

AC INTERFERENCE STUDY ON PIPELINE: OHEW SPLIT FACTOR IMPACTS ON THE INDUCED VOLTAGE

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Abstract: Human Safety due to electrical induced voltage is gaining more attention in the area of high voltage sector. In existing researches, no evidence is cited on the effect that the OHEW split factor has on the induced voltage due to HV transmission lines AC interference. This paper discusses the effect that the OHEW return fault current has on the AC interference analysis. Moreover, the induced voltage reading error when neglecting the OHEW return current is discussed. Case study is included.

Key words: Induced Voltage, soil resistivity Structure, Split Factor

1. Introduction

The benefits of electricity are numerous but a tremendously safe operation should be entailed to reduce damages to properties, injuries and fatalities to human life. High voltage substations are fed by transmission lines. In many cases these transmission lines are running parallel to conductive pipelines within the same easement corridor. This arrangement initiates the AC interference between the HV transmission lines and pipelines. This interference has been studied for many years; numerous countries produced their own standards and elected the maximum acceptable induced voltage on pipelines. The induced voltage on pipelines introduces the following hazards [1-2]:

- Induced voltage that could reach a limit which jeopardizes the safety of the people
- Pipeline coating damage
- Creating fire and explosion
- Jeopardize the use of the pipeline as communications links
- Static charge which affects personnel entering and leaving vehicles
- Difficulty in measuring the DC potential
- Corrosion and maintenance limitations

Numerous researches were completed to aid in computing the induced voltage due to the AC interference. The most frequently used equations to analyze the induced voltage are Westinghouse and Carson equations [1]. Also the electromagnetic field theory and the FEM were used to compute the induced voltage [3-4].

The AC interference study depends on multiple factors. The soil resistivity structure has a direct impact on the

induced voltage [5]. This impact is due to the self and mutual impedances between the HV lines and pipelines [6-8]. The FEM is also used along with the mutual and self-impedance to compute the impact on the HV interference on pipelines [9-10]. Furthermore, the transmission pole earth grids along with the type of the overhead earth wire (OHEW) have an impact on the induced voltage [11].

Parts of these researches consider the OHEW effect on the induced voltage during the computation process. Unfortunately, within the cited references, there are no considerations for the effect that the OHEW split factor has on the induced voltage. The existing works address the following scenarios:

- Normal condition with neutral wire
- Normal condition with earth return path
- Unbalanced system
- Single line to ground fault
- Fault fed from both sides of the transmission line
- Transmission line structure fault

Based on all these scenarios, the OHEW has constant effect on the induced voltage along the entire line. This effect is known as the OHEW shielding factor.

Under substation HV fault, the fault current splits into two sub currents under the presence of the OHEW:

- Grid fault current
- OHEW return fault current

The OHEW split factor determines the percentage of the fault current that uses the OHEW as a return path to the source. The OHEW return current induces voltages on the pipeline with opposite polarity to the one induced by the fault current. This paper aims to provide information about the effect that the split factor has on pipeline induced voltage. Also, it estimates the induced voltage error when neglecting the return current during the analysis. Case study is also presented. Current Distribution, Electromagnetic Fields, Grounding and Soil Structure Analysis (CDEGS) along with Matlab and Excel software's tools are used in this paper.

2. Soil Resistivity

Soil resistivity structure of the area is considered one of the key elements in the study of the induced voltage [12]. There are multiple methods to measure the soil resistivity

structure, the most frequently used ones are [13]:

- Wenner Method
- Schlumberger Array
- Driven Rod Method

This paper practices Wenner Method to compute the soil resistivity of the ground.

A. Wenner Method

Four probes are required to perform Wenner Method as shown in fig. 1. The two external ones are used for current injection and the two middle ones are for potential measurements [14].

