Voltage Multiple-Zero-Crossings at Buses Feeding Large Triac-Controlled Loads

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Abstract—Triac-controlled loads operating in three-phase four-wire electric networks produce large zero-sequence current harmonics that cause large currents in the neutral conductor. Under certain conditions, the phase-to-neutral voltage (PTNV) at the bus feeding a large triac-controlled load is distorted to such a degree that multiple zero crossings (MZC) appear in the voltage waveform. This situation may cause malfunction of the triac control systems or any other control systems that are based on the detection of voltage zero crossings. The influence of various parameters of the triac-controlled load and of the cable feeding it, on the appearance of voltage MZC, is investigated. A simulation model is built with alternative transients program version of Electromagnetic Transients Program and is validated by comparison with measurements taken at a real theater lighting installation controlled by triacs. The occurrence of MZC in the voltage waveform is also explained by an analytical approximation. It is shown that certain cable configurations should be avoided when feeding large triac-controlled loads, or otherwise, MZC will appear in the PTNV.

Index Terms—Cable inductance, harmonic distortion, triac, voltage zero crossings, zero-sequence harmonics.

I. INTRODUCTION

TRIACS ARE used widely in commercial and industrial applications to control the voltage applied to a load. Two of the most common applications are the dimming of professional lighting and motor soft starting.

When a phase-angle control is used, the resulting load voltage contains high odd-order harmonics. Voltage harmonics force the load to draw nonsinusoidal current. The amplitude of the current harmonics depends on the inductance of the load and on the value of the triac firing angle. The amplitude of the zero-sequence (3rd, 9th, 15th, etc.) current harmonics is significant with respect to the fundamental harmonic for triac firing angles larger than $90^\circ$ [1]. Thus, when the triacs are used to control single- or three-phase loads in three-phase four-wire networks, the current in the neutral conductor may become very large.

The current harmonics that flow in the phase and neutral conductors may cause a significant harmonic distortion in the phase-to-neutral voltage (PTNV) in distribution switchboards upstream from the triacs. The distortion of the voltage depends on the order and amplitude of the current harmonics and on the parameters and configuration of the cables feeding the distribution switchboard. By cable configuration, it is meant the arrangement of one or more single-core and/or multicore cables that together serve the same load. The voltage can be distorted to such extent that multiple zero crossings (MZC) may appear in the waveform of the PTNV, as shown in previous work [2]. This situation will cause the malfunction of control systems that are fed from the specific switchboard and are based on the detection of voltage zero crossings [3]. The importance of accurate detection of a voltage zero crossing in 50/60-Hz power networks has led in several research efforts in this field [4]–[9]. Although the appearance of MZC in the voltage waveform is a power-quality issue, it is not yet addressed by the relative standards [10], [11].

The malfunction of a large triac-controlled light-dimming system in the Royal Theater of Thessaloniki, Greece, due to the appearance of MZC in the waveform of the PTNV that fed the triacs, is presented and analyzed in this paper. An accurate model of the system is built with the alternative transients program (ATP) version of the Electromagnetic Transients Program (EMTP) software. The simulation model is validated by comparison with measurements taken at the real light-dimming installation.

Subsequently, the simulation model is used to investigate how the parameters of the triac-controlled load and the parameters of the cable that supplies the load affect the appearance or not of MZC in the voltage waveform at the bus feeding the load. The triac-controlled load is assumed to be part of a TN-S type low-voltage network [12], i.e., a three-phase four-wire 400-V, 50-Hz network.

The cable parameters that were examined are the configuration of the cable, its length, and the cross section of the cable's conductors. The load parameters taken into consideration are the magnitude, the power factor (PF), and the degree of asymmetry.

The high harmonic distortion of the PTNV and the consequent appearance of MZC are also explained theoretically by an analytical approximation.

Passive or active harmonic filters could be employed to reduce or even eliminate the distortion in the PTNV [13]–[18]. However, this should be the last measure to be taken. First, measures to reduce the effective impedance of the cable and particularly of the neutral conductor should be taken so that the harmonic distortion of the PTNV is reduced.

It is shown that the selection of the cable that feeds a large triac-controlled load should be based not only on the ampacity and on the allowable voltage drop [19], [20] but also certain cable configurations should be avoided so as to ensure that MZC will not appear in the waveform of the PTNV.

It is known that the cable configuration affects the sharing of the current among parallel-operating cables and may
also lead to asymmetries in three-phase networks operating at 50 Hz [21], [22]. However, the magnitude of the impedance of the neutral conductor in the presence of zero-sequence harmonics and its significance in the harmonic distortion of the PTNV are not well-documented. The present day standards [10], [19] and [20] state that an engineer should select carefully the cross section of the neutral conductor when zero-sequence harmonic currents are present, but nothing is mentioned on the effective impedance of the neutral conductor. This paper aims to present, in a clear way, the influence of cable geometry on the effective impedance of the neutral conductor and, thus, on the harmonic distortion of the PTNV.

