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Measurement and Assessment of Reactive, Unbalanced and Harmonic Line Losses

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Abstract: This study investigates the feasibility of utilizing the line loss power factor to assess the reactive, unbalanced, and harmonic line losses in low-voltage distribution networks and explores the method of calculating decoupled line loss values based on this factor. To achieve this objective, we establish preliminary definitions of single-phase and three-phase reactive, unbalanced, and harmonic line loss power factors, drawing upon the principles of electrical theory outlined in IEEE Standard 1459. These power factors serve as crucial indicators for evaluating the severity of line losses caused by reactive power, unbalance, and harmonic problems. Subsequently, the values of line loss attributed to reactive, unbalanced, and harmonic components are decoupled and quantified using the line loss power factor as a fundamental parameter. The effectiveness and accuracy of the proposed method were verified in Matlab simulation and physical experiments.

Keywords: harmonic; line loss; three-phase imbalance; IEEE Std. 1459-2010; power factor; power quality; power measurement

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1. Introduction

The proliferation of non-linear power loads in power systems has been observed alongside the expanding scale of power consumption, necessitating the resolution of corresponding power quality issues [1–3]. Notably, China's low-voltage distribution network incurs a significant proportion amounting to 60% of the total power supply and distribution network loss, as evidenced by relevant statistical data [4]. This directly impacts the economic benefits of power grid enterprises [5,6]. There are many causes of power quality problems, such as voltage fluctuations, flicker, transient overvoltage, reactive power, harmonics, three-phase imbalance, etc., of which reactive power, harmonics, and three-phase imbalance have a very obvious impact on the grid line loss. They are the key factors leading to a significant increase in line loss [7]. When there is a slight power quality loss in the line, the cost of governing the line may not be justified. To maximize the input–output ratio, reactive, unbalanced, and harmonic line loss assessment indicators can be used as criteria for deciding whether governance is necessary or not. Consequently, achieving precise computation and assessment of line loss components assumes paramount significance in promoting improvements in electric energy conservation and loss reduction endeavors.

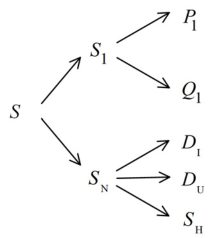
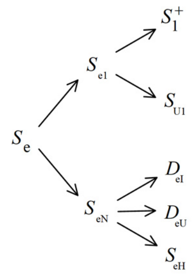
The line loss study of distribution networks can be categorized into two main areas: (1) Theoretical line loss calculation research. This line loss research primarily employs accurate modeling to simulate line operations and calculate line loss. The quantitative investigation of theoretical line loss involves the precise determination of line resistance values. For example, in reference [8], the calculation of a power distribution network under harmonic influence was studied, where transmission line AC coefficients and transformer harmonic loss were introduced to construct line models. Reference [9] examined a line harmonic loss model considering the skin effect. This model provides more accurate calculations of harmonic loss compared to traditional models. Reference [10] proposed a theoretical line loss computation approach via matrix completion and a ReliefF-convolutional neural network (CNN) for LVDN. Reference [11] proposed a continuous line loss calculation method for the distribution network with higher calculation accuracy. Reference [12] proposed an optimized distributed generation allocation method aimed at minimizing total losses in distribution systems, while reference [13] introduced a novel approach to calculate line loss under three-phase imbalance conditions. However, these studies only address single power quality issues and cannot be applied to composite power quality problems. Considering the effects of composite power quality, reference [14] proposed a composite power quality loss model for a 10 kV distribution grid, considering harmonics, unbalanced three-phase currents, and voltage deviations. The FLUKE 435 Power Quality and Energy Analyzer can separate line currents, input line resistance, and subsequently calculate individual component line loss. Nevertheless, accurately determining harmonic resistance values is challenging due to the skin effect and proximity under harmonic conditions, which can cause significant deviations in line loss calculations using the decoupled line loss calculation method of the FLUKE 435 Power Quality and Energy Analyzer, lacking practical application guidance. Meanwhile, in the actual working conditions of the low-voltage distribution network, measuring the line length accurately is usually challenging. As a result, the calculated line impedance based on the line length may have a certain degree of error.

(2) Statistical line loss calculation research. Statistical line loss research obtains relevant data by subtracting electricity sales data from electricity input data. Statistical line loss calculations avoid the need to determine equivalent line resistances. However, the decoupling of bus losses cannot be accomplished utilizing the conventional technique of utilizing the meter data from the primary end of the transformer outlet line meter minus the meter data from the client side of the meter at the conclusion of all branches, via the conventional power theory. Additionally, most research on statistical line loss calculations is qualitative, with limited quantitative studies on the impact of composite power energy quality. Reference [15] examined the differences between theoretical line loss and statistical line loss and analyzed the causes of these discrepancies. Reference [16] investigated the sources of error that affect the accuracy of statistical line loss data. In addition to this, references [17–19] conducted corresponding studies considering the main factors affecting line losses and methods to reduce them. In summary, it is vital to consider quantitative line loss calculations for composite power quality in low-voltage distribution networks.

Accurate measurement, calculation, and assessment of line loss are essential for making informed decisions regarding line management and loss reduction measures. This study is based on the aforementioned research foundation and proposes a methodology for deriving power quality line loss values without the need to solve for equivalent resistances. The paper begins by defining four types of power quality line loss power factors, based on the power theory outlined in IEEE Std. 1459 [20–23]. The IEEE Std. 1459 is underpinned by Emanuel power theory [20] and encompasses both sinusoidal and non-sinusoidal situations, as well as balanced and unbalanced states. Notably, this power theory introduces the concept of "equivalent", wherein a fully compensating system is employed to replace the actual line and load. This equivalent system exhibits a perfectly sinusoidal positive sequence current, with the neutral line current being zero. The power loss in this hypothetical system matches the actual power loss that generates the same thermal stress. This concept provides a theoretical foundation for conducting line loss research based on IEEE Std. 1459. The IEEE Working Group is in the process of improving the IEEE 1459 standard considering the physical meaning of the measurement theory and reactive power definitions [24,25], but this does not affect the application of the IEEE 1459 standard in line loss calculations and line loss analyses, due to the fact that the line loss itself is caused by the current flowing through the line.

The power decomposition for both single-phase and three-phase systems is depicted in Table 1. The four power quality line loss power factors based on the power decomposition are defined in Table 1.

Table 1. IEEE Std. 1459 effective resolution [23].

	Power Decomposition	Power Quantities	Combined	Fundamental	Nonfundamental
Single-Phase		Apparent (VA)	$S = UI$	$S_1 = U_1 I_1$	$S_N = \sqrt{S^2 - S_1^2}$ $S_H = U_H I_H$
		Active (W)	$P = \frac{1}{kT} \cdot \int_{\tau}^{\tau+kT} uidt$	$P_1 = U_1 I_1 \cos\varphi_1$	$P_H = P - P_1$
		Nonactive (VAR)	$N = \sqrt{S^2 - P^2}$	$Q_1 = U_1 I_1 \sin\varphi_1$	$D_I = U_1 I_H$ $D_U = U_H I_1$
Three-Phase		Apparent (VA)	$S_e = 3U_e I_e$	$S_{e1} = 3U_{e1} I_{e1}$ $S_1^+ = 3U_1^+ I_1^+$ $S_{U1} = \sqrt{S_{e1}^2 - (S_1^+)^2}$	$S_{eN} = \sqrt{S_e^2 - S_{e1}^2}$ $S_{eH} = 3U_{eH} I_{eH}$
		Active (W)	$P = \sum_{a,b,c} \frac{1}{kT} \cdot \int_{\tau}^{\tau+kT} uidt$	$P_1^+ = 3U_1^+ I_1^+ \cos\varphi_1^+$	$P_H = P - P_1$
		Nonactive (VAR)	$N = \sqrt{S_e^2 - P^2}$	$Q_1^+ = 3U_1^+ I_1^+ \sin\varphi_1^+$	$D_{eI} = 3U_{e1} I_{eH}$ $D_{eU} = U_{eH} I_{e1}$

U_h and I_h are the rms value of the harmonic components of single-phase voltage and current, φ_1 is their displacement. U_e, U_{e1}, U_{eh}, are the value of three-phase effective voltages; I_e, I_{e1}, I_{eh}, are the value of three-phase effective currents.