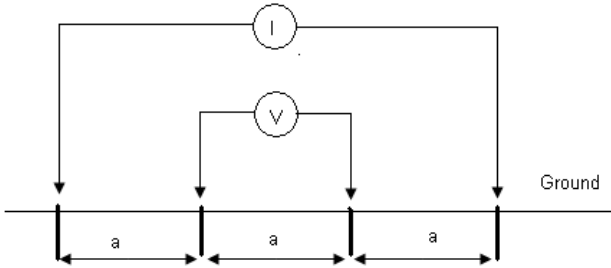


Fig. 1 Wenner Method arrangement

Equation 1 represents the soil resistivity as per Wenner Method:

$$\rho = 2\pi a R \quad (1)$$

Where:

a is the probe spacing in meters

R is the resistance measured in Ohms

Four people are required to perform Wenner array in short time. This makes it the least efficient from labor perspective. On the other hand it is the finest technique when it comes to the ratio of received voltage per unit of transmitted current.

3. Proposed Methodology

As discussed previously, the works in this paper take into consideration the effect that the OHEW return current has on the induced voltage. Fig. 2 represents the electric circuit of a transmission line under substation fault. The phase fault current splits into two sub-currents under the presence of the OHEW; the approach of this paper is to take the effect of the phase fault current on the pipe line and the effect of the OHEW return current on the pipeline. Due to the direction of the currents, these two effects will have opposite polarity on the pipeline.

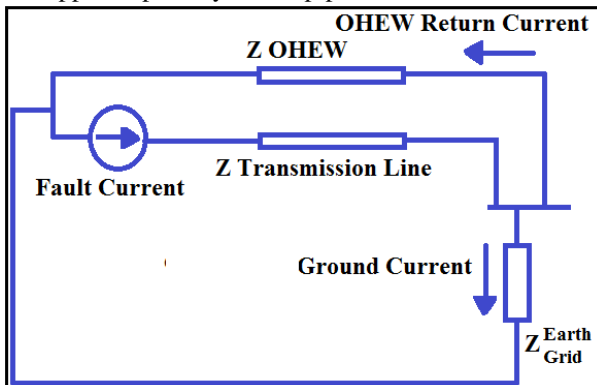


Fig. 2. Transmission line fault current distribution

The following factors are considered in this methodology:

- Single line to ground fault
- Transmission line length (finite or infinite)
- Separation between transmission line and pipeline
- Soil resistivity structure
- Self and mutual impedance of the OHEW in respect to the phase conductor
- Self and mutual impedance of the pipeline in respect to the OHEW and phase conductor
- OHEW split factor

4. Theoretical Study

An electromagnetic field is continuously set at 90 degrees of the current vector [15]. This field induces voltage on any conductive structure running parallel to the current vector. Therefore, any conductive pipeline running parallel to an energized transmission line is exposing to induced voltage. This approach applies for the phase current and OHEW return current.

The induced voltage is interrelated to the impedance relation amid the phase conductor and the pipeline. This impedance can be computed using Carson's equations. Fig. 3 characterizes the circuit of a 3-phase HV power line and the pipe line with the absence of the OHEW.

Equation 2 signifies the induced voltage on the pipeline due to the phase fault current with the absence of the OHEW [14]:

$$V_p = I_{fault} Z_{phase-p} \quad (2)$$

Where

V_p is the voltage induced on the pipeline in Volts

due to phase fault

I_{fault} is the single line to ground phase fault in

Amps

$Z_{phase-p}$ is the mutual impedance between the

phase conductor and the pipeline in ohms.km

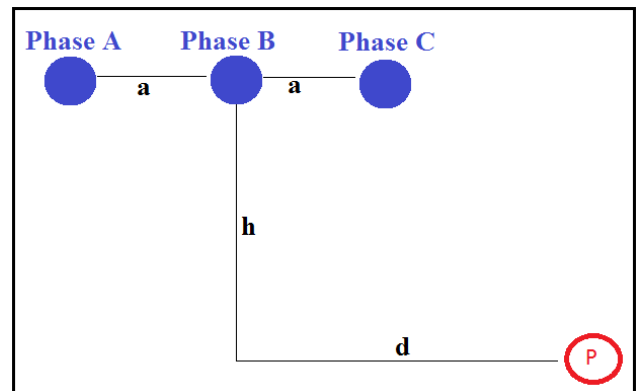


Fig. 3. HV transmission line and pipeline without the OHEW

Equation 3 signifies the mutual impedance between the

phase and the pipeline:

$$Z_{\text{phase-p}} = 9.88 \times 10^{-7} f + j28.938 \times 10^{-7} f \log_{10} \left(\frac{D_e}{D_{\text{phase-pipe}}} \right) \quad (3)$$

