Earth Potential Rise (EPR) Computation for a Fault on Transmission Mains Pole

M. Nassereddine, J. Rizk, A. Hellany, and M. Nagrial

Abstract—The prologue of new High Voltage (HV) transmission mains into the community necessitates earthing design to ensure safety compliance of the system. Conductive structures such as steel or concrete poles are widely used in HV transmission mains. The earth potential rise (EPR) generated by a fault on these structures could result to an unsafe condition. This paper discusses information on the input impedance of the over head earth wire (OHEW) system for finite and infinite transmission mains. The definition of finite and infinite system is discussed, maximum EPR due to pole fault. The simplified equations for EPR assessments are introduced and discussed for the finite and infinite conditions. A case study is also shown.

Keywords—Coupling Factor, Earth Grid, EPR, Fault Current Distribution, High Voltage, Line Impedance, OHEW, Split Factor, Transmission Mains.

I. INTRODUCTION

THE benefits of electricity are numerous but require extremely safe operation to reduce damages to properties, injuries and fatalities to human life. High voltage transmission deploys conductive poles such as steel and concrete structure. The assumption that any grounded object can be safely touched is not always correct. A serious hazard may result during a ground fault. The fault on transmission mains structure create an earth potential rise (EPR) which could lead to unsafe touch condition on these structure or unsafe transfer voltage to nearby conductive infrastructure. High voltage substations are fed by transmission mains. The route of transmission mains could be in close proximity to residential and community infrastructures. It is generally believed that grounded transmission mains are safe. This statement is not always correct, and only holds if the earthing system at the base of the pole is capable of absorbing the fault energy generated by the high voltage fault.

The EPR generated on the structure could lead to unsafe voltage transfer to by near conductive infrastructures such as metal fence, water pipe line and telecommunication circuits.

Transmission poles are exposed to two types of fault conditions:

- Fault at the high voltage substation due to the split

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factor concept
- Fault at the transmission poles

The transmission mains are further divided into two categories depending on its length:

- Infinite transmission mains
- Finite transmission mains

This paper discusses the transmission mains EPR under pole fault for the two length conditions. It examines the EPR on the faulted pole and its maximum possible magnitude.

This paper introduces an estimated methodology for quick assessment of the maximum EPR under pole fault. Few case studies are discussed and the results are also shown.

II. THEORETICAL STUDY

A. Design Factors

The earth potential rise on the transmission pole under fault will depend on the following factors. These factors are considered the most important elements when it comes to pole EPR assessment:

- Fault location
- Fault current magnitude on the structure
- Infinite or finite transmission mains
- Substation earth grid resistance
- Pole earth grid resistance as seen from the OHEW connection point
- Conductor arrangement on the transmission poles
- Type of the OHEW
- Numbers of the OHEW
- Soil resistivity structure
- Pole surrounding infrastructure

In this paper, transmission mains pole fault is assumed to have the same magnitude as substation fault.

B. Line Impedance

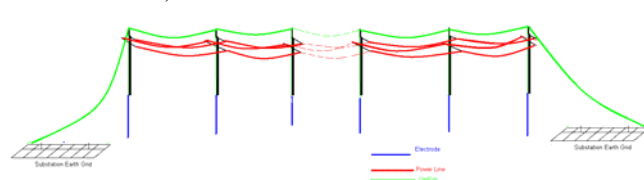Fig. 1 represents an overhead transmission line that connect two substations,

Fig. 1 OH transmission mains layout with OHEW

For the transmission line to be considered infinite, equation 1 shall be satisfied [1]:

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$$l\sqrt{\frac{z_s}{z_p}} \succ 2 \tag{1}$$

