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Analysis of Induced Voltage on Telecommunication Line in Parallel Distribution System

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Abstract – A current flowing through a distribution conductor produces induced voltage, which is harmful to a telecommunication line. Previous research on induced voltage has been focused on single-circuit lines in the distribution system. However, the double-circuit lines, referred to as parallel distribution lines, are widely used in distribution systems because they have significant economic and environmental advantages over single-circuit lines. Therefore, a study on the induced voltage in double-circuit lines is needed. This paper presents a method of calculating the induced voltage in a parallel distribution system using four-terminal parameters and vector analysis. The calculation method is verified by the Electromagnetic Transient Program (EMTP) simulation.

Keywords: Distribution system, EMTP, Induced voltage, Telecommunication line, Vector analysis

1. Introduction

Overhead lines electrified with an alternating current (AC) can induce voltage into a telecommunication line. In general, the induced voltage on a telecommunication line has harmful effects; it may result in damage to telecommunication facilities, danger to maintenance workers, deterioration of telecommunication transmission quality, or disturbance of the signal [1].

In a distribution system, the induced voltage on a telecommunication line is important to consider when designing a joint right-of-way, as an unbalanced current can increase the induced voltage on the telecommunication line [2-4]. Therefore, the induced voltage should be calculated on the basis of agreements between the telecommunications company and electric power company. These calculations should be performed before an existing electric transmission facility is moved, expanded, or constructed. If the inducted voltage is above a certain limit, appropriate measures for the induced voltage should be taken.

Double-circuit lines have recently become fairly common in distribution systems, and it is easy to find instances where distribution lines are physically parallel due to the significant economic and environmental advantage over single-circuit lines. The parallel combination may require both distribution lines to be constructed on the same pole, or the two lines may run on separate, parallel poles on the same right-of-way. Until now, the studies for induced voltage in distribution systems have been performed only on single-circuit lines, so it is necessary to consider the induced voltage from double-circuit lines [5, 6].

In this paper, the calculation method using four-terminal parameters is presented for determining induced voltage on a telecommunication line. Parallel overhead distribution lines and the telecommunication line are represented by series impedance and shunt admittance matrices. These matrices are applied for the calculation of the induced voltage on the telecommunication line and take into account the coupling with adjacent parallel distribution lines. Carson's formula is used to calculate both the impedance and admittance. Effects on the induced voltage according to the load condition and pole type of the distribution lines are analyzed by using the calculation method based on four-terminal parameters.

2. Calculation of Induced Voltage on Telecommunication Line [4]

2.1 Calculation of induced voltage in single-circuit lines

To calculate an induced voltage on a telecommunication line, a system model of single-circuit lines is shown in Fig. 1.

On the basis of Fig. 1, the telecommunication line laid parallel with overhead distribution lines can be expressed as the relation of voltage and current using an equivalent PI circuit. In this paper, the self and mutual impedance and admittance are obtained using Carson's formula [6]. The system frequency is 60 [Hz] and the earth's resistivity is

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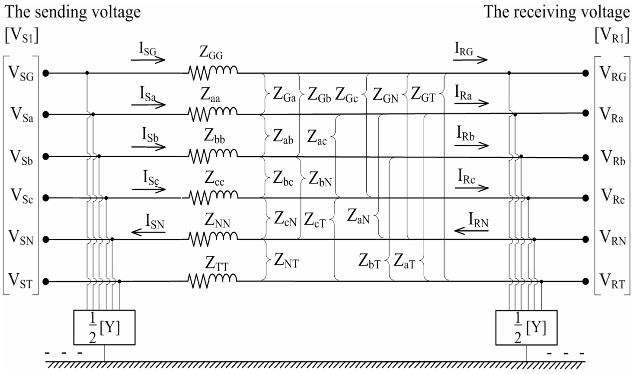