These power factors serve as evaluative metrics for assessing line loss in single-phase and three-phase systems under composite power quality problems. Furthermore, utilizing these power factors, this study deduces the line loss caused by reactive power problems, harmonic problems, and imbalance problems. It also calculates the ratio of the fundamental active line loss to the decoupled line loss values. To validate the proposed methodology, we conduct simulations using the Matlab/Simulink tool and perform physical experiments. An error analysis of the experimental results confirms the feasibility and accuracy of the theoretical derivation presented in this study, underscoring its potential as a practical guide for real-world applications.

2. Line Loss Power Factor Presentation

Line loss ΔP_{Loss} refers to the power loss that occurs during the transmission of electric energy from the power source to the load through the transmission lines. When the power factor PF is equal to 1, the line loss is minimized. The minimum line loss $\Delta P_{\text{Loss-min}}$ is obtained when $PF = 1$. $\Delta P_{\text{Loss-min}}$ can be calculated using (2) by fully compensating for the non-active current, ensuring that the load current consists solely of an active current and the line transmits only active power. In (1) and (2), R is the line resistance, and U is the voltage at the first end of the line.

$$\Delta P_{\text{Loss}} = \frac{S^2}{U^2} R \tag{1}$$

$$\Delta P_{\text{Loss-min}} = \frac{P^2}{U^2} R \tag{2}$$

Based on the aforementioned analysis, the power factor *PF* can be calculated as depicted in (3) and (4).

$$\frac{\Delta P_{\text{Loss-min}}}{\Delta P_{\text{Loss}}} = \frac{P^2}{S^2} = PF^2 \tag{3}$$

$$PF = \sqrt{\frac{\Delta P_{\text{Loss-min}}}{\Delta P_{\text{Loss}}}} \tag{4}$$

Equation (4) provides the definition of power factor *PF* in terms of line loss, and, likewise, *PF* can be employed to evaluate line loss resulting from non-active power. The subsequent section elucidates the line loss power factor in the context of both single-phase and three-phase systems.

A. Single-Phase Case

The model of transmission lines in power systems can be categorized into two types based on the length of the line: lumped-parameter equivalent model and distributed-parameter equivalent model. Low-voltage distribution lines, which are considered short lines, typically utilize lumped-parameter π-type equivalent circuit models, as illustrated in Figure 1.

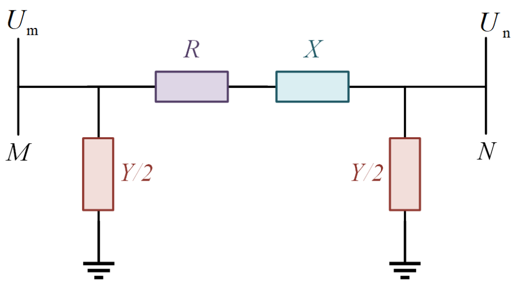


Figure 1. π-type equivalent circuit of low-voltage distribution line.

Figure 1 depicts *R* as the equivalent resistance of the low-voltage distribution line, and *X* is the equivalent reactance.

The line loss in short lines can be approximately equal to the resistive power; hence, reactance and shunt admittance are disregarded in the analysis of line loss [9]. Figure 2 shows a schematic diagram for loss analysis in the single-phase low-voltage state [26]. In the figure, *R* represents the line resistance of the circuit in the low-voltage distribution network, while *I* denotes the current flowing through the line, and the voltage across the load is represented by *U*.

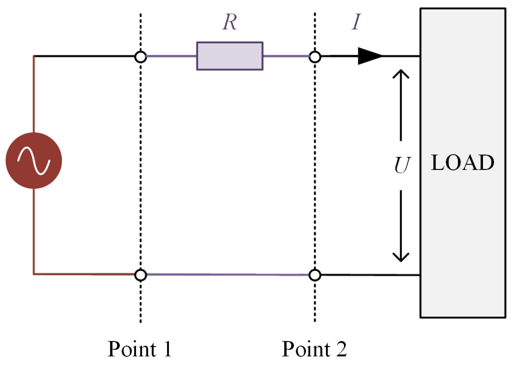


Figure 2. Schematic diagram for loss analysis in single-phase low-voltage distribution network.

When a non-linear load is connected to the system, the current flowing through the single-phase non-sinusoidal system induces a line loss in the line resistance. To analyze this, voltage, current, and phase angle data are collected at Point 2. The original single-phase system is then transformed equivalently, and the load is measured by decomposing the apparent power S. The line loss can be expressed using (5).

$$\begin{aligned} \Delta P_{\text{Loss}} &= I^2 R = \frac{S^2}{U^2} R \\ &= \frac{\left(P_1^2 + Q_1^2 + D_I^2 + D_U^2 + S_H^2\right)}{U^2} R \\ &\approx \frac{\left(P_1^2 + Q_1^2 + D_I^2\right)}{U^2} R \\ &= \Delta P_{\text{P-min}} + \Delta P_{\text{Q}} + \Delta P_{\text{H}} \end{aligned} \quad (5)$$

In (5), the apparent power S is considered using IEEE Std. 1459, and the decomposition process is shown in Table 1. From (5), it is evident that all components of the apparent power S contribute to line loss. However, given the minimal voltage distortion in the line, the impact of voltage distortion power D_u and harmonic apparent power S_H in line loss can be disregarded. The total line loss ΔP_{Loss} can be decomposed based on power quality problems into the following components, fundamental active line loss $\Delta P_{\text{P-min}}$, reactive additional line loss ΔP_{Q}, and harmonic additional line loss ΔP_{H}. It should be noted that only the fundamental active line loss $\Delta P_{\text{P-min}}$ is attributed to the line itself, while the remaining components represent additional loss resulting from power quality factors.

To evaluate the quality of line loss and quantify the reactive additional line loss caused by reactive power and the harmonic additional line loss resulting from current distortion power, three power factors are defined for a single-phase system. These power factors, namely the active line loss power factor PF_{P}, the reactive line loss power factor PF_{Q}, and the harmonic line loss power factor PF_{H}, are analogous to the single-phase fundamental power factor PF_1. The definitions of power factor for the power quality of a single-phase system are presented below. In the following equations, S_{Loss} denotes the total line loss apparent power, S_1 denotes the fundamental apparent power, and S_{PH} denotes the harmonic line loss apparent power.

$$\begin{cases} PF_{\text{P}} = \dfrac{P_1}{\sqrt{P_1^2 + Q_1^2 + D_I^2}} = \dfrac{P_1}{S_{\text{Loss}}} \\ PF_{\text{Q}} = \dfrac{P_1}{\sqrt{P_1^2 + Q_1^2}} = \dfrac{P_1}{S_1} \\ PF_{\text{H}} = \dfrac{P_1}{\sqrt{P_1^2 + D_I^2}} = \dfrac{P_1}{S_{\text{PH}}} \end{cases} \quad (6)$$

The active line loss power factor PF_{P} is employed to evaluate the quality of line loss by quantifying the contribution of fundamental active power P_1 to the total line loss. Its value ranges between 0 and 1, reflecting the proportion of line loss attributed to the fundamental active power. A PF_{P} value of 1 signifies the absence of additional line loss in the system due to power quality factors.

The reactive line loss power factor PF_{Q} is utilized to assess the contribution of reactive power to the reactive additive line loss, ranging between 0 and 1. As the reactive additive line loss increases, the PF_{Q} value decreases. A PF_{Q} value of 1 indicates the absence of additional reactive line loss in the system.

The harmonic line loss power factor PF_{H} is employed to assess the impact of a distorted current on the harmonic additive line loss. Its value ranges between 0 and 1 and decreases as the harmonic additive line loss increases. A PF_{H} value of 1 indicates the absence of harmonic additional line loss in the system.

The power cubes of the active line loss power factor PF_{P}, reactive line loss power factor PF_{Q}, and harmonic line loss power factor PF_{H} are presented in Figure 3. It represents the relationship between the decomposed individual powers on the vector.

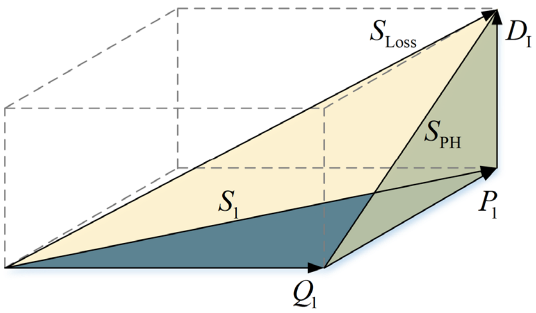


Figure 3. Schematic diagram of a single-phase power cube.

