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# Variation in Phase Shift of Multi-Circuits HVTLs Phase Conductor Arrangements on the Induced Voltage on Buried Pipeline: A Theoretical Study

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**Abstract**—Alternating current interference from power transmission lines on nearby metallic pipelines has been a topic of research in the past years. Of particular interest is the induced voltage on metallic pipelines due to the time varying electromagnetic fields coupling from the transmission lines. Several related studies dealing with this problem have been published. Nevertheless, the issue of current phase shift variation and its effect on the voltage induced on metallic pipelines has not been fully covered yet. In view of this, we present the computation of the induced open circuit voltage on a buried metallic pipeline running in parallel with the power transmission lines in three Rand Water sites, South Africa. The computation was performed using Carson's relations and power system concepts of mutual impedances between two circuits. The variation in current phase shift was considered for six different phase conductor arrangements. The overall simulation results yield useful information. The computations show that the induced open circuit voltage changes significantly with different phase arrangements and with variations in the current phase shift between the two circuits. In this work, the characteristic nature of the variation in the induced open circuit voltage for the six phase arrangements and phase shifts are examined in more detail. We concluded that in placing buried pipelines in the vicinity of AC double-circuits power lines, it is essential to consider the phase arrangement of the line and current phase shift between the two circuits. These, together with other line parameters, are vital in evaluating the induced voltage with the pipe position before installation and for the design of effective AC mitigation techniques.

## 1. INTRODUCTION

The general earth does not provide shielding to magnetic field, and this therefore makes underground metallic pipelines in proximity to overhead AC high voltage power transmission lines (HVTLs) to be prone to inductive coupling from the power line. This coupling exists under both normal operating conditions and short circuit conditions on the power line, and induces longitudinal voltages or electromotive forces (EMFs) on the pipeline [1–10]. These induced voltages produce stress on the pipeline and can cause currents to circulate in the pipeline [11]. The induced voltage on the pipeline causes accelerated corrosion of the pipeline material due to an exchange of AC-induced current and voltage between the pipeline and the surrounding soil. Depending on condition on the power line (steady state condition or fault condition), the induced voltage can pose a danger to working personnel on the pipeline. It can damage the materials of the pipeline coating and adversely affects the performance of cathodic protection (CP) system of the pipeline [6, 12–15]. Therefore, the relevance to this interference is always increasing for safety of operational personnel and for the protection of buried metallic pipelines

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from corrosion. Several standards have been published to provide a guide for protection of operating personnel touching the exposed part of the pipeline [16–18]. NACE recommended that for safety of operating personnel, the steady state induced potential should be considered dangerous and be mitigated if the measured or estimated potential on the pipeline exceeds 15 $V_{r.m.s}$ [17]. To adhere strictly to these regulations, the influence of some parameters on the level of AC induced voltage for any particular power line geometry must be estimated. The current phase shift of the phase conductors of multi-circuits lines is one of these parameters.

The magnitude of the induced voltage on the underground pipeline within the inductive zone of influence of the power lines varies with the magnitude of the field below the power line where the pipeline is located. This also varies with some physical line parameters, and operating conditions of the power line. The inductive zone of influence of the power line is influenced by the earth's resistivity [11]. For buried metallic pipelines that run in parallel with the power line, the horizontal component of the magnetic field plays a major role in inducing voltage on the pipeline [19]. Numerous research efforts dealing with this problem can be found in the literature. Nevertheless, the issue of current phase shift variation of multi-circuits lines and its effect on the voltage induced on metallic pipelines has not been fully covered, which has been the focus of this research work.

On double-circuits power lines, there are six possible phase configurations of the second circuit with respect to the first circuit. The voltage induced on the pipeline underneath the power line as a result of the magnetic fields will be influenced greatly by the relative position of the corresponding phases and phase sequence arrangement. It is also dependent on the phase shift between corresponding phase currents of the two circuits. Research works in [20–22] have shown that neglecting the current phase shift effects of double-circuits lines can lead to significant errors in magnetic field calculations larger than 45%. Additionally, works in [23, 24] also showed that neglecting the effect of current phase shifts can result in overestimation (or under estimation) of induced voltages on nearby buried metallic pipelines from AC double-circuits HVTLs between 10% and 75%. Theoretically the highest induced voltage should occur when the phase arrangements in both circuits are the same, 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. Assuming identical conductor characteristics for the two circuits, and by allowing for changes in the phase arrangements, the worst-case double-circuit phase combination may be obtained from computations.

In this work, we present the computation of the induced voltage on a Rand Water buried metallic pipeline running in parallel with the double-circuits power transmission lines. The current phase shifts from the lines for six different phase arrangements were considered. Three of the Rand Water site in Gauteng Province, South Africa were used as case studies. The computation of the longitudinal induced voltage in the pipeline was performed using Carson's relations of mutual impedances and power system relations already established in the literature [11, 25–27]. All conductors of the power lines and the pipeline are assumed to be straight, horizontal, and parallel. The soil is assumed to be homogenous of constant resistivity.

