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Derivation of Neutral Conductor Design Parameters in Low-Voltage Systems Supplying Nonlinear Electronic Loads: An Applied Study

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Abstract

This study presents an applied methodology for deriving design parameters for neutral conductor sizing in low-voltage three-phase, four-wire electrical systems supplying nonlinear electronic loads. The study addresses the combined effects of load imbalance and triplen harmonic currents on the neutral conductor and develops a calculation procedure for representing these effects within a proposed mathematical model. The methodology is based on field measurement data reported in the literature for a three-phase, four-wire low-voltage distribution system serving nonlinear electronic loads, together with published harmonic-spectrum data used to characterize the harmonic behavior of such loads. The reported phase-current and neutral-current measurements are examined and evaluated for their suitability for deriving the model parameters. The average phase current is determined from the reported phase-current measurements, while the neutral-current components associated with load imbalance and triplen harmonics are used to derive the corresponding model factors according to the definitions adopted in the study. The published harmonic spectrum is analyzed separately to determine the individual harmonic current components and the resulting RMS phase current, while the measured triplen harmonic neutral-current component is retained as the basis for the Triplen Harmonic Factor adopted in the proposed model. The derived parameters are subsequently combined to obtain the Neutral Conductor Upsizing Factor and to establish a quantitative basis for estimating the required neutral conductor cross-sectional area during the preliminary electrical design stage. The presented procedure provides a reproducible link between reported field measurements, published harmonic data, and the design parameters used in the proposed neutral conductor sizing model.

Keywords: Neutral Conductor, Neutral Conductor Sizing, Nonlinear Electronic Loads, Triplen Harmonics, Load Imbalance, Low-Voltage Systems, Neutral Conductor Upsizing Factor, Harmonic Current

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1. Introduction

The development of a mathematical model for neutral conductor sizing requires design parameters that can be derived from measurable electrical quantities rather than introduced as assumed values. Published field studies, however, do not necessarily present their measurement results in the form required by a newly proposed model. This applied study demonstrates a procedure for extracting and processing reported electrical data to derive the parameters required by the proposed neutral conductor sizing model. The study uses previously reported field measurements from a three-phase, four-wire low-voltage distribution system supplying nonlinear electronic loads. The relevant phase-current and neutral-current measurements are identified and evaluated according to the mathematical definitions adopted in the present study.

The reported phase-current values are used to establish the reference phase-current quantity, while the neutral-current components associated with load imbalance and triplen harmonics are used to derive their respective model parameters. A published harmonic spectrum is also analyzed independently to convert the reported harmonic percentages into actual current components and to determine the RMS phase current. This harmonic-spectrum analysis is kept separate from the derivation of the Triplen Harmonic Factor, which is based on the measured triplen harmonic component of the neutral current. The derived parameters are then combined according to the proposed mathematical relationship to obtain the Neutral Conductor Upsizing Factor and establish the basis for determining the required neutral conductor cross-sectional area. The study therefore provides a reproducible calculation procedure linking reported field measurements and published harmonic data to the design parameters required by the proposed model.

2. Reference Used
The derivation of the model parameters for the office building design scenario presented in this appendix is based on the following reference [1]. The selection of this reference is based on the fact that it contains actual field measurements of nonlinear loads in an office building, together with quantitative data on load currents and harmonic components measured at several locations within the internal electrical distribution system. These characteristics make the reference suitable for deriving the parameters of the proposed mathematical model [1].

3. Reference Evaluation
The selected reference was evaluated against the evaluation criteria adopted in the present study, as summarized in Table 1.

Criterion	Evaluation
Based on actual field measurements.	✓
Represents an office building supplied with nonlinear loads.	✓
Three-phase, four-wire low-voltage distribution system with a neutral conductor.	✓
Provides quantitative data on load currents and harmonic components.	✓
Enables the derivation of the proposed model parameters.	✓

Table1: Evaluation of the Reference Used for the Derivation of the Model Parameters for the Office Building Design Scenario

4. Facility Description
The study was conducted in a multi-story office building in Hong Kong, incorporating a computer center occupying several floors of the building [1]. The nonlinear loads investigated included computers, printers, fluorescent lighting units equipped with electronic ballasts, and other office equipment supplied by Switched-Mode Power Supplies (SMPSs). The measurements were carried out in accordance with the requirements of IEC 61000-4-7 using a power quality analyzer, with measurements recorded at one-minute intervals during different operating periods [1].