B. *Three-Phase Case*

The line loss analysis of the three-phase system of the low-voltage distribution network is carried out for the three-phase four-wire system, for example, according to Figure 4 for the three-phase four-wire system. Four lines of the same model are used in the analysis, ignoring the differences in the parameters of these four lines [9].

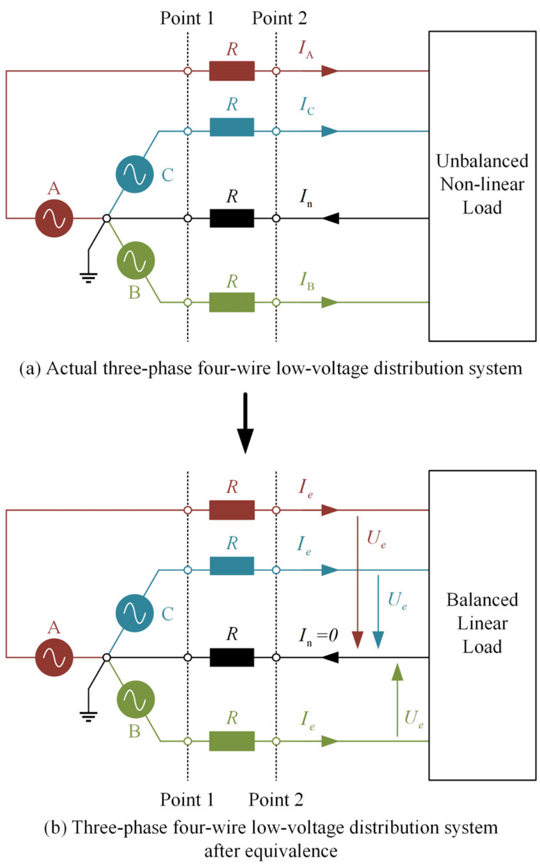


Figure 4. The actual and equivalent three-phase four-wire low-voltage distribution network line loss analysis diagrams.

In Figure 4, R is the line resistance. When a non-linear load is connected to the system, the three-phase currents I_A, I_B, $I_{C,}$ and neutral current In produce line loss in the line resistance R. The three-phase voltage, current, and phase angle information at measurement Point 2 is collected, and the original three-phase system is equivalently transformed to decompose the load measurement equivalent apparent power S_e [24,25]. The equivalent system has the same line power losses as the actual distribution system, and Figure 4 shows a schematic diagram of the three-phase, four-wire low-voltage distribution system after introducing the equivalence.

The total line loss $\Delta P_{\mathrm{eLoss}}$ can be represented by (7).

$$\begin{aligned}\Delta P_{\mathrm{eLoss}} &= \left(I_{\mathrm{A}}^2+I_{\mathrm{B}}^2+I_{\mathrm{C}}^2+I_{\mathrm{N}}^2\right)R = 3I_{\mathrm{e}}^2R = \frac{S_{\mathrm{e}}^2}{3U_{\mathrm{e}}^2}R \\ &= \frac{\left(\left(P_1^+\right)^2+\left(Q_1^+\right)^2+S_{\mathrm{U1}}^2+D_{\mathrm{eI}}^2+D_{\mathrm{eU}}^2+S_{\mathrm{eH}}^2\right)}{3U_{\mathrm{e}}^2}R \\ &\approx \frac{\left(\left(P_1^+\right)^2+\left(Q_1^+\right)^2+S_{\mathrm{U1}}^2+D_{\mathrm{eI}}^2\right)}{3U_{\mathrm{e}}^2}R \\ &= \Delta P_{\mathrm{eP\text{-}min}}+\Delta P_{\mathrm{eQ}}+\Delta P_{\mathrm{eU}}+\Delta P_{\mathrm{eH}}\end{aligned} \tag{7}$$

In (7), the load measurement equivalent apparent power S_{e} is performed using IEEE Std. 1459, and the decomposition process is shown in Table 1. As observed from (7), each component of the equivalent apparent power S_{e} contributes to line loss. These line losses can be further decomposed into the following components based on power quality issues, fundamental positive sequence active line loss $\Delta P_{\mathrm{eP\text{-}min}}$, fundamental positive sequence reactive additional line loss ΔP_{eQ}, unbalanced additional line loss ΔP_{eU}, and harmonic additional line loss ΔP_{eH}.

By drawing an analogy to the three-phase fundamental positive sequence power factor $PF_1{}^+$, the following power factors are defined for the three-phase system, the fundamental positive sequence active line loss power factor PF_{eP}, the reactive line loss power factor PF_{eQ}, the unbalanced line loss power factor PF_{eU}, and the harmonic line loss power factor PF_{eH}. The maximum value of these line loss power factors is 1. These factors for power line loss enable the assessment of line loss due to power quality issues in three-phase systems. In the following formulas, S_{eLoss} denotes the total line loss apparent power, $S_1{}^+$ denotes the fundamental positive sequence apparent power, S_{ePU} denotes the unbalanced line loss apparent power, and S_{ePH} denotes the harmonic line loss apparent power.

$$\begin{cases} PF_{\mathrm{eP}} = \dfrac{P_1^+}{\sqrt{\left(P_1^+\right)^2+\left(Q_1^+\right)^2+S_{\mathrm{U1}}^2+D_{\mathrm{eI}}^2}} = \dfrac{P_1^+}{S_{\mathrm{eLoss}}} \\ PF_{\mathrm{eQ}} = \dfrac{P_1^+}{\sqrt{\left(P_1^+\right)^2+\left(Q_1^+\right)^2}} = \dfrac{P_1^+}{S_1^+} \\ PF_{\mathrm{eU}} = \dfrac{P_1^+}{\sqrt{\left(P_1^+\right)^2+S_{\mathrm{U1}}^2}} = \dfrac{P_1^+}{S_{\mathrm{ePU}}} \\ PF_{\mathrm{eH}} = \dfrac{P_1^+}{\sqrt{\left(P_1^+\right)^2+D_{\mathrm{eI}}^2}} = \dfrac{P_1^+}{S_{\mathrm{ePH}}} \end{cases} \tag{8}$$

The line loss power factors for a three-phase system serve as valuable metrics to evaluate the line loss. The values of the fundamental positive sequence active line loss power factor PF_{eP}, the reactive line loss power factor PF_{eQ}, the unbalanced line loss power factor PF_{eU}, and the harmonic line loss power factor PF_{eH} range between 0 and 1, diminishing as power-quality-related additional line losses increase. When there are no power quality-related additional line losses in the system, the values of all four line loss power factors are equal to 1.

3. Line Loss Ratio and Decoupling Presentation

The line loss power factor is a critical tool for evaluating the influence of power quality issues on line loss. Furthermore, it allows for the calculation of the ratio between power quality line loss and fundamental active line loss, aiding in the assessment of whether reactive power problems, harmonic problems, and imbalance problems need to be addressed. Additionally, it enables the decoupling of the values of different components of power quality line loss without the requirement to measure line loss resistance values.

A. Single-Phase Case

In a single-phase system, the formulas for calculating the ratio between power quality line loss and fundamental active line loss are presented below.

$$\begin{cases} \frac{\Delta P_{Q}}{\Delta P_{\text{P-min}}} = \frac{Q_1^2}{P_1^2} = \frac{1}{(PF_Q)^2} - 1 \\ \frac{\Delta P_{H}}{\Delta P_{\text{P-min}}} = \frac{D_I^2}{P_1^2} = \frac{1}{(PF_H)^2} - 1 \end{cases} \quad (9)$$

This is because the fundamental active line loss represents the loss caused by the line itself. The power quality line loss ratio values can be utilized to assess whether the corresponding power quality problems need to be addressed.

