Effect of HVTL Phase Transposition on Pipelines Induced Voltage

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Abstract

In this work, a study of the effect of the phase conductor transposition for a multi-circuit high voltage power transmission lines on the induced voltage on a buried pipeline was conducted and considered through modelling. The modelling was done applying Carson's concept of mutual impedances for a double circuit, three circuits and four circuit power transmission line on a buried pipeline. The simulated results obtained showed that the transmission line with un-transposed phase combination has the greater effect on the induced voltage while for the one or more of the other combinations, a cancellation or reduction can occur. This also is dependent on the tower geometry and the relative position of the pipeline and the transmission line. Also, the magnitude of the induced voltage increases with increasing number of circuits.

Keywords*: AC interference, Inductive coupling, Induce voltage, Phase transposition, pipelines, Transmission lines*

1. Introduction

As a result of the ever increasing cost of right of way suitable for transmission line and pipelines, coupled with environmental factors to protect nature and wildlife, there are more tendencies of installing pipelines near an existing power transmission lines. The current flowing through this transmission line phase conductors produces a time-varying magnetic field which couples to metallic structures in its right of way as shown in Figure 1.

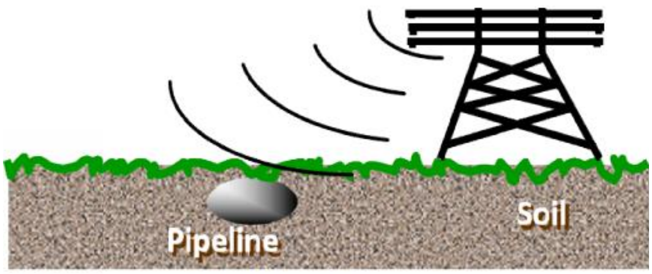

Figure 1. Coupling from a high voltage power transmission line on a buried pipeline

As a result of this coupling, voltage is induced in such structure. The induction can occur under both steady state and fault condition of the power transmission line [1, 2]. The interference from a high voltage power transmission line and a neighbouring pipeline can occur due to inductive, conductive and capacitive coupling [3-10]. Inductive coupling affects both aerial and underground pipelines that run parallel to or at an angle with a power transmission line while capacitive coupling only affects metallic structures located above the ground [8, 9]. In this type of coupling (capacitive coupling), "the pipeline picks up a voltage relative to the soil, which is proportional to the voltage on the transmission line [11, 12]. For structures located below the earth's surface, the effect of capacitive coupling is negligible because of the screening effect of the earth against electric fields. The resistive coupling between a transmission line and a nearby buried pipeline is only relevant during ground faults where

Received December 11, 2015; Revised March 16, 2016; Accepted April 8, 2016

significant levels of current flows into the ground [7, 13, 14]. Irrespective of the type of coupling, buried pipeline experience induction through any of these coupling or a combination of them which can pose danger to personnel working on the pipeline and can also compromise the materials of the pipe.

The interference from the power transmission lines on buried pipelines which varies with the electrical characteristics and geometry of the individual system [15], is also known to accelerate the corrosion process of pipelines [16-19]. AC corrosion case histories can be traced back to 1970 when cathodically protected pipeline was found perforated in Germany, as a result of AC interfering with the pipeline [20], thereby accelerating the corrosion process. In particular, there have been increasing reports of AC induced corrosion and failure of pipelines in recent years, drawing attention to this important problem. This problem has been a threat to the integrity of pipeline and therefore became a major topic of discussion among authors around the world. The subject has become more important for safety of personnel and prevention of pipeline from corrosion. Thereafter, NACE recommended that for safety of personnel working on the pipeline, the steady state induced potential should be considered dangerous and be mitigated if the measured or calculated potential on the pipeline exceeds 15 $V_{r.m.s}$ [21].

Furthermore, because of the increasing growth of energy demand and to ensure adequate supply of electric power and to cater for losses on the line, more multi-circuits, power transmission line is being used to transmit power for several kilometres across the Nation. The phase conductors of these multi-circuit lines are not always symmetrical, allowing for phase transpositions of the first circuit with respect to the other. The relative position of each phase with respect to the other is known to affect the magnetic field produced by the line current and can cause a drastic reduction in the magnetic field which in turn will have the effect of the voltage induced on buried metallic structure in this energy utility corridor. To ensure safety of the personnel touching the exposed part of the buried structure, the worst-case phase transposition which will give a minimal inductive effect on metallic structures needed to be obtained for the multi-circuits lines.