Fig. 1. System model of single-circuit lines

100 [Ω·m]. Using four-terminal parameters, the sending voltage and current (V_{S1}, I_{S1}), and the receiving voltage and current (V_{R1}, I_{R1}) are as follows [6]:

$$\begin{bmatrix}[V_{S1}]\\ [I_{S1}]\end{bmatrix}=\begin{bmatrix}[A] & [B]\\ [C] & [D]\end{bmatrix}\begin{bmatrix}[V_{R1}]\\ [I_{R1}]\end{bmatrix} \tag{1}$$

where

$$\begin{aligned}
&[A]=[u]+\frac{1}{2}[Z]\ [Y]\\
&[B]=[Z]\\
&[C]=[Y]+\frac{1}{4}[Y]\ [Z]\ [Y]\\
&[D]=[u]+\frac{1}{2}[Z]\ [Y]\\
&[u]=\text{unit matrix}
\end{aligned}$$

In (1), sub-matrices are defined as (2).

$$[V_{S1}]=\begin{bmatrix}V_{SG}\\ V_{Sa}\\ V_{Sb}\\ V_{Sc}\\ V_{SN}\\ V_{ST}\end{bmatrix},\ [I_{S1}]=\begin{bmatrix}I_{SG}\\ I_{Sa}\\ I_{Sb}\\ I_{Sc}\\ I_{SN}\\ I_{ST}\end{bmatrix},\ [V_{R1}]=\begin{bmatrix}V_{RG}\\ V_{Ra}\\ V_{Rb}\\ V_{Rc}\\ V_{RN}\\ V_{RT}\end{bmatrix},\ [I_{R1}]=\begin{bmatrix}I_{RG}\\ I_{Ra}\\ I_{Rb}\\ I_{Rc}\\ I_{RN}\\ I_{RT}\end{bmatrix} \tag{2}$$

In (2), subscripts denote;

- G: overhead ground wire
- a, b, and c: 3-phase lines
- N: neutral wire
- T: telecommunication line

Overhead ground wires laid on the top of the distribution lines are installed for the purpose of preventing lightning and are grounded, so V_{SG} and V_{RG} can be assumed almost equal to zero. Accordingly, V_{RG} is rewritten as follows:

$$\begin{aligned}
V_{RG} &= V_{SG}-[B]\ [I_{S1}]\\
0 &= Z_{GG}I_{SG}+Z_{Gabc}I_{Sabc}+Z_{GN}I_{SN}
\end{aligned} \tag{3}$$

where

$$Z_{Gabc}I_{Sabc}=Z_{Ga}I_{Sa}+Z_{Gb}I_{Sb}+Z_{Gc}I_{Sc}$$

The sending current of the overhead ground wire can be obtained from (4).

$$I_{SG}=-\frac{Z_{Gabc}I_{Sabc}+Z_{GN}I_{SN}}{Z_{GG}} \tag{4}$$

The sending neutral current is I_{SN}, and V_{ST} is grounded. So the induced voltage on the telecommunication line (V_{RT}) can be calculated using (5).

$$\begin{aligned}
V_{RT} &= V_{ST}-[B]\ [I_{S1}]\\
&=-[B]\ [I_{S1}]\\
&=-\left(Z_{TG}I_{SG}+Z_{Tabc}I_{Sabc}+Z_{TN}I_{SN}\right)
\end{aligned} \tag{5}$$

where

$$Z_{Tabc}I_{Sabc}=Z_{Ta}I_{Sa}+Z_{Tb}I_{Sb}+Z_{Tc}I_{Sc}$$

2.2 Calculation of induced voltage in double-circuit lines

Fig. 2 is a system model of double-circuit lines used to calculate an induced voltage on a telecommunication line.

