Eliminating the Transmission Pole Earth Potential Rise Within Residential Area by Using High Resistance Steel Structures

M. Nassereddine *Member IEEE*, J. Rizk, M. Nagrial *Sr. Member IEEE* and A. Hellany *Member IEEE*

Abstract: **High Voltage (HV) transmission mains form important assets in electrical networks. The existence of this infrastructure within the community necessitates effective earthing design to ensure safety compliance of the system. OHEW (Over Head Earth Wire) forms parts of the HV transmission mains, as such the OHEW plays an important role when it comes to fault current distributions and lightning protection for the transmission mains assets. The bonding between the OHEW and the conductive poles introduces the risk of step and touch voltages under substation fault. This research designs the pole earth grid to reduce the actual touch and step voltages to an acceptable limit. No research cited addresses the design of the steel poles to eliminate the high step and touch voltages. This paper endeavors to provide information in regards to the split factor and its relation to the pole grid resistance. Furthermore, the works introduces the novel arrangement of the steel poles to eliminate the EPR issues at the transmission structures under substation fault. The paper shows the advanced accuracy of the proposed new method in respect to the existing research methods. A Case study is also addressed to support the proposed theoretical study.**

Key words: Coupling Factor, Fault Current Distribution, OHEW, Split Factor, Steel Poles

I. Definitions

OHEW: Over Head Earth Wire, also known as the ground wire.
EPR: Earth Potential Rise.
I_g : Substation fault current. The current that flows into the substation earth grid under fault condition
I_f : Fault current
I_e : is the OHEW return fault current as seen from the substation
Z_s is the OHEW self-impedance of the average span in ohms
z_s is the OHEW self-impedance in ohm.km
z_{gw} is the mutual impedance of the OHEW in ohm.km
R_S is the OHEW AC resistance as per the manufacturer specification
Z_p is the pole earth grid resistance in ohms
D_{GM} = The distance between the OHEW and the faulted phase in meters
$Z_{OHEW-in}$ is the OHEW input impedance
R_{GM} is the OHEW geometric mean radius
n is the number of poles
I_{P1} is the current in the pole grid for the first pole out of the substation
I_{Pn} is the current in the pole grid for pole number n
δ_f : is the Substation Split Factor. It represents the percentage of the fault current that is injected into the substation earth grid.
Infinite condition: When the OHEW input impedance at the fault location cannot capture the entire length of the system and therefore only a section of the OHEW system is considered for $Z_{OHEW-in}$

II. Introduction

HV projects are expanding worldwide to meet the increase in human population. The rate of neighboring between high voltage infrastructure and residential area is increasing. Substation and transmission lines are located within high density population. As the safety of people sits on top of the highest priorities, earthing system design forms an important part of the power augmentation. Under substation fault condition, the ground voltage rises due to the fault current; the high earth potential rise (EPR) could reach a value which jeopardizes the safety of workers and people. Many standards address the allowable safety limits for human body [1-4].

Within the substation, engineers can apply controls to ensure that step and touch voltages are within the acceptable limits, these controls can be in the form of bonding all conductive structures to the earth grid to ensure same potential levels across the entire area [5, 6]. The engineer could also deploy high soil resistivity top layer to increase the allowable safety limits [7, 8]. These measures are not available when it comes to conductive transmission poles. Transmission poles are located near residential properties, close proximities to fences, water pipes, and play grounds. Bonding all the surrounding conductive structures to the earth grid of the pole is not an option in many cases.

Many researchers address the earthing system design for transmission poles; the approach is to ensure that the earth grid is low to decrease the EPR value to acceptable limits [9-

M. Nassereddine, J. Rizk, M. Nagrial and A. Hellany are with the University of Western Sydney, Locked Bag 1797 Penrith South DC 1797, NSW Australia(e-mail: m.nassereddine@uws.edu.au)

12]. Lowering the earth grid of the poles requires design and grid installation, these two steps cost money and human resources.