Where

z_s is defined by $z_s = \dfrac{Z_s}{Ls}$

Z_s is the OHEW self-impedance for the average span in ohms

z_p is defined by $z_p = Z_p L_s$

Z_p is the pole earth grid resistance in ohms

l is the total length of the transmission mains in km

L_s is the average span in km

The line impedance under the infinite condition can be represented by equation 2: [2]

$$Z_e = \frac{Z_s}{2} + \sqrt{Z_s Z_p} \tag{2}$$

Where

Z_e is the line impedance as seen from the fault

Fig. 2 represents the line impedance Z_e under a fault at the substation. The line impedance is represented in Z_e as shown in Fig. 2.
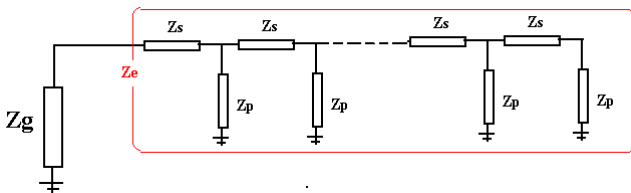

Fig. 2 Line impedance for a fault at the substation

For a fault at a pole located in the middle of the transmission line to be considered as an infinite system, equation 3 shall be satisfied:

$$\frac{l}{2}\sqrt{\frac{z_s}{z_p}} \succ 2 \tag{3}$$

Fig. 3 represents a fault on the transmission mains pole. If equation 3 is satisfied and the fault is located in the middle of the feeder, equation 2 can be used to determine Z_{e1} and Z_{e2} as shown.
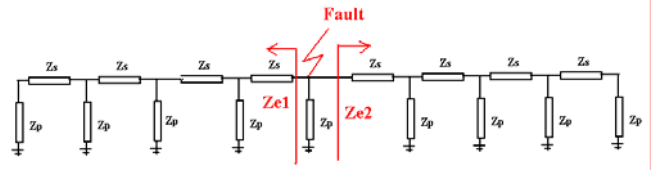

Fig. 3 Fault at the transmission pole

Under the infinite condition, the maximum pole earth potential rise can be found using equation 4:

$$Pole_{EPR} = (1-\varsigma)I_f Z_T \tag{4}$$

Where

ς is the coupling factor and is defined in equation 5

I_f is the fault current

Z_T is the total impedance as defined by equation 6

$$\varsigma = \frac{Z_m}{Z_s} \tag{5}$$

Where

Z_m is the mutual impedance between the OHEW and the phase conductor for the average span in ohms

$$Z_T = Z_p \,//\, Z_{e1} \,//\, Z_{e1} \tag{6}$$

Under the infinite condition, Z_{e1} and Z_{e2} are equal in value, therefore equation 6 can be simplified as equation 7:

$$Z_T = \frac{Z_p Z_{e1}}{2Z_p + Z_{e1}} \tag{7}$$

Equation 8 can be generated by replacing Z_T in equation 4 with its value from equation 7. It is acceptable to compute the pole EPR using equation 9 under the condition where $Z_p \succ\succ\succ Z_{e1}$.

$$Pole_{EPR} = (1-\varsigma)I_f \frac{Z_p Z_{e1}}{2Z_p + Z_{e1}} \tag{8}$$

$$Pole_{EPR} = (1-\varsigma)I_f \frac{Z_{e1}}{2} \tag{9}$$

Under the assumption that the fault current at the substation is the same as the one on the transmission poles, equation 10 represents the relation between the substation EPR and the pole EPR:

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$$Pole_{EPR} = (1-\varsigma)EPR_{substation}\frac{Z_e + Z_g}{2Z_g} \qquad (10)$$

It shows that it is possible to compute the maximum possible EPR at the pole under fault with only the following inputs:

- Self impedance of the line
- Mutual impedance of the line
- Pole earth grid
- Fault current

If the computed pole EPR is lower than the allowable touch voltage, no further analysis required from touch perspective. If the computed EPR is higher than the allowable touch voltage, mesh voltage shall be determined [2].