Pipeline being installed near an existing high voltage power transmission line is subject to inductive coupling from the line as a result of the time varying magnetic field produced by the transmission line current. The strength of the coupling depends, among other factors, on the relative position of the pipeline and the transmission line phase conductors. Different research works in the past and in recent times, have worked on the effect of the transmission line phase conductor combination [22, 23] and phase shifts [24-26] on the magnetic field produced by the line. However, the effect of this phase transposition/combination on the induced voltage on pipelines for safety of personnel and protection of pipelines from corrosion has not been fully covered yet. This work annexes the effect of the phase transposition of a multi-circuit power transmission lines on the induced voltage on buried steel pipeline, using one of the Rand Water sites, South Africa as a case study. In a double-circuit power transmission line, there are six possible phase combination/transposition of the first circuit with respect to the other as shown Figure 2. These phase transpositions are RWB-RWB, RWB-BWR, RWB-BRW, RWB-WRB, RWB-RBW, and RWB-WBR as shown in Figure 2.

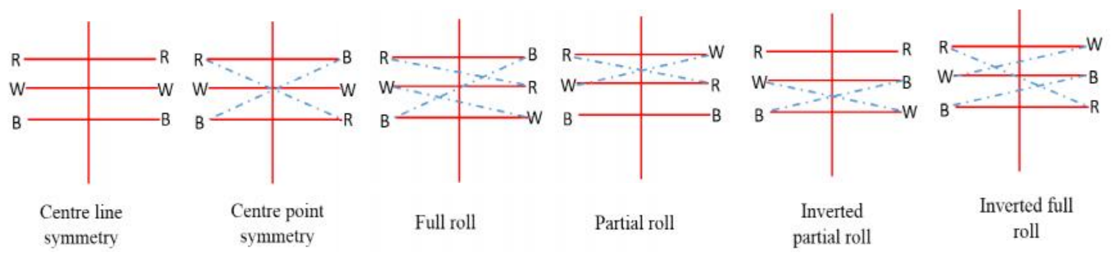

Figure 2. Possible phase transposition of a double circuit power transmission line

Assuming identical phase conductor characteristics and steady state current in each circuit with a different phase combination, the worst case phase transposition can be obtained which will be useful in designing AC mitigation system accordingly and reduce the danger of shock hazard to personnel. With three or more circuits on a power line, the number of possible combinations to simulate increases.

2. Materials and Method

2.1. Model Description and Evaluation

In this work, the effect of the phase conductor transposition of a double-circuit, three-circuit and four circuit power transmission lines on the inductive coupling effect resulting in an induced voltage on a buried steel pipeline was modelled and simulated. Figure 3 and Figure 4 show the schematic diagram and snapshot of the transmission line-pipeline right of way under study.