Furthermore, the contribution of each line loss component can be separately determined using the single-phase line loss power factor and the difference in line losses ΔP_{Loss} measured at Point 1 and Point 2 in the single-phase system diagram depicted in Figure 1. This decoupling process does not necessitate solving for line resistance values. The values for each decoupled line loss component can be calculated as follows.

$$\begin{cases} \Delta P_{\text{P-min}} = \Delta P_{\text{Loss}} \cdot (PF_P)^2 \\ \Delta P_Q = \Delta P_{\text{Loss}} \cdot (PF_P)^2 \cdot \left[(PF_Q)^{-2} - 1\right] \\ \Delta P_H = \Delta P_{\text{Loss}} \cdot (PF_P)^2 \cdot \left[(PF_H)^{-2} - 1\right] \end{cases} \quad (10)$$

By leveraging the active line loss power factor PF_P, reactive line loss power factor PF_Q, and harmonic line loss power factor PF_H of a single-phase system, it is possible to decouple and analyze the total line loss. This approach allows for a comprehensive evaluation of the line loss associated with single-phase energy quality.

Line losses can also be calculated using the equivalent resistance method, i.e., as shown in (11), which is a commonly used method for calculating line losses.

$$\Delta P_{\text{Loss}} = I^2 R \quad (11)$$

The equivalent resistance method uses current and line resistance to make line loss measurements. Unfortunately, resistance measurement is a very difficult problem when there is a harmonic influence, and research has been slow to progress, which leads to large measurement errors in the resistance data when calculating line losses using the equivalent current method, which can affect the accuracy of the results [25]. In contrast, the use of the power quality line loss power factor to calculate line loss power is able to circumvent the measurement of resistance due to the influence of harmonics and, at the same time, convert small values of current and resistance measurements into large values of power measurements on the customer side, improving the accuracy of line loss calculations.

B. Three-Phase Case

The calculation of the power quality line loss ratio and line loss decoupling for a three-phase system is analogous to that for a single-phase system, as demonstrated in the following equations. The line loss ΔP_{eLoss} represents the discrepancy between active power measurements at Point 1 and Point 2 in Figure 4.

$$\begin{cases} \frac{\Delta P_{eQ}}{\Delta P_{\text{eP-min}}} = \frac{(Q_1^+)^2}{(P_1^+)^2} = (PF_{eQ})^{-2} - 1 \\ \frac{\Delta P_{eU}}{\Delta P_{\text{eP-min}}} = \frac{S_{U1}^2}{(P_1^+)^2} = (PF_{eU})^{-2} - 1 \\ \frac{\Delta P_{eH}}{\Delta P_{\text{eP-min}}} = \frac{D_{eI}^2}{(P_1^+)^2} = (PF_{eH})^{-2} - 1 \end{cases} \quad (12)$$

$$\begin{cases} \Delta P_{\text{eP-min}} = \Delta P_{\text{eLoss}} \cdot (PF_{\text{eP}})^2 \\ \Delta P_{\text{eQ}} = \Delta P_{\text{eLoss}} \cdot (PF_{\text{eP}})^2 \cdot \left[(PF_{\text{eQ}})^{-2} - 1\right] \\ \Delta P_{\text{eU}} = \Delta P_{\text{eLoss}} \cdot (PF_{\text{eU}})^2 \cdot \left[(PF_{\text{eU}})^{-2} - 1\right] \\ \Delta P_{\text{eH}} = \Delta P_{\text{eLoss}} \cdot (PF_{\text{eP}})^2 \cdot \left[(PF_{\text{eH}})^{-2} - 1\right] \end{cases} \quad (13)$$

The decoupling of total line loss and the evaluation of three-phase power quality line loss are achieved through the utilization of base-wave positive sequence power factors, namely PF_{eP} for active line loss, PF_{eQ} for reactive line loss, PF_{eU} for unbalanced line loss, and PF_{eH} for harmonic line loss within the context of the three-phase system. This comprehensive approach allows for the disentanglement and accurate quantification of distinct components contributing to line loss, enabling a thorough analysis of power system performance and quality.

4. Indicator Characterization Simulation and Experimental Results

A. Single-Phase Case Simulation Results

The proposed method underwent validation using a simplistic test system, as illustrated in Figure 5, to address the single-phase non-sinusoidal scenario. Among them, Group 1 is a perfect single-phase sinusoidal simulation group with a power factor of 1.0. Groups 2–4 are single-phase sinusoidal simulation groups with reactive power, current harmonic content THD_I of 0%, and power factor gradually decreasing from 0.9 to 0.7 in steps of 0.1. Groups 5–7 are single-phase harmonic simulation groups with a power factor of 1.0, and current harmonic content THD_I gradually increases from 10% to 30% in steps of 10%. Groups 8–10 are single-phase harmonic simulation groups with compound power quality problems. Simulink was employed to manipulate the reactive and harmonic power at varying levels, facilitating the simulation of different degrees of reactive and harmonic problem load groups, thereby emulating diverse system operation states.

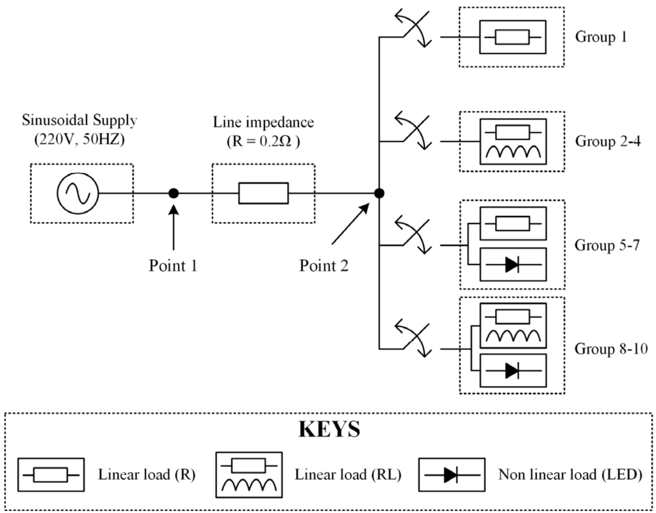


Figure 5. Single-phase test system.

The single-phase simulation system was configured with a rated frequency of 50 Hz for the single-phase AC supply, a voltage RMS of 220 V, and a phase angle of 0°. The line impedance Z was set to R = 0.2 Ω. The single-phase simulation model is shown in Figure 6.

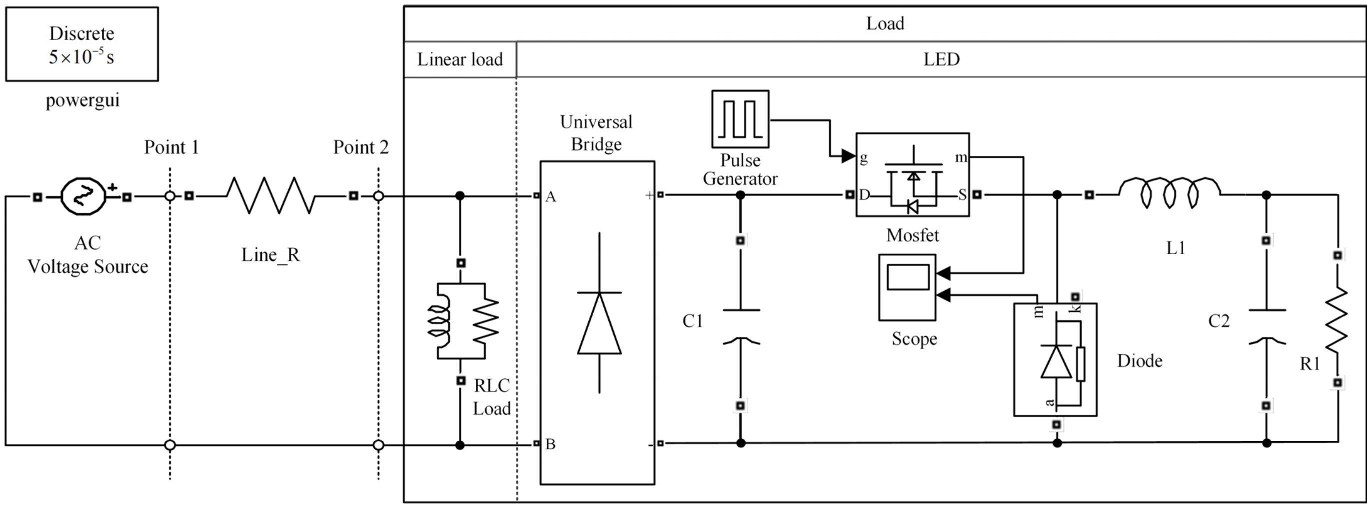


Figure 6. Single-phase simulation model.