In the double-circuit lines, voltages and currents on the sending and receiving ends are V_{S2}, I_{S2} and V_{R2}, I_{R2} respectively, so the relations between the sending and receiving are expressed by (6) [7].

$$\begin{bmatrix}[V_{S2}]\\ [I_{S2}]\end{bmatrix}=\begin{bmatrix}[A] & [B]\\ [C] & [D]\end{bmatrix}\begin{bmatrix}[V_{R2}]\\ [I_{R2}]\end{bmatrix} \tag{6}$$

In (6), sub-matrices are defined as follows (7):

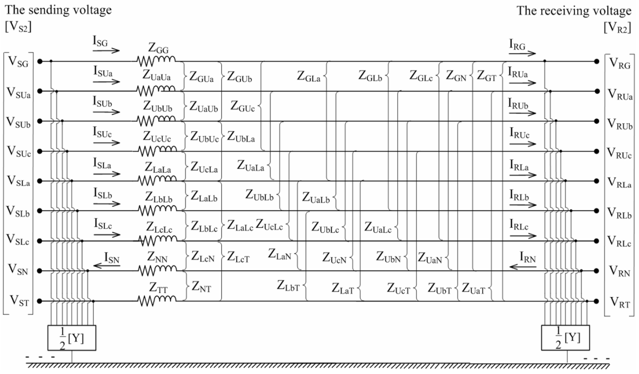

Fig. 2. System model of double-circuit lines

$$[V_{S2}]=\begin{bmatrix}V_{SG}\\V_{SUa}\\V_{SUb}\\V_{SUc}\\V_{SLa}\\V_{SUb}\\V_{SLc}\\V_{SN}\\V_{ST}\end{bmatrix},\ [I_{S2}]=\begin{bmatrix}I_{SG}\\I_{SUa}\\I_{SUb}\\I_{SUc}\\I_{SLa}\\I_{SLb}\\I_{SLc}\\I_{SN}\\I_{ST}\end{bmatrix},\ [V_{R2}]=\begin{bmatrix}V_{RG}\\V_{RUa}\\V_{RUb}\\V_{RUc}\\V_{RLa}\\V_{RLb}\\V_{RLc}\\V_{RN}\\V_{RT}\end{bmatrix},\ [I_{R2}]=\begin{bmatrix}I_{RG}\\I_{RUa}\\I_{RUb}\\I_{RUc}\\I_{RLa}\\I_{RLb}\\I_{RLc}\\I_{RN}\\I_{RT}\end{bmatrix} \tag{7}$$

In (7), Ua, Ub, and Uc indicate 3-phase lines in the upper side, and La, Lb, and Lc indicate 3-phase lines in the lower side. The relation between the receiving voltage and current is as follows:

$$\begin{bmatrix}[V_{R2}]\\ [I_{R2}]\end{bmatrix}=\begin{bmatrix}[A] & [B]\\ [C] & [D]\end{bmatrix}^{-1}\begin{bmatrix}[V_{S2}]\\ [I_{S2}]\end{bmatrix}=\begin{bmatrix}[A] & -[B]\\ -[C] & [D]\end{bmatrix}\begin{bmatrix}[V_{S2}]\\ [I_{S2}]\end{bmatrix} \tag{8}$$

The receiving voltage of the overhead ground wire in the double-circuit lines can be obtained using (9).

$$\begin{aligned}V_{RG} &= V_{SG}-[B]\,[I_{S2}]\\ &= Z_{GG}I_{SG}+Z_{GUabc}I_{SUabc}+Z_{GLabc}I_{SLabc}+Z_{GN}I_{SN}\end{aligned} \tag{9}$$

where

$$\begin{aligned}Z_{GUabc}I_{SUabc} &= Z_{GUa}I_{SUa}+Z_{GUb}I_{SUb}+Z_{GUc}I_{SUc}\\ Z_{GLabc}I_{SLabc} &= Z_{GLa}I_{SLa}+Z_{GLb}I_{SLb}+Z_{GLc}I_{SLc}\end{aligned}$$

Because V_{SG} and V_{RG} can be also assumed to be almost zero in the double-circuit lines, the sending current of overhead ground wire can be expressed as follows:

$$I_{SG}=-\frac{Z_{GUabc}I_{SUabc}+Z_{GLabc}I_{SLabc}+Z_{GN}I_{SN}}{Z_{GG}} \tag{10}$$