Where

$D_{\text{phase-pipe}}$ is the mean distance between the phase and the pipeline,
 f is the frequency.

$$D_e = 658.4 \sqrt{\frac{\rho}{f}} \quad (4)$$

Comparable method is followed to compute the induced voltage on the pipeline due to the OHEW return current. Equation 5 signifies the induced voltage related to the OHEW return current.

$$V_{p\text{-OHEW}} = I_{\text{OHEW}} Z_{\text{OHEW-p}} \quad (5)$$

Where

$Z_{\text{OHEW-p}}$ can be found using equation 3.

In order to compute the OHEW return current, the OHEW split factor should be found.

5. OHEW Split Factor

The OHEW split factor determines the percentage of the return fault current under substation fault. Fig. 4 shows the electric circuit for the analysis of the split factor. Equation 6 can be derived by analyzing the circuit in fig. 4.

$$\delta_e = \frac{Z_g + Z_m}{Z_{\text{OHEW-in}} + Z_g} \quad (6)$$

Where:

δ_e is the OHEW split factor

Z_g is the faulted substation grid resistance

Z_m is the mutual coupling between the faulted phase and the OHEW

$Z_{\text{OHEW-in}}$ is the input impedance of the OHEW system

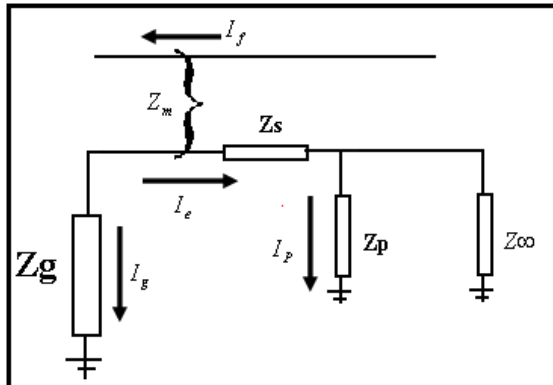


Fig. 4. Split factor circuit

The input impedance of the OHEW under infinite length condition can be found using equation 7 [16]:

$$Z_{\text{OHEW-in}} = \frac{Z_s}{2} + \sqrt{Z_s Z_p} \quad (7)$$

Where

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

Z_p is the pole earth grid resistance in ohms

Equation 8 is used to compute the OHEW input impedance under finite length [17]. Equation 9 can be used to determine the infinite length of the transmission line [18].

$$Z_{\text{OHEW-in-finite}} = \frac{0.5N(N+1)Z_s Z_p + Z_p^2}{\frac{N(N^2-1)}{6} Z_s + N Z_p} \quad (8)$$

Where

N is the number of poles

$$l \sqrt{\frac{z_s}{z_p}} > 2 \quad (9)$$

Where

z_s is defined by $z_s = \frac{Z_s}{L_s}$

z_p is defined by $z_p = Z_p L_s$

l is the total length of the transmission mains in km

L_s is the average span in km

The OHEW current is computed using equation 10:

$$I_{\text{OHEW}} = I_{\text{fault}} \times \delta_e \quad (10)$$

Due to the discharge of the OHEW current at the earth grid of each pole, the fault current magnitude as per equation 10 is valid for the first span of the OHEW.

Fig. 5 shows the OHEW sections fault current behavior along the transmission line as per the simulation in [19]. This shows how the OHEW section currents drop at the beginning of the feeder and then pick up its strength toward the source substation. This drop is due to the fault current being discharged at the base of each pole along the transmission line.