Fig. 4 shows the relation between the pole EPR under equations 8 and 9 for the following inputs:

- 4000A fault current
- Mutual impedance of 0.0398 per average span
- Self impedance of 0.0631 per average span
- Soil resistivity is 10ohm.m
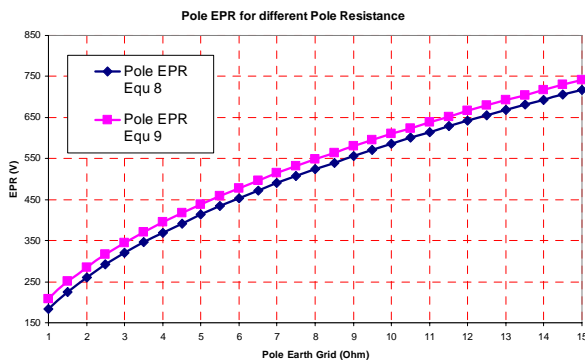
Pole EPR for different Pole Resistance

Fig. 4 EPR for pole fault with equations 8 and 9

Fig. 5 shows the percentage difference in the pole EPR when using equation 9 instead of equation 8. The difference is less than 10% for a pole grid resistance higher than 2 ohms. The average pole resistance is around 10ohms for transmission mains, and the change for 10 ohms pole grid resistance is only 4 percents

Fig. 6 shows the pole EPR with different separation distances between the phase conductor and the OHEW. This figure is based on a 10 ohms pole earth grid, 0.0631ohm self impedance per average span and 4000A fault current. There is an increase of more than 100 volts in the pole EPR if the separation distance increases by 2.3 meters. This means that the layout of the phase conductors on the pole has an impact on its EPR. The worst case scenario is represented by a fault on the phase located at a greater distance d where d is the distance between the Phase conductor under fault and the OHEW.

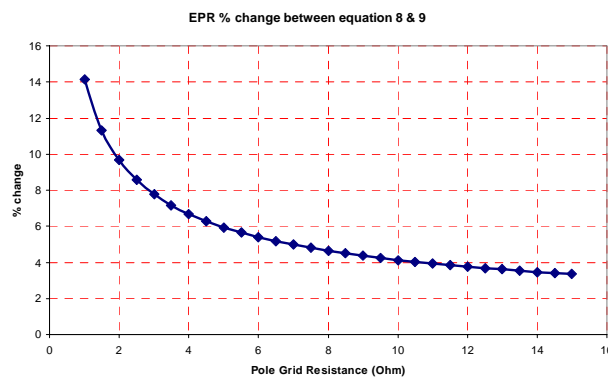**EPR % change between equation 8 & 9**

Fig. 5 EPR percentage change when using equation 9

Fig. 7 shows the phase conductor arrangements in relation to the OHEW. The fault on phase C represents the worse case scenario when assessing the EPR for a fault on this pole.

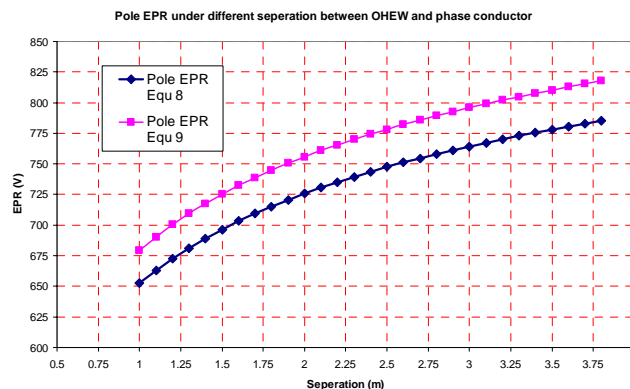**Pole EPR under different seperation between OHEW and phase conductor**

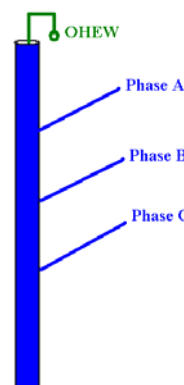Fig. 6 Pole EPR under different separation between the phase and OHEW

Fig. 7 Conductor Phase arrangement on transmission pole

The system compliance under phase C fault will ensure the compliance under phase A and B faults. This information also assists in determining the injection phase during the earthing system commissioning using the current injection test method (CIT). In order for the CIT to yield the best results, the injection should use phase C as a path.