5. Data Used in the Present Study
The original study reported separate measurements at three locations within the electrical distribution system [1].
- Lighting load.
- Socket outlet and computer load circuits.
- Tee-off Point (Main Supply Point).

Since the proposed mathematical model developed in this study is intended to estimate the required neutral conductor cross-sectional area for the entire facility, the measurements obtained at the Tee-off Point were adopted, as they represent the combined effect of all loads connected to the distribution board, including the effects of load imbalance and harmonics generated by nonlinear loads [1]. The measurements obtained from the lighting and socket outlet circuits were used only to characterize the load characteristics and were not directly employed in the derivation of the model parameters.

6. Data Extraction from the Reference
The present study is based on the data published in the selected reference, which represent actual field measurements of nonlinear loads in an office building [1]. The original study reported measurements at three different locations within the building's internal electrical distribution system: the Lighting Load, the Socket Outlet circuits, and the Tee-off Point [1]. To achieve the objective of the present study, only the measurements representing the total building load at the Tee-off Point were extracted, since they reflect the combined effect of all loads connected to the distribution system and are therefore consistent with the objective of estimating the required cross-sectional area of the main neutral conductor. The data presented in Table 2 were extracted directly from the original study without modification or processing [1].

Item	Extracted Data
Measurement location	Tee-off Point
Load type	Total building load
System configuration	Three-phase, four-wire low-voltage distribution system with a neutral conductor
Measured quantity	RMS current

Citation: Shtat, H. (2026). Derivation of Neutral Conductor Design Parameters in Low-Voltage Systems Supplying Nonlinear Electronic Loads: An Applied Study. *Eng Appl Sci J, 3*(4), 1-14.

Measured quantity	Fundamental current
Measured quantity	Individual harmonic components (3rd, 5th, 7th, 9th, and 11th)
Measured quantity	Total Harmonic Distortion of Current (THDI)
Measured quantity	Neutral conductor current
Measurement method	Field measurements performed using a power quality analyzer in accordance with IEC 61000-4-7 [Ab2]
Recording interval	Measurements recorded at one-minute intervals during different operating periods

Table 2: Data Extracted from the Tee-off Point

7. Suitability of the Extracted Data for Deriving the Model Parameters

The data reported in the selected reference include direct measurements of load currents and harmonic components at the Tee-off Point, making them suitable for deriving the harmonic-related component of the proposed mathematical model [1]. The study also provides sufficient information to characterize the predominant nonlinear loads within the office building and to evaluate the contribution of harmonic components to the neutral conductor current [1]. However, the derivation of all model parameters requires verification that the published data are consistent with the mathematical definitions adopted in the present study, particularly with respect to the Load Imbalance Factor ((K_U)). Accordingly, the extracted data are analyzed in the following sections before being adopted for the derivation of the proposed model parameters.

8. Derivation of the Triplen Harmonic Factor ((K_H))

In the present study, the Triplen Harmonic Factor (K_H) is defined as the ratio of the neutral conductor current component resulting from triplen harmonics to the average phase current and is expressed as follows.

$$K_H = I_N, H/I_p h, avg$$

where I_N,H represents the neutral conductor, current component resulting from triplen harmonics, while I_p h,avg represents the average phase current calculated from the three reported phase-current values.