The simulation model was created in the Simulink environment. The load used to simulate users consisted of linear load and LED. The load in Groups 1 to 4 only contains linear load, and the load in Groups 5 to 10 contains both linear load and LED, as shown in Figure 6. In the LED simulation model, capacitor C1 is set to 440×10^{-6} F, capacitor C2 is set to 200×10^{-5} F, and inductor L1 is set to 200×10^{-5} H. The settings of the Pulse Generator module, Mosfet module, and diode module are shown in Table 2. The varying degrees of power quality problems in the single-phase simulation model are realized by changing the value of R1 in the LED module and the RLC load. The load settings in Groups 1 to 10 are shown in Table 3.

Table 2. Simulation settings of LED.

Module	Pulse Generator		Mosfet		Diode	
Parameters	Pulse type	Time based	FET resistance Ron (Ohms)	0.1	Resistance Ron (Ohms)	0.001
	Time (t)	Use simulation time	Internal diode inductance Lon (H)	0	Inductance Lon (H)	0
	Amplitude	1	Internal diode resistance Rd (Ohms)	0.01	Forward voltage Vf (V)	0.8
	Period (s)	2×10^{-5}	Internal diode forward voltage Vf (V)	0	Initial current Ic (A)	0
	Pulse Width (% of period)	40	Snubber resistance Rs (Ohms)	1×10^{5}	Snubber resistance Rs (Ohms)	500
	Phase delay (s)	0	Snubber capacitance Cs (F)	inf	Snubber capacitance Cs (F)	250×10^{-9}

Initially, three line loss power factors, i.e., active line loss power factor PF_{P}, reactive line loss power factor PF_{Q}, and harmonic line loss power factor PF_{H}, are measured at Point 2 to evaluate the line loss of the single-phase simulated system and calculating the line loss percentage. The calculated results are also compared with the difference in power measured at the beginning and end of the line, i.e., the difference in power measured at Point 1 and Point 2.

Table 3. Simulation settings of load in Groups 1 to 10.

Group	Load Powers (Fundamental)		Load Settings		LED Settings (R1)
	W	var	Φ	ζ	Ω
1	5300	0	1.0	0%	×
2	4770	2310	0.9	0%	×
3	4240	3180	0.8		×
4	3710	3785	0.7		×
5	5300	0	1.0	10%	360
6	5300	0		20%	49
7	5300	0		30%	18.5
8	4767	2317	0.9	10%	360
9	4227	3197	0.8	20%	52
10	3648	3845	0.7	30%	17.5

Φ represents the power factor on the user side; $\zeta = THD_I = I_H/I_1$.

The simulation results of the single-phase system are shown in Table 4a,b and Figures 7 and 8. Error/% in Table 4b indicates the error between the simulated and calculated values.

Table 4. (**a**) Simulation results of line loss power factor; (**b**) Simulation results of the proportion of power quality line losses in single-phase system.

(**a**)

Group	PF_P	PF_Q	PF_H
1	1.000	1.000	1.000
2	0.900	0.900	1.000
3	0.800	0.800	
4	0.700	0.700	
5	0.995	1.000	0.995
6	0.981		0.981
7	0.958		0.958
8	0.895	0.900	0.994
9	0.785	0.800	0.970
10	0.670	0.700	0.919

(**b**)

$\Delta P_Q/\Delta P_{P\text{-min}}$		$\Delta P_H/\Delta P_{P\text{-min}}$	
Group	Error/%	Group	Error/%
2	0.01	5	0.04
3	0.02	6	1.26
4	0.01	7	0.03
8	0.01	8	2.55
9	0.01	9	0.83
10	0.02	10	0.16

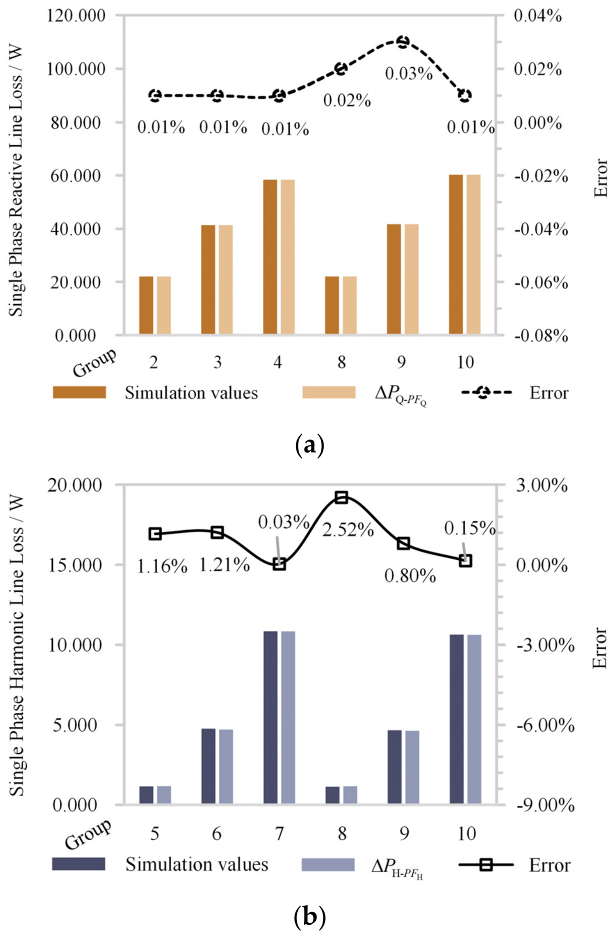


Figure 7. (**a**) Single-phase simulated reactive line loss comparison chart; (**b**) Single-phase simulated harmonic line loss comparison chart.

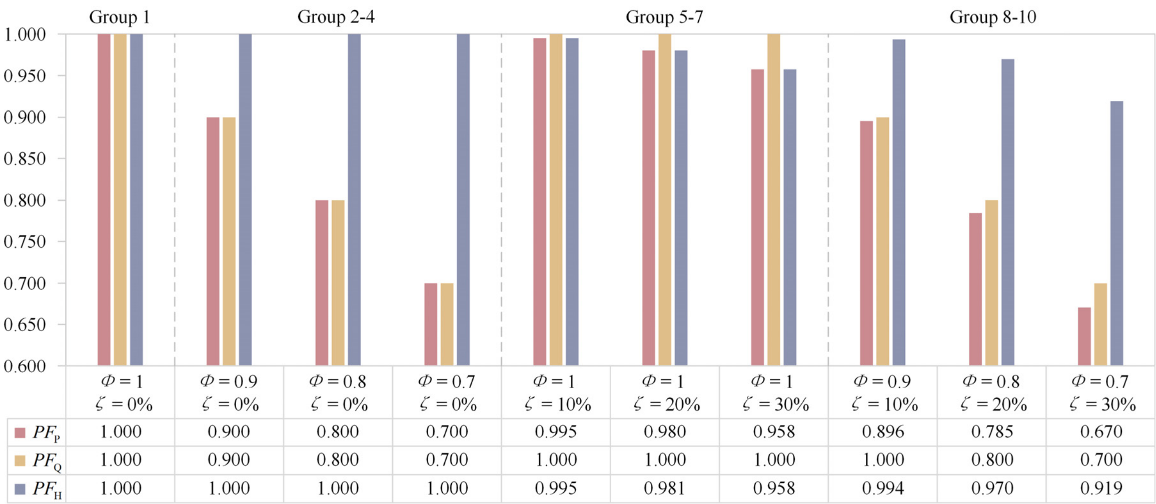


Figure 8. Single-phase simulated line loss power factor results.

As can be seen from Table 4a,b and Figure 7, the decoupled power quality line loss errors and line loss percentage errors obtained using the three types of line loss power factors are very small. The errors of the 10 sets of simulation results are below 3%, and the calculated results obtained are very close to the simulated measurement results, which indicates that the method of calculating the line loss using the line loss power factor on the customer side is feasible.

As can be seen from Figure 8, when the system has no reactive and harmonic problems, i.e., in a "perfect" single-phase system, the active line power factor PF_Q, the reactive line loss assessment index PF_Q, and the harmonic line loss assessment index PF_H are one; when the power factor Φ decreases and the current harmonic content ζ increases, the active line power factor PF_P, the reactive line loss assessment index PF_Q, and the harmonic line loss assessment index PF_H are reduced. In addition, the three line loss assessment indicators can clearly characterize the severity of the system's line loss caused by power quality problems, whether it is a single power quality problem or a compound power quality problem, which shows that it is feasible to use the three line loss power factors to assess the system's power quality line loss.