The use of conductive poles is increasing worldwide due to its low maintenance and production cost. The installation of the conductive poles reduces the grid resistance of the transmission poles due to their conductive characteristics. However, the conductive poles introduce the risk of touch voltage at the pole. This touch voltage can be controlled by following the earthing design steps. The work in this paper revolves around the steel poles. The following shows the advantages that the steel poles have over concrete poles:

- Steel is lighter than Concrete poles
- Cost less to ship
- Less expensive equipment to handle and install.
- Under accident damage, replace only the bottom section

In addition to the above advantages, the paper highlights the possibility of the steel pole to be designed to eliminate the EPR issue at the base of the pole. As the pole EPR is related to the pole grid resistance and the pole grid current, the paper works on the pole resistance as seen from the overhead earth wire (OHEW) connection points. The work endeavors to provide information in regards to how to control the pole EPR by controlling the resistance as seen from the OHEW connection point. The simulation and the case study results within the paper show the advanced accuracy for the proposed method and the safety enhancement around conductive poles. A case study is included.

III. THEORETICAL STUDY

A. Design Factors

Substation fault current splits between the substation earth grid and the OHEW input system. The magnitude of the OHEW current depends on the following factors:

- Fault current magnitude at the substation
- Substation earth grid resistance
- Pole earth grid resistance as seen from the OHEW connection point
- Conductor arrangement on the poles
- Type of the OHEW
- Number of the OHEW (in this paper, a single OHEW is used)
- Soil resistivity structure

B. EPR Analysis

Under substation fault, the fault current splits between the substation earth grid and the input impedance of the OHEW system. The split factor depends on the following:

- Substation earth grid resistance
- Pole Grid Resistance as seen from the OHEW connection point
- Mutual impedance between the OHEW and the faulted phase
- Self-impedance of the OHEW

Under an infinite condition, equation 1 can be used to compute the OHEW input impedance. Equation 2 can be used to compute the split factor.

$$Z_{OHEW-in} = \frac{Z_s}{2} + \sqrt{\frac{Z_s^2}{4} + Z_s Z_p} \quad (1)$$

$$\delta_f = \frac{\left(1 - \frac{z_{gw}}{z_s}\right) Z_{OHEW-in}}{Z_{OHEW-in} + Z_g} \quad (2)$$

The mutual impedance z_{gw} can be found using equation 3 and the self-impedance z_s can be found using equation 4 [13, 14]

$$z_{gw} = 9.88 \times 10^{-7} f + j28.938 \times 10^{-7} f \log_{10}\left(\frac{D_e}{D_{GM}}\right) \quad (3)$$

$$z_s = R_s + 9.88 \times 10^{-7} f + j28.938 \times 10^{-7} f \log_{10}\left(\frac{D_e}{R_{GM}}\right) \quad (4)$$

$$D_e = 658.4\sqrt{\frac{\rho}{f}} \quad (5)$$

The substation grid fault current that used the OHEW as a return path can be found using equations 6 and 7 [15, 16]

$$I_g = I_f \times \delta_f \quad (6)$$

$$I_e = I_f \left(1 - \delta_f\right) \quad (7)$$

From previous works [17, 18], the pole grid current can be found using equations 8 and 9

$$I_{P1} = \frac{\delta_e Z_{OHEW-in} - \frac{z_{gw}}{z_s} Z_{OHEW-in}}{Z_{OHEW-in} + Z_P} I_f \quad (8)$$

$$I_{Pn} = \left[\frac{Z_P}{Z_\infty + Z_P}\right]^{n-1} I_{P1} \quad (9)$$

From previous works [19, 20], the remaining current into the OHEW sections can be found using equation 10:

$$I_{OHEW-\mathrm{Re}maining} = \frac{z_{gw}}{z_s} I_f \quad (10)$$

As per the above equations, the pole resistance as seen from the OHEW connection point plays an important role when it comes to fault current distribution. Figure 1 shows the behavior of the split factor under different pole grid resistances. The output of the figure shows that by increasing the pole grid resistance the fault current split factor increases thus leading to higher percentage of the fault current to be injected at the substation grid.