9. Evaluation of the Suitability of the Reference for Deriving the Model Parameters

The analysis of the extracted data indicates that the selected reference provides direct field measurements of the neutral conductor current and its reported components at the Tee-off Point, together with individual harmonic components and the Total Harmonic Distortion of Current (THDi). The reference also provides the phase-current entries identified as L1, L2, and L3 at the Tee-off Point. These data make the reference suitable for deriving the parameters required by the proposed mathematical model [1]. The reported neutral conductor data include a load imbalance component of 20.75 A and a reported triplen harmonic component of 54.80 A. These measurements are used in the present study to characterize the neutral conductor current and the contribution of triplen harmonics under the investigated operating conditions [1]. The reported triplen harmonic component is used as the numerator in the derivation of the Triplen Harmonic Factor adopted in the present study, whereas the average phase current calculated from the reported L1, L2, and L3 phase-current values is used as its denominator. The phase-current values identified as L1, L2, and L3 are therefore used to determine the average phase current required for the derivation of the Load Imbalance Factor and the Triplen Harmonic Factor. Accordingly, the average phase current is calculated from the three reported phase-current values as follows.

$$I_a vg = (I_A + I_B + I_C)/3$$

The resulting average phase current is then used as the common denominator in the calculation of both the Load Imbalance Factor (K_U) and the Triplen Harmonic Factor (K_H). The detailed numerical derivation of these parameters is presented in the subsequent sections.

10. Derivation of the Model Parameters

The derivation of the model parameters was based on the data reported in the selected reference. In Table 7, the standard notation L1, L2, and L3, followed by L1(N), L2(N), and L3(N), is used. This notation is conventionally employed in power quality analyzers to identify the three phase conductors and their corresponding neutral measurements [1]. The reported L1, L2, and L3 entries were therefore used as the three phase-current measurements at the Tee-off Point for the derivation of the Load Imbalance Factor.

Variable	Symbol	Value	Unit
Phase A current	(I_A)	62.32	A
Phase B current	(I_B)	9.92	A
Phase C current	(I_C)	31.16	A
Neutral current component resulting from load imbalance	(ΔI_RMS)	20.75	A
Reported triplen harmonic component	—	54.80	A

Table 4: Data Used for the Derivation of the Model Parameters

The average phase current is calculated as follows.

$$I_avg = (I_A + I_B + I_C)/3$$

Substituting the corresponding values yields:

$$I_avg = (62.32 + 9.92 + 31.16)/3 = 34.47A$$

The Load Imbalance Factor is then calculated as follows:

$$K_U = \Delta I_RMS/I_avg$$

$$K_U = 20.75/34.47 = 0.602$$

The resulting model parameters are subsequently used to determine the Neutral Conductor Upsizing Factor according to the proposed mathematical model.

This result represents the theoretical requirement predicted by the proposed mathematical model based on the electrical data reported in the selected reference. The neutral conductor cross-sectional area adopted in the final design is determined during the engineering design stage after considering project-specific factors, particularly the demand factor, future load growth, and the required safety margin, in accordance with the applicable code requirements and the characteristics of the connected loads.

11. Derivation of the Triplen Harmonic Factor from the Published Harmonic Spectrum

The published harmonic spectrum reported in the referenced literature [Ab6] is used in the present study to characterize the harmonic content of nonlinear electronic loads and to determine the RMS phase current.

The reference [Ab6] provides the relative magnitudes of the individual harmonic components of electronic loads, including the triplen harmonic orders. These data are used to characterize the harmonic content of the nonlinear electronic load and to support the analysis of the contribution of harmonic components within the mathematical model developed in the present study.

The triplen harmonic orders considered in the present study are the 3rd, 9th, 15th, 21st, 27th, and 33rd harmonic orders. These harmonic components are of particular importance for the neutral conductor because triplen harmonics are zero-sequence components and therefore accumulate in the neutral conductor. The published harmonic spectrum is not used to replace the measured triplen harmonic neutral-current component reported at the Tee-off Point. The Triplen Harmonic Factor adopted in the present study is derived from the measured triplen harmonic neutral-current component and the average phase current, as detailed in Section A.15. The subsequent sections present the published harmonic spectrum and the calculation procedure used to determine the individual harmonic current components and the RMS phase current.

Table A.5.

