International Journal of Electrical, Electronic and Communication Sciences
ISSN: 2517-9438
Vol:5, No:12, 2011

Safety Compliance of Substation Earthing Design

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***Abstract*—**As new challenges emerge in power electrical workplace safety, it is the responsibility of the systems designer to seek out new approaches and solutions that address them. Design decisions made today will impact cost, safety and serviceability of the installed systems for 40 or 50 years during the useful life for the owner. Studies have shown that this cost is an order of magnitude of 7 to 10 times the installed cost of the power distribution equipment. This paper reviews some aspects of earthing system design in power substation surrounded by residential houses. The electrical potential rise and split factors are discussed and a few recommendations are provided to achieve a safety voltage in the area beyond the boundary of the substation.

***Keywords*—**EPR, Split Factor, Earthing Design

I. Introduction

THE benefits of electricity are numerous but mishandling it can cause damages to properties and may inflict injuries and fatalities. Electrical management is the key element in human safety, also not underestimating the importance of protection equipment in the wide area of electrical infrastructure can be another added factor in raising the risk factor. Earthing must be the primary concern during the design and operations of electrical infrastructure.

People often assume that any grounded object can be safely touched. A low substation ground resistance is not, in itself, a guarantee of safety. Step and Touch voltage need to be assessed in and around the substation boundaries. A serious hazard may result during a ground fault from the transfer of potential between the substation ground grid area and outside locations. This transferred potential may be transmitted by communication circuits, conduits, pipes, metallic fences, low-voltage neutral wires, etc. The danger is usually from contact of the touch type. An investigation into possible transferred potential hazards is essential in the design of a safe substation grounding network.

This paper discusses the management of earthing system design to meet the safety requirements as per the Australian and IEEE standards. In addition this paper investigates the area of concerns when dealing with the earthing system and what factors should be taken into when reviewing the design

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II. Earthing Design; Scope of works

The high demand on electricity and expansion of the power grid nowadays made it essential to have high voltage (HV) substations within the residential area and in some cases some zone substations and transmission substation are surrounded with residential houses. It is important to remember that the earthing design scopes can be summarised in the followings but not limited to:

- Grid Resistance
- Current Split Study
- Earth Potential Rise (EPR)
- Touch Voltage
- Step Voltage
- Voltage Transfer

The neighbouring between the HV substations and the residential houses will force the designer and the reviewer to pay extra attention on the EPR contour of the substations under malfunction and fault conditions. Also this neighbouring will highlight the touch voltage on pipeline. Usually in an earthing design, the main safety criteria will be determined using the clearance time and the surface soil resistivity of the area to compute the touch and step voltage. It is a common practice to use IEEE 80:2000 or AS/NZS 60479:2002 standards and the recommended calculation method to determine the safety requirement for touch and step voltage. The close neighbouring will raise the requirement for the pipeline safety, as determined in the Australian and New Zeeland Standards AS/NZS 4853:2000, Table 5.3 in this standards state the safety requirements for different clearance time but it doesn't specify or relate this to soil resistivity value [1-2].

Normally such substations are supplied either by underground cable (UG) or overheard conductor (OH). These feeders can have pole electrodes or joint bay earthing system. The neighboring between the substation and residential houses, force the pole electrodes to be sometimes in the public footpath. For the same reason the joint bay earthing system can be located in an area accesses by children, pregnant women and bare foot passing by residents. These electrodes and the whole earthing system will facilitate and assist in transferring the EPR from the substations to the surrounding area frequented by the community and closer to residents. This will require from the designer and the reviewer to carry more extensive study and analysis around these electrodes and to apply the coordination design technique stated in the "substation Earthing Guide" which is the equivalent of IEEE80 in Australia that is accomplished through 23 steps. It is not recommended in some cases to use an electrode with

less 10 Ω or 5 Ω or even less than 1 Ω to ensure the safety and the compliance of the earthing system. In some cases these 10 or 5 Ω do not meet the safety requirement, since the touch and step voltage may have a value that above the safety limit. There is a need to follow step by step the coordination design technique and to ensure that safety aspects are fully considered during the design and the commissioning of the system. This paper is addressing only the EPR aspect of the earthing design and exploring how EPR can lead to unsafe conditions