## 2. RESEARCH METHODS

The computation of the induced voltage on the buried metallic pipeline due to the double-circuits lines was performed for three types of configurations: the vertical, the horizontal, and delta geometries shown in Fig. 1. These are based on the power line geometries sharing the same corridor with Rand Water pipelines at three locations in Gauteng Province, South Africa. The phase conductors of the power line are labelled A, B, and C. In Fig. 1(a), the two circuits are separated by $W$, $H_t$ represents the distance of the lowest conductor from the ground at the tower while $a$ denotes the vertical separation between the phase conductors. In Fig. 1(b), a represents the horizontal separation of the phase conductor per circuit while in Fig. 1(c), it represents the vertical separation between the phase conductors. The two towers in Fig. 1(b) and Fig. 1(c) are separated by $T_c$. For the computations, the medium is assumed to be linear, and the ground is assumed to be homogenous, conductive but magnetically transparent [28].

The computation of the longitudinal induced open circuit voltage on the pipeline, under steady state conditions was performed using simple power system concepts and Carson's relations of mutual impedances between the phase conductors and the pipeline [11, 25–27].

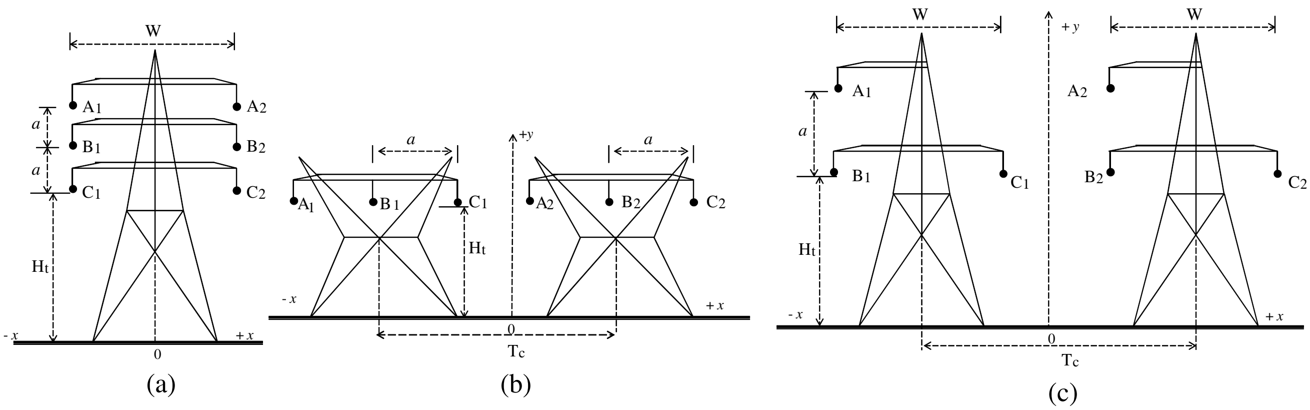


**Figure 1.** Schematic of the double-circuit power lines (a) vertical configuration, (b) horizontal configuration, and (c) delta configuration.

Considering a single-circuit overhead line with one earth wire, each current induces a voltage on the pipeline through the appropriate mutual impedance between the pipeline and the conductor. The longitudinal emf induced on the pipeline due to the three-phase currents $I_A$, $I_B$, $I_C$ and the earth wire current $I_E$ is given by

$$E_p = -\left(I_A Z_{pA} + I_B Z_{pB} + I_C Z_{pC} + I_E Z_{pE}\right) \tag{1}$$

where $Z_{pA}$, $Z_{pB}$, $Z_{pC}$ are the mutual impedances between the respective phase conductors and the pipeline, and $Z_{pE}$ is the mutual impedance between the earth wire conductor and the pipeline.

Assume that the voltage drop across the earth wire conductor is zero, which is given by

$$\Delta V_E = I_A Z_{EA} + I_B Z_{EB} + I_C Z_{EC} + I_E Z_{EE} = 0 \,\text{giving} \tag{2}$$

$$I_E = -\frac{1}{Z_{EE}}\left(I_A Z_{EA} + I_B Z_{EB} + I_C Z_{EC}\right) \tag{3}$$

where $Z_{EE}$ is the self-impedance of the earth wire conductor, and $Z_{EA}$, $Z_{EB}$, $Z_{EC}$ are the mutual impedances between the respective phase conductors and the earth wire conductor.

Substituting $I_E$ into Equation (1),

$$E_p = -\left[\left(I_A Z_{pA} + I_B Z_{pB} + I_C Z_{pC}\right) - \frac{Z_{pE}}{Z_{EE}}\left(I_A Z_{EA} + I_B Z_{EB} + I_C Z_{EC}\right)\right] \tag{4}$$

Equation (4) can be used whether the phase currents are balanced or not.