Data Used for the Derivation of the Triplen Harmonic Factor (K_H) from the Published Harmonic Spectrum [Ab6]

Published harmonic spectrum for electronic loads used in the derivation of K_H

Harmonic order	Magnitude (% of fundamental)
1	100.0
3	65.7
5	37.7
7	12.7
9	4.4

Citation: Shtat, H. (2026). Derivation of Neutral Conductor Design Parameters in Low-Voltage Systems Supplying Nonlinear Electronic Loads: An Applied Study. *Eng Appl Sci J, 3*(4), 1-14.

11	5.3
13	2.5
15	1.9
17	1.8
19	1.1
21	0.6
23	0.8
25	0.4
27	0.2
29	0.2
31	0.2
33	0.2

Table A.5.

Source: [Ab6] Analysis of Harmonic Distortion Levels in Commercial Buildings.

12. Calculation of the Individual Harmonic Current Components

The fundamental current reported in the reference was adopted as the basis for calculating the individual harmonic current components. The fundamental current was I_1=58.50A.
The current of each harmonic component was then calculated using the following equation:

$$I_h = (H_h/100)I_1$$

where [Ab5]:

- I_h: Current of the harmonic component of order h.
- H_h: Published percentage of the harmonic component.
- I_1: Fundamental current reported in the reference.

Using this equation, all harmonic current components required for the characterization of the harmonic spectrum are calculated.

The triplen harmonic components are considered in evaluating the contribution of triplen harmonics to the neutral conductor current, while the complete harmonic spectrum is used to characterize the RMS phase current [Ab3].

13. Conversion of the Published Harmonic Spectrum into Actual Current Values

Based on the fundamental current reported in the reference, (I_1 = 58.50 A), the current of each harmonic component was calculated by multiplying the published harmonic percentage by the fundamental current.
The following table presents the harmonic current components used in the subsequent calculation of the RMS phase current and in the characterization of the triplen harmonic content of the nonlinear electronic load.

These values represent the harmonic spectrum of nonlinear electronic loads falling within the categories addressed by the harmonic emission standard IEC 61000-3-2 [Ab4], with the harmonic orders defined in accordance with the standard terminology [Ab5].

Harmonic order	Magnitude (%)	Current (A)
1	100.0	58.50
3	65.7	38.43
5	37.7	22.05
7	12.7	7.43
9	4.4	2.57
11	5.3	3.10
13	2.5	1.46
15	1.9	1.11

17	1.8	1.05
19	1.1	0.64
21	0.6	0.35
23	0.8	0.47
25	0.4	0.23
27	0.2	0.12
29	0.2	0.12
31	0.2	0.12
33	0.2	0.12

[Ab6] Calculated from the published harmonic spectrum using the equation presented in Section A.12.

14. Calculation of the RMS Phase Current

After determining the current of each harmonic component, the RMS phase current was calculated as the square root of the sum of the squares of all current components reported in the published harmonic spectrum, according to the following equation [Ab5]

$$I_phase, RMS = \sqrt{(I_1{}^2 + I_3{}^2 + I_5{}^2 + I_7{}^2 + I_9{}^2 + I_{11}{}^2 + I_{13}{}^2 + I_{15}{}^2 + I_{17}{}^2 + I_{19}{}^2 + I_{21}{}^2 + I_{23}{}^2 + I_{25}{}^2 + I_{27}{}^2 + I_{29}{}^2 + I_{31}{}^2 + I_{33}{}^2)}$$

Using the current values listed in Table A.6 gives:

$$I_phase, RMS = \sqrt{(58.50^2 + 38.43^2 + 22.05^2 + 7.43^2 + 2.57^2 + 3.10^2 + 1.46^2 + 1.11^2 + 1.05^2 + 0.64^2 + 0.35^2 + 0.47^2 + 0.23^2 + 0.12^2 + 0.12^2 + 0.12^2 + 0.12^2)}$$

$$I_phase, RMS = 73.91A$$

The complete published harmonic spectrum was used in the calculation to obtain the RMS phase current from all harmonic components reported in the reference [Ab6].

15. Derivation of the Triplen Harmonic Factor

The Triplen Harmonic Factor (K_H)adopted in the present study is derived from the measured neutral conductor current component resulting from triplen harmonics reported at the Tee-off Point in the selected reference [Ab1].