B. Three-Phase Case Simulation Results

The proposed method is validated using a simplistic three-phase test system, illustrated in Figure 9, to address a three-phase non-sinusoidal unbalanced scenario. There are 13 three-phase simulation groups, among which Group 1 is a perfect three-phase balanced sinusoidal simulation group with a power factor of 1.0. Groups 2–4 are three-phase balanced sinusoidal simulation groups with reactive power, and the power factor decreases gradually from 0.9 to 0.7 in steps of 0.1. Groups 5–7 are three-phase unbalanced sinusoidal simulation groups with a power factor of 1.0, and the degree of negative-sequence imbalance increases from 0.1 to 0.3 in steps of 0.1. Groups 8–10 are three-phase balanced harmonic simulation groups with a power factor of 1.0 and current harmonic content THD_{eI} in steps of 10% increases from 10% to 30%. Groups 11–13 are three-phase unbalanced harmonic simulation groups, containing reactive power and compound power quality problems.

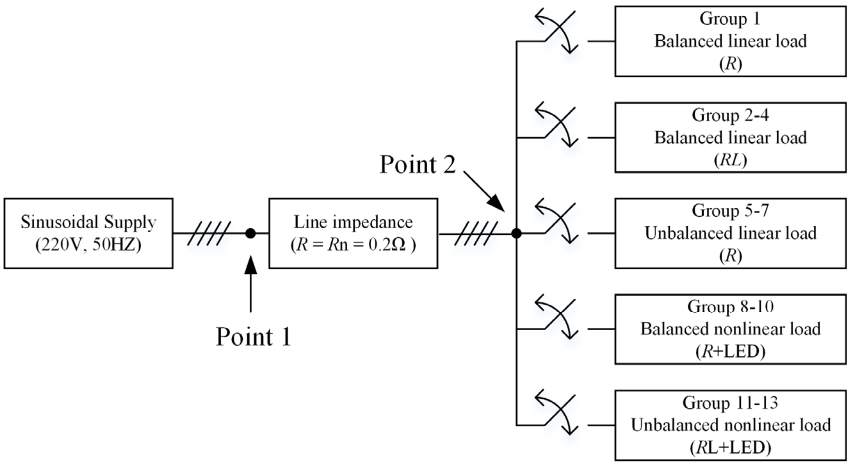


Figure 9. Three-phase test system.

The three-phase simulation system was configured with a rated frequency of 50 Hz for the three-phase AC supply and an RMS voltage value of 220 V. The line impedance was set to $R = R_n = 0.2\ \Omega$. The three-phase simulation model is shown in Figure 10. The load settings in Groups 1 to 10 are shown in Table 5.

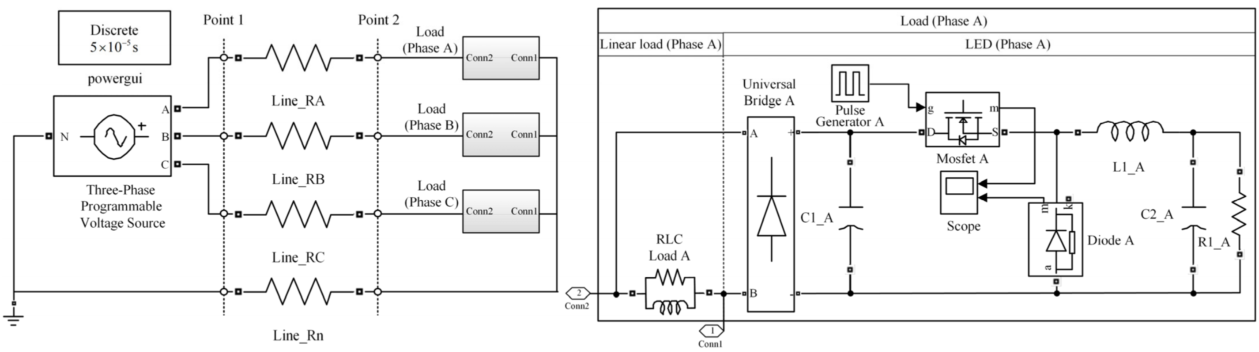


Figure 10. Three-phase simulation model.

Table 5. Simulation settings of load in Groups 1 to 13.

Group	Load Settings			Load Powers (Fundamental)						LED Settings (R1)		
				Phase A		Phase B		Phase C		Phase A	Phase B	Phase C
	Φ	ε	ζ	W	var	W	var	W	var		Ω	
1	1.0	0.0	0%	5300	0	5300	0	5300	0		×	
2	0.9			4770	2310	4770	2310	4770	2310		×	
3	0.8	0.0	0%	4240	3180	4240	3180	4240	3180		×	
4	0.7			3710	3785	3710	3785	3710	3785		×	
5		0.1		6208	0	5215	0	4477	0		×	
6	1.0	0.2	0%	7197	0	4886	0	3818	0		×	
7		0.3		8164	0	4637	0	3099	0		×	
8			10%	5300	0	5300	0	5300	0		1000	
9	1.0	0.0	20%	5300	0	5300	0	5300	0		130	
10			30%	5300	0	5300	0	5300	0		44	
11	0.9	0.1	10%	4244	2110	5008	1958	5024	2865	950	950	44
12	0.8	0.2	20%	2665	2918	5157	2921	4772	3672	300	90	90
13	0.7	0.3	30%	2127	1659	3182	3724	5618	6116	68	26	15

Φ represents the power factor on the user side; ε is the degree of fundamental negative-sequence imbalance; $\varepsilon = I_1^- / I_1^+$; ζ is THD_{eI}, $\zeta = I_{eH} / I_{e1}$.

The simulation model was created in the Simulink environment, and the load used to simulate users consisted of a linear load and LED. The load in Groups 1 to 7 only contains linear load, and the load in Groups 8 to 13 contains both linear load and LED, as shown in Figure 10. The varying degrees of power quality problems in the three-phase simulation model are realized by changing the value of R1 in the LED module and the RLC load. In the LED simulation model for phase A, capacitor C1_A is set to 440×10^{-6} F, capacitor C2_A is set to 200×10^{-5} F, and inductor L1_A is set to 200×10^{-5} H. The settings of the Pulse Generator module, Mosfet module, and diode module for phase A are shown in Table 2. The LED module simulation settings for phase B and phase C are the same as for phase A.

Initially, four line loss power factors, i.e., fundamental positive sequence active line loss power factor PF_{eP}, reactive line loss power factor PF_{eQ}, unbalanced line loss power factor PF_{eU}, and harmonic line loss power factor PF_{eH}, are measured at Point 2 for evaluating the line loss of the three-phase simulated system and calculating the line loss percentage. The calculated results are also compared with the difference in power measured at the beginning and end of the line, i.e., the difference in power measured at Point 1 and Point 2.

The calculated results are also compared with the difference in power measured at the beginning and end of the line, i.e., the difference in power measured at Point 1 and Point 2. The results are shown in Table 6a,b and Figures 11 and 12. The current spectra of the neutral line harmonic simulation data for Groups 8 to 13 are shown in Table 7.

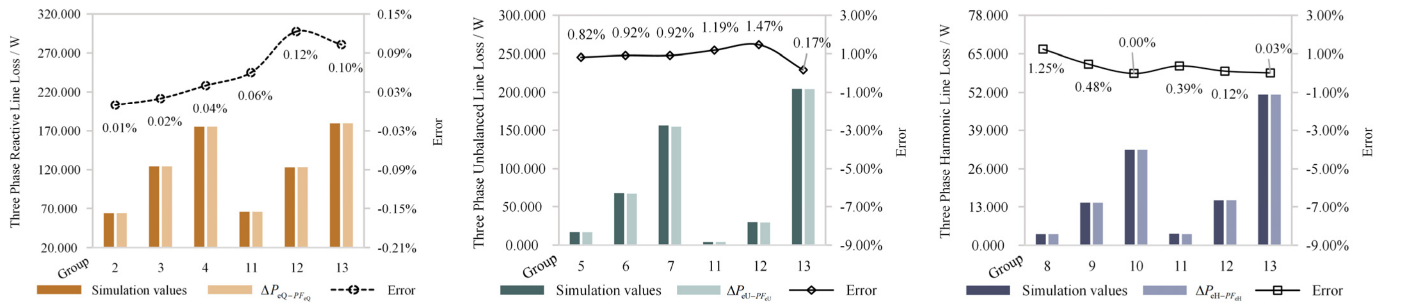
Table 6. (**a**) Simulation results of line loss power factor in three-phase system. (**b**) Simulation results of the proportion of power quality line losses in three-phase system.