III. EPR and Safety Criteria

In an urban substation-Feeder systems, where there is no houses near by, applying the IEEE and AS standards formula can generate a limit for safety criteria. Taking as example a zone substation of 132/11kV with an EPR contour of 500V at around 150 meters radius outside the boundary fence. If we consider that the substation is in an area with a uniform soil resistivity of 100 Ωm and a if we take the clearance time to be 500ms, after applying the IEEE and AS formulas then table

TABLE I
REPRESENTS THE SAFETY THRESHOLD FOR THE DESIGN

Soil Resistivity Ω/m	50 Kg Person		70 Kg Person	
	V Touch	V step	V Touch	V step
100	188.66	264.48	255.41	355.25

Based on table I, the design needs to be limited to 188.66V for the touch voltage and 262.48V for the step voltage. Moving this substation to a residential area where there are water pipe line connected to houses where people resides with the possibility of having children, elderly with bare feet living inside these house. Using AS/NZS 4853:2000 standard, the Australian standards which contain the allowable voltage under different clearance time, yields a maximum touch voltage on any pipe line for un-skilled people to be 100V [3-4].

Now the new maximum limit for the touch voltage outside the substation is 100V as per AS/NZS 4853:2000 requirement. The EPR contour of the 100V should be plotted and assessed to ensure that there is no pipe line within the boundary of this contour. If water pipe exists within the 100V contour, a touch simulation should be conducted to ensure that the touch voltage will be under the acceptable 100V limit. Due to the feeding arrangement, not only the area within the 100V contour need to be studied, also the area along the feeding route need to be assessed as each pole electrode and joint bay earthing system will create an EPR that can give rise to touch voltage issue [5-8].

The fault current at the HV infrastructure will be split into the ground system and the auxiliary system. This split will create an EPR in the Auxiliary earthing system that needs to be studied to ensure the compliance with the corresponding standards and regulations.

Split Study

The fault current at the substation can be divided into sub-currents:

- Current flow in the earth grid
- Current flow in the auxiliary earthing system

Auxiliary earthing system can be represented by Over Head Earth Wire (OHEW) knows as a ground wire, and by the cable sheath of the cable. This auxiliary path acts as a path for partial of the fault current, and reduces the current that flow into the ground. The return current value can be determined after calculating the slip factor. The split factor determines the percentage of the current that flow into the ground the portion that flow into the auxiliary path.

A. Split Factor

Split factor S_f, is vital to be determined when designing an earthing system that have an auxiliary path for the fault current. Split factor is essential for determining the actual EPR at the substation and gives an indication of the EPR around the auxiliary path. In addition, it ensures the compliance of any transfer voltage or EPR along the auxiliary path.

The split factor can be determined using equation 1:

$$S_f = 1 - \left(\frac{Z_{gm}}{Z_{gw}} \right) \quad (1)$$

Where:

Z_{gw} is the self impedance of the OHEW in Ω/m.

Z_{gm} is the mutual impedance per meter between OHEW and phase conductors in Ω/m.

The Ground current is determined using equation 2:

$$I_g = S_f \times I_f \quad (2)$$

The auxiliary path current is determined using equation 3:

$$I_e = I_f - I_g \quad (3)$$

The auxiliary path current value will assist in assessing the safety of the auxiliary path under any fault at the nominated HV infrastructure. The split factor is used to determine the final impedance of the line as shown in equation 4 [3]:

$$Z_{total} = \frac{S_f R_g}{1 - S_f} \quad (4)$$

B. EPR and Split Factor

The EPR at the substation is determined using the earth grid resistance and the fault current. Equation 5 shows the EPR calculation, This EPR is under the assumption that there is no auxiliary system which mean the split current is 1:

$$EPR_{substation} = I_f \times R_g \quad (5)$$

Recalculating EPR Using the Split Factor, shows how the split factor value can reduce the EPR value at the nominated HV infrastructure. This EPR is for the substation EPR under the existence of auxiliary path for the fault current

$$EPR = S_f \times I_f \times R_g \quad (6)$$

The maximum possible value for the split factor is 1, Figure 1 shows a simulation value for the EPR under grid resistance of 1 ohm and fault current of 1000 amperes.