In the double-circuit lines, the sending neutral current can be calculated assuming that the upper and lower sides share the ground point of the neutral line and the neutral current is equal to the total current of the upper and lower side using the principle of superposition. If these things are true, then the neutral current is the same as (11) [8].

$$I_{SN}=-\left(I_{SUa}+I_{SUb}+I_{SUc}+I_{SLa}+I_{SLb}+I_{SLc}\right) \tag{11}$$

In conclusion, the induced voltage on the telecommunication line (V_{RT}) is represented by (12). Since the V_{ST} is grounded, it can be assumed to be almost zero. In shorthand form, V_{RT} is expressed as follows:

$$\begin{aligned}V_{RT} &= V_{ST}-[B]\,[I_{S2}]\\ &= -[B]\,[I_{S2}]\\ &= -\left(Z_{TG}I_{SG}+Z_{TUabc}I_{SUabc}+Z_{TLabc}I_{SLabc}+Z_{TN}I_{SN}\right)\end{aligned} \tag{12}$$

where

$$\begin{aligned}Z_{TUabc}I_{SUabc} &= Z_{TUa}I_{SUa}+Z_{TUb}I_{SUb}+Z_{TUc}I_{SUc}\\ Z_{TLabc}I_{SLabc} &= Z_{TLa}I_{SLa}+Z_{TLb}I_{SLb}+Z_{TLc}I_{SLc}\end{aligned}$$

3. System Modeling [4]

To verify the calculation method, Fig. 3 illustrates the configuration of the overhead distribution lines and the telecommunication line.

The induced voltage on the telecommunication line is analyzed according to the pole type in case studies; Fig. 3 (a) is of single-circuit lines. Fig. 3 (b) is of double-circuit lines.

For this case study, the induced voltage with respect to load condition and pole type is measured by EMTP. All results of the case study are measured and calculated on the basis of 1 km parallel distance. In case studies, V_{RT} is a calculation value using four-terminal parameters, the EMTP simulation result is V_{EMTP}, and the error is calculated on the basis of V_{EMTP}. The unbalance ratio of the load is not more than 30%. To analyze the induced voltage in the

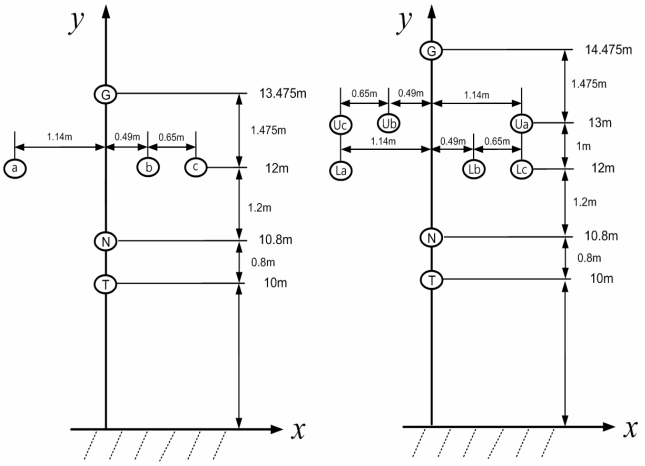

Fig. 3. Configuration of distribution lines and telecommunication line

Table 1. Induced voltage results in single-circuit lines

	Load [MVA]			V_{RT} [V] rms	V_{EMTP} [V] rms	Error [%]
	a	b	c			
Case 1	1	1	1	0.426	0.429	0.70
Case 2A	1.3	1	1	2.332	2.322	0.43
Case 2B	1	1.3	1	1.503	1.486	1.14
Case 2C	1	1	1.3	1.989	1.982	0.35
Case 3	1	1.1	1.2	0.971	0.969	0.21

single- and double-circuit lines, vector analysis is also applied.

4. Case Study in Single-Circuit Lines

4.1 Simulation results

Table 1 shows the calculated induced voltages and the EMTP simulation results. For the case study of the single-circuit lines, as shown in Table 1, Case 1 has a balanced load, Case 2A ~ 2C have a single-phase unbalanced load, and Case 3 has a 3-phase unbalanced load. The numerical error in the difference between the EMTP simulation results and the calculated value of (5) is less than 1.14 [%].