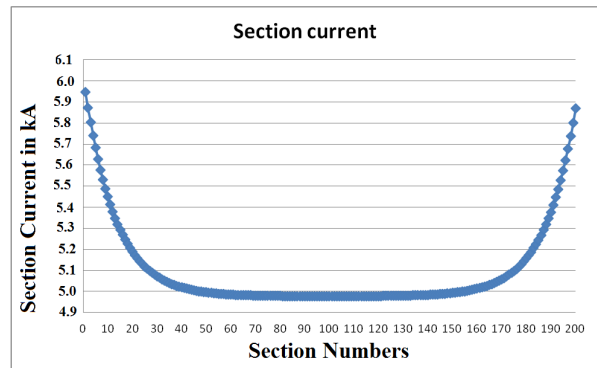


Fig. 5. OHEW section current shape for typical

6. Pipeline Induced Voltage

The pipeline induced voltage in the paper approach is computed using equation 11.

$$V_{induced-p} = V_{Phase-p} - V_{OHEW-p} \quad (11)$$

The variable in equation 11 is the OHEW section current. As shown in fig. 5, the OHEW section current changes for the first few spans each side of the transmission line. Fig. 6 shows the typical coating voltage on pipeline running parallel to the transmission line. Where the OHEW return current increases, this means that the split factor as per equation 6 is higher, the coating voltage on the pipeline is reduced. In fig. 6, the typical coating voltage changes due to the change in the OHEW return current. High coating voltage represents lower OHEW split factor.

Under the consideration that the OHEW has a constant effect on the pipeline along its entire run, equation 12 represents the induced voltage

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

Where

K is the Shielding factor and is computed using equation 13:

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

Where

$Z_{Phase-p}$, Z_{Ep} and $Z_{phase-E}$ are determined using equation 3.

Z_{OHEW} is the OHEW self-impedance and is determined using equation 14

$$Z_E = R_E + 9.88 \times 10^{-7} f + j28.938 \times 10^{-7} f \log_{10} \left(\frac{D_e}{R_{GM}} \right) \quad (14)$$

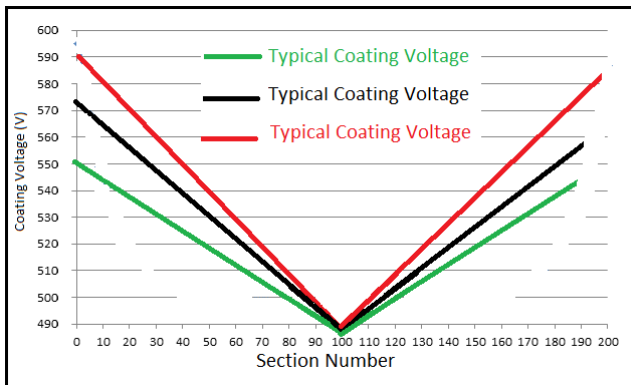


Fig. 6. Induced voltage under the paper methodology

Based on these equations, the OHEW return fault currents do not have any impact on the induced voltage. Fig. 7 illustrates the arrangement of HV transmission line with

the OHEW. Equation 3 is used to compute the mutual-impedance between the phase and pipeline, also between the OHEW and pipeline. The equation has three variables:

- Frequency, the phase and OHEW currents have the same frequency
- D_e , has the same value due to the unchanged in the frequency and soil resistivity structure
- $D_{Phase-p}$ and D_{OHEW-p} , the separation distances are different

It should be noted that the type of the OHEW has an effect on the shielding factor in equation 13 due to its self-impedance as shown in equation 14. In fig. 7, D_{AP} is smaller than D_{EP} which means Z_{AP} is higher than Z_{EP} . A similar approach is applied on phase B, it shows that Z_{EP} is lower than Z_{BP} . The separation between phase A and the OHEW is the same as the separation between phase B and the OHEW. This means $Z_{p-earth}$, $Z_{phase-earth}$ and Z_E in equation 13 are the same when computing a fault on phase A or B. The only difference is the impedance between the pipeline and the phase.

