Shielding effect of multi-grounded neutral wire in the distribution system

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SUMMARY

The voltage induced by the power line on the nearby conductors, like telephone lines and pipelines, is investigated in this paper. The relationship between the phase currents and the neutral current plays an important role in reducing the induced voltage. Firstly, the impact of the MGN (multi-grounded neutral) configurations on the induced voltage is analyzed. It is found that the MGN-I (Islanded MGN) is the most practical configuration to reduce the induced voltage. Then a new method to calculate the neutral current for MGN-I is proposed. Based on the proposed method, a series of charts for neutral wire selections are given to facilitate the field engineers select the proper neutral wire. Finally, the validation of the proposed method is verified by the results obtained from EMTP-based multiphase harmonic load flow (MHLF) program. Copyright © 2010 John Wiley & Sons, Ltd.

KEY WORDS: power line; multi-grounded neutral wire; interference; induced voltage

1. INTRODUCTION

Due to the environmental constraints, it becomes common that the power lines, communication cables, pipelines, and other similar conductors share the same right of way [1]. Although the joint use of rights of way for power lines and other services is well-accepted as a practical and economical application, there are a lot of problems imposed by the electromagnetic interference between the different conductors. Among all those electromagnetic interference problems, the one induced by the power line is the most severe one due to the large currents. In the meantime, more harmonic producing loads are used in the power system. Thus the magnetic fields generated from power lines are much more complicated and aggravated.

Many scientific organizations and research institutes have begun to analyze this electromagnetic interference problem since the early 1960s [2]. Numbers of reports, papers, and standards [3] on calculation of these coupling effects (or induced voltages) have been published. A practical calculation method and computer program have been presented in Reference [2], which assuming a multi-conductor power line is parallel to the nearby conductors. To overcome the limitations on the geometric topologies of the power lines and nearby conductors, a general applicable model, which can be used for any configuration, has been presented in Reference [4]. Meanwhile, to improve the calculation accuracy, many advanced mathematic methods have been introduced into this subject [1,5–7]. Through the method of source transformations, Levey [5] presented a simplified calculation method using ladder network reduction. Finite-element method (FEM) also has been introduced in this induced voltage calculation to handle the cases of certain terrain irregularities or discontinuities of soil characteristics [6]. Since the two dimensional FEM is only applicable to symmetrical cases and to cases where the pipeline has a perfect coating, Christoforidis et al. [1] presented a hybrid method,
which utilizes both FEM calculations and circuit analysis. A comparison method to FEM, the finite-difference method (FDM) has also been introduced in this induced voltage calculation by Micu et al. [7], although its performance is not as good as FEM.

These complex models and advanced methods do improve a lot in terms of accuracy. However, they make it very difficult for the power system engineers to find a suitable solution to the interference problems. The real interference problems have to be analyzed case by case without a generalized solution, such as the problems encountered in References [7–10]. Especially when only a small part of the power lines is coupled with nearby conductors (this is very common for the current power systems), there is not a simple and practical guide to solve this interference problem.

Through studying the relationship between the phase currents and the neutral current, this paper analyzes the impact of the MGN configurations on the induced voltage. A simple formula to calculate the induced voltage mitigation effect is obtained. Furthermore, a series of neutral wire selection charts, which can be a generalized solution to facilitate the field engineers design the proper neutral wire, is presented.

The paper is organized in the following sequence. In Section 2, the impact of the different MGN configurations on the induced voltage is analyzed. Based on these results, the islanded MGN configuration is selected and further investigated in Section 3. A simple and practical formula to calculate the induced voltage is derived in Section 4. A sample power line and telephone line interference case is studied in Section 5. Section 6 summaries the conclusions obtained through this study.