II. CASE STUDIED

The theatrical lighting system in the Royal Theatre in Thessaloniki, Greece, is used as a case study. The three-phase system uses 25 triacs with a total rated power of 500 kVA for the dimming of the lights.

Fig. 1 shows the single-line diagram of the electrical installation. Two distribution transformers, operating in parallel and rated 1000 kVA, \( u_k = 6\% \), 20/0.4 kV, 50 Hz, are feeding the low-voltage main switchboard (Bus1 in Fig. 1). The triac-controlled lights are supplied from their own subdistribution board (Bus2 in Fig. 1). Bus2 is fed from the main distribution board (Bus1) by six cables that are laid out, as shown in Fig. 2.

The cables are laid flat on perforated metallic trays, and their length is 120 m, approximately. Three of them are low-voltage four-core PVC-insulated cables (J1VV-R4G 3 × 95 + 50 according to CENELEC Standard HD603), while the other three are single-core PVC cables with 50-mm\(^2\) cross section (J1VV-R 1 × 50).

Each phase of Bus2 is fed by three 95-mm\(^2\) cores connected in parallel. The 50-mm\(^2\) cores of the four-core cables are connected in parallel to form the protective earth (PE) conductor.
The three single-core cables (J1VV-R 1 × 50) are connected in parallel to form the neutral conductor with an equivalent cross section of 150 mm².

Each of the 25 dimmers is fed from Bus2 via a five-core PVC-insulated cable, as shown in Fig. 1. Each core of this cable has a cross section of 10 mm² with an average length of 10 m.

The selection of the cables was based on their amperacity. According to [19], the amperacity of the PVC-insulated cables with 95-mm² cross section is 290 A. Therefore, having three cables in parallel, the total amperacity is 870 A.

III. MEASUREMENTS

The waveforms and the harmonic signature of the voltages and currents at Bus2 (Fig. 1) were measured for various triac firing angles. The measurements were conducted with an Electrex Vip-System3 instrument with a sampling frequency of 4 kHz. The outputs of the instrument—among other parameters—are the rms values and phase angles of the voltage and current harmonics up to the 25th harmonic (1250 Hz). The instrument uses discrete Fourier transform to calculate the harmonic voltages and currents from the acquired samples. The accuracy of the instrument is

\[
0.4\% \cdot \text{Reading} + 0.3\% \cdot \text{Full Scale}
\]

for the measurement of the total rms value of the voltage and current and

\[
1\% \cdot \text{Reading} + 0.6\% \cdot \text{Full Scale}
\]

for the measurement of individual harmonics. The full scale is 600 V for the voltage and 1000 A for the current. The voltage is measured directly, i.e., no transducer is involved. The current is measured by clamps, which are actually 1000-A/1-Vrms transducers. The accuracy of these transducers, for the frequency range from 48 to 1000 Hz, is as follows:

1) ±0.5\% · Reading ± 0.05 A from 10 to 1000 A;
2) ±0.8\% · Reading ± 0.05 A from 2 to 10 A;
3) ±1.5\% · Reading ± 0.05 A from 0.5 to 2 A.

The manufacturer of the instrument does not specify the accuracy of the current clamps for frequencies above 1 kHz. The error in the measurement of the current is the sum of the errors introduced by the instrument and the current clamps.

Each dimmer controller (Fig. 1) uses the PTNV at each dimmer (which is practically equal to the voltage at Bus2) to detect the zero crossings and, thus, generate the triac firing pulse. The dimming-control system malfunctioned when the firing angle of the triac was 130°. At 130° firing angle, the dimming level is relatively high, corresponding to about 25% of the luminous flux of the light bulbs.

Fig. 3 shows the waveforms of the measured line currents at Bus 2 when the firing angle of the triacs was 130°. The waveforms are shown for 20 ms, i.e., for one period of the fundamental frequency. The load in this particular case was nearly balanced and resistive since it consisted of halogen light bulbs. The total rms values of the currents were 273, 278, and 261 A for phases L1, L2, and L3, respectively. As expected, the harmonic distortion of the phase currents is very large. The harmonic analysis of the line currents is shown in Fig. 4. Although the instrument measures up to the 25th harmonic, Fig. 4 shows up to the 21st harmonic (1050 Hz) because the accuracy of the current clamps is specified by the manufacturer up to this frequency. The total harmonic distortion of the line currents is 116%, approximately.

The neutral conductor carries the vector sum of the line currents. The vector sum is equal to the algebraic sum when zero-sequence harmonics are considered. Since the load is almost balanced, the harmonic currents that do not form a zero-sequence system are expected to be very small in the neutral conductor. The harmonic analysis of the measured current in the neutral conductors, under these conditions, is shown in Fig. 5. The total rms value of the neutral current is 467 A.

The PTNVS measured at Bus2 under the same conditions are shown in Fig. 6. The MZC appearing in the PTNVS at Bus2 eventually caused the malfunction of the dimming control system. The total harmonic distortion of the voltage is 11.7%, 10.2%, and 13.2%, for phases L1, L2, and L3, respectively. The main harmonic components are the third and the ninth. The third harmonic is 8.63%, 7.66%, and 9.36% for phases L1, L2, and L3, respectively. The 9th harmonic is 5.12%, 4.48%, and 5.81% for phases L1, L2, and L3, respectively.