The mutual impedance $Z_{pq}$ between the pipeline and an overhead line conductor (or earth wire conductor), with earth return conductor is given by

$$Z_{pq} = \frac{\mu_0 \omega}{8} + j\frac{\mu_0 \omega}{2\pi} \ln\left(\frac{D_{erc}}{d_{pq}}\right) \tag{5}$$

where $d_{pq}$ is the distance between the centre of the pipeline and the line conductor (or earth wire conductor); $\omega$ is the angular frequency of the current; $D_{erc}$ is the depth of an equivalent earth return conductor and is related to the earth's skin depth (depth of penetration), $\delta$ given by [11]

$$D_{erc} = 1.309125\delta \tag{6}$$

The earth's skin depth (depth of penetration) is given by

$$\delta = \sqrt{\frac{\rho_e}{\mu_o \pi f}} \tag{7}$$

where $\rho_e$ is the resistivity of the earth, $\mu_o$ the permeability of free space (assuming earth relative permeability of unity), and $f$ the frequency of the source current.

Equation (5) also holds for the mutual impedance between an overhead line conductor and the earth wire conductor, with earth return conductor. The self-impedance $Z_{EE}$ of the earth wire conductor is given by

$$Z_{EE} = R_{EE} + \frac{\mu_0 \omega}{8} + j\frac{\mu_0 \omega}{2\pi}\left[\frac{1}{4} + \ln\left(\frac{D_{erc}}{r_{0em}}\right)\right] \tag{8}$$

where $R_{EE}$ is the earth wire conductor AC resistance and $r_{0em}$ the geometric mean radius of the earth wire conductor. For a non-magnetic solid conductor with a relative permeability of unity, and radius $r_{0e}$ [11],

$$r_{0em} = 0.7788 r_{0e} \tag{9}$$

If the earth wire is neglected, then Equation (1) is reduced to

$$E_p = -\left(I_A Z_{pA} + I_B Z_{pB} + I_C Z_{pC}\right) \tag{10}$$

For a double-circuit line, each circuit of the line will induce voltage on the pipeline. The total longitudinal induced open circuit voltage on the pipeline will be the sum of the induced voltages due to each circuit of the line. If the longitudinal induced voltages due to each of the two circuits of the double-circuit line are $E_{p1}$ and $E_{p2}$ respectively, then the total longitudinal induced emf is given by

$$E_{pT} = E_{p1} + E_{p2} \tag{11}$$

If the pipeline runs in parallel with the line for a length $L$, then the induced open circuit voltage $V_p$ on the pipeline is

$$V_p = E_{pT} L \tag{12}$$

The induced open circuit voltage in Equation (12) is applied only to a pipeline which is totally insulated from the earth and with no leakage impedance to the earth and zero series impedance along the longitudinal length of the pipeline conductor. The steady state current in the three phase conductors of a circuit varies sinusoidally with a phase angle $\varphi$ to one another. It is assumed that the phase currents of the second circuit have a phase shift $\alpha$ to the corresponding phase currents of the first circuit. Then for different phase arrangements and variations in the current phase shift, they are taken care of in the expressions for the phase currents of each circuit of the double-circuits line in Equations (4) and (10). The magnitude of the induced voltage can then be obtained by taking the modulus of $V_p$ in Equation (12).

### 2.1. Case Study Parameter Used for Computation

Table 1 shows the parameters of the transmission lines in Fig. 1 used for the simulation. In the computation, the induced open circuit voltage on the buried pipeline below the power lines was obtained for a balanced system in which the current in the conductors is at a phase angle $\varphi$ of 120° to one another.

For the power lines at the three sites, symmetrical load current and earth's resistivity of 100 Ωm were considered. Also, the effects of overhead earth wire on the circuits was neglected. The pipe's

**Table 1.** Transmission line parameters.

| Transmission line configuration type | Double circuits vertical | Double circuits horizontal | Double circuits delta |
|---|---|---|---|
| Load current. | 400 A | 400 A | 400 A |
| Distance from the ground to the lowest conductor on the tower. | 22 m | 17 m | 17 m |
| Maximum mid-span sag. | 10 m | 5 m | 5 m |
| Mid-span ground clearance. | 12 m | 12 m | 12 m |
| Separation between the phase conductors of each circuit. | 10 m | 10 m | 12 m |
| Separation between the two circuits. | 15 m | 32 m | 15 m |

radius is 0.5 m buried at centre of pipe-to-soil surface distance of 1.5 m. The pipeline is assumed to have a length of parallelism with the power line of 1 km. The longitudinal induced open circuit voltage was evaluated for the pipeline placed at varying horizontal distances of up to 50 m from the power lines in both directions in the transverse plane. Transmission line servitude by Eskom in South Africa for 275 kV–400 kV lines is 23.5 m measured from the centre line of the power line [29]. Current phase shifts between the circuits was considered from $-180°$ to $+180°$. Computations were performed for six possible different phase arrangements of the double-circuits, and the combinations are ABC-ABC, ABC-CBA, ABC-BAC, ABC-CAB, ABC-ACB and ABC-BCA. MATLAB software was used for the computation and presentation of result.