Based on this information, the worst case scenario is presented for a fault on phase A for a Delta arrangement transmission line as per fig. 7. It is recommended to locate the pipeline on the side where one phase is presented. This arrangement ensures that the effect of the OHEW current is at its maximum where two of the three phases are in fault.

Equation 15 represents the induced voltage in the paper approach and is derived using equations 2, 5 & 10.

$$V_{induced-p} = I_{fault} Z_{phase-p} - \sum_{n=1}^m I_{e_n} Z_{OHEW-p-span} \quad (15)$$

Where

m is the number of section

$Z_{OHEW-p-span}$ is the mutual impedance per span

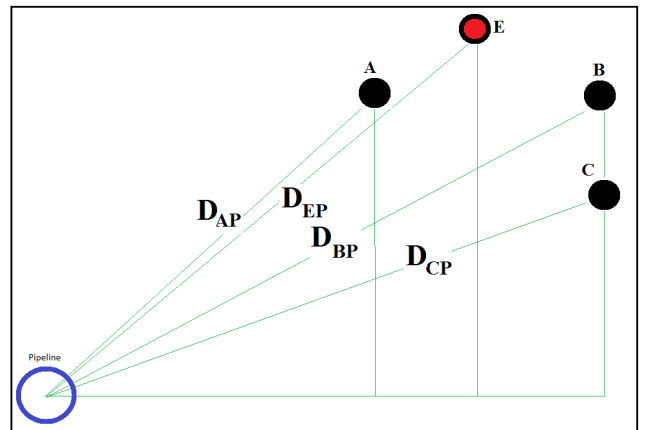


Fig. 7. Transmission line and pipeline arrangement with OHEW

The OHEW section current I_{en} can be found using the analytical approach as per [19, 20]

The simulation in fig. 8 is completed using the following input data:

$Z_{phase-p}$ is 0.256 ohm.km

Z_{OHEW-p} is 0.248 ohm.km

Z_E is 0.64 ohm.km

$Z_{phase-earth}$ is 0.38 ohm.km

The split factor changes due to changes in the proposed transmission line pole grid resistance. The simulation outputs show lower induced voltage when considering the OHEW return current. Fig. 9 shows the induced voltage between 1 and 2km on the distance axis. It is clearly shown that increasing split factor reduces the induced voltage.

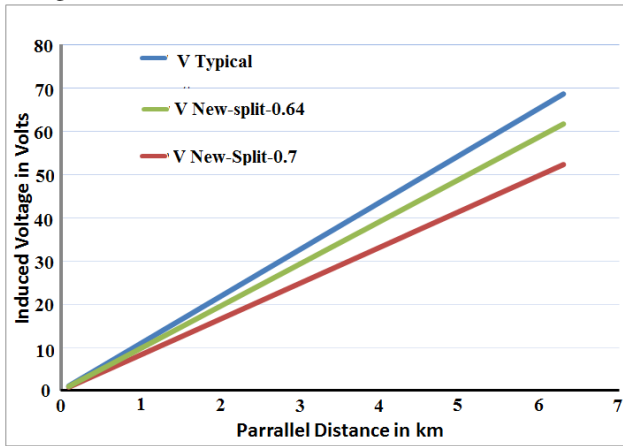


Fig. 8. Induced voltage on pile line under different split factors

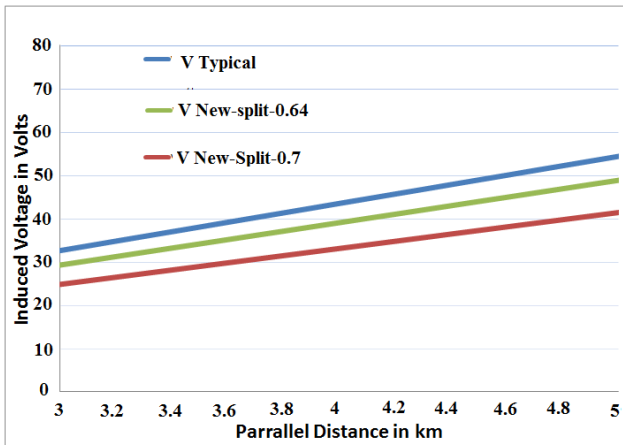


Fig. 9. Induced voltage computation along a small section of the pipeline

7. Case study

A joint easement between 132kV transmission line and conductive water pipe is chosen for the case study. The transmission line has delta arrangement. The following is

the study inputs:

- Transmission Line Length is 12.5km
- Single Line to ground fault is 10kA
- Pipe line running parallel with the transmission line for 12.5km

The first analysis step is completed using equations 12 and 13:

$$K = 0.42 \quad \text{and} \quad V_p = 1075.2V / km$$

The second step is completed using equation 15. Fig. 10 shows the analysis outputs comparison between equations 12 and 15. Fig. 11 shows the error percentage between the outputs of equations 12 and 15. As shown in fig. 11, the outputs of equation 12 are always higher than the outputs of equation 15. Therefore, it is always a positive error, this means; using equation 12 is more conservative. The error percentage decreases as the parallel distance increases. It should be noted, when the error is high, the induced voltage is at its minimum strength.

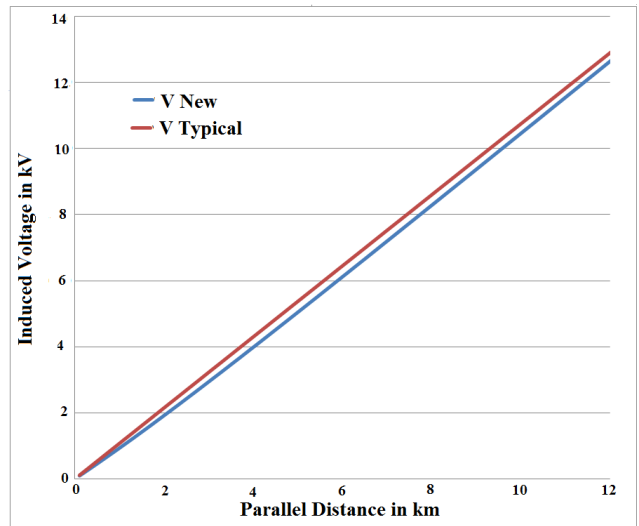


Fig. 10. Induced Voltage on the pipe line as per both methods

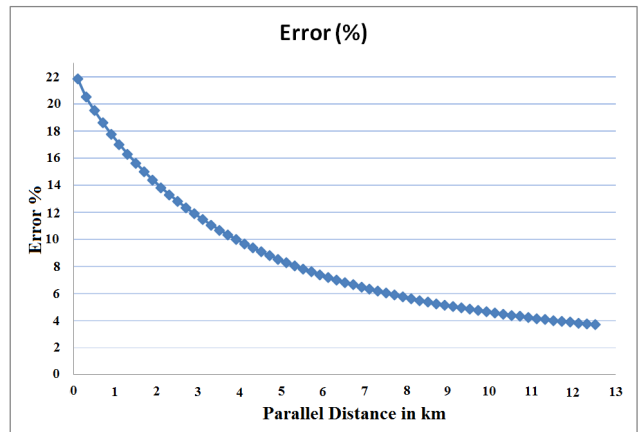


Fig. 11. Error percentage between the paper proposed method and equation 12 approach

8. Conclusion

The existing of the OHEW on high voltage transmission line lowers the induced voltage on any conductive object running parallel to the transmission line. This paper shows the relation between the OHEW split factor and the induced voltage. The work shows how it is possible to reduce the induced voltage by enhancing the OHEW split factor. The error analysis between the two methods decreases as the parallel distance increases. The work shows that by using the shielding factor as per equation 12 always represents more conservative analysis for long parallel distance and is considered to be over engineered for short parallel distance near the fault location.

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