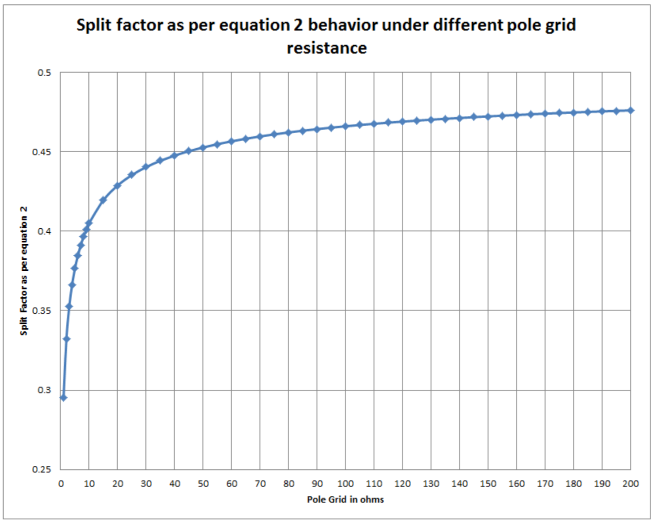

Figure 1: split factor behavior under different pole grid current

Figure 2 shows the pole EPR under substation fault for different pole grid resistance, higher pole grid resistance leads to higher pole EPR. Figure 3 shows the pole shunt current behavior under different pole grid resistance; it is shown that higher grid resistance as seen from the OHEW connection leads to lower pole grid resistance.

The following observations were deduced from figures 2 and 3:

- Higher pole grid resistance leads to lower pole grid current under substation fault. However, the pole EPR is higher under higher pole grid resistance
- Lower pole grid resistance leads to higher pole grid current under substation fault. However, the pole EPR is lower under lower pole grid resistance.

Based on the above two points, the idea is to have the pole grid as seen from the OHEW connection to have high resistance while the pole grid located below ground surface has low resistance.

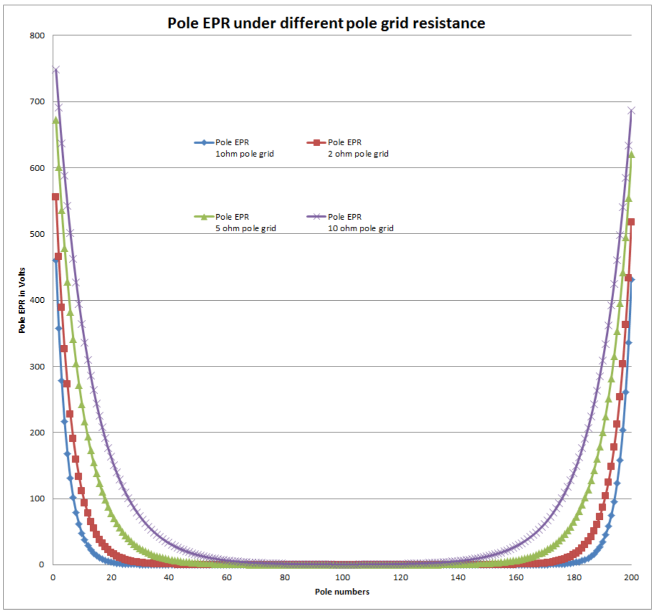

Figure 2: Pole EPR under substation fault under different pole grid resistance

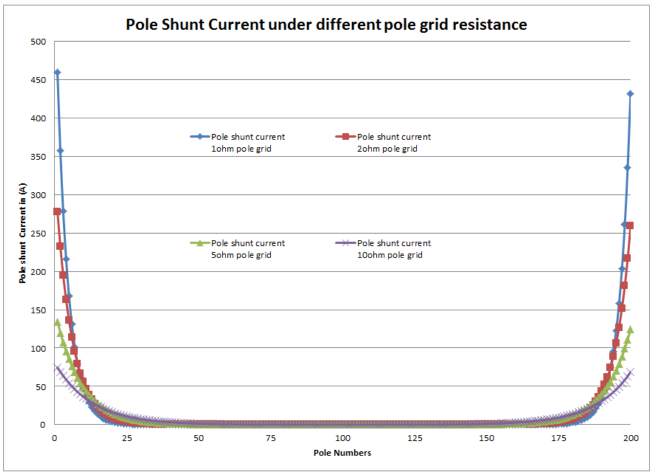

Figure 3: Pole Shunt Current under different pole grid resistance

IV. Transmission Pole Novel Arrangement

Figure 4 shows the pole resistance arrangement as seen from the OHEW connection for a conductive pole. The resistance for the section located above ground is formed by the steel pole. The idea is to increase the impedance located above ground to a high resistance while the section located below ground has low resistance. The pole EPR that is related to step and touch voltages is presented by the grid resistance located below the ground level. Figure 5 shows the pole EPR under high impedance section located in the middle of the pole. The steel tower resistance is increased by increasing the above ground resistance as defined in figure 4. The simulation inputs are the same as the one in figure 2 except for the grid resistance for the section located below the ground that has 10 ohm grid resistance. The reduction in the EPR under the proposed condition is clearly shown. The high pole input impedance as seen from the OHEW which is dominated by the section located above ground, forces low current to flow to the ground. The low current with the standard 10 ohm grid resistance leads to low pole EPR.