## 3. RESULTS AND DISCUSSION

### 3.1. Induced Voltage with Phase Arrangement: Vertical Configuration

Figure 2 shows the computed longitudinal induced open circuit voltage on the buried metallic pipeline at varying horizontal distances to the centre of the power line, of all the six phase arrangements with a phase shift of 0° between the corresponding phase currents of the two circuits, for the balanced double-circuit vertical configuration.

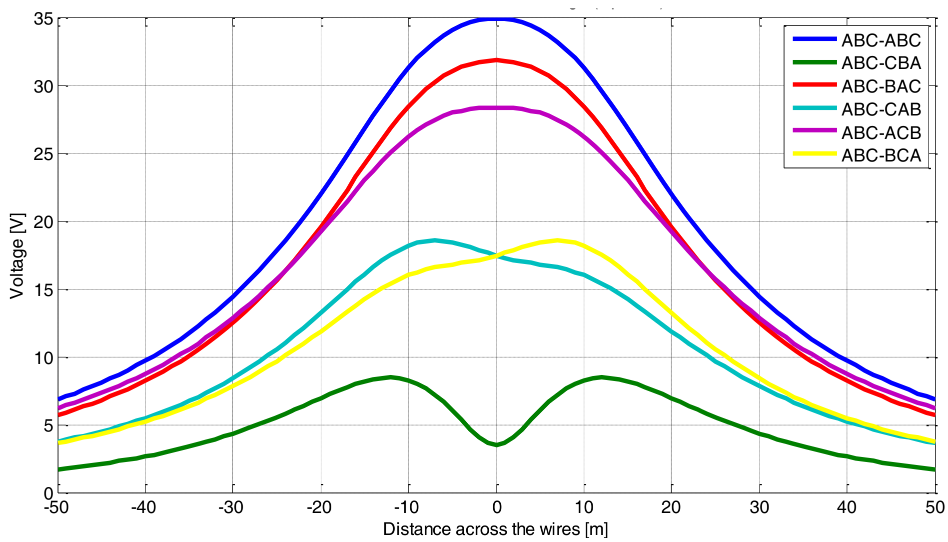


**Figure 2.** The computed induced open circuit voltage on the buried pipeline at varying distances to the centre of the line of all the six phase arrangements with a phase shift of 0° between the corresponding phase currents of the two circuits, for the balanced double-circuit vertical configuration.

From this figure, one can see that the untransposed phase arrangement ABC-ABC shows maximum value of the induced voltage on the pipeline at the centre between the two circuits, while the directly transposed phase arrangement ABC-CBA gives the minimum at the centre. Also, at all other horizontal distances of the pipeline from the power line, the untransposed phase arrangement gives the maximum values, while the directly transposed arrangement gives the minimum values. The values of the other phase arrangements lie within. This shows that the phase arrangement of the line conductors influences the magnitude of the induced open circuit voltage on the pipeline at a location from the line. Also, it should be noted that the result presented here is dependent upon the transmission line configuration type. For other types of configuration, a different result might be observed.

### 3.2. Induced Voltage with Phase Arrangement: Horizontal Configuration

Figure 3 shows the computed longitudinal induced open circuit voltage on the buried metallic pipeline at varying distances to the mid-distance of the lateral separation of the centres of the two circuits of