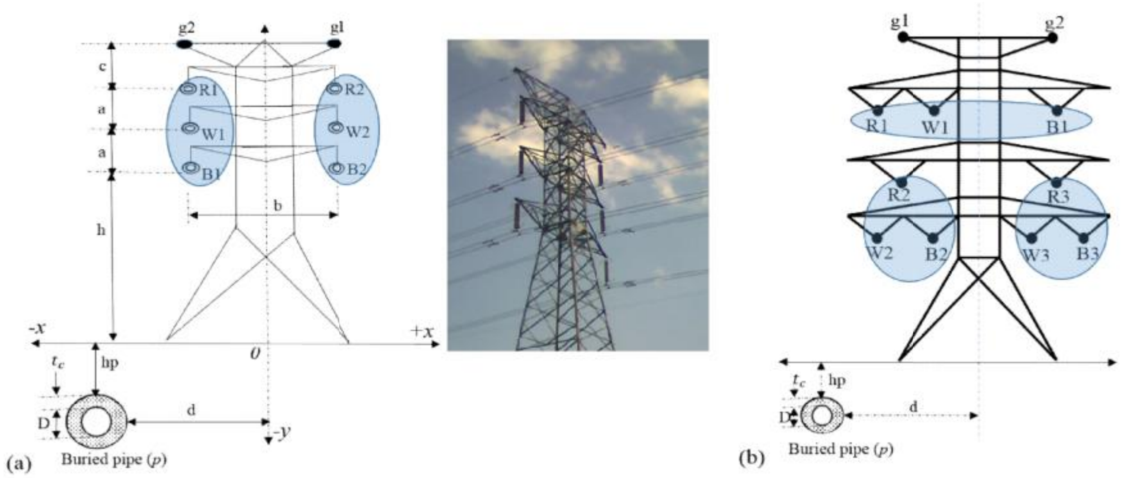

Figure 3. Schematic diagram and snapshot of the transmission line-pipeline right of way (a) double-circuit line (b) three-circuit line

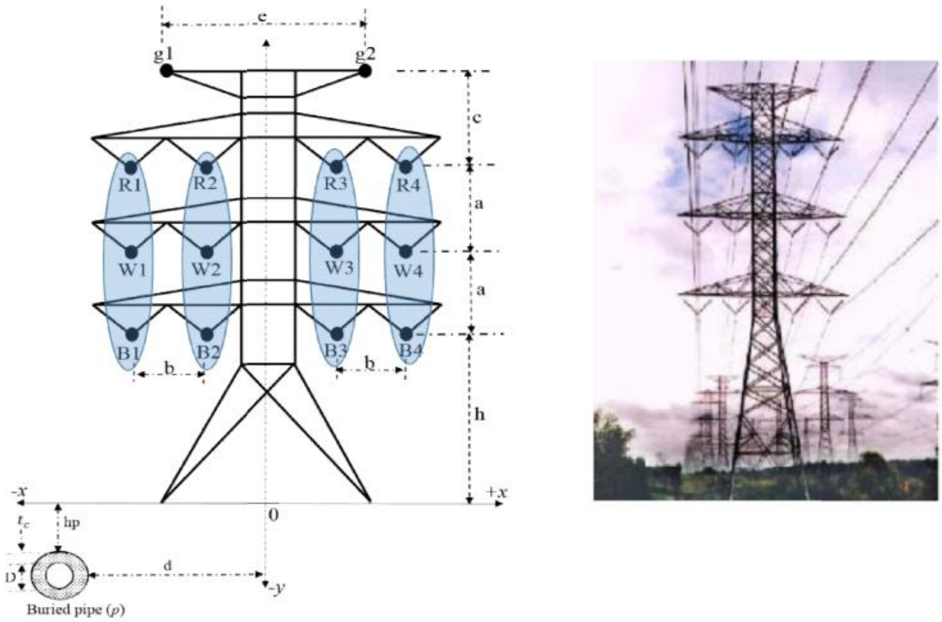

Figure 4. Schematic diagram and snapshot of a four-circuit transmission line-pipeline right of way

The simulation was done for the effect of the inductive coupling from these lines on the buried pipeline under steady state operation, using the Carson's concept of mutual impedance between the transmission line phase/earth wire conductors and the pipeline [27]. Using this concept, the longitudinal induced electromotive force (emf) on the pipeline due to the inductive coupling effect of the transmission line is given by

$$E_p = \sum_{i=1}^{N}\left[I_{R_i}\left(Z_{R_i p} - \sum_{j=1}^{k}\left(Z_{R_i g_j}\frac{Z_{g_j p}}{Z_{g_j}} \right)\right) + I_{W_i}\left(Z_{W_i p} - \sum_{j=1}^{k}\left(Z_{W_i g_j}\frac{Z_{g_j p}}{Z_{g_j}} \right)\right) + I_{B_i}\left(Z_{B_i p} - \sum_{j=1}^{k}\left(Z_{B_i g_j}\frac{Z_{g_j p}}{Z_{g_j}} \right)\right)\right] \quad (1)$$