Fig. 3. Line currents at Bus2 when the triac firing angle is 130°.

Fig. 4. Harmonic spectrum amplitude of line currents at Bus2 when the firing angle of the triac is 130°. RMS values of harmonic currents are shown.
where $\omega_0 = 2\pi f_0$ is the fundamental angular frequency, and $\overline{U}_{L_{1,1}}(h)$, $\overline{U}_{L_{1,2}}(h)$, $\overline{U}_{N_{1,1}}(h)$, and $\overline{U}_{N_{1,2}}(h)$ are the voltages with respect to ground of phase-L1 conductor and neutral conductor at Bus1 and Bus2, respectively, at the harmonic frequency $h \times f_0$. $r_1$ and $r_N$ are the resistances per unit length of phase-L1 conductor and neutral conductor, respectively. $L_{ij}$, with $i, j$ taking the values 1, 2, 3, and $N$ are the self- and mutual inductances per unit length of the phase and neutral conductors. $\overline{T}_i(h)$, with $i$ taking the values 1, 2, 3, and $N$ are vectors, at the harmonic frequency $h \times f_0$, of the line currents, as shown in Fig. 7(a). $l$ is the length of the cable.

In a TN-S system, the neutral conductor is grounded at the main low-voltage switchboard. Assuming that Bus1 is the main low-voltage switchboard, then

$$\overline{U}_{N_{1,1}}(h) = 0.$$  \hspace{1cm} (3)

By using (1)–(3), the PTNV at Bus2 is given by

$$\overline{U}_{L_{1,2}}(h) - \overline{U}_{N_{2,2}}(h) = \overline{U}_{L_{1,1}}(h) + \left\{ [-r_1 + j \omega_0 (L_{1N} - L_{11})] \cdot \overline{T}_1(h) \
+j r_N + j \omega_0 (L_{NN} - L_{1N}) \right\} \overline{T}_N(h)$$

$$+ j h \omega_0 (L_{2N} - L_{12}) \overline{T}_2(h)$$

$$+ j h \omega_0 (L_{3N} - L_{13}) \overline{T}_3(h) \right\} \cdot \ell.$$ \hspace{1cm} (4)

The self-($L_{ii}$) and mutual ($L_{ij}$) inductances are functions of the cable geometry [23] and are defined by the following equations:

$$L_{ii} = \frac{\mu_0}{2\pi} \ln \frac{A}{d_m}$$ \hspace{1cm} (5)

$$L_{ij} = \frac{\mu_0}{2\pi} \ln \frac{A}{D_{ij}}$$ \hspace{1cm} (6)

where $\mu_0 = 4\pi 10^{-7}$ H/m is the magnetic permeability of free space, $A$ is the radius of a fictitious cylinder that is considered as the return path of the conductor currents, $D_{ij}$ is the distance between the centers of conductors $i$ and $j$, and $d_m = R \times e^{-0.25}$ is the geometric mean radius of a conductor with radius equal to $R$. The value of $A$ can be arbitrary since the terms $L_{ii}$ and $L_{ij}$ always appear as differences when calculating voltage drops. However, $A$ should be selected to be much larger than any $D_{ij}$ so that $A$ can be considered as a constant magnetic flux area.

By using (5) and (6), (4) becomes

$$\overline{U}_{L_{1,2}}(h) - \overline{U}_{N_{2,2}}(h) = \overline{U}_{L_{1,1}}(h) + \left\{ [-r_1 + j \omega_0 \frac{\mu_0}{2\pi} \ln \frac{d_m}{D_{1N}}] \cdot \overline{T}_1(h) \
+j r_N + j \omega_0 \frac{\mu_0}{2\pi} \ln \frac{D_{1N}}{D_{mN}} \right\} \overline{T}_N(h)$$

$$+ j h \omega_0 \frac{\mu_0}{2\pi} \ln \frac{D_{12}}{D_{2N}} \overline{T}_2(h)$$

$$+ j h \omega_0 \frac{\mu_0}{2\pi} \ln \frac{D_{13}}{D_{3N}} \overline{T}_3(h) \right\} \cdot \ell.$$ \hspace{1cm} (7)

IV. ANALYTICAL APPROACH

The influence of cable configuration on the development of voltage harmonics and, thereby, on voltage distortion, when harmonic currents flow, will be demonstrated by the analytical examination of a simple case, as shown in Fig. 7. A four-core and a single-core cable connect Bus1 with Bus2. The single-core cable may be used either as the PE conductor [Fig. 7(b)] or as a neutral conductor [Fig. 7(c)]. It will be shown that the role assumed by the single-core cable is significant for the magnitude of the voltage harmonic distortion and the appearance of the MZC in the PTNV at Bus2.