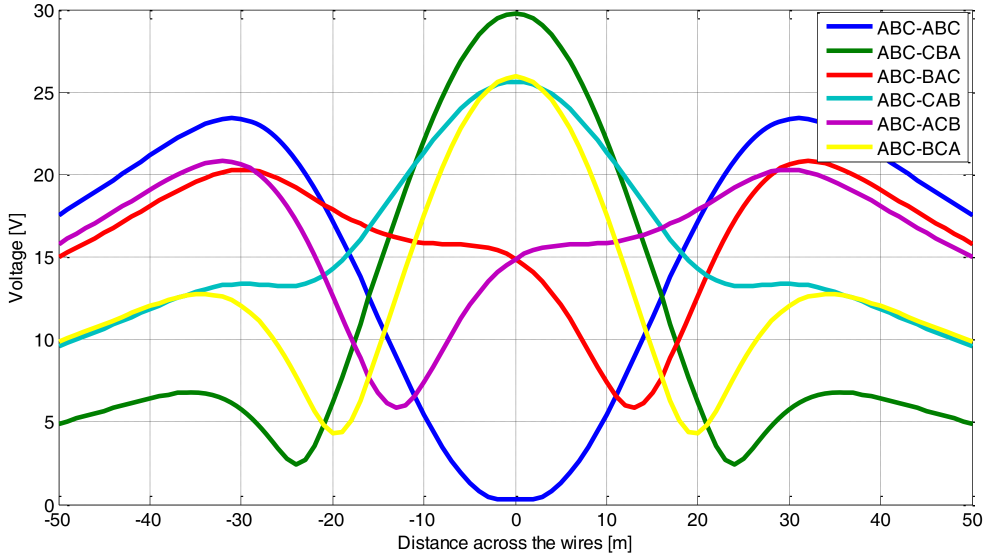


**Figure 3.** The computed induced open circuit voltage on the buried pipeline at varying distances to the centre of the line of all the six phase arrangements with a phase shift of 0° between the corresponding phase currents of the two circuits, for the balanced two-circuit horizontal (two towers) configuration.

the power line, of all the six phase arrangements with a phase shift of 0° between the corresponding phase currents of the two circuits, for the balanced two-circuit horizontal (two towers) configuration.

For this geometry, the directly transposed phase arrangement ABC-CBA shows the maximum value of the induced voltage on the pipeline at the mid-distance of the lateral separation of the centres of the two circuits. Other phase arrangements have reduced values with the untransposed phase arrangement ABC-ABC showing the minimum. Beyond the outermost conductors of the two circuits, the reverse is the case with the untransposed arrangement, giving maximum values of the induced voltage and the directly transposed arrangement showing minimum values. In addition, one can see that the phase arrangements ABC-BAC and ABC-ACB is like a mirror reflection of the other and are not symmetrical in nature at every point on the curve as compared to other phase arrangements. This is observed for this type of double-circuits (two towers) horizontal power line configuration. For other types of double-circuits horizontal configuration, a different result might be observed.

### 3.3. Induced Voltage with Phase Arrangement: Delta Configuration

Figure 4 shows the computed induced open circuit voltage on the buried metallic pipeline at varying distances to the mid-distance of the lateral separation of the centres of the two circuits of the power line, of all the six phase arrangements with a phase shift of 0° between the corresponding phase currents of the two circuits, for the balanced two-circuit delta (two towers) configuration.

At the mid-distance of the lateral separation of the centres of the two circuits, only the phase arrangements ABC-CAB and ABC-ACB show maximum induced voltage. At a pipe location of about +14 m to +16 m from the mid-distance of the lateral separation of the centres of the two circuits, phase arrangement ABC-BCA shows minimum value. This corresponds to the location of the two vertical conductors of the second circuit of the two-circuit line. The transposed phase arrangement ABC-CBA shows a minimum for the pipe position close to the +20 m distance. At a distance of about +40 m and beyond, the untransposed phase arrangement gives the maximum value while the transposed phase arrangement gives the minimum. But at a distance of about −40 m and beyond, the untransposed arrangement ABC-ABC gives the maximum value while the phase arrangement ABC-ACB gives the minimum. The pattern of the induced voltage profile can be attributed to the particular arrangement of the conductors for this delta configuration. For the other conductor arrangement of delta configuration, a different pattern might be observed.

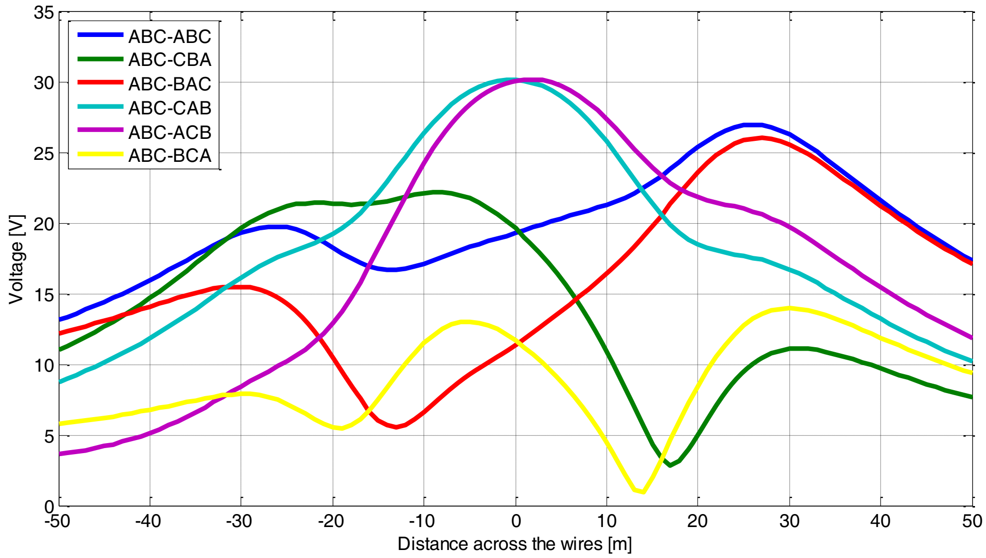


**Figure 4.** The computed induced open circuit voltage on the buried pipeline at varying distances to the centre of the line of all the six phase arrangements with a phase shift of 0° between the corresponding phase currents of the two circuits, for the balanced two-circuit delta (two towers) configuration.