where, *i* and *j* are positive integers with range of *i=1,2,……N*, and *j=1,2,…k*. *N* represents the number of circuits while *k* is the number of overhead earth wire on the transmission line. I_{Ri}, I_{wi} and I_{Bi} are the steady state current on the i^th circuit of the transmission line, Z_{Rip}, Z_{Wip} and Z_{Bip} are the mutual impedances between the R-W-B phase conductor of the i^th circuit and the pipeline. More also, Z_{gjp} represents the mutual impedance between the j^th earth wire conductor and the pipeline while Z_{Rigj}, Z_{Rigj} and Z_{Rigj} are the mutual impedance between the R-W-B phase conductors of the i^th circuit and the j^th earth wire. In addition to this, Z_{gj} is the self-impedance of the j^th earth wire conductor.
The mutual impedance (in Ω/m) between a pipeline *p*, and an overhead transmission line phase conductor *R*, *W*, *B* or earth wire conductor *g*, with earth return is evaluated using Equation (2) [28] as

$$Z_{pn} = \frac{\omega\mu_0}{8} + j\left(\frac{\omega\mu_0}{2\pi}\log_e\left(\frac{\delta_e}{D_{pn}} \right)\right) \quad \text{where } n=R_i,\ W_i,\ B_i \text{ or } g_j \quad (2)$$

where, μ_0 is the magnetic permeability of free space, ω is the angular frequency of operation of the transmission line, δ_e is the depth of equivalent earth return and D_{pn} is the geometric mean distances (GMDs) between the pipeline, transmission line phase conductor *R-W-B* or earth wire conductor *g* of the *i*^th transmission line circuit. Also, the self-impedance of the j^th earth wire conductor transmission line, with earth return is given as

$$Z_{g_j} = R_{g_j} + \frac{\omega\mu_0}{8} + j\left(\frac{\omega\mu_0}{2\pi}\left[\frac{1}{4} + \log_e\left(\frac{\delta_e}{R_{GM_j}} \right)\right]\right) \quad (3)$$

In Equation (3), R_{gj} is the AC resistance of the earth j^th wire and R_{GMj} is the geometric mean radius of the earth wire conductors of the transmission line. The depth of equivalent earth return is a function of soil resistivity ρ_{soil} and the transmission line operating frequency *f* [28-30], evaluated as

$$\delta_e = 658.87\sqrt{\frac{\rho_{soil}}{f}} \quad (4)$$

The various GMDs between the phase conductors of each circuit and the pipeline or the ground wire for the three case studies are derived from the Powerline-pipeline coordinates system shown in Figure 5.

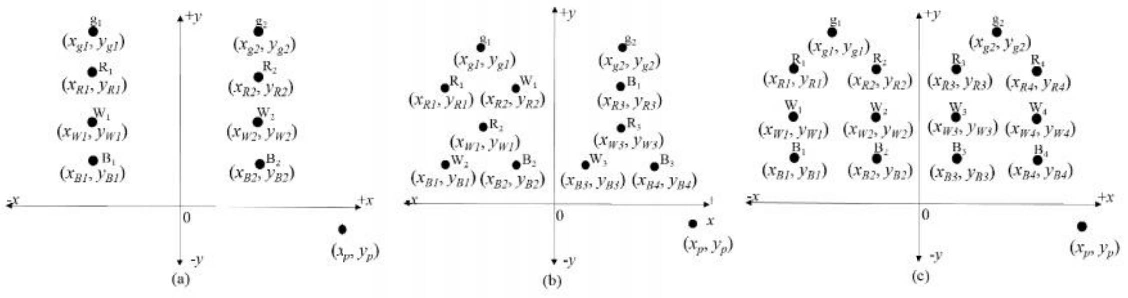

Figure 5. Powerline-pipeline coordinate system (a) double-circuits, (b) three-circuits (c) four-circuits