The proposed novel method is most suitable for the steel pole due to the following factors:

- In order for the timber poles to reflect the novel method, a resistor with high value should be installed between the drop earth lead and the ground electrode. This process costs money and adds load and maintenance on the pole.
- In order for the concrete pole to reflect the novel method, the following should be met:
  - The OHEW should be electrically isolated from the pole steel
  - Drop earth wire should be used with high resistor value to connect the OHEW to the pole electrode, similar condition to the timber poles
- Figure 6 represents the novel arrangement of the steel pole. The nonconductive material exists to provide the high strength ability for the pole. the semi conductive material exist to provide the required resistance value for the steel pole as seen from

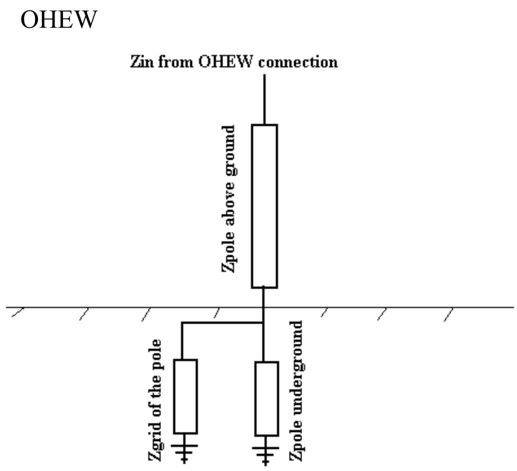

Figure 4: Pole Grid resistance as seen from the OHEW connection

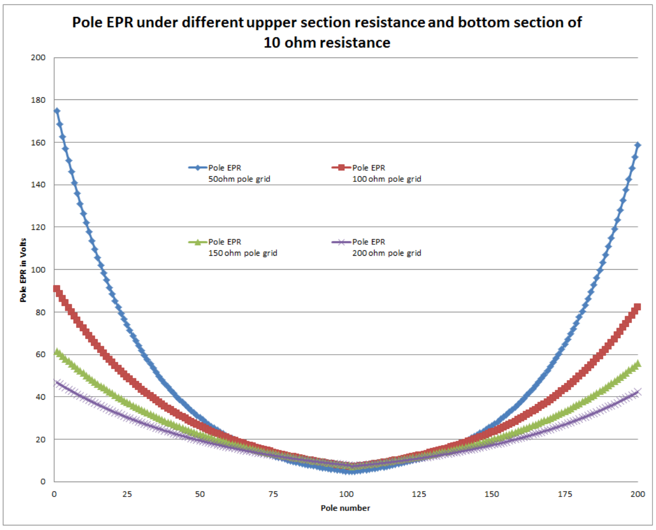

Figure 5: Pole EPR under different upper section resistance

The arrangement in figure 6 is easy to construct due to the following:

- Transmission steel poles are formed of minimum two sections
- Easy to modify steels
- Semiconductor can be chosen from a wide range
- Non-conductive materials with high physical strength are widely available
- The designer have the control to locate the high strength non-conductive material at the location where minimum forces exist
- The semiconductor material can be located where minimum physical tension is applied.
- The semiconductor material can be supported by non-conductive material for more strength if required.

V. Proposed Novel Method and Fault Current Distribution

The fault current distribution between the OHEW and the substation grid will change in value when the pole grid resistance changes. Figure 2 shows the increase in the split factor which will lead to the increase in the substation grid when the pole grid resistance increases. Also the increase will reach the saturation stage where the OHEW current maintains its strength as per equation 10. Figure 2 shows an increase of less than 10% for the substation grid current when the pole grid increases from 10 ohm to 200 ohms. This increase in the substation fault current can be controlled using existing control measures as detailed in the introduction. It should be noted, the OHEW can be chosen to reduce the increase of the substation grid current [20, 21].