### 3.4. Induced Voltage with Current Phase Shift

Figure 5 shows the computed lateral profile of the induced open circuit voltage on the pipeline at varying distances to the centre of the power line with variations in current phase shift from −180° to +180°, of the balanced double-circuits vertical configuration, for all the six phase arrangements.

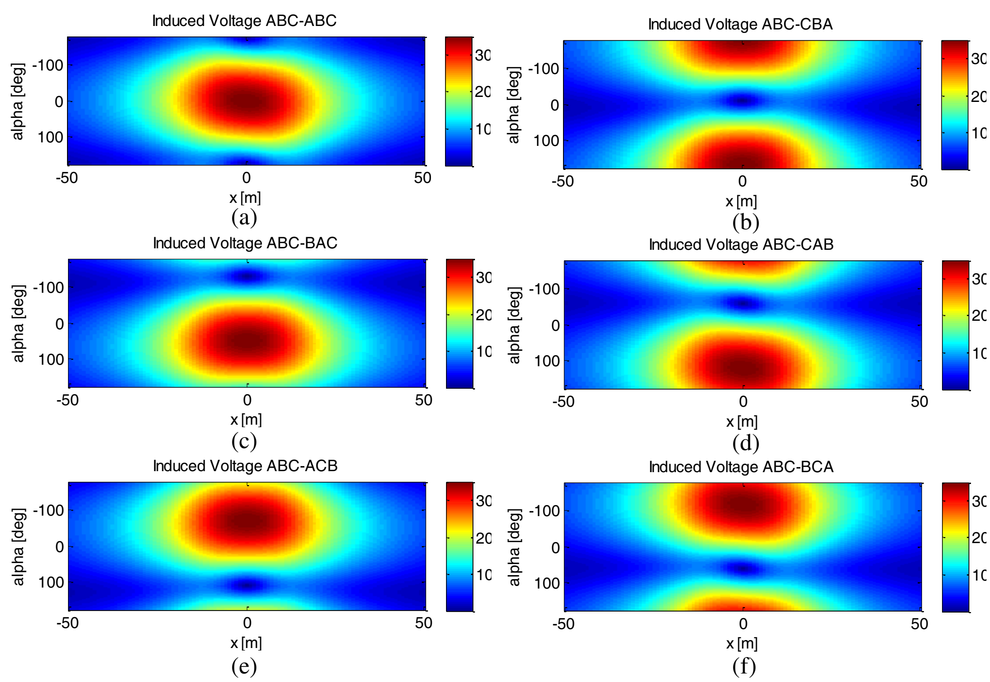


**Figure 5.** Lateral profile of the induced open circuit voltage on the buried pipeline with variations in current phase shift, of the balanced, double-circuit, vertical configuration, for all the six phase arrangements.