The reported triplen harmonic component of the neutral conductor current was 54.80 A. The average phase current was determined from the three reported phase-current values as:

$$I_avg = (I_A + I_B + I_C)/3$$

Using the reported phase-current values:

$$I_avg = (62.32 + 9.92 + 31.16)/3 = 34.47A$$

The Triplen Harmonic Factor was then determined in accordance with the definition adopted in the present study:

$$K_H = I_N, H/I_avg$$

Substituting the reported triplen harmonic neutral-current component and the calculated average phase current gives:

$$K_H = 54.80/34.47 = 1.590$$

Accordingly, the Triplen Harmonic Factor adopted in the present study is:

$$K_H = 1.590$$

The published harmonic spectrum presented in the subsequent sections is used to characterize the harmonic content of the nonlinear electronic load and to document the harmonic characteristics supporting the adopted model parameter.
The value of K_H used in the proposed mathematical model remains the value derived from the measured data reported in the selected reference [Ab1].

16. Calculation of the RMS Phase Current from the Published Harmonic Spectrum

Based on the harmonic current components calculated in Table A.6, the RMS phase current was determined using the root-sum-square (RSS) of all published harmonic current components.

The complete harmonic spectrum from the 1st to the 33rd order was included in the calculation. Using the values presented in Table A.6, the resulting RMS phase current is:

$$I_phase, RMS = 73.91A$$

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The harmonic spectrum was also used to characterize the triplen harmonic content of the nonlinear electronic load. The triplen harmonic orders considered in the present study are the 3rd, 9th, 15th, 21st, 27th, and 33rd harmonic orders.

The Triplen Harmonic Factor adopted in the proposed mathematical model, however, is based on the measured triplen harmonic neutral-current component reported in the selected reference, as established in Section A.15. Accordingly:

$$K_H = 54.80/34.47 = 1.590$$

Thus, the RMS phase current derived from the published harmonic spectrum is used to characterize the harmonic load and to support the subsequent analysis, whereas the value of the Triplen Harmonic Factor adopted in the proposed mathematical model remains:

$$K_H = 1.590$$

Quantity	**Value**
Fundamental current	58.50 A
Phase RMS current from the published harmonic spectrum	73.91 A
Measured neutral current component resulting from load imbalance	20.75 A
Measured neutral current component resulting from triplen harmonics	54.80 A
Average phase current	34.47 A
Load Imbalance Factor *($K_{LI} \equiv K_U$)*	0.602
Triplen Harmonic Factor (K_H)	1.590

Table 7: Derived Quantities for the Electronic Load Harmonic Spectrum

Accordingly, the Triplen Harmonic Factor is calculated from the measured triplen harmonic neutral-current component and the average phase current:

$$K_H = I_N, H/I_a vg$$

$$K_H = 54.80/34.47 = 1.590$$

The results indicate that the Triplen Harmonic Factor (K_H) is equal to 1.590, representing a relatively high value that reflects the significant contribution of triplen harmonics to the neutral conductor current in electronic loads characterized by nonlinear current waveforms.

This finding is consistent with the harmonic characteristics reported for electronic loads supplied by Switch-Mode Power Supplies (SMPS), for which the third harmonic constitutes a significant component of the harmonic current spectrum [Ab4], [Ab6].

Because triplen harmonics are zero-sequence harmonics, their components are in phase and therefore accumulate in the neutral conductor. Consequently, the neutral conductor current resulting from triplen harmonics can become comparable to, or exceed, the phase current under conditions of significant nonlinear loading [Ab5], [Ab6].

In the present study, the Triplen Harmonic Factor (K_H) was derived from the measured triplen harmonic neutral-current component and the average phase current obtained from the reported phase-current measurements. The resulting value of K_H=1.590 therefore reflects the adopted definition of the factor and the measured operating conditions reported in the selected reference.

The complete published harmonic spectrum was also analyzed separately to determine the RMS phase current and to characterize the harmonic content of the electronic load. However, the published spectrum was not used as a replacement for the measured triplen harmonic neutral-current component in the final derivation of K_H.