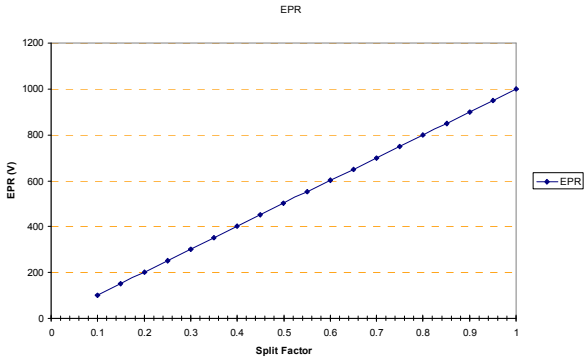

Fig. 1 EPR Vs Split Factor

Figure 1 clearly shows how the split factor values impact on the EPR at the Substation, it is vital to determine this value as it will reduce the EPR at the nominated HV infrastructure which will lead to a less expensive earth grid. The auxiliary current depend on the split factor and can create an unsafe condition along the auxiliary path,. for more information refer [9-10]

IV. Split Factor and Auxiliary Path

The split factor depend on the type and configuration of the auxiliary path, for example if the auxiliary path represented by an OHEW, then different type of OHEW will result in different value of split factor For more information refer to [4]. The EPR at the Auxiliary earthing system is determined using equation 7, this EPR is for the auxiliary system. A part of the fault current uses the auxiliary system as a path to the source, the auxiliary system has resistance value, then EPR can be determined taking into account the auxiliary current and the auxiliary resistance

$$EPR = I_f\left(1 - S_f\right) \times R_{Aux} \quad (7)$$

The auxiliary earthing path is normally including a number of electrodes running along the transmission feed. A current distribution study and analysis needs to be conducted in order to determine the shunt and section current in each electrode along the line. **C**urrent **D**istribution, **E**lectromagnetic Fields, **G**rounding and **S**oil Structure Analysis (CDEGS) software is used to determine the flowing current in each section of the auxiliary earthing path, Figure 2 and 3 shows the fault current in the OHEW under a fault condition. Figure 2 clearly shows that the fault current in the first 10 electrodes is high. In addition, it is possible to determine the value of the current flowing in each electrode. The calculated current is used to determine the EPR around each electrode. Figure 2 shows the need tor the earthing system at the first few poles, due to high current, to be assessed more than the poles between section 10 and section 60 [11-12].

Figure 3 shows the section current magnitude that is flowing in the OHEW and returning to the fault source. Figure4 shows the magnitude of the current that flows in the electrode at pole No 3, the value is around 300A, this value will assist in controlling the EPR around this pole, the designer can target an earthing system for this electrode to meet the safety requirement. Equation 8 is used to determine the maximum grid resistance for this electrode to ensure the compliance with safety voltage Vsafe.

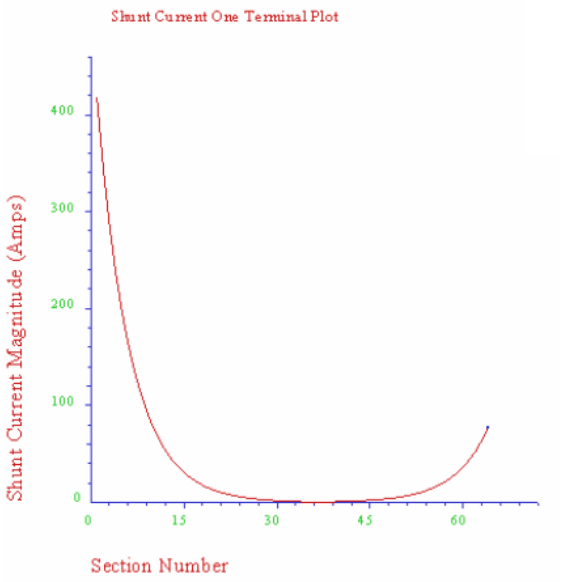

Fig. 2 Shunt Current Magnitude

$$R_{Electrode} = \frac{V_{safe}}{I_{electrode}} \quad (8)$$

For example if the safety voltage is 100V and the current is 300A, an electrode system of 0.33 Ω will insure the safety compliance of the system. In some cases and due to practical reasons this value cannot be met. Then it is recommended to conduct more analysis as required under the EG1 coordination design technique [13].