If the transmission length does not meet equation 1, the line is defined as finite transmission mains, the input impedance of the transmission mains can be computed using equation 11:

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$$Z_e = Z_{NEEC} // (Z_{s1} + Z_g) \qquad (11)$$

Where

Z_{NEEC} is the line impedance for N number of poles and it is defined in equation 12.

Z_{s1} is the OHEW self impedance between the last pole and the substation:

$$Z_{NEEC} = \frac{0.5N(N+1)Z_s Z_P + Z_P^2}{\frac{N(N^2-1)}{6}Z_s + NZ_P} \qquad (12)$$

Where

N is the number of poles

Under the finite transmission mains condition, the EPR at the pole can be computed using equation 13:

$$Pole_{EPR} = (1-\varsigma)I_f \frac{Z_p Z_{e1} Z_{e2}}{Z_p Z_{e1} + Z_p Z_{e2} + Z_{e1} Z_{e2}} \qquad (13)$$

Fig. 8 shows a fault on a pole for a finite transmission line. Z_{e1} can be found using equations 11 and 12, where N represents the numbers of poles between the faulted pole and the substation earth grid Z_{g1}. Similarly Z_{e2} can be computed where N is the number of poles between the faulted pole and the substation earth grid Z_{g2}
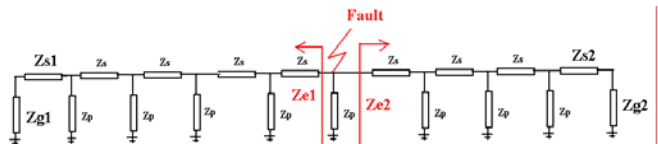

Fig. 8 Pole fault for finite transmission line

As both substation earth grid are taking into consideration under finite transmission line conditions, equation 14 can be used to estimate the maximum EPR possible at the faulted pole, please note that that actual pole EPR will always be lower to the one in equation 14, also this equation stand under the assumption that Z_{s1} and Z_{s2} are too small which is usually the case as it consist of small span.

$$Pole_{EPR} = (1-\varsigma)I_f \frac{Z_p Z_{g1} Z_{g2}}{Z_p(Z_{g1}+Z_{g2}) + Z_{g1} Z_{g2}} \qquad (14)$$

For substation with small earth grid resistance, equation 14 can be reduced to equation 15 when it comes to EPR determination on the faulted pole

$$Pole_{EPR} = (1-\varsigma)I_f \frac{Z_{g1} Z_{g2}}{Z_{g1} + Z_{g2}} \qquad (15)$$

Fig. 9 shows the pole EPR under the following conditions:

- Z_{g1} is 0.4 ohm
- Z_{g2} is 0.6 ohm
- Mutual impedance is 0.0398 for average span
- Self impedance is 0.0631 for average span
- Z_{s1} is 0.01577 ohm
- Z_{s2} is 0.021 ohm
- Pole grid resistance is 10 ohms
- Fault current is 4000A
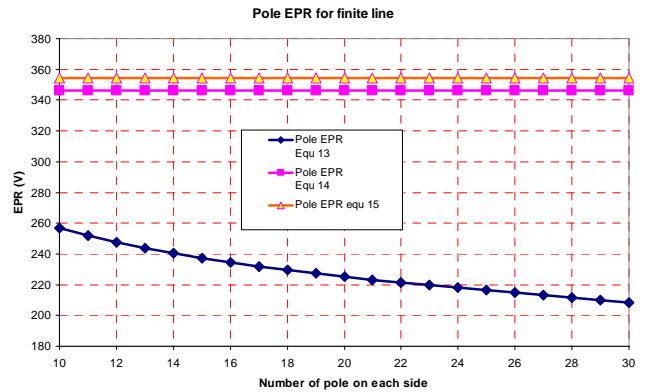- Soil resistivity is 10ohm.m

Fig. 9 Pole EPR for finite line for a fault a pole located in the middle of the line