4.2 Vector analysis

To analyze the induced voltage in the single-circuit lines, vector analysis is applied. The V_{RT} may be divided into two sides from (5), the inducing side (V_P) and the shielding side (V_{GN}). V_{RT} in the single-circuit lines is expressed as follows:

$$V_{RT} = V_P + V_{GN} \tag{13}$$

where

$$V_P = -\left(Z_{Tabc} I_{Sabc}\right), \quad V_{GN} = -\left(Z_{TG} I_{SG} + Z_{TN} I_{SN}\right)$$

Using the calculation method presented in (13), $V_{P,}$ V_{GN} and V_{RT} in partitioned from are displayed in Table 2.

Table 2. Vector analysis results in single-circuit lines

	V_P [V] rms	V_{GN} [V] rms	V_{RT} [V] rms
Case 1	$0.634\angle 123.94^\circ$	$0.325\angle -18.26^\circ$	$0.426\angle 96.1^\circ$
Case 2A	$9.902\angle -127.31^\circ$	$12.126\angle 56.37^\circ$	$2.332\angle 72.21^\circ$
Case 2B	$10.94\angle 116.67^\circ$	$12.352\angle -60.78^\circ$	$1.503\angle -41.91^\circ$
Case 2C	$9.748\angle -0.97^\circ$	$11.732\angle 178.31^\circ$	$1.989\angle 174.75^\circ$
Case 3	$5.793\angle 32.97^\circ$	$6.712\angle -149.9^\circ$	$0.971\angle -167.28^\circ$

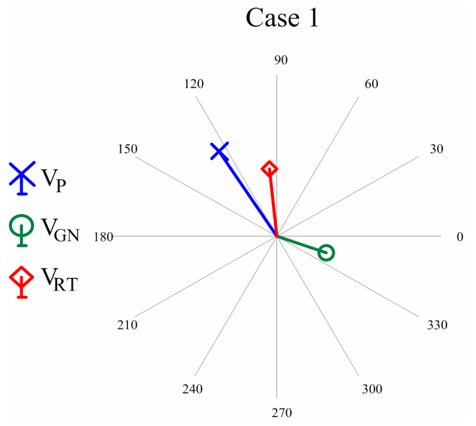

Fig. 4. Vector analysis in single-circuit lines (Case 1)

In Table 2, V_P is caused by a 3-phase current and V_{GN} is caused by the current of an overhead ground wire and a neutral wire. For example, Fig. 4 shows the resultant vector of Case 1 in the single-circuit lines.

5. Case Study in Double-Circuit Lines

5.1 Simulation results

Table 3 shows the calculated induced voltages and the EMTP simulation results. In Table 3, the upper and lower side loads were changed. The calculation results of (12), using the four-terminal parameters and the EMTP simulation, are compared below.

In Table 3, load conditions are as follows:

- Case 4: 3-phase balanced load in both the upper and lower sides
- Case 5: Single-phase (Uc, Lc-phase) unbalanced load in both the upper and lower sides
- Case 6: 3-phase unbalanced load in both the upper and lower sides
- Case 7A~7C: Single-phase unbalanced load in the upper side and balanced load in the lower side
- Case 8A~8C: Balanced load in the upper side and single- phase unbalanced load in the lower side

The results of the case studies listed in Table 3 show that the numerical error in the difference between the EMTP simulation results and the calculated value of (12) is less than 3.38 [%], so it can be regarded as an exact method.