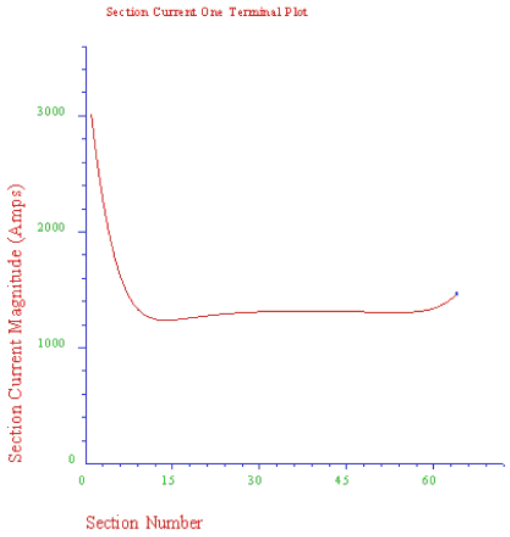

Fig. 3 Section Current Magnitude

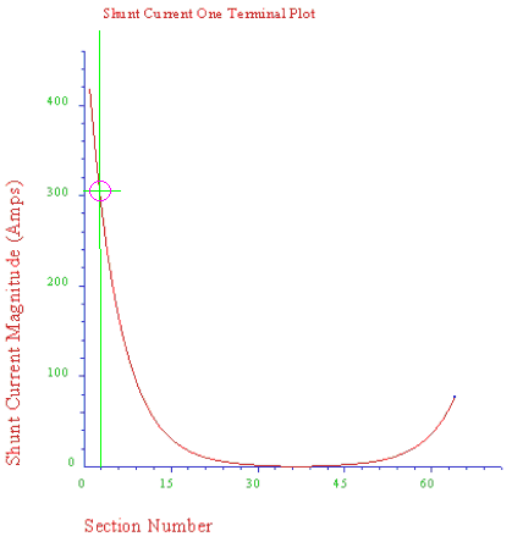

Fig. 4 Pole number 3 shunt current magnitude

V. Case Study

Toufikiya is a 132/11kV zone substation that fed from Harbata transmission substation situated 60 spans away; each span is 100 meters in length. Toufikiya earthing system is 1 Ω and the Harbata earthing system is 0.5 Ω. The maximum single line to ground fault is 5000 amperes with 0.5s clearance time. Each electrode at the bottom of each pole is a 5 Ω system. Using CDEGS engineering software to compute the split factors give the followings:

Terminal ground system (magn./angle)

- Total Earth Current 1558.9 Amps/163.77 deg.
- Earth Potential Rise 779.45 Volts/163.77 deg.
- Total Fault Current 5000.0 Amps
- Total Neutral Current 3995.7 Amps/6.9190 degrees
- Total Earth Current 1140.0 Amps/24.977 degrees
- Ground Potential Rise (GPR) 1140.0 Volts / 24.977 degrees

Figures 5 and 6 show that the 100V contour will exist around the first 20 pole from Toufikia Zone Substation ZS, and in the last 15 poles to Harbata Transmission Substation TS. For a metallic pipeline running three meter from the electrode, CDEGS simulation gives the following results:

Earth Potential Computations

- Main Electrode Potential Rise (GPR) 1000.0 volts
- Buried Metallic Structure Potential Rise (GPR) 246.89 volts