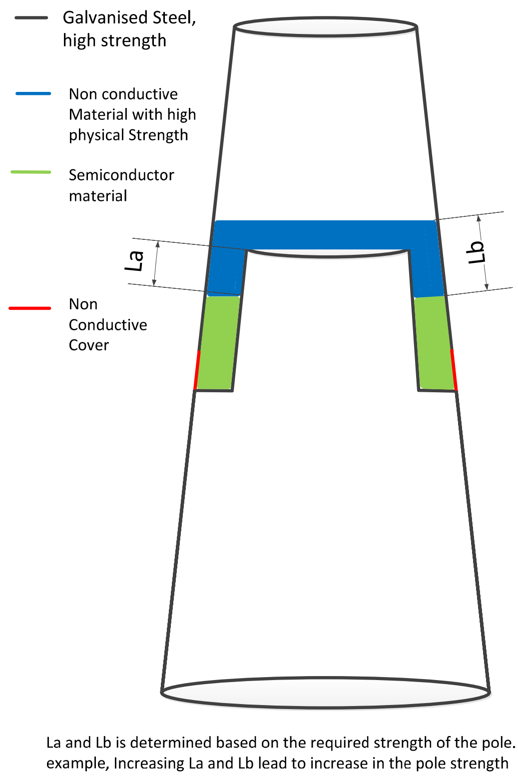

Figure 6: Steel pole arrangement to reflect the high resistance upper section

VI. Novel Method Discussions

The aim of this paper is to reduce the pole EPR at the base of the pole to ensure safety compliance when it comes to step, touch and transfer voltages. Section 2 shows the relation between the split factor and the pole grid resistance. The increase in the pole grid resistance as seen from the OHEW connection point reduces the pole grid current as shown in equations 8 and 9. The reduction in the pole grid resistance for the section located below ground (refer to figure 4 for more information) reduced the pole EPR which reflect on the step and touch voltages.

Section 3 used the findings in section 2 to show the reduction in the pole EPR when the pole resistance increases as seen from the OHEW connection point while the pole grid for the section located below ground is maintaining low resistance value. Figure 5 shows the reduction in the pole EPR under different steel pole resistance. The changes in the steel pole resistance as seen from the OHEW connection is due to the changes in the semi-conductive material characteristics installed as per figure 6. The findings in this paper clearly show how it is possible to control the pole EPR that is related to the step and touch voltages using high resistance section within the steel pole. This novel method ensures safety compliance for the steel transmission poles under substation fault. Furthermore, the findings within the paper enhance the use of the steel poles within the transmission networks especially where the steel poles are located within high density population.

VII. Case Study

An approval to construct a new 132kV substation is granted for a remote area in NSW, the substation will be located in high population density at the end of the development. Also, the first 10 poles are located within the same high density area while the other 70 poles are located in a remote area. The following is the design inputs:

- Feeder total length is 8km
- Average span is 100m
- OPGW is used as the OHEW
- Vertical arrangement is used
- Phase C (distance to the OHEW) is 3m
- Single line to ground fault current is 7000A
- Primary clearance time is 350ms
- New substation earth grid resistance is 0.2 ohm
- The supply substation earth grid is 0.2 ohm
- Average soil resistivity is 30ohm.m
- Pole grid resistance is 10 ohm

Equations 3 and 4 are used to compute the mutual and self-impedance of the OPGW

$$z_{gw} = 0.0494 + j0.322\,\Omega.km$$

$$z_s = 0.284 + j0.756\Omega.km$$

In Australia, AS7000 states that for remote areas, no earthing assessment for step and touch voltage is required. Therefore, the interest lies in the first 10 poles as well as the substation. Figure 7 shows the pole EPR for the first 20 poles. The figure shows high EPR at the first 15 poles. It should be noted: this assessment is made for a standard steel pole without the high resistance section. The first pole is exposed to 630V EPR.

The split factor is computed using equation 2:

$$\delta_f = 0.49$$

The grid current is computed using equation 6:

$$I_g = 3442A$$

The substation EPR is computed to be 688Volts

The transmission system re-assessed using the steel poles arrangement as per figure 6 with 200ohm upper section resistance. Figure 8 shows the EPR for the first 20 poles. The first pole is now exposed to 37V EPR.