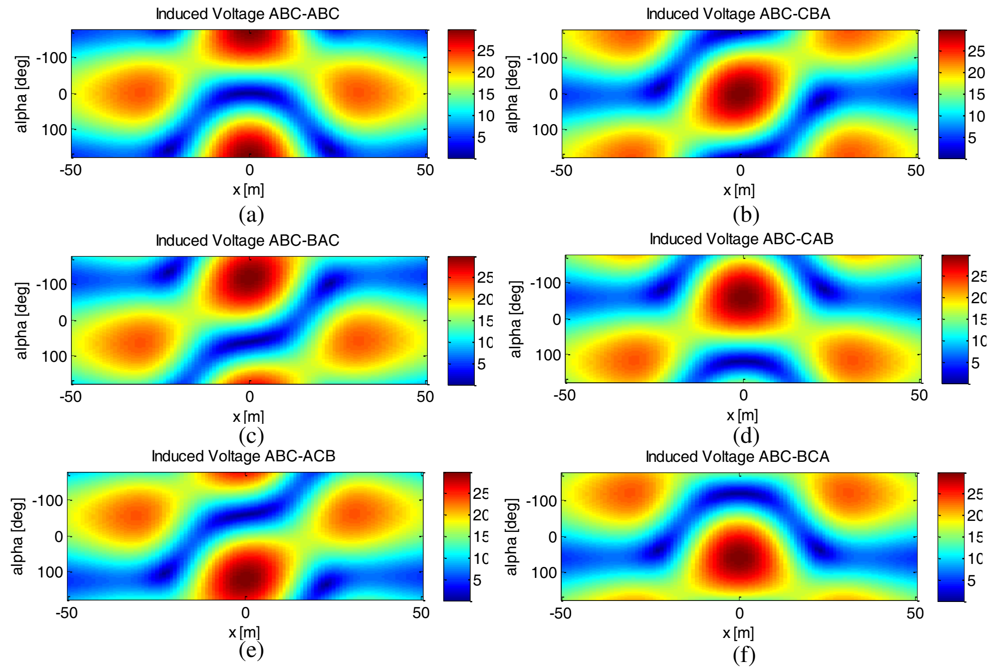


**Figure 6.** Lateral profile of the induced open circuit voltage on the buried pipeline with variations in current phase shift, of the balanced two-circuit, horizontal (two towers) configuration, for all the six phase arrangements.

Considering the patterns of each phase arrangement in the figure, it can be observed that the lateral profiles and magnitude of the induced open circuit voltage on the pipeline vary with the current phase shift angle $\alpha$ for all the six phase arrangements, which also supports [23, 24]. Also, the largest width of the lateral profile of the induced open circuit voltage for each phase arrangement occurs at different angles of the current phase shift. Moreover, the pattern of variation of the lateral profile and magnitude of the induced open circuit voltage with current phase shift can be observed to be only unique for two phase arrangements (untransposed ABC-ABC, and directly transposed ABC-CBA), while patterns of other phase arrangements are equivalent patterns of those two but phase shifted. The patterns of phase arrangement ABC-CAB and ABC-BCA are the equivalent of a pattern of untransposed phase arrangement ABC-ABC but phase shifted by $-120°$ and $+120°$ respectively. Similarly, the patterns of the phase arrangement ABC-BAC and ABC-ACB are the equivalent of a pattern of transposed phase arrangement ABC-CBA but phase shifted by $+120°$ and $-120°$, respectively. This was also indicated in [23, 24].

In Fig. 6, we illustrate the computed lateral profile of the induced open circuit voltage on the pipeline at varying distances to the mid-distance of the lateral separation of the centres of the two circuits of the power line with variations in current phase shift from $-180°$ to $+180°$, of the balanced two-circuit, horizontal (two towers) configuration, for all the six phase arrangements.

As for the case of the vertical configuration, the lateral profiles and the magnitude of the induced open circuit voltage on the pipeline for all the six phase arrangements also vary with the current phase shift angle $\alpha$ for this case. Also, the largest width of the lateral profile of the induced open circuit voltage for each phase arrangement occurs at different angles of the current phase shift. Though for this configuration, the pattern of variation of the lateral profiles of the induced open circuit voltage with current phase shift is different to that of the vertical configuration, nevertheless, the pattern of variation of the lateral profiles can also be observed to be only unique for two phase arrangements (untransposed ABC-ABC, and directly transposed ABC-CBA), while the patterns of other phase arrangements are equivalent patterns of those two but phase shifted. The patterns of phase arrangement ABC-CAB and ABC-BCA are the equivalent of a pattern of untransposed phase arrangement ABC-ABC but phase shifted by $-120°$ and $+120°$, respectively, and similarly, the patterns of phase arrangement ABC-BAC and ABC-ACB are the equivalent of a pattern of transposed phase arrangement ABC-CBA, but phase