The voltage drop along the conductor of phase-L1 and the neutral conductor for every harmonic order $h$ is given by the following equations:

$$\overline{U}_{L_{1,1}}(h) - \overline{U}_{L_{1,2}}(h) = \left\{ [r_1 + j \omega_0 L_{11}] \cdot \overline{T}_1(h) + j h \omega_0 L_{12} \overline{T}_2(h) \
+j h \omega_0 L_{13} \overline{T}_3(h) + j h \omega_0 L_{1N} \overline{T}_N(h) \right\} \cdot \ell \hspace{1cm} (1)$$

$$\overline{U}_{N_{1,1}}(h) - \overline{U}_{N_{1,2}}(h) = \left\{ [r_N + j \omega_0 L_{NN}] \cdot \overline{T}_N(h) + j h \omega_0 L_{1N} \overline{T}_1(h) \
+j h \omega_0 L_{2N} \overline{T}_2(h) + j h \omega_0 L_{3N} \overline{T}_3(h) \right\} \cdot \ell \hspace{1cm} (2)$$

**Fig. 6.** Measured waveforms of PTNVs at Bus2 (Fig. 1) when the triac firing angle of the triac is $130^\circ$. RMS values of harmonic currents are shown.

**Fig. 5.** Harmonic spectrum amplitude of neutral current when the firing angle of the triac is $130^\circ$. RMS values of harmonic currents are shown.
where \( d_{m1} = R_1 \times e^{-0.25} \) and \( d_{mN} = R_N \times e^{-0.25} \) are the geometric mean radii of phase-L1 and neutral conductors, respectively.

If a symmetrical three-phase triac-controlled load is connected at Bus2 and the voltage at Bus1 is assumed to be free of harmonics, then at frequencies corresponding to zero-sequence harmonics, the following relations apply:

\[
U_{L1,1}(h) = 0, \quad \text{for } h = 3 \cdot k, \quad k \in Z_+ \quad (8)
\]

\[
T_1(h) = T_2(h) = T_3(h) = -\frac{T_N(h)}{3}, \quad \text{for } h = 3 \cdot k, \quad k \in Z_+. \quad (9)
\]

Therefore, at zero-sequence harmonic frequencies, (7) becomes

\[
\begin{align*}
\bar{U}_{L1,2}(h) - \bar{U}_{N2}(h) &= \left[ r_N + \frac{r_1}{3} \right] \cdot \ell \cdot T_N(h) + j \hbar_0 \ell \frac{\mu_0 T_N(h)}{2\pi} \\
&\times \ln \left( \frac{D_{1N}^2 \cdot D_{2N} \cdot D_{3N}}{d_{m1} \cdot d_{mN}^2 \cdot D_{12} \cdot D_{13}} \right) \\
&= T_N(h) \cdot \bar{Z}_{1N}(h), \\
&\quad \text{for } h = 3 \cdot k, \quad k \in Z_+. \quad (10)
\end{align*}
\]

The PTNV that is developed at Bus2 at zero-sequence harmonic frequencies is proportional to the neutral current at the same frequency and to an effective impedance \( \bar{Z}_{1N}(h) \) that is a function of the cross section of phase and neutral conductors of the frequency and of the cable’s configuration. It is evident in (10) that, by increasing the distances \( D_{1N}, D_{2N}, \) and \( D_{3N} \), the harmonic voltage developed at Bus2 increases. Distances \( D_{1N}, D_{2N}, \) and \( D_{3N} \) are larger in the case where the single-core cable is used as neutral conductor and the forth core of the four-core cable is used as PE conductor [Fig. 7(c)] when compared to the case as in Fig. 7(b).

At zero-sequence harmonics, the reactive part of \( \bar{Z}_{1N}(h) \) can become larger than the resistive part particularly when the distance of the neutral conductor from the phase conductors is relatively large. Table I demonstrates this for the case of a \( 3 \times 95 + 50 \text{ mm}^2 \) PVC-insulated 0.6/1.0-kV cable. Two cases are presented: First, the neutral conductor is formed by the forth

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>EFFECTIVE IMPEDANCE OF NEUTRAL CONDUCTOR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Neutral conductor inside four-core cable (Fig. 7b)</td>
</tr>
<tr>
<td>Geometric Data</td>
<td></td>
</tr>
<tr>
<td>( D_{1N} \text{ mm} )</td>
<td>17</td>
</tr>
<tr>
<td>( D_{2N} \text{ mm} )</td>
<td>17</td>
</tr>
<tr>
<td>( D_{3N} \text{ mm} )</td>
<td>19</td>
</tr>
<tr>
<td>( D_{m1} \text{ mm} )</td>
<td>26</td>
</tr>
<tr>
<td>Data from Cable Manufacturer</td>
<td></td>
</tr>
<tr>
<td>( r_1 \text{ m\Omega/m} )</td>
<td>0.19</td>
</tr>
<tr>
<td>( r_N \text{ m\Omega/m} )</td>
<td>0.39</td>
</tr>
<tr>
<td>Data Calculated from Eq. 10</td>
<td></td>
</tr>
<tr>
<td>Resistive part of ( Z_{1N} ) at 150Hz, m\Omega/m</td>
<td>0.453</td>
</tr>
<tr>
<td>Reactive part of ( Z_{1N} ) at 150Hz, m\Omega/m</td>
<td>0.395</td>
</tr>
<tr>
<td>Reactive part of ( Z_{1N} ) at 450Hz, m\Omega/m</td>
<td>1.184</td>
</tr>
</tbody>
</table>