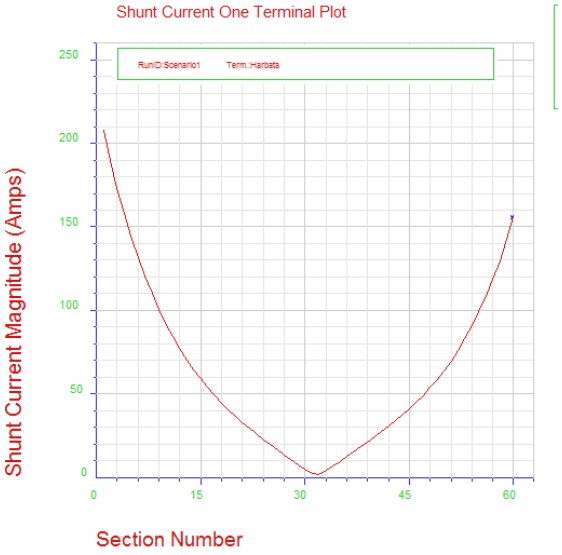

Fig. 5 shunt Current Magnitude

The EPR at the metallic line will be 246.89 V, this value exceed the 100V value, then more analysis is required to ensure that this transfer EPR does not create an unsafe condition. This can be achieved studying the current flow in the ground to determine the amount that is impacting on the pipeline; more details can be found in EG1, IEEE80, publication [1-4] Figures 7 and 8 show the EPR contour around the pole electrode and the touch contour. A close look at these figures shows that the 100V contour will include the pipe line.

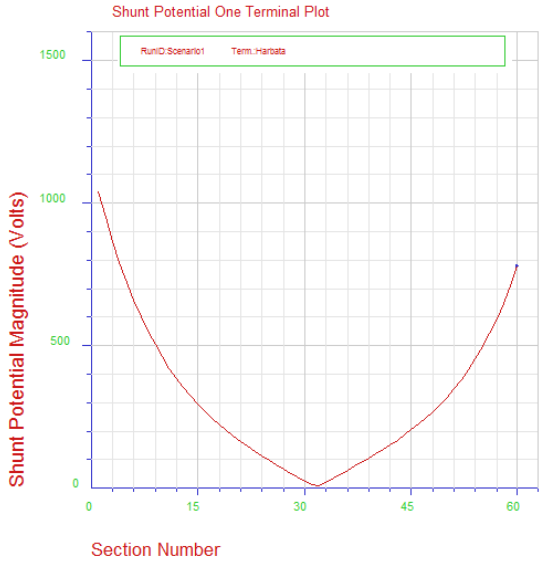

Fig. 6 Shunt Potential Magnitude

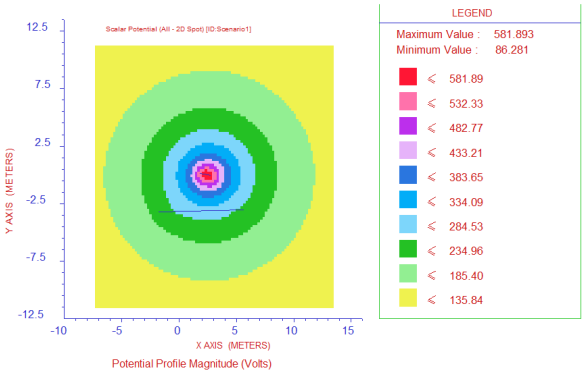

Fig. 7 Simulated contour around the pole electrode

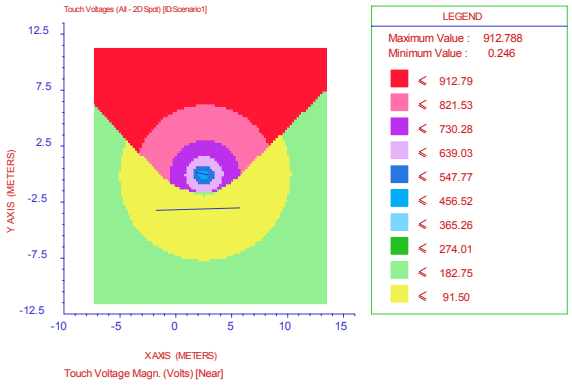

Fig. 8 Touch Voltage Contour

VI. Conclusion

This paper shows that high voltage substation earthing design in a residential area need to take into account the area beyond the boundary fence of the substations. Further study need to take place to ensure that the auxiliary path of the fault condition is not creating unsafe conditions. This paper recommends the following steps to be included in the design process of an earthing system of power substation:

- Spilt study even when the substation is compliance under any fault condition
- Examine the EPR around each auxiliary path
- Assess the EPR along the auxiliary path

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