The split factor is computed using the new steel pole resistance as seen from the OHEW connection point, the substation grid current and the substation EPR are reassessed:

$$\delta_f = 0.569 \quad I_g = 3983A \quad EPR_{Sub} = 796.6V$$

The substation EPR increases by 108V. Table 1 represents the findings of the case study. The findings show the advance in EPR under the novel condition.

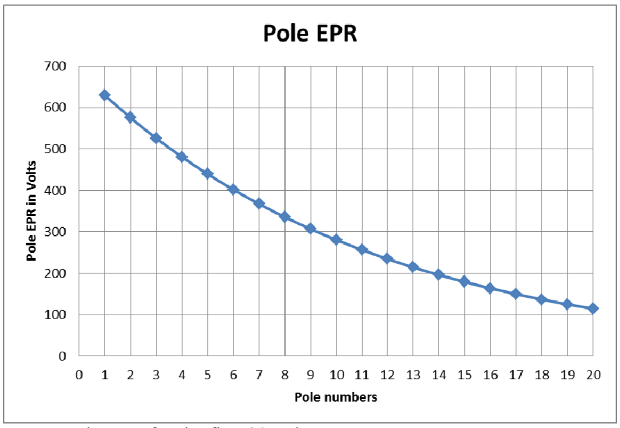

Figure 7: Pole EPR for the first 20 poles.

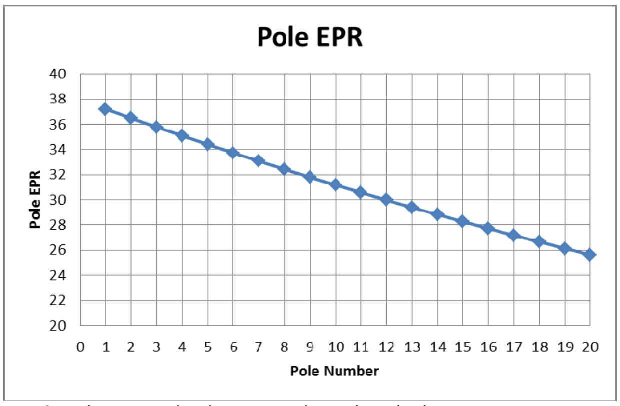

Figure 8: Pole EPR under the proposed novel method

Table 1: Pole and Substation EPR under existing and proposed novel method

Pole Numbers	EPR under normal Analysis (V)	EPR under the proposed Method (V)	Difference (V)
1	629.25	37.20	-592.05
2	575.25	36.48	-538.77
3	525.89	35.77	-490.12
4	480.76	35.07	-445.68
5	439.50	34.39	-405.11
6	401.79	33.73	-368.06
7	367.31	33.07	-334.24
8	335.79	32.43	-303.36
9	306.97	31.80	-275.17
10	280.63	31.18	-249.45
Substation	688.00	796.60	108.60

VIII. Case Study Discussions

The case study shows the advance in using the proposed method especially when it comes to EPR and human safety. The findings in table 1 show that the proposed method reduces the pole EPR within the residential area by a significant value. The new method reduces the first pole EPR to almost 5% of the existing method pole EPR. The reduction is from 629.25V to 37.2V.This reduction eliminates the issues of the touch and step voltages on transmission poles. The novel arrangement increases the substation EPR by only 108.6V. This increase is insignificant to the substation due to its large area in comparison to the pole grid area. Furthermore, the existing mitigation can be used to ensure that this addition 108V will not have any safety impact on the substation.

The steel pole can be designed to ensure the pole EPR is always lower than the allowable touch and step voltages. This eliminates the design requirements for the transmission pole. This elimination reduces cost during the design stage as well as construction stage.

IX. Conclusion

This paper introduces the new layout of the transmission steel pole to eliminate the risk of step and touch voltages at transmission line under substation fault. The theoretical study which is supported by the case study shows that it is possible to eliminate the risk associated with the pole EPR by following the proposed concept. It is clearly shown that the pole EPR can be reduced significantly under the proposed layout of the steel poles with minimum impact on the substation EPR. The result came as expected during the design stage and shows advanced accuracy in respect to the existing research methods. This innovation has a significant positive impact on the human safety when it comes to transmission pole EPR under substation fault. Also it has a significant reduction in cost as it eliminates the need for earthing system design as well as earth grid installation at the base of each pole.