(**a**)

Group	PF_{eP}	PF_{eQ}	PF_{eU}	PF_{eH}
1	1.000	1.000	1.000	1.000
2	0.900	0.900		
3	0.800	0.800	1.000	1.000
4	0.700	0.700		
5	0.977		0.977	
6	0.916	1.000	0.916	1.000
7	0.835		0.835	
8	0.995			0.995
9	0.981	1.000	1.000	0.981
10	0.958			0.958
11	0.890	0.900	0.993	0.994
12	0.753	0.800	0.939	0.968
13	0.533	0.700	0.677	0.880

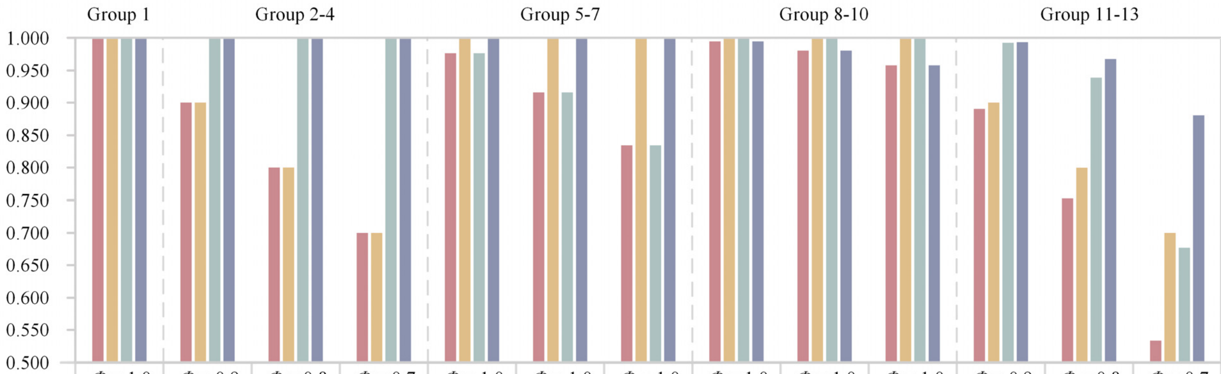
(**b**)

$\Delta P_{eQ}/\Delta P_{eP\text{-min}}$		$\Delta P_{eU}/\Delta P_{eP\text{-min}}$		$\Delta P_{eH}/\Delta P_{eP\text{-min}}$	
Group	Error/%	Group	Error/%	Group	Error/%
2	0.01	5	0.87	8	1.11
3	0.01	6	1.09	9	0.80
4	0.02	7	1.32	10	0.47
11	0.01	11	1.20	11	0.38
12	0.02	12	1.59	12	0.01
13	0.02	13	0.27	13	0.13



(**a**) (**b**) (**c**)

Figure 11. (**a**) Three-phase simulated reactive line loss comparison chart; (**b**) Three-phase simulated unbalanced line loss comparison chart; (**c**) Three-phase simulated harmonic line loss comparison chart.



	Φ = 1.0, ε = 0.0, ζ = 0%	Φ = 0.9, ε = 0.0, ζ = 0%	Φ = 0.8, ε = 0.0, ζ = 0%	Φ = 0.7, ε = 0.0, ζ = 0%	Φ = 1.0, ε = 0.1, ζ = 0%	Φ = 1.0, ε = 0.2, ζ = 0%	Φ = 1.0, ε = 0.3, ζ = 0%	Φ = 1.0, ε = 0.0, ζ = 10%	Φ = 1.0, ε = 0.0, ζ = 20%	Φ = 1.0, ε = 0.0, ζ = 30%	Φ = 0.9, ε = 0.1, ζ = 10%	Φ = 0.8, ε = 0.2, ζ = 20%	Φ = 0.7, ε = 0.3, ζ = 30%
PF_{eP}	1.000	0.900	0.800	0.700	0.977	0.916	0.835	0.995	0.981	0.958	0.890	0.753	0.534
PF_{eQ}	1.000	0.900	0.800	0.700	1.000	1.000	1.000	1.000	1.000	1.000	0.900	0.800	0.700
PF_{eU}	1.000	1.000	1.000	1.000	0.977	0.916	0.835	1.000	1.000	1.000	0.993	0.939	0.677
PF_{eH}	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.995	0.981	0.958	0.994	0.968	0.880

Figure 12. Three-phase simulated power quality line loss comparison chart.

Table 7. Current spectra of neutral line harmonic simulation data.

Harmonic Order (Line N)		1	3	5	7	9	11	13	15
Group 8	Amplitude	0	1.153	0	0	1.011	0	0	0.771
	Phase	−84.0	195.2	13.4	159.7	46.1	204.7	46.0	258.3
Group 9	Amplitude	0	4.674	0	0	3.005	0	0	1.60
	Phase	−72.7	214.8	88.6	61.3	108.2	−15.2	−54	25.4
Group 10	Amplitude	0	8.372	0	0	3.415	0	0	1.605
	Phase	102.5	228.4	170.5	−52.2	161.6	73.3	65.4	163.9
Group 11	Amplitude	1	0.821	0.008	0.007	0.718	0.012	0.011	0.541
	Phase	93.8	197.9	−16.9	93.3	52.3	197.0	−52.8	268.5
Group 12	Amplitude	1	0.629	0.115	0.092	0.373	0.092	0.078	0.104
	Phase	178.6	219.3	−86.9	137.1	118.8	212.2	81.7	44.8
Group 13	Amplitude	1	0.438	0.060	0.141	0.043	0.021	0.081	0.022
	Phase	93.9	242.0	8.4	218.3	246.7	0.9	236.7	8.6

As can be seen in Table 6a,b and Figure 11, compared to the simulated measured line loss values for the three-phase system, the error in the calculated line loss values for each component using the four line loss power factors is small, with the error in all 13 sets of simulated results not exceeding 2%, which indicates that it is theoretically feasible to calculate the additional line loss values for the decoupled power quality using the four line loss power factors.

As can be seen from Figure 12, when the system has no reactive, harmonic, and unbalance problems, i.e., in a "perfect" three-phase system, all four power quality line loss power factors are 1. When the power factor Φ decreases, the current harmonic content ζ increases and the unbalance ε increases, the fundamental positive sequence active line loss power factor PF_{eP}, reactive line loss power factor PF_{eQ}, unbalanced line loss power factor PF_{eU}, and harmonic line loss power factor PF_{eH} will decrease. Whether the system has a single power quality problem or a compound power quality problem, the line loss power factor is an effective way to assess the severity of the system's power quality line loss problem.

C. *Three-Phase Case Experimental Results*

In the simulation section, simulated single-phase and three-phase systems were employed to illustrate the theoretical viability of the line loss calculation using line power factors. Subsequently, an experiment involving a three-phase non-sinusoidal unbalanced system was established. The system was configured at 220 V for a low-voltage distribution network and was composed of linear RL loads along with LED light banks. The wiring diagram of the physical experiment is depicted in Figure 13. Comprehensive loads' data can be found in Table 8.

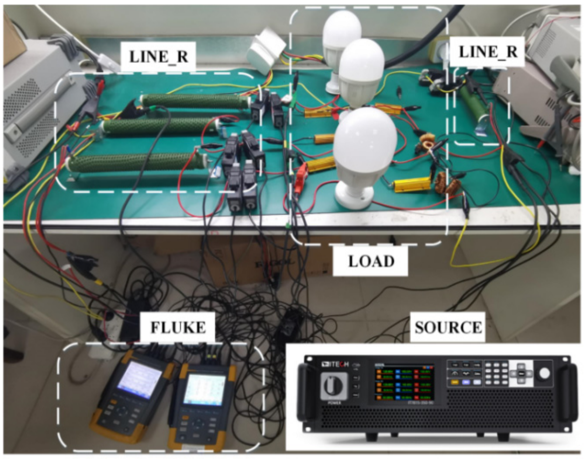


Figure 13. Three-phase system physical experiment.