5.2 Vector analysis

Similar to the vector analysis of the single-circuit lines, the V_{RT} may be divided into an inducing side (V_P) and a shielding side (V_{GN}). Because of double-circuit lines, V_P may be again divided into an upper (V_{UP}) and lower side (V_{LP}) using (13). V_{RT} is expressed as follows:

$$V_{RT} = V_P + V_{GN} = V_{UP} + V_{LP} + V_{GN} \tag{14}$$

Where

Table 3. Induced voltage results in double-circuit lines

	Load [MVA]						V_{RT} [V] rms	V_{EMTP} [V] rms	Error [%]
	Ua	Ub	Uc	La	Lb	Lc			
Case 4	1	1	1	1	1	1	0.650	0.653	0.46
Case 5	1	1	1.3	1	1	1.3	4.628	4.568	1.31
Case 6	1	1.1	1.2	1	1.1	1.2	2.382	2.352	1.28
Case 7A	1.3	1	1	1	1	1	3.214	3.181	1.04
Case 7B	1	1.3	1	1	1	1	2.090	2.048	2.05
Case 7C	1	1	1.3	1	1	1	2.735	2.710	0.92
Case 8A	1	1	1	1.3	1	1	2.487	2.455	1.30
Case 8B	1	1	1	1	1.3	1	1.225	1.185	3.38
Case 8C	1	1	1	1	1	1.3	2.058	2.037	1.03

Table 4. Vector analysis results in double-circuit lines

	V_P [V] rms			V_{GN} [V] rms	V_{RT} [V] rms
	V_{UP}	V_{LP}	$V_{UP}+V_{LP}$		
Case 4	0.308 ∠123.94°	0.634 ∠123.94°	0.942 ∠123.94°	0.442 ∠-18.65°	0.65 ∠99.54°
Case 5	9.377 ∠-2.88°	9.748 ∠-0.97°	19.123 ∠-1.9°	23.749 ∠178.35°	4.628 ∠179.4°
Case 6	5.485 ∠29.19°	5.793 ∠32.97°	11.272 ∠31.13°	13.629 ∠-150.44°	2.382 ∠-157.86°
Case 7A	9.456 ∠-126.09°	0.634 ∠123.94°	9.258 ∠-129.78°	12.264 ∠56.34°	3.214 ∠74.25°
Case 7B	9.962 ∠115.97°		10.59 ∠116.45°	12.553 ∠-59.98°	2.09 ∠-41.61°
Case 7C	9.377 ∠-2.88°		9.012 ∠0.35°	11.735 ∠178.99°	2.735 ∠174.48°
Case 8A	0.308 ∠123.94°	9.903 ∠-127.31°	9.808 ∠-129.02°	12.127 ∠55.7°	2.487 ∠74.63°
Case 8B		10.94 ∠116.67°	11.246 ∠116.87°	12.368 ∠-60.73°	1.225 ∠-38.19°
Case 8C		9.748 ∠-0.97°	9.575 ∠0.55°	11.592 ∠178.34°	2.058 ∠168.05°

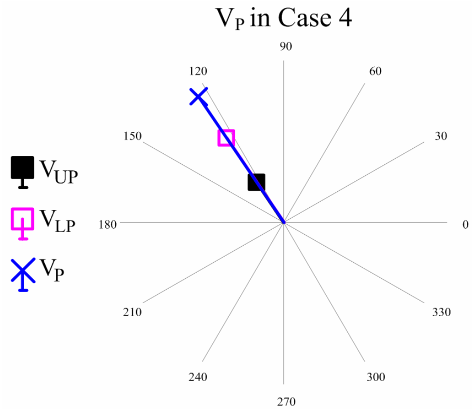

Fig. 5. Induced voltage(V_P) is caused by a 3-phase current of the upper and lower sides in double-circuit lines (Case 4)

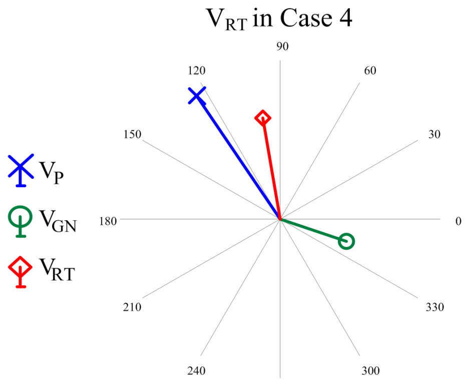

Fig. 6. Vector analysis in double-circuit lines (Case 4)

$$V_{UP} = -\left(Z_{TUabc} I_{SUabc}\right),\ V_{LP} = -\left(Z_{TLabc} I_{SLabc}\right)$$
$$V_{GN} = -\left(Z_{TG} I_{SG} + Z_{GN} I_{SN}\right)$$

In (14), V_{UP}, V_{LP}, V_{GN}, and V_{RT} in partitioned form are displayed in Table 5.