From Figure 5 (a), the GMD between the R-W-B phase conductors of the i[th] transmission line circuit and the pipeline is given by

$$\left.\begin{aligned} D_{R_i p} &= \left[\left(x_p - x_{R_i}\right)^2 + \left(y_{R_i} - y_p\right)^2\right]^{\frac{1}{2}} \\ D_{W_i p} &= \left[\left(x_p - x_{W_i}\right)^2 + \left(y_{W_i} - y_p\right)^2\right]^{\frac{1}{2}} \\ D_{B_i p} &= \left[\left(x_p - x_{B_i}\right)^2 + \left(y_{B_i} - y_p\right)^2\right]^{\frac{1}{2}} \end{aligned}\right\} \tag{5}$$

x_p, y_p, x_{Ri}, x_{Wi}, x_{Bi}; y_{Ri}, y_{Wi} and y_{Bi} are the horizontal and vertical position of the pipeline and the phase conductors of the i[th] circuit as shown in Figure 5. Also, the GMD between the j[th] earth wire conductors and the pipeline is given by

$$D_{g_j p} = \left[\left(x_p - x_{g_j}\right)^2 + \left(y_{g_j} - y_p\right)^2\right]^{\frac{1}{2}} \tag{6}$$

Other GMDs are derived using the same method. Thereafter, the induced voltage V_p, on the entire parallel exposure length L, of the pipeline is given by

$$V_p = E_p \times L \tag{7}$$

2.2. Case Study Parameter used for Simulation

As stated earlier, the effect of phase transposition for three different multi-circuit lines on the induced voltage on an 800 mm diameter pipe buried 1 m beneath the soil surface, was considered. The pipeline was parallel with the transmission line for a length of 1 km. The three phase current on the line were considered under steady state condition with maximum load current of 410 A for zebra typed conductor used in South Africa. The transmission lines operating at 50 Hz, have phase conductors separated at a distance of 6 m from each other with a ground clearance of 12 m. The transmission line overhead earth wires with a 13.48 mm diameter has an AC resistance of 3.44 Ω/km. The earth is assumed to be flat, free from irregularities and homogenous with a resistivity of 100 Ωm.

3. Results and Analysis

The induced voltage on a buried steel pipeline due to the inductive coupling effect of the phase conductor transposition of multi-circuits, power transmission lines have been computed and the results presented. Figure 6 shows the effect of the phase transposition of a double-circuit power transmission line on the magnitude of the induced voltage on the pipeline.

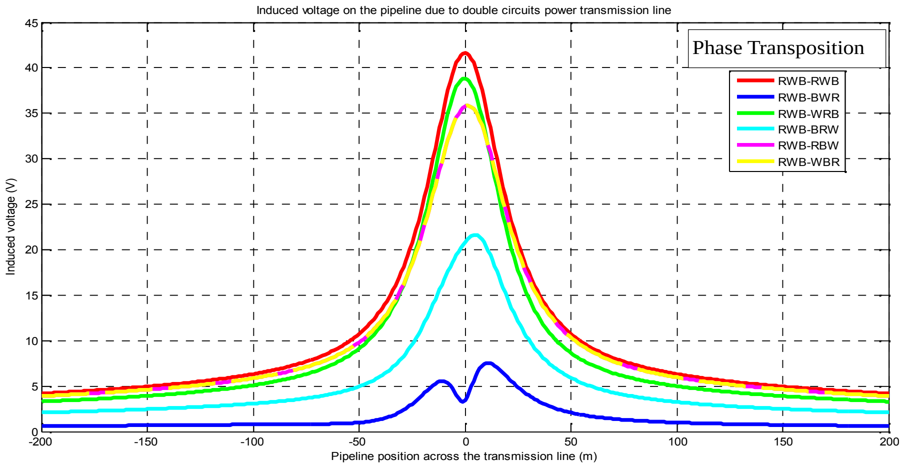

Figure 6. Induced voltage on buried pipeline due to phase transposition of a double-circuit power transmission line

Looking at the Figure, it is observed that there is a drastic reduction in the magnitude of the induced voltage for a directly phase transposed, that is, RWB-BWR while for an un-transposed condition, its effect is relatively higher than others phase transposition shown in the Figure. It is also, observed that the directly phase transposed decreases slightly with distance while for another phase transposition, they decreases drastically with increasing distance.

Considering Figure 7, a different pattern of results is observed. At some points 15 m beyond the centre line of the transmission line, the phase transposition with RWB-BWR-RWB gives the least inductive effect on the pipeline. However, as the distance increases beyond 50 m, phase combination with RWB-RWB-WBR has the least effect. This pattern of results is obtained due to the phase configuration of this type of transmission line (a combination of horizontal and delta configuration).