The outputs of equations 14 and 15 are very similar; it is possible to use equation 15 for quick EPR assessment. For substation with low grid resistance, using equation 15 could lead to proper approximation, Fig. 10 shows the EPR under number of poles N is 30 and for different substation earth grid, both earth grid are assumed to have the same value.
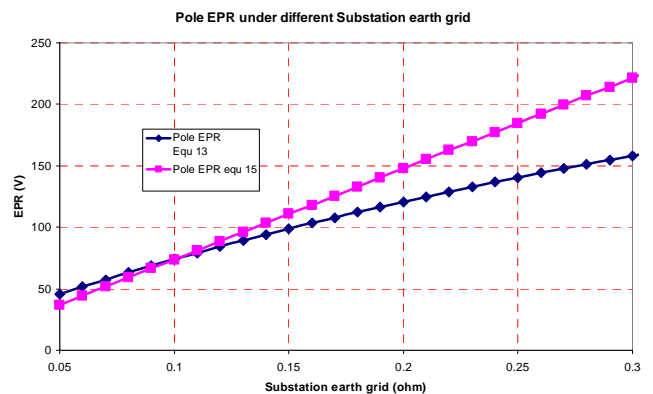

Fig. 10 Pole EPR under different substation earth grid

Fig. 10 shows that for low earth grid resistance around 0.15 ohm, equation 15 yield to similar results as equation 13, it

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shall be noted that for the section where the substation earth grid is between 0.05 and 0.1, equation 15 has lower EPR due to Z_{s1} and Z_{s2} values.

Similar to the infinite line, the separation distance between the OHEW and faulted phase has an impact on the pole EPR, the worth case scenario is represented with the fault on the phase located far to the OHEW, similar to the infinite line, the finite line with pole arrangement as shown in Fig. 7, fault on phase C represents the worse case scenario.

III. CASE STUDY

A new development for Harbata has been approved for 3500 houses, the existing substation of the area is not capable to supporting the new load, a new 132kV feeder were approved to be installed between Labweh substation and Harbata Substation, an earthing assessment is required to determine the EPR for a pole fault located half way between Harbata and Labweh ZS, below the input of the design:

- Feeder length is 5km
- Average span is 100m
- Number of poles 51
- AC resistance for the OHEW is 0.0955 ohm.m
- OHEW RGM is 0.013m
- Soil Resistivity along the line is 10 ohm.m
- Pole arrangements are as per Fig. 7
- Phase C distance to the OHEW is 3.8m
- Single line to ground fault current is 4200A
- Primary Clearance time is 300ms
- Pole earth grid resistance is 10ohms
- Harbata SS earth grid resistance is 0.2 ohm
- Labweh SS earth grid resistance is 0.18ohm
- The final span to Harbata SS has 25 meters of length
- The final span for Labweh SS has a 30 meters of length
- The fault is located on pole 26 from Harbata SS

In order to determine if the line is finite or infinite, the self impedance of the OHEW shall be determined; equation 16 was used to compute the self impedance of the line [3]:

$$Z_s = R_s + 9.88 \times 10^{-7} f +$$
$$j28.938 \times 10^{-7} f \log_{10}\left(\frac{D_e}{R_{GM}}\right) \tag{16}$$

Where

$$D_e = 658.4 \sqrt{\frac{\rho}{f}} \tag{17}$$

$$Z_s = 0.643 \Omega.km$$

From equation 1, the line is a finite one.

$$2.4\sqrt{\frac{0.643}{1}} = 1.92 \prec 2$$

First step in assessing the EPR at the faulted pole (pole 26) equation 15 were applied

$$Pole_{EPR} = \left(1 - \frac{0.276}{0.643}\right)4200\frac{0.2 \times 0.18}{0.2 + 0.18} = 227V$$