Accordingly, the resulting value of K_H=1.590 represents the parameter adopted in the present study for the proposed mathematical model and is consistent with the calculation procedure and the measured data reported in the selected reference.

17. Adoption of the Triplen Harmonic Factor in the Proposed Mathematical Model

Based on the foregoing derivation, the Triplen Harmonic Factor (K_H) adopted in the present study is
K_H=1.590.
This value was derived from the measured triplen harmonic neutral-current component and the average phase current

obtained from the reported phase-current measurements in the selected reference [Ab1].

The published harmonic spectrum of the electronic load [Ab6] was used separately to determine the RMS phase current and to characterize the harmonic content of the load, as described in the preceding sections. It was not used as the basis for replacing the measured triplen harmonic neutral-current component in the final derivation of K_H.

Accordingly, the adopted value of K_His used together with the Load Imbalance Factor (K_U) to calculate the Neutral Conductor Upsizing Factor (K_N)in accordance with the relationship adopted in the present study:

$$K_N = \sqrt{(K_U{}^2 + K_H{}^2)}$$

Using:

$$K_U = 0.602$$

$$K_H = 1.590$$

Therefore:

$$K_N = \sqrt{(0.602^2 + 1.590^2)}$$

$$K_N = 1.700$$

For the preliminary design stage, the relationship between the required neutral conductor ampacity and its cross-sectional area is treated as an approximate design relationship within the proposed mathematical model. Accordingly, the resulting neutral conductor cross-sectional area represents a preliminary design value and does not replace the final ampacity verification for the selected conductor under the actual installation conditions and applicable cable-rating requirements.

The required neutral conductor cross-sectional area is then expressed as:

$$S_N, req = K_N S_P$$

Accordingly:

$$S_N, req = 1.700 S_P$$

This derivation is subsequently used in the office building application presented in Chapter 5, whereas the complete derivation procedure and the intermediate calculations are documented in the present appendix.

18. Notes on the Scope and Limitations of the Derivation

The derivation presented in this appendix combines field measurement data reported in the selected reference with the published harmonic spectrum of electronic loads reported in the referenced study.
Accordingly, the derived parameters represent the electrical characteristics and harmonic behavior reflected by these source data and should be interpreted within the measurement and operating conditions associated with the respective references.

The Triplen Harmonic Factor (K_H)adopted in the present study is based on the measured neutral-current component resulting from triplen harmonics and the average phase current obtained from the reported phase-current measurements. The published harmonic spectrum is used separately to determine the RMS phase current and to characterize the harmonic content of the nonlinear electronic load.

The published harmonic spectrum includes the triplen harmonic orders (3, 9, 15, 21, 27, and 33), which are analyzed to characterize the triplen harmonic content of the nonlinear electronic load. However, the triplen harmonic neutral-current component used in the final derivation of the Triplen Harmonic Factor is the measured value reported at the Tee-off Point. The effects of non-triplen harmonics are included in the calculation of the RMS phase current, while load imbalance is represented independently by the Load Imbalance Factor (K_U).

The effects of non-triplen harmonics are therefore not included in the triplen harmonic neutral-current component, although they are included in the calculation of the RMS phase current. Load imbalance is represented independently by the Load Imbalance Factor (K_U).

19. Appendix Summary

This appendix documents the complete derivation procedure of the proposed mathematical model parameters based on the field measurement data and the published harmonic spectrum reported in the referenced literature. The derivation begins with the extraction of the required reference data, followed by the calculation of the Load Imbalance Factor ((K_U)) and the Triplen Harmonic Factor ((K_H)), and concludes with the derivation of the Neutral Conductor Upsizing Factor ((K_N)). All derivation steps and mathematical calculations are presented in this appendix to ensure the reproducibility and verifiability of the results, whereas Chapter 5 presents only the final parameter values and the application of the proposed model to the selected design scenarios.

Notes

All derivations, equations, and tables presented in this appendix are based on the field measurement data and the published harmonic spectrum reported in the referenced studies on which this dissertation is based [1,6]. All mathematical derivations and calculations presented herein were performed within the framework of the methodology proposed in the present study

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