Table 8. Three-phase system loads' data.

Line Settings	Phase A		Phase B		Phase C	
LINE_R	R	10 Ω	R	10 Ω	R	10 Ω
LOAD	R	310 Ω	R	530 Ω	R	600 Ω
			L	4 mH	L	4 mH
	LED	30 W	LED	30 W	LED	30 W
Source	IT7800 AC/DC Power Supply					
Measuring instruments	Fluke 438 Power Quality Analyzer					
	Fluke 435 Power Quality and Energy Analyzer					
	HIOKI IM 3536 LCR METER					

In the physical experiment without power on, HIOKI IM 3536 LCR METER was used to measure the line resistance labelled as 10 Ω, and the result was 9.75 Ω. At the same time, in the line resistance at both ends of the parallel connection voltmeter, a series connection ammeter was used in the power supply to measure the harmonic effects of the line resistance of the voltage and current values, so as to calculate the consideration of the skin effect of the line resistance value of 9.99 Ω. These two resistance values are entered into FLUKE 435 to calculate the line loss value. Meanwhile, measurement points were established at both ends of the physical experimental line. At the initial end, a Fluke 438 Power Quality Analyzer was utilized, while at the terminal end, a Fluke 435 Power Quality and Energy Analyzer was employed. These meters simultaneously sampled voltage, current, and power values at the respective ends to ensure data synchronicity. The discrepancy between the two ends was considered the measured line loss value.

A comparison between the approach proposed in this study and the measurements obtained from FLUKE 435 is illustrated in Table 9a–d.

Table 9. (**a**) Three-phase system active line loss experiment results; (**b**) Three-phase system reactive line loss experiment results; (**c**) Three-phase system unbalanced line loss experiment results; (**d**) Three-phase system harmonic line loss experiment results.

(a)				
PF_{eP}	True Value-$_P$/W	Calculated Value/W		Error/%
0.8738	11.662	Fluke 435 (LINE_R = 9.75 Ω)	10.777	7.587
		Fluke 435 (LINE_R = 9.99 Ω)	11.042	4.845
		$\Delta P_{eP\text{-}min}$	11.605	0.490
(b)				
PF_{eQ}	True Value-$_Q$/W	Calculated Value/W		Error/%
0.9984	0.038	Fluke 435 (LINE_R = 9.75 Ω)	0.035	7.539
Φ		Fluke 435 (LINE_R = 9.99 Ω)	0.036	5.263
0.9984		ΔP_{eQ}	0.038	0.490
(c)				
PF_{eU}	True Value-$_U$/W	Calculated Value/W		Error/%
0.9434	1.400	Fluke 435 (LINE_R = 9.75 Ω)	1.325	5.380
ε/%		Fluke 435 (LINE_R = 9.99 Ω)	1.357	3.051
16.23		ΔP_{eU}	1.435	2.501
(d)				
PF_{eH}	True Value-$_H$/W	Calculated Value/W		Error/%
0.9194	2.100	Fluke 435 (LINE_R = 9.75 Ω)	1.976	5.900
ζ/%		Fluke 435 (LINE_R = 9.99 Ω)	2.025	3.584
40.32		ΔP_{eH}	2.122	1.065

Table 9a shows the results of the active line loss experiment. In Table 9a, PF_{eP} is 0.8738. True value-$_P$ represents the line loss of the positive sequence active current generated by the fundamental frequency, which is calculated by multiplying the difference between the positive sequence active power at the start and end of the line by the square of the sine of the phase angle of the positive sequence current.

When comparing the errors of the proposed method to the FLUKE 435 measurement method in this study, it is evident that the FLUKE 435 recorded the greatest error in the active line loss, which had a value of 7.587%, without taking skin effect into consideration. After accounting for the skin effect, the measurement error of the FLUKE 435 was reduced to a value of 4.845%. However, there is still a certain error with True value-P because it is impossible to measure the line loss on the conductor. The method proposed in this study produced the line loss value with the lowest error, at 0.490%.

Table 9b shows the results of the reactive line loss experiment. In Table 9b, the power factor Φ of the three-phase experimental circuit stands at 0.9984, and PF_{eQ} is 0.9984. The line loss caused by the base-sequence reactive current is represented by True value-$_Q$, which is calculated by multiplying the difference between the fundamental-sequence active power at the beginning and end of the line by the square of the cosine of the phase angle of the fundamental-sequence current. The line loss calculated by the method proposed in this paper has the smallest error, with a value of 0.490%, compared to the measurement results obtained from FLUKE 435.

Table 9c shows the results of the unbalanced line loss experiment. In Table 9c, the three-phase imbalance ε *is* 16.23%, and PF_{eQ} is 0.9434. True value-$_U$ denotes the line loss of unbalanced current. It is calculated by subtracting the fundamental positive sequence active power from the fundamental active power at the beginning and end of the line.

Our proposed method calculates the line loss value with a minimal error of 2.501% when compared to the measurements obtained from FLUKE 435.

Table 9d shows the results of the harmonic line loss experiment. In Table 9d, the negative sequence current manifests a harmonic content ζ of 40.32%, and PF_{eU} is 0.9194. True value-$_{\text{H}}$ denotes the line loss due to harmonic currents, which is obtained by subtracting the harmonic active power from the first and last ends of the line. Compared with the FLUKE 435 measurements, the line loss value calculated by the proposed method in this paper has the smallest error, with a value of 1.065%.

From Table 9a–d, it can be observed that PF_{eQ}, PF_{eU}, and PF_{eH} are 0.9984, 0.9434, and 0.9194, respectively. Notably, the values of these power quality line loss factors fall within a range of 0 to 1, all being below 1. This signifies that PF_{eQ}, PF_{eU}, and PF_{eH} can effectively evaluate the system's power quality line loss problem when line loss due to power quality problems is present. Concurrently, in comparison with line loss values calculated using Fluke 435, the line loss values computed through the power quality line loss power factor presented in this paper exhibit closer alignment with measured quantities and manifest smaller errors. This emphasizes the feasibility of employing the proposed power quality line loss power factor method for calculating and decoupling power quality line losses on the customer side.

In line loss measurement and analysis, using traditional power theory, i.e., the method of subtracting the first and last meters, can calculate the total loss of the line, but it is not possible to further decouple the total line loss; using Fluke 435 for measurement, it is necessary to manually enter the value of the line impedance, so as to decouple the total loss of the line, but the decoupled results have a certain degree of error compared with the actual line loss. Errors in the FLUKE 435 are mainly caused by errors in the value of the line resistance. Due to the presence of harmonics in the system, the skin effect and the collinear effect can cause changes in the resistance value, thus affecting the line resistance and the accurate measurement of the line loss value. The use of the line power factor enables the calculation of the power quality of each component without the need to solve for line resistance, thus effectively avoiding the errors caused by line resistance.

5. Conclusions

This work focuses on analyzing losses caused by reactive, unbalance, and harmonic issues in electrical lines and decoupling total line losses to quantify individual contributions. Based on IEEE Std. 1459 power theory, four line loss power factors are proposed to evaluate the severity of reactive, unbalance, and harmonic problems. These factors enable the calculation of decoupled line loss values for each line component without needing to solve for line resistance, given the total line loss is known.

Compared to traditional power theory, which relies on circuit impedance for line loss calculations, this method simplifies the process significantly. Measuring line impedance accurately is challenging and prone to errors. The proposed method avoids the need for impedance measurement altogether, shifting the focus to the direct measurement of line loss and utilizing end-of-line analysis for assessing power values on the user side. This approach provides essential metrics for line loss management and evaluation. It offers significant guidance for power grid companies aiming to reduce energy consumption and enhance economic efficiency.

This provides an overview of unbalanced compensation techniques using power electronic converters for active distribution systems with renewable generation.

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List of Symbols

U	Voltage RMS (V)
U_1	Fundamental voltage RMS (V)
U_H	Harmonic voltage RMS (V)
U_e	Equivalent voltage RMS (V)
U_{e1}	Fundamental equivalent voltage RMS (V)
U_1^+	Fundamental positive sequence voltage RMS (V)
U