Based on IEEE80:2000 the allowable touch voltage for a 70kg person under 300ms is 290.95V and for 50kg person is 214.96V. The initial assessment for the EPR at the pole shows that the system is compliance under 70kg person and no compliance under 50kg person. It is possible to compute the touch voltage on the pole using the 227V EPR as an input, or determine the maximum EPR under equation 13, Fig. 11 shows the computed touch voltage under 227V EPR, the maximum touch voltage for someone standing 1 meter away from the pole is 176V, the system is compliance to the touch and step voltage for 50 and 70kg person.
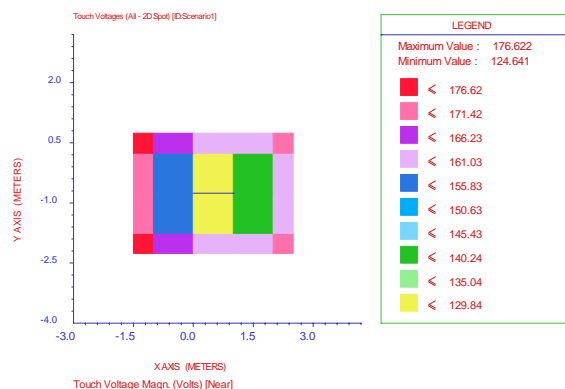

Fig. 11 Touch Voltage computation under 227V EPR

The output of equation 13 shows a maximum EPR of 192V, this value is compliance to the touch voltage under 50kg and 70kg person. This shows that the maximum EPR at a fault on pole 26 has a maximum value of 192V which is lower than the allowable touch voltage of 214.96V. Equation 13 can be used to compute the entire pole fault scenario starting from pole 2 to pole 48; Fig. 12 shows the Maximum EPR under pole fault along the transmission mains. This initial assessment gives the designer an indication where pole fault might jeopardize the safe limits. Based on Fig. 12, EPR based on a pole fault located on all poles except 26 have higher EPR than the allowable touch voltage. Fig. 12 shows a maximum EPR for a fault located on a pole near the substation, it shall be noted that if equation 3 stands, the maximum EPR is represented by a fault located on the middle pole (pole half way between the two substations)

At pole 26, the dip in the voltage due to the followings:
- The transmission mains both end of pole 26 is

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considered to be finite

- For other pole faults, one side is considered to be finite and the other section is considered to be infinite
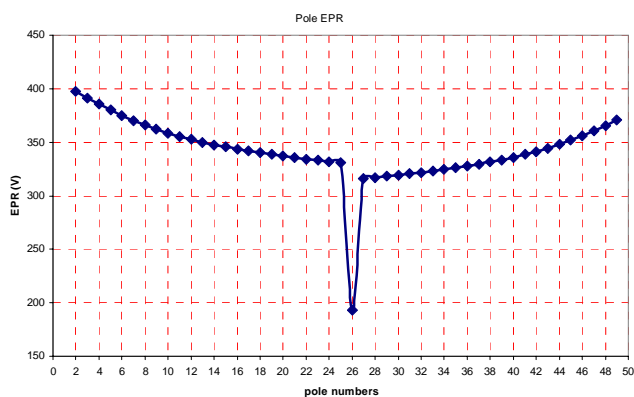

Fig. 12 Pole fault along the transmission line

IV. CONCLUSION

This paper provides a process on how to assess the maximum EPR under pole fault; it shows that for infinite transmission mains it is possible to estimate the maximum EPR value with minimum input data. For an infinite system it is possible to estimate the maximum possible EPR under pole fault if the following information is available:

- Type of OHEW
- Layout of the OHEW and phase conductor
- Soil Resistivity

For a finite system, it is possible to estimate the maximum EPR under pole fault if the following information is available:

- Earth grid resistance at both end of the feeder

This paper shows how it is possible to estimate the EPR along the feeder route under different pole fault location; it shows that the worst case scenario is presented with a pole fault near the substation. This approach enhance the process of earthing design when it comes to transmission mains, it gives the designer guidance if pole earth grid design is required for touch and step voltage compliance. It shall be noted that the pole earth grid shall comply with the lightning strike requirements.

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