2. CALCULATION OF THE VOLTAGE INDUCED BY THE MULTI-GROUNDED POWER LINE

The general topology of power lines and nearby conductors is shown in Figure 1 [9]. The phase conductors, the MGN-I wire, and the nearby conductors are magnetically coupled together. There are normally four different neutral wire configurations, including MGN (which means one end of the neutral is connected to the source neutral point, and the other end is connected to the load neutral

![Figure 1. General topology of the power line and nearby conductors.](image-url)
point), MGN-I (islanded MGN, the neutral wire is isolated from the source and load), MGN-S (one end terminated at the source and other end isolated from the load neutral), and MGN-L (one end connected to the load neutral and the other end isolated from the source). Due to the small current carried by the nearby conductors (NC) (such as, telephone line and gas pipelines), the magnetic field produced by the nearby conductors can always be ignored.

At each neutral segment (between two grounding points, the length can be expressed as \( l \)), the induced voltage on the nearby conductors by the phase currents and the neutral current can be obtained by Equation (1).

\[
\dot{V}_{T,l} = Z_{ANC}I_A + Z_{BNC}I_B + Z_{CNC}I_C - Z_{NNC}I_N
\]

where \( \dot{V}_{T,l} \) is the induced voltage, \( Z_{ANC}, Z_{BNC}, Z_{CNC}, \) and \( Z_{NNC} \) are the mutual impedances between each phase conductor, the neutral wire, and the nearby conductors, respectively. Current vector \( I_x (x = A, B, C, N) \) stands for the current flowing in phase conductors and the neutral wire, respectively.

Under normal condition, due to the physical arrangement of the power line and the nearby conductors, shown in Figure 1(a), the nearby conductor is almost at the same distance from the different phase conductors. As a result, the mutual impedances \( Z_{ANC}, Z_{BNC}, \) and \( Z_{CNC} \) are basically same.

\[
Z_{PNC} = Z_{ANC} = Z_{BNC} = Z_{CNC}
\]

Substituting Equation (2) into (1), we get,

\[
\dot{V}_{T,l} = Z_{PNC}(I_A + I_B + I_C) - Z_{NNC}I_N = Z_{PNC}(3I_0) - Z_{NNC}I_N
\]

Equation (3) reveals that the voltage induced by phase currents is mainly caused by the zero sequence current. If we further consider that the neutral has approximately the same distance to the nearby conductors as that of the phase conductors, the assumption of \( Z_{NNC} = Z_{PNC} \) can also be made. Then the induced voltage becomes,

\[
\dot{V}_{T,l} = Z_{PNC}(3I_0) - Z_{NNC}I_N = 3Z_{PNC}I_0 \left( \frac{1 - I_N}{3I_0} \right)
\]

The above equation is very significant—it shows that the reduction of induced voltage due to the neutral wire is related to the ratio \( k = \frac{I_N}{3I_0} \). If this ratio is equal to 1, i.e., if the neutral returns the entire zero sequence phase current, the impact of power line on the nearby conductors can be reduced almost to zero.

Depending on the configuration, the neutral current consists of one or two components. These two components are: (1) the conducted zero sequence current flowing back to the substation, and (2) the current induced by the power line phase currents.

### 2.1. Conducted current

Figure 2 shows the distribution of the conducted current. It can be seen that all zero sequence current returns to the neutral point \( N \) of the load. With increase in the ground resistance, the neutral current will

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**Figure 2.** Distribution of conducted neutral current.
increase since the effect of current diversion is lessened. As $I_N = 3I_0$ is the best scenario for induced voltage reduction, the ungrounded neutral arrangement (the grounding resistance is infinity) is the most effective solution to reduce induced voltage. However, ungrounded neutral is not practical due to other power system considerations [11].

2.2. Induced current

The current induced by the power line phase currents can be shown by Figure 3. It shows the case where the neutral conductor is not connected to the load grounding point. There is no conducted current flowing in the neutral in this arrangement. The voltage induced on the neutral by the phase currents can be modeled as voltage sources. These voltage sources drive an induced current in the neutral (the loop current).

If the grounding resistance is increased, the neutral current will decrease since there is more resistance in the path of the circuit loop. The highest induced current that can be achieved is when the grounding resistances are zero, i.e., the perfect grounding condition. For the 25 kV feeder case we studied, the highest induced current is estimated as 30% of the ideal neutral current ($3I_0$), which leads to a 30% reduction of voltage interference level compared with the earth return scheme (no neutral wire presented).

2.3. Actual neutral current

The actual neutral current is the combination of the conducted and induced neutral currents. Its distribution along a feeder is shown in Figure 4 for the full length MGN configuration. For a study case of 7Ω grounding resistance and 500 m grounding interval, numerical study shows that the neutral current settles to a steady-state value of $30\% \times 3I_0$ at about 4 km from the load neutral point.

2.4. Comparison of the neutral currents

The neutral currents of different MGN configurations were examined by using the EMTP-based multiphase harmonic load flow (MHLF) program. The configurations of two incomplete MGNs, MGN-I and MGNL, are shown in Figure 5. A 25 kV system with 12 km feeder, 7Ω neutral grounding resistance, 0.5 km grounding interval, and 0.15Ω substation grounding resistance was used. The
unbalanced lumped load comprising 5 MVA (100%), 110% less and 90% on individual three phases was connected at the end of the feeder.

The neutral current profiles are shown in Figure 6. The MGN-I and full MGN configurations have about the same magnitude of neutral currents about the middle span of the neutral wire. In other words, they have similar mitigation effects. This result has an important meaning. In real systems, the nearby conductor is normally paralleled with the power line for a short length only. Therefore, an islanded neutral wire configuration (MGN-I), which has a similar shielding effect as that of full MGN, is an economical design option to reduce the induced voltage. This configuration is further analyzed in the following sections.

3. ISLANDED MULTI-GROUNDED NEUTRAL WIRE CURRENT CALCULATION

For an islanded MGN system, the neutral current can be calculated by solving the equivalent electric circuit of the neutral wire, as shown in Figure 7.
In Figure 7, $\dot{E} = Z_{PN} (\dot{I}_A + \dot{I}_B + \dot{I}_C)$ stands for the induced voltage on the neutral wire by the phase lines, $Z_{PN}$ is the mutual impedance between the phase lines and the neutral wire and $Z_{NS}$ is the self impedance of the neutral wire.

From Figure 7, the following matrix can be obtained based on Kirchhoff’s voltage law.

$$
\begin{bmatrix}
Z_{NS} + 2R_g & -R_g & 0 & 0 \\
-R_g & Z_{NS} + 2R_g & -R_g & 0 \\
0 & \ddots & \ddots & \ddots \\
0 & 0 & -R_g & Z_{NS} + 2R_g
\end{bmatrix}
\begin{bmatrix}
\dot{I}_1 \\
\dot{I}_2 \\
\ddots \\
\dot{I}_n
\end{bmatrix}
= \begin{bmatrix}
\dot{E} \\
\dot{E} \\
\ddots \\
\dot{E}
\end{bmatrix}
$$

(5)

Meanwhile, based on Equation (3), the induced voltage on the nearby conductors can be obtained by Equation (6).

$$
\dot{V}_T = \sum_{i=1}^{n} \dot{V}_{T,i} = nZ_{PNC}(\dot{I}_A + \dot{I}_B + \dot{I}_C) - \sum_{i=1}^{n} Z_{NNC}\dot{I}_i
$$

(6)

The neutral wire current for each segment can be calculated by solving the current loop matrix described by Equation (5) and the induced voltage can be obtained by Equation (6). However, this method is too complicated. Furthermore, it is not easy to perform the sensitivity studies on the key parameters of the neutral wire, such as the grounding resistance, the length of the neutral wire, and the grounding interval.

In this paper, an alternative method to calculate the current is proposed. It is an analytical equation with the explicit expression of all the parameters mentioned before. This analytical equation offers an easy solution for the system engineers to design a proper islanded neutral wire configuration to solve the power line interference problem. This method is described by the following equations.

Based on Equation (6), if we define the summation of neutral current $\dot{I}_{\text{total}}$ as

$$
\dot{I}_{\text{total}} = \dot{I}_1 + \dot{I}_2 + \cdots + \dot{I}_n
$$

(7)

then the induced voltage is actually determined by the current $\dot{I}_{\text{total}}$.

$$
\dot{V}_T = nZ_{PNC}(\dot{I}_A + \dot{I}_B + \dot{I}_C) - Z_{NNC}\dot{I}_{\text{total}}
$$

(8)

Meanwhile, from Equation (5), we get

$$
Z_{NS}(\dot{I}_1 + \dot{I}_2 + \cdots + \dot{I}_n) + R_g\dot{I}_1 + R_g\dot{I}_n = n\dot{E}
$$

(9)

Due to the symmetrical characteristics, $\dot{I}_1 = \dot{I}_n$. Thus,

$$
\dot{I}_{\text{total}} = \dot{I}_1 + \dot{I}_2 + \cdots + \dot{I}_n = \frac{n\dot{E} - R_g(\dot{I}_1 + \dot{I}_n)}{Z_{NS}} = \frac{n\dot{E} - 2R_g\dot{I}_1}{Z_{NS}}
$$

(10)

Therefore, to calculate the current $\dot{I}_{\text{total}}$, we need to know the current $\dot{I}_1$. The Norton equivalent circuit of Figure 7 is shown in Figure 8(a). The current source is given by Equation (11). Since the current source for every segment has the same value, the circuit can be further reduced as depicted by
Due to the symmetrical characteristics of the MGN-I, the voltage at the middle point of the neutral wire will be the same as the ground potential. Therefore, the circuit can be divided into two halves without affecting the current values. The left half of the equivalent circuit is shown in Figure 9.

In Figure 9, \( Z_{n/2} \) is the impedance between the center point of the neutral wire (\( n/2 \)) and the ground; \( n \) is the total number of the segments. Due to the symmetrical characteristics of the circuit, the impedance \( Z_{n/2} \) can be obtained by Equation (12).

\[
Z_{n/2} = \begin{cases} 
\frac{Z_{NS}}{2}, & n \text{ is odd} \\
0, & n \text{ is even}
\end{cases}
\]  

(12)

Based on Figure 9(b), the current flowed in the first neutral segment can be obtained by Equation (13).

\[
I_1 = \frac{Z_{NS} + Z_{net}}{Z_{NS} + Z_{net} + R_g} I = \frac{Z_{NS} + Z_{net}}{Z_{NS} + Z_{net} + R_g} \frac{E}{Z_{NS}}
\]  

(13)

Substituting Equation (13) into (10), we get

\[
I_{total} = \frac{nE Z_{NS}}{Z_{NS}^2} - \frac{2R_g}{R_g + \frac{Z_{NS} + Z_{net}}{2}} E
\]  

(14)

where \( R_g \) is the grounding resistance of the neutral wire. \( Z_{net} \) is the equivalent impedance of the circuit shown in Figure 9(b), which is a typical ladder network.
Hence the neutral current can be calculated by Equation (14). The significant characteristic of Equation (14) is that it explicitly expresses the neutral current as a function of the self-impedance of the neutral wire, the grounding resistance, and the length of the neutral wire. The simplified method is based on the assumptions that the neutral wire is long enough so that the original voltages on its grounded nodes are not affected when the neutral is cut at the middle. Generally speaking, more than 10 grounding spans in one-half of the neutral length will be enough. In a typical MGN system, this condition is almost always met. Another underlying assumption was that the grounding resistances are equal. Although, the grounding resistances will vary along the length of the line due to variation in soil conditions, the effect on the results of Equation (14) will be negligible. The $R_g$ in Equation (14) is the grounding resistance of the last span only and its value can be taken realistically. On the other hand, the effect of other individual $R_g$ values along the neutral length will be absorbed in $Z_{\text{net}}$, which is much smaller than the individual $R_g$. Therefore, the results of Equation (14) will be reasonably good in a practical situation.

4. SHIELDING EFFECT OF MGN-I NEUTRAL WIRE

To simplify the induced voltage calculation, we assume that the current flowing in each shielding wire segment is the same by ignoring the end-effect [12]. Then the average current of each segment can be obtained by Equation (15).

$$I_{\text{mean}} = \frac{I_{\text{total}}}{n} = \frac{E}{Z_{\text{NS}}} - \frac{2E}{Z_{\text{NS}}} \frac{R_g (Z_{\text{NS}} + Z_{\text{net}})}{n (R_g + Z_{\text{NS}} + Z_{\text{net}})}$$

(15)

Based on Equation (15), the maximum neutral current is obtained when the grounding resistance is zero (solidly ground). Assume the coupled conductors span $m$ segments; we can define the neutral wire effect $S_{\text{effect}}$ by Equation (16).

$$S_{\text{effect}} = \left| \frac{I_{\text{mean, mn}}}{I_{\text{std}}} \right|$$

(16)

where, $I_{\text{std}} = \frac{E}{Z_{\text{NS}}}$, $I_{\text{mean, mn}} = \begin{cases} \frac{I_{\text{total}}}{n}, n \geq m \\ \frac{I_{\text{total}}}{m}, 0 < n < m \end{cases}$

Substituting Equations (14) and (15) into (16), we get

$$S_{\text{effect}} = \begin{cases} 1 - \frac{2R_g (Z_{\text{NS}} + Z_{\text{net}})}{nZ_{\text{NS}} (R_g + Z_{\text{NS}} + Z_{\text{net}})}, & n \geq m \\ \frac{n}{m} \left[ 1 - \frac{2R_g (Z_{\text{NS}} + Z_{\text{net}})}{nZ_{\text{NS}} (R_g + Z_{\text{NS}} + Z_{\text{net}})} \right], & 0 < n < m \end{cases}$$

(17)

Equation (17) gives the relationship between $S_{\text{effect}}$ and the grounding resistance, the number of segments, and the self impedance of the neutral wire. A series of practical charts for designing the MGN-I, including the grounding resistance, can be obtained and will be shown in the following sections.

Thereafter the effectiveness is defined as the induced voltage in per cent of the ideally grounded condition. Hundred per cent means that the neutral is grounded with zero grounding resistances.

4.1. Length of neutral wire

For a given grounding resistance and a given grounding interval, the length of the neutral wire will be the only parameter to determine the effectiveness of the neutral wire.

Figure 10 shows the recommended neutral length for a given coupled conductor length with the condition that the grounding resistance is 7 $\Omega$ and the grounding interval of the neutral wire is 300 m.
For example, if the conductor length is 3000 m and we choose 85% effectiveness of shielding, the neutral length should be 6000 m for 60 Hz interference or 3000 m for 1500 Hz interference.

It is not surprising that the recommended neutral length is a function of frequency. The result reveals that the islanded neutral is more close to the ideally grounded case when the frequency increases. Since most telephone interference problems involve high frequency induction, we can conclude that if the neutral is about 1.2–1.5 times longer than the parallel telephone cable, adequate interference shielding effect can be provided by an islanded neutral.

4.2. Combination of grounding resistance and length of the neutral wire

For a real system, to design the neutral wire is actually to find a best combination of the grounding resistance and the length of the neutral wire.

Figure 11 describes those different combinations of the length of neutral wire and grounding resistance to get same shielding effects for a coupled conductor with a fixed length (2500 m), self impedance \(9.4602 \times 10^{-2} + j9.1142 \times 10^{-2} \Omega/km\), and the grounding interval (500 m).

5. APPLICATION OF MGN-I ON THE TELEPHONE INTERFERENCE MITIGATION

The system, described in Section 2.4, with a parallel telephone line was used to examine the mitigation effects of MGN-I. In this case, the islanded neutral is 7.5 km, and 2.5 km of telephone line is parallel with the power line. It was assumed that a line-to-ground on one phase has 3 kA fault current, and the current on the other two phases was neglected. The mutual impedances are shown in Table I.

The results given by the proposed calculation method are in good agreement with those obtained by MHLF program [13] as shown in Table II. The analytical results in Table II were obtained by Equation...
In the simulation method, first the induced voltages were obtained for different conditions and the shielding effect was calculated by Equation (18).

\[
\text{Shielding effect} = \left( 1 - \frac{V_{t,R_g=x} - V_{t,R_g=0}}{V_t - V_{t,R_g=0}} \right) \times 100\%
\]

(18) where, \(V_t\) is the induced voltage on the telephone line without the neutral wire, \(V_{t,R_g=x}\) is the induced voltage on the telephone line with the neutral wire having arbitrary grounding resistances of \(x\Omega\), and \(V_{t,R_g=0}\) is the induced voltage when the neutral is solidly grounded (i.e., \(R_g = 0\)). The case of \(R_g = 0\Omega\) gives the maximum shielding effect and the results for other cases with \(R_g > 0\) are normalized with respect to \(R_g = 0\Omega\) case.

6. CONCLUSIONS

The following important conclusions on the MGN wire can be drawn from the above analysis:

The conducted current increases when the grounding resistance increases; while the induced current, on the other hand, decreases if the grounding resistance increases. As a result, improvement on the grounding condition (i.e., reduced grounding resistance) does not necessarily lead to reduction in the induced voltage level.

The typical neutral current is about 30–40% of the ideal case \((I_N = 3I_0)\). The MGN scheme can, therefore, yield about 30–40% reduction on the induced voltage.
The islanded MGN has the similar shielding effect as the full MGN configuration. A simple equation to calculate the islanded neutral wire shielding effects on the power line interference mitigation has been presented. The accuracy of the proposed method is verified by comparison with the results calculated by MHLF. A series of practical design charts are obtained from this analytical equation and they can be used to facilitate the power engineers to design a suitable MGN-I neutral wire.

### 7. List of Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\dot{V}_{T,l}$</td>
<td>power line induced voltage on the nearby conductors</td>
</tr>
<tr>
<td>$Z_{ANC}$, $Z_{BNC}$, $Z_{CNC}$, and $Z_{NNC}$</td>
<td>the mutual impedance between each phase conductor, the neutral wire, and the nearby conductors, respectively.</td>
</tr>
<tr>
<td>$I_x(x = A, B, C, N)$</td>
<td>the current flowing in phase conductors and the neutral wire</td>
</tr>
<tr>
<td>$I_0$</td>
<td>zero-sequence current in the power line</td>
</tr>
<tr>
<td>$k = IN/3I_0$</td>
<td>ratio between neutral current and the zero-sequence current</td>
</tr>
<tr>
<td>$\dot{E}$</td>
<td>induced voltage on the neutral wire by the phase lines</td>
</tr>
<tr>
<td>$Z_{PN}$</td>
<td>mutual impedance between the phase lines and the neutral wire</td>
</tr>
<tr>
<td>$Z_{NS}$</td>
<td>self impedance of the neutral wire</td>
</tr>
<tr>
<td>$I_{total}$</td>
<td>summation of the neutral wire currents</td>
</tr>
<tr>
<td>$I_{mean}$</td>
<td>average value of the neutral wire currents</td>
</tr>
<tr>
<td>$n$</td>
<td>number of the neutral wire segments</td>
</tr>
<tr>
<td>$m$</td>
<td>number of the telephone line segments</td>
</tr>
<tr>
<td>$S_{effect}$</td>
<td>neutral wire shielding effect calculated by formula proposed in this paper</td>
</tr>
<tr>
<td>$S_{ef,mhf}$</td>
<td>neutral wire shielding effect calculated by MHLF</td>
</tr>
<tr>
<td>$V_i$</td>
<td>induced voltage on the telephone line without the neutral wire</td>
</tr>
<tr>
<td>$V_{i,R_g=x}$</td>
<td>induced voltage on the telephone line with the neutral wire grounding resistance is equal to $x$, and $x = 0, 0.5, 1, 2,$ and $3$.</td>
</tr>
</tbody>
</table>

### References