The following relations apply:

Fig. 7. (a) Cable system connecting Bus1 with Bus2 in a TN-S system. The control of the load is based on the detection of zero crossings of the voltage at Bus2. (b) Neutral conductor is part of the four-core cable. (c) Neutral conductor is formed by a separate single-core cable.
core of the multicore cable [Fig. 7(b)], and second, the neutral conductor is formed by the single-core cable [Fig. 7(c)].

It can be deduced from Table I that impedance $Z_{1N}(h)$ at, for example, the ninth harmonic (450 Hz) is increased from $Z_{1N}(9) = 0.453 + j1.184 = 1.268 \angle 69^\circ$ m$\Omega$/m to $Z_{1N}(9) = 0.453 + j1.609 = 1.671 \angle 74.2^\circ$ m$\Omega$/m when the neutral conductor is outside the four-core cable. This 32% increase in the value of $Z_{1N}(9)$ will cause, for the same $7_N(9)$, an analogous increase in the ninth harmonic voltage developed at Bus2.

At higher zero-sequence harmonic frequencies, for example at 15th and 21st, the reactive character of $Z_{1N}(h)$ is more pronounced, and therefore, the position of the neutral conductor affects the magnitude of $Z_{1N}(h)$ to a larger extent.

The mainly reactive character of $Z_{1N}(h)$ means that, by increasing the cross section of the neutral conductor, the magnitude of $Z_{1N}(h)$ will not decrease proportionally. Indeed, for the second case [Fig. 7(c)], if the cross section of the neutral conductor is made 95 mm$^2$, i.e., almost doubled, $Z_{1N}(9)$ will become $Z_{1N}(9) = 0.253 + j1.467 = 1.489 \angle 80.2^\circ$ m$\Omega$/m, which is just 11% smaller than its value (1.671 m$\Omega$/m), where the neutral conductor is 50 mm$^2$ in cross section.

Although the actual cable system shown in Fig. 2 is rather complicated, since it consists of fifteen conductors, the appearance of MZC in the voltage waveforms in the system shown in Fig. 1 can be explained using the cable system shown in Fig. 8 and with the aid of (8)–(10). It can be assumed—without introducing a big error—that the load is balanced and that the line currents are equally distributed among the three conductors that form, in parallel, each phase and the neutral.

The relative position of cables C2 and C5 in Fig. 8 can be considered to give the average distances between the neutral and phase conductors. The distance between the neutral and the phase conductors in this case is $D_{1N} = 83$ mm, $D_{2N} = 102$ mm, and $D_{3N} = 104$ mm. The radii of the phase and neutral conductors are $R_1 = 4.28$ mm and $R_N = 2.99$ mm, respectively, and the distances between the phase conductors are $D_{12} = 18$ mm and $D_{13} = 26$ mm. By using (8)–(10), the phase-L1-to-neutral voltage at various zero-sequence harmonic frequencies is calculated for a cable length of 120 m, and the results are shown in Table II.

The phase angles of the harmonic currents depend on the firing angle of the triac (130° in this case) and were calculated according to the formulas given in [1]. The fundamental harmonic of the PTNV at Bus2 can be considered approximately equal in magnitude to the voltage at Bus1 since the voltage drop on the cable at this frequency is very small. Thus, the fundamental harmonic of the PTNV at Bus2 can be assumed to be equal to $230 \angle 0^\circ$ V. The last row of Table II shows the harmonic voltages as percentages of the fundamental frequency voltage at Bus2. The respective measured values are shown in parentheses. It is evident that the calculated and measured voltages are in very good agreement.

The calculated harmonic components and the resultant waveform of the phase-L1 voltage with respect to the neutral at Bus2.

V. ANALYSIS WITH ATP-EMTP SIMULATION

The ATP version of the EMTP was used to investigate the influence of cable and load parameters on the appearance of MZC in the waveform of PTNV. The network shown in Fig. 1 was simulated with the cable configuration in accordance with Fig. 8, i.e., including all 15 conductors. The model is verified by comparing the simulation results with measurements of the PTNVs (Fig. 10) and of the line currents (Fig. 11) at load bus (Bus2 in Fig. 1).