X. Further Research

Further tests to verify the above proposed method are ongoing at the University of Western Sydney grounds. A mini transmission line of 20 spans is currently under construction to allow further investigation in this area. The tests also cover the construction of a mini transmission steel pole as shown in figure 6 to study the behavior of the semiconductor materials during weather changes and fault currents. The results will be published in future papers.

References

[1] IEEE80 guide to safety in AC substation grounding, 2000' (IEEE, New York, 2000).

[2] AS2067-2008 Substation and high voltage installations exceeding 1kV AC

[3] AS7000:2010 Overhead line design-detailed procedures

[4] AS/NZS 60479:2010 – Effects of current on human beings and livestock

[5] Nahman J, Paunovic I. " Mesh Voltages at Earthing Grids Buried in Multi-layer Soil" 2010 Elsevier, Electric Power System Research 80, 556-561

[6] Nassereddine M, Hellany A, Rizk J, 2009, How to design an effective earthing system to ensure the safety of the people, 2009 International Conference on Advances in Computational Tools for Engineering Applications, pp 416-421

[7] Nassereddine M, Hellany A, Nagrial M. Rizk J. "Soil Resistivity Structure and its implication on the Earth Grid of HV substation" 2011 World Academy of Science, engineering and Technology , Vol 60, pp 1322-1326

[8] Afa. T. J. and Ngobia F. Soil characteristics and substation earthing in Bayelsa state" European scientific journal, Edition Vol 9, No. 9, March 2013

[9] Nassereddine M, Rizk J, Nagrial M andHellany A. "Transmission mains earthing design and concrete pole deployments" 2012 World Academy of Science, engineering and Technology , Perth Australia

[10] Hellany A.Nassereddine M, NagrialM and rizkJ."Transmission mains Earthing Design: Under Ground to Over Head pole Transition"2012 World Academy of Science, engineering and Technology, Phuket, Thailand

[11] Hans R. 'A practical approach for computation of grid current', IEEE transactions on power delivery, Vol. 14, No. 3, July 1999

[12] Dawalibi F. Finney W. "Transmission Line Tower Grounding Performance in Non-Uniform Soil" 1980 IEEE Transaction on Power Apparatus and Systems, Vol. 99, No. 2

[13] C.N. Chang, "computation of current-division factors and assessment of earth-grid safety at 161/69kV indoor-type and outdoor-type substations" IEE proc.-Gener. Transm. Distrib., Vol. 152, No. 6, November 2005.

[14] Nassereddine M andHellany A, 2009, AC interference study on pipeline: the impact of the OHEW under full load and fault current, Proceeding in the 2009 International Conference on Computer and Electrical Engineering, pp 497-501

[15] El-Fergany A. "Design and Optimise Substation Grounding Grid Based on IEEE STD.80-2000 Using GUI and Matlab Codes" International Journal of Engineering Science and Technology, Vol. 3 No. 7. 2.11

[16] Shahrtash S., Nabiollah R. "A Novel Method to Determine earth Fault Split Factor for Grounding Grid Design of HV Subsations" 2006 IEEE. International Conference on Power Technology

[17] Nassereddine M., Rizk J., Hellany A. and Nagrial M. "Transmission Mains pole earth potential rise (EPR) under substation fault" International journal of emerging electric power systems-Volume 14, Issue 5, Pages 449-507

[18] Nassereddine M., Rizk J., Hellany A. and Nagrial M. "Relation between transmission lines coupling factor and OHEW length; its impacts on fault current *distribution*" IET Generation, Transmission & Distribution Journal Vol. 8, Issue 4. PP600-608 2014

[19] Nassereddine M., Rizk J., Hellany A. and Nagrial M. "Induced Voltage Behaviour on Pipelines Due to HV AC Interference under Broken OHEW" The Australasian Universities Power Engineering Conference. AUPEC 2013.

[20] Nassereddine M., Rizk J., Hellany A. and Nagrial M. "AC Interference study on pipeline: OHEW split factor impacts on the induced voltage" Journal of Electrical Engineering-Vol. 14. 2014 Edition:1 PP. 132-138

[21] Nassereddine M., Rizk J., Hellany A. and Nagrial M. "OHEW types and its implication on pole EPR under pole fault" The 8th IEEE Conference on Industrial Electronics and Applications, Melb. Australia 2013.