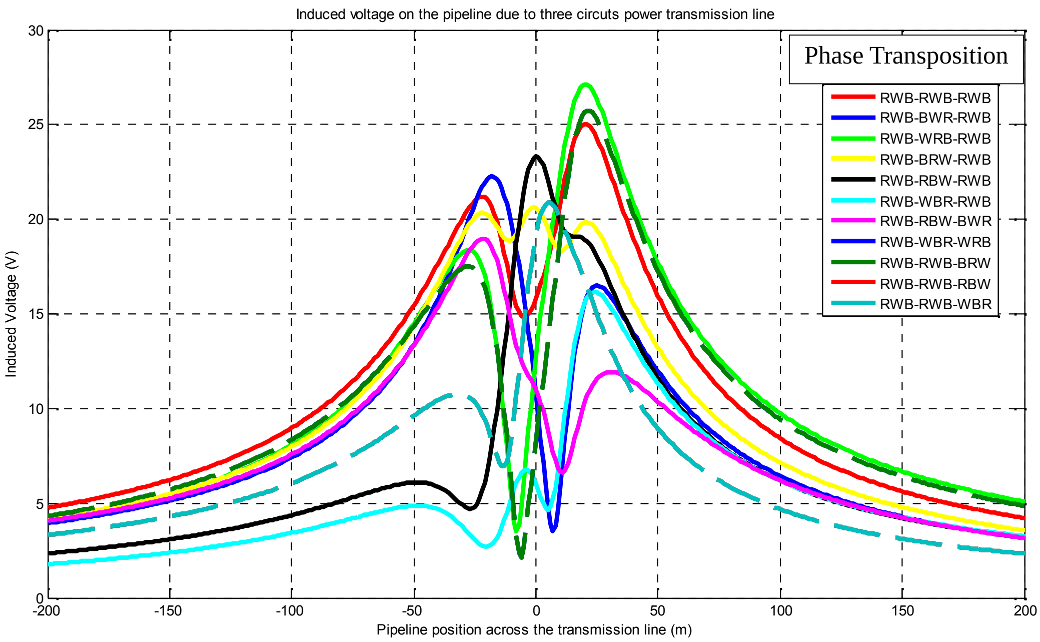

Figure 7. Induced voltage on buried pipeline due to phase transposition of a three-circuit power transmission line

In Figure 8, the effect of the transmission line phase conductor transposition on the induced voltage on a pipeline buried near a four-circuit power transmission line is presented. Considering this figure, in line with Figure 6, the un-transposed phase combination has the highest effect while the one with RWB-BWR-RWB-BWR and RWB-RWB-BWR-RWB has the least effect. Some other phase transposition, also gives a little reduction in the magnitude of the induced voltage as shown in Figure 8. Furthermore, symmetrical and asymmetrical nature is observed, as some are symmetrical about the centre line of power transmission line tower while some shows a little offside asymmetry about the centre line. This is related to the results obtained in [23, 24] for magnetic field produced from a multi-circuits line. All the phase combinations decrease drastically with distance up to about 50 m, after which they decrease slightly with increasing distance.