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**Table II**

<table>
<thead>
<tr>
<th>Harmonic Order, h</th>
<th>3rd</th>
<th>9th</th>
<th>15th</th>
<th>21st</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z_{1N}$ m$\Omega$/m</td>
<td>0.453 + j1.01</td>
<td>0.453 + j3.03</td>
<td>0.453 + j5.05</td>
<td>0.453 + j7.07</td>
</tr>
<tr>
<td>$I_{inA}$ A</td>
<td>146 $\angle$-100°</td>
<td>28 $\angle$-6°</td>
<td>14 $\angle$61°</td>
<td>8.5 $\angle$121°</td>
</tr>
<tr>
<td>Voltage at Bus2</td>
<td>19.4 $\angle$-34°</td>
<td>10.3 $\angle$75°</td>
<td>8.5 $\angle$146°</td>
<td>7.2 $\angle$-153°</td>
</tr>
<tr>
<td>$U_p/U_1$</td>
<td>8.43% (8.63%)</td>
<td>4.48% (5.12%)</td>
<td>3.69% (4.46%)</td>
<td>3.13% (3.79%)</td>
</tr>
</tbody>
</table>

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Fig. 8. Cable layout showing the average distance between phase conductors and neutral conductor.

Fig. 9. Calculated harmonic components and the resultant waveform of the phase-L1 voltage with respect to the neutral at Bus2.
Although a specific system is simulated, the results of the investigation apply to any other system consisting of two buses (Bus1 and Bus2) connected via a cable system, with Bus2 feeding a triac-controlled load and Bus1 supplying a sinusoidal voltage. This assumption is valid because the impedance of the power transformers shown in Fig. 1 is negligible compared to the impedance of the cable from Bus1 to Bus2.

In the investigation that follows, as “MZC” was considered the case where at least three successive zero crossings at intervals of more than 100 $\mu$s (approximately 2° at 50 Hz) appear near the ideal zero crossing in any of the three PTNV waveforms at the load bus (Bus2 in Fig. 1).

The parameters examined are the magnitude, PF, and asymmetry of the load and the length, cross section, and configuration of the cable system that feeds the triac-controlled load.

A. Cable Configuration and Neutral Conductor Cross Section

According to the analytical approach, the main reason for the high distortion in the waveform of the PTNV at the load bus is the relatively high neutral-to-ground voltage developed at this bus, which is caused by the high effective impedance of the neutral conductor and the high harmonic currents that flow in it. The harmonic currents in the neutral conductor can be reduced by using passive or active harmonic filters [13]–[18], but this should be the last measure to be taken. The first measure should be the reduction of the effective impedance of the neutral conductor. This can be done by changing either the cross section of the neutral conductor or the configuration of the cable system. However, in (10) and [23], it can be deduced that an increase in the neutral conductor cross section would result in a minor decrease of its effective impedance. On the other hand, the latter is strongly reduced by decreasing the distance between the neutral conductor and the phase conductors.

To prove these arguments, the following cases were simulated: In the first case, the cable configuration shown in Figs. 2 and 8 was used. In the second case, a new cable configuration, as shown in Fig. 12, was assumed where the neutral conductor is formed by the fourth core of the four-core cables. The PE conductor is now formed by the three single-core cables in parallel. In both cases, the cross section of the neutral conductor was increased from $3 \times 50$ to $3 \times 95$ mm$^2$.

The result of the simulation is shown in Figs. 13 and 14. The load was simulated as a resistance with 0.26 $\Omega$ per phase. The firing angle of the triacs was assumed to be 130°, which results in line currents with total rms value equal to approximately 270 A, as in the real case that was examined in Section III. At zero firing angle, the rms value of the line current would be 880 A, which is also the total ampacity of the three parallel cables.

It is evident in Figs. 13 and 14 that the increase of the cross section of the neutral conductors hardly affected the waveform of the PTNV at the load bus since MZC are still present. On the contrary, in the case of configuration shown in Fig. 12, the PTNV has no MZC because the effective inductance of the neutral conductor is reduced significantly.

B. Cable Length

For a given cable configuration, the impedance of the neutral conductor is proportional to the length of the cable. It is therefore expected that, as the cable length increases, the distortion of the PTNV at the load bus will increase. The distortion of the PTNV depends also on the current harmonics, thus on the firing angle of the triacs.

To investigate the influence of cable length on the appearance of MZC in the waveform of PTNV, the following cases were examined: In the first case, the cable configuration shown in Fig. 8 was assumed, and in the second case is the cable configuration shown in Fig. 12. In both cases, a cable with 95-mm$^2$ cross section in all conductors was assumed. Also, in both cases, the load was assumed to be resistive with 0.26 $\Omega$ per phase which, at zero firing angle, corresponds to a line current equal to the ampacity of the cable. This load is defined as 1 pu. The firing angle of the triacs was varied from 110° to 135°, because in this region, the zero-sequence current harmonics are significant with respect to the fundamental current harmonic. In the first case, the simulation results showed that the minimum
Fig. 12. New configuration for the cable from Bus1 to Bus2.

Fig. 13. Waveforms of PTNV at load bus for two different cable configurations; the cross section of neutral conductor is $3 \times 50 \text{ mm}^2$ and the cable length is 120 m. The waveforms are the result of simulation.