In Table 4, V_{UP} is caused by a 3-phase current in the upper side. V_{LP} is caused by a 3-phase current in the lower side. For example, Fig. 5 shows t resultant vector of Case 4 in V_P of the double-circuit lines.

The total induced voltage in the double-circuit lines is given as a vector sum ($V_{RT} = V_{UP} + V_{LP} + V_{GN}$). The resultant vector is shown in Fig. 6, and the above results agree with the vector analysis.

6. Comparison of Case Study

Fig. 7 shows the induced voltage on a telecommunication line over which the single- and double-circuit lines carry the same load type. The results indicate that the induced voltage in the double-circuit lines is larger than the induced voltage in the single-circuit lines.

Fig. 8 shows the induced voltage on a telecommunication line through which the single-circuit lines and the upper and lower sides of the double-circuit lines carry the same single-phase unbalanced load.

When comparing Case 2B in the single-circuit lines and Case 8B in the double-circuit lines, regardless of the pole type listed in Fig. 8, the induced voltage of the double-circuit lines is smaller than the induced voltage in the single-circuit lines. When comparing the upper and lower sides of the double-circuit lines, the induced voltage of the lower side is smaller than the upper side. This is because of

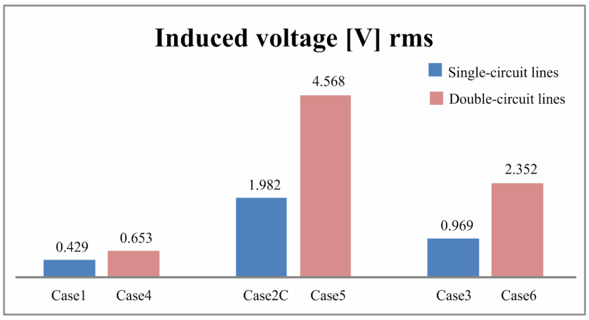

Fig. 7. Comparison of single and double-circuit lines

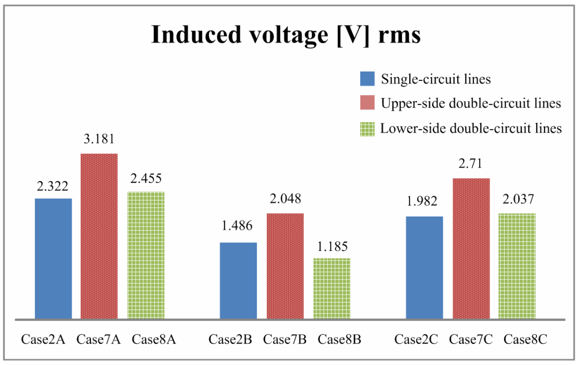

Fig. 8. Comparison of induced voltage results

the screening effect of neutral current, which is closely arranged to the b-phase line and the lower sides of the double-circuit lines.

7. Conclusion

This paper presented a method to calculate the induced voltage on a telecommunication line in a parallel distribution system. For more actual analysis on the induced voltage from a practical point, parallel overhead distribution lines and the telecommunication line were represented by series impedance and shunt admittance matrices. These matrices were applied to calculate the induced voltage on the telecommunication line. The advantage of this method was that it uses the actual neutral current value and four-terminal parameters to calculate the induced voltage in the double-circuit lines. The calculation method was verified by both the EMTP and vector analysis. Also, various case studies were compared and analyzed according to the load condition and pole type of the distribution system. From the results which did not generate very much of an error when calculating the induced voltage, it is expected that the proposed method be useful to a real system.

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