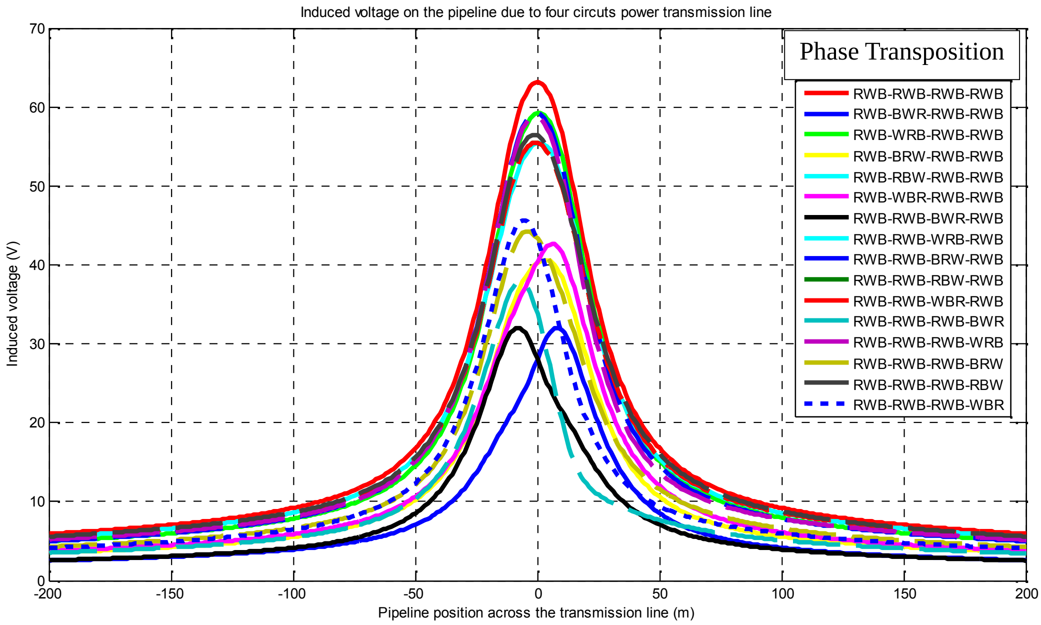

Figure 8. Induced voltage on buried pipeline due to phase transposition of a four-circuit power transmission line

3.1. Effects of the Number of Circuits

Figure 9 shows the effect of increase in the number of circuits on the induced voltage on the buried pipeline. It is evident from the figure that this increase has a great effect on the induced voltage. The effect is more pronounced on the pipeline at few distances (less than 50 m) from the centre line of the transmission line. However, with increasing distance, the effect reduces gradually to almost a negligible value.

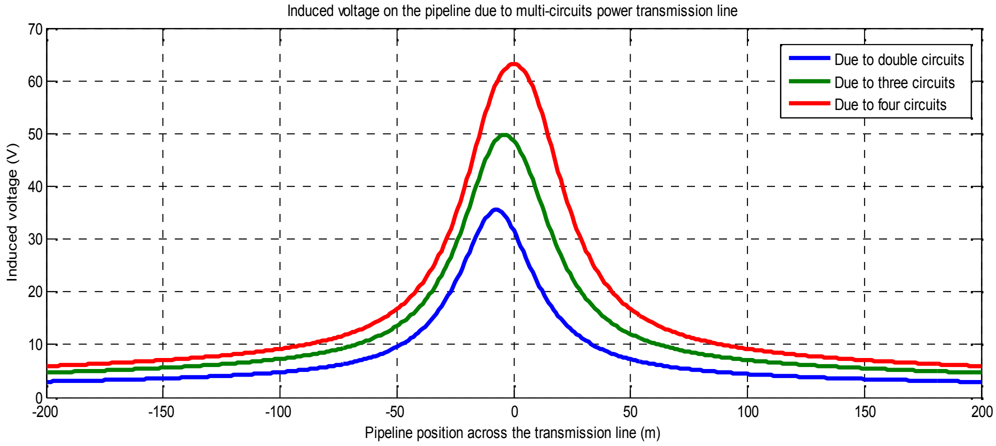

Figure 9. Induced voltage on buried pipeline due to multi-circuits power transmission line

4. Conclusion

The effect of the phase conductor transposition of a multi-circuit power transmission lines on the magnitude of the induced voltage on a buried steel pipeline have been computed and the simulated results from MATLAB software presented and analysed. It is obvious from these results that phase conductors with a direct phase transposition of the first phase with respect to the other shows a better reduction in the magnitude of the induced voltage on the pipeline for most of the lines. Also for one or more combination, a cancellation or reduction in the magnitude of the induced voltage is observed. Therefore, for installing metallic structures such as pipelines in the energy utility corridor consisting of a multi-circuit high voltage power transmission lines, the effect of the phase transposition of these lines must be taken into consideration to limit the danger that might occur due to shock hazard to personnel touching an exposed part of these metallic structure. The number of circuits on a power transmission line is also known to have a greater effect on the induced voltage on metallic pipelines buried near existing lines.

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