Fig. 14. Waveforms of PTNV at load bus for two different cable configurations; the cross section of neutral conductor is $3 \times 95 \text{ mm}^2$ and the cable length is 120 m. The waveforms are the result of simulation.

cable length at which MZC appear in the PTNV waveform is 57 m, while in the second case is 200 m. Since cable lengths larger than 200 m are hardly met in practice, the cable configuration shown in Fig. 12 will never cause MZC as long as the load current is within the ampacity rating of the cable.

The minimum cable length is the length at which MZC—according to the definition given previously—start appearing, i.e., three successive zero crossings at intervals of $100 \mu s$ appear near the ideal zero crossing in at least one of the three PTNV waveforms at the load bus. At cable lengths larger than the minimum, the intervals between the successive zero crossings are larger than $100 \mu s$. An example is shown in Fig. 10, where for a cable length of 120 m, the successive zero crossings appear at intervals of 300 $\mu s$ approximately. If the cable length is reduced to the minimum value, i.e., 57 m as mentioned previously, the successive zero crossings will appear at intervals of $100 \mu s$.

C. PF and Magnitude of Load

To investigate the influence of the load PF, it was assumed that the load magnitude is equal to the maximum permissible, i.e., equal to the ampacity of the cable, and its PF varied from 0.9 to 0.5 inductive.

For a given firing angle of the triacs, an inductive load draws smaller current harmonics than a resistive load that is the same in magnitude [1]. Thus, the current in the neutral conductor is expected to be smaller when the load is inductive.

If the cable configuration shown in Fig. 8 is used, for a cable with 95-mm$^2$ cross section in all conductors and for PF equal to 0.9 inductive, then the simulation showed that the cable length should be more than 210 m in order for MZC to appear in the PTNV waveform. For inductive PF equal to 0.8, 0.7, 0.6, and 0.5, the cable lengths are 250, 300, 320, and 340 m, respectively. The firing angle of the triacs, at which MZC appeared, was within the region $120^\circ$–$125^\circ$ for the various load PF. If the cable configuration shown in Fig. 12 is used, the simulation showed that MZC appear for cable lengths longer than 600 m for PF equal to 0.9 or less.

To investigate the influence of load magnitude on the appearance of MZC in the PTNV waveform, loads corresponding to 0.5–0.9 pu of the ampacity of the cable were considered. This situation also corresponds to the case where a cable with ampacity larger than the maximum load has been selected. The load PF was also assumed to vary from unity to 0.9 inductive. Table III shows the minimum cable length for MZC to appear in the PTNV waveform for cables with 95-mm$^2$ cross section in all conductors and configuration, as shown in Fig. 8. The values of the cable lengths shown in Table III were obtained through simulation. The firing angle of the triacs, at which MZC appeared, was within the region $125^\circ$–$130^\circ$ for the various
load PF. If the configuration shown in Fig. 12 is used, simulation showed that the minimum cable length is in the region of 200–900 m for the various load magnitudes and PFs shown in Table III.

From the above, it can be concluded that MZC appear at longer cable lengths as the PF and load magnitude decrease.

### D. Load Asymmetry

When the load is not symmetric, the current in the neutral conductor consists not only of zero-sequence harmonics but also of all odd-order harmonics that are present in the line currents. Two types of load asymmetry were examined: asymmetry in the amplitude of line currents and asymmetry of the load PF.

To investigate how the asymmetry in the amplitude of line currents influences the appearance of MZC in the PTNV waveform, the load in the three phases was assumed to be as follows: first, equal to 1, 0.9, and 0.9 pu, and second, equal to 1, 0.9 inductive, and 0.8 inductive for phases L1, L2, and L3, respectively. In both cases, the load PF was assumed to be unity in all phases because this was proven to be the worst case for the appearance of MZC. Again, the configuration shown in Fig. 8 was assumed with all conductors having 95-mm$^2$ cross section. Table IV shows the main harmonics of the line and neutral currents for the two cases of load asymmetry and the minimum cable length at which—according to the simulation results—MZC appear in the PTNV waveform. For comparison, the case of the symmetric load is also shown.

As shown in Table IV, the current in the neutral conductor decreases as the load asymmetry increases because there is a reduction in the zero-sequence harmonics. Since the current in the neutral conductor is reduced, MZC appear at longer cables. The firing angles at which MZC appear in the three cases of Table IV are, respectively, 124°, 126°, and 127°. Due to the difference in firing angle, the current in phase L1 is not the same in all cases, although the load impedance, for this phase, is the same.

If the configuration shown in Fig. 12 is used, then—according to simulation results—the minimum cable length at which MZC appear in the PTNV waveform is more than 190 and 220 m for the first and second cases, respectively.