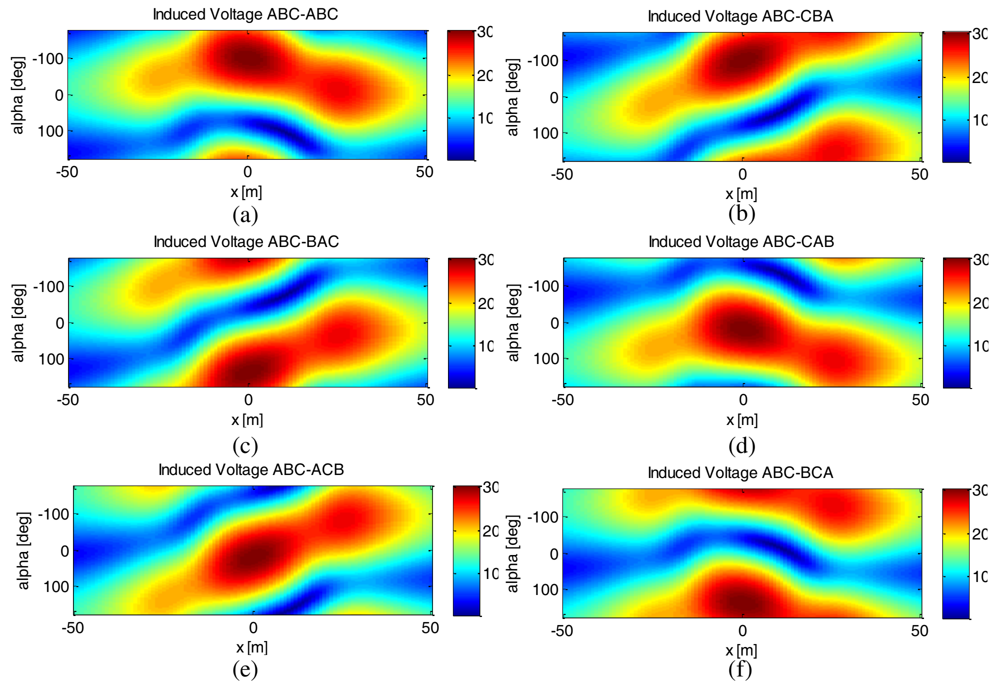


**Figure 7.** Lateral profile of the induced open circuit voltage on the buried pipeline with variations in current phase shift, of the balanced two-circuit, delta (two towers) configuration, for all the six phase arrangements.

shifted by +120° and −120° respectively.

Figure 7 shows the computed lateral profile of the induced voltage on the pipeline at varying distances to the mid-distance of the lateral separation of the centres of the two circuits of the power line with variations in current phase shift from −180° to +180°, of the balanced two-circuit, delta (two towers) configuration, for all the six phase arrangements.

For this case too, the lateral profiles and the magnitude of the induced open circuit voltage on the pipeline also vary with the current phase shift angle $\alpha$ for all the six phase arrangements. Also, the largest width of the lateral profile of the induced open circuit voltage for each phase arrangement occurs at different angles of the current phase shift. Like that of the other two configurations previously considered, the pattern of variation of the lateral profiles of the induced open circuit voltage for this configuration can also be observed to be only unique for two phase arrangements (untransposed ABC-ABC, and directly transposed ABC-CBA). The patterns of other phase arrangements are equivalent patterns of those two but phase shifted. The patterns of phase arrangement ABC-CAB and ABC-BCA are equivalent of a pattern of untransposed phase arrangement ABC-ABC but phase shifted by −120° and +120°, respectively, and similarly, the patterns of phase arrangement ABC-BAC and ABC-ACB are equivalent of a pattern of transposed phase arrangement ABC-CBA but phase shifted by +120° and −120°, respectively.

It should be noted that the patterns shown in Figs. 5 to 7 are for balanced circuits with the same magnitude of current flowing in the two circuits. Different patterns will be observed for unbalanced conditions on the lines. Another point from this study is that it can be generalized that for all balanced AC overhead double circuits or two circuits, the lateral profile of the induced open circuit voltage on a buried metallic pipeline with pipeline position from the line in the transverse plane to the axes of the phase conductors, is only unique for two phase arrangements (untransposed ABC-ABC, and directly transposed ABC-CBA). The profile of phase arrangement ABC-CAB and ABC-BCA are equivalent of profile of untransposed phase arrangement ABC-ABC but current phase shifted by −120° and +120° respectively. Similarly, the profile of phase arrangement ABC-BAC and ABC-ACB are equivalent of profile of transposed phase arrangement ABC-CBA but current phase shifted by +120° and −120°, respectively.

## 4. CONCLUSION

In this work, we investigate the variation in current phase shift of six phase arrangements on the induced open circuit voltage on a buried pipeline. A balanced overhead AC double-circuits power lines of vertical, horizontal, and delta geometries at three of Rand Water sites in South Africa was used as case study. The induced open circuit voltage on the pipeline depends, among other factors, on the circuit configuration, conductors' phase sequence arrangements, and the current phase shifts. This is in line with the findings in [23, 24]. The characteristic nature of the variation of the induced open circuit voltage for these phase arrangements and phase shifts are examined in more detail. The overall simulation results yield vital information that can be useful for pipeline corrosion engineers and utility companies in designing appropriate AC mitigation techniques. The results presented showed that the magnitude of the open circuit induced voltage varies significantly with the current phase shifts of the transmission lines.

Therefore, in placing buried metallic pipelines in the vicinity of AC double-circuits power lines, it is essential to consider the phase arrangement of the line and current phase shift between the two circuits, together with other line parameters, in evaluating the induced voltage with the pipe position before installation. If the historical load current and phase shift data of the line are known, the induced voltage on the underground pipeline can then be continuously computed by monitoring only the phase currents on the line as suggested for field distribution in [30]. For the Rand Water sites considered in this work, with already operational pipelines and power lines, we suggest that mitigation methods to be adopted against induced voltage on the pipelines from the lines should be based, if possible, on the worst-case phase arrangement and current phase shift combination with maximum load capacity of the lines.

In general conclusion, the effect of the current phase shifts and the phase arrangement of multi-circuits lines should be taken into consideration for operating personnel safety when designing AC mitigation techniques.

## 5. CONFLICTS OF INTEREST

The authors of this work declare no conflicts of interests.

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