unless it is required for different activities

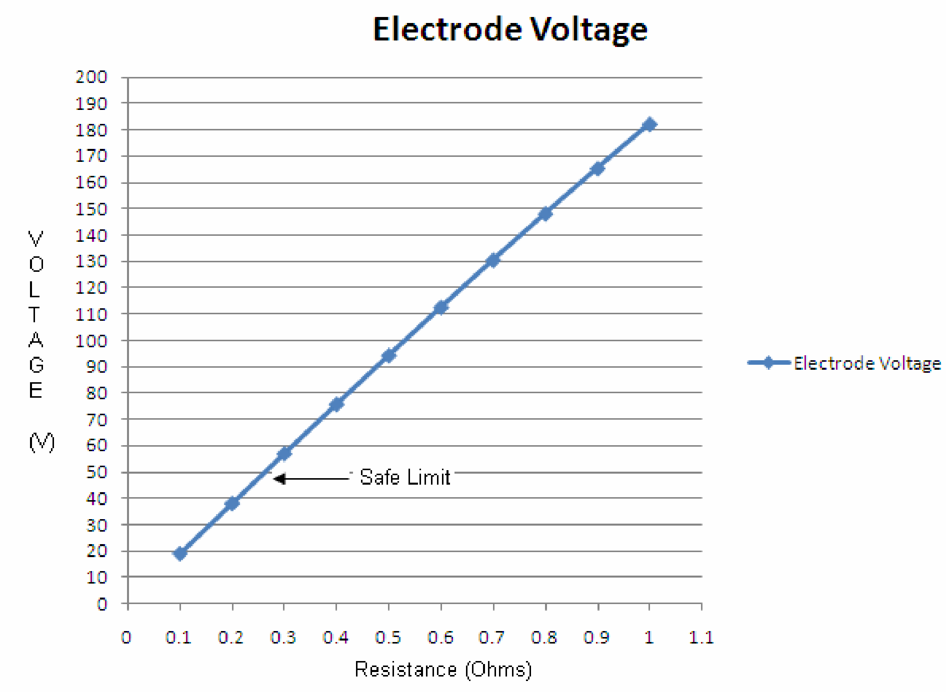

Figure 9. Induced voltage against the electrode resistivity.

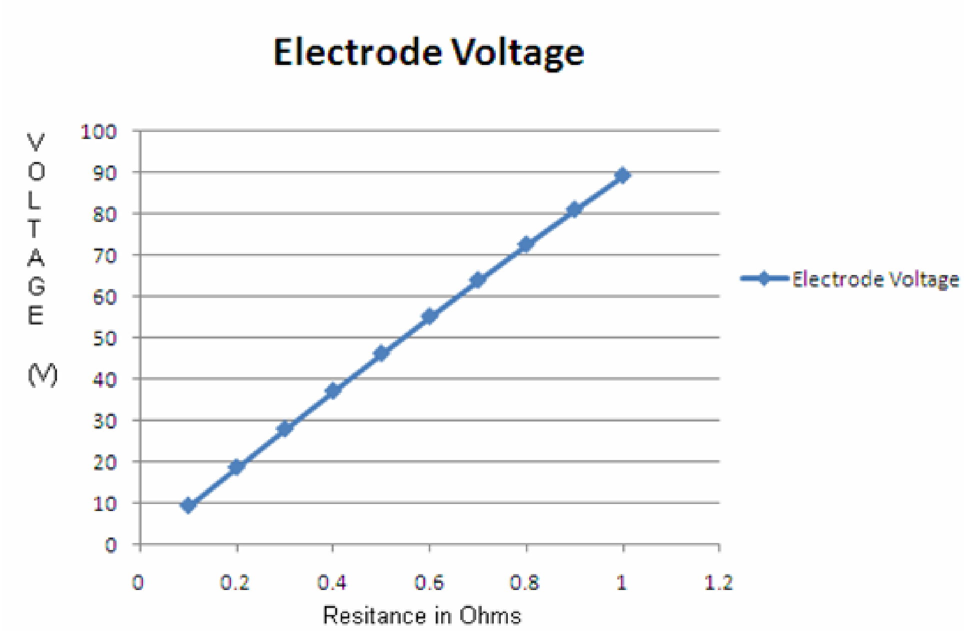

Figure 10. Electrode voltage under the existing of the OHEW.

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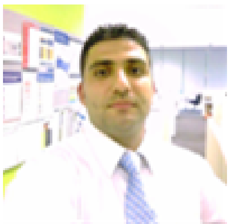

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