If the load is asymmetric with respect to the PF, then the current in the neutral conductor is again smaller with respect to the case of symmetric load. Simulation results showed that, for a load with magnitude equal to 1 pu in all phases and PF equal to 1, 0.9 inductive, and 0.9 inductive for phases L1, L2, and L3, respectively, the minimum cable length for the appearance of MZC is 70 m, and the firing angle should be 124°. If the PF is 1, 0.9 inductive, and 0.8 inductive for phases L1, L2, and L3, respectively, then the minimum cable length is 75 m, and the firing angle of the triacs should be 124°. If the configuration shown in Fig. 12 is used, the simulation showed that the minimum cable length for the appearance of MZC is more than 240 and 250 m for the first and second cases, respectively.

### E. Cable Cross Section

To examine the influence of cable cross section on the appearance of MZC, besides the 95 mm$^2$, two more values, 50 and 185 mm$^2$, were used for simulation. The load was simulated as a resistance, which, at zero firing angle, draws a current equal to the ampacity of the cable (540 and 1302 A for the cables with 50- and 185-mm$^2$ cross sections, respectively [19]). The cables were assumed to be laid, as shown in Fig. 8.

Simulation showed that the minimum cable length, at which MZC appear in the PTNV waveform, is 80 and 40 m for the cables with 50- and 185-mm$^2$ cross sections, respectively. The firing angles, at which MZC appeared, were 123° and 124°, respectively. The difference in the cable length can be explained by the difference in the distances between the phase conductors and the neutral conductor. The distances are smaller in cables with small cross sections, and thus, the effective impedance per unit length of the neutral conductor is also smaller. Therefore, MZC appear at longer cables.

If the cable configuration shown in Fig. 12 is used, simulation showed that the minimum length of the cable at which MZC appear in the PTNV waveform is more than 210 and 150 m for the 50- and 185-mm$^2$ cable, respectively.

### VI. DISCUSSION OF RESULTS

The appearance of MZC depends on the configuration, cross section, and length of the cable and also on the PF, magnitude, and asymmetry of the load. In general, MZC appear in the PTNV waveform when the current and/or the effective impedance of the neutral conductor are high enough. Therefore, the elimination of MZC should be based on the reduction of either or both of these neutral conductor parameters.

The current in the neutral conductor is reduced as the PF and the magnitude of the load decrease and as the asymmetry of the load increases. The effective impedance of the neutral conductor decreases as the cross section decreases, which makes MZC appear at longer cable lengths.
conductor is reduced when four-core cables, with the fourth core being the neutral conductor, are employed. Other cable configurations, such as the one shown in Fig. 8, or in the case of multiple single-core cables laid flat on cable trays, increase the effective impedance of the neutral conductor due to its large distance from one or more phase conductors. In such cases, only short cables (< 40 m) retain a small effective impedance for the neutral conductor.

Using cable configurations such as the one shown in Fig. 12 eliminates the appearance of MZC independently of the load parameters (PF, asymmetry, etc.) and of the cross section of the cable conductors for cables as long as 150 m, i.e., for almost all practical situations. On the contrary, when using cable configurations where the neutral conductor is relatively far from the phase conductors, the appearance of MZC depends on the load parameters because the effective impedance of the neutral conductor is relatively large. In such cases, MZC appear at cable lengths between 40 and 150 m even at asymmetric loads or at loads that draw currents less than the cable’s ampacity. The increase of the cross section of the neutral conductor does not improve the situation because the effective reactance of the neutral conductor remains relatively large. Increasing the cross section of the phase conductors too worsens the situation because the effective reactance of the neutral conductor increases due to the increase of its distance from the phase conductors. However, this worsening is small when the configuration shown in Fig. 12 is employed.

VII. CONCLUSION

The selection of the cable that feeds a large triac-controlled load should be based not only on the ampacity and on the allowable voltage drop as the standards suggest but also certain cable configurations should be avoided to ensure that MZC would not appear in the waveform of PTNV. The present relevant standards allow the selection of any cable configuration (for example, single- or multicore cables where the neutral conductor may run separately or within the same cable as the phase conductors, etc.) provided that the ampacity and the allowable voltage drop are within the specified limits.

Triac-controlled loads operating in networks of the TN-S type produce large zero-sequence current harmonics that can cause MZC in the PTNV at the bus that feeds the load. The MZC appear in the PTNV waveforms due to the rise of the neutral-to-ground voltage caused by the high effective impedance of the neutral conductor and by the high harmonic currents that flow in it. This was confirmed both analytically and through measurements in a real installation.

When the neutral conductor runs in the same cable with the phase conductors, its effective impedance is reduced significantly, resulting in the elimination of MZC even for cables with large cross section (185 mm$^2$) and length (150 m), i.e., for almost all practical situations.

In the case where the neutral conductor runs separately, as for example shown in Fig. 8, or when multiple single-core cables are laid flat on cable trays and are connected in parallel to feed large triac-controlled loads, MZC may appear in PTNV waveform for cable lengths and cross sections that are usually met in practice. It was shown that the exact cable length at which MZC will appear depends on the magnitude, asymmetry, and PF of the load and also on the cable cross section. Therefore, in this case, the selection of the cable should be based not only on the ampacity and on the allowable voltage drop but also an analysis of the specific network is required to determine if, under any operating points, MZC appear in the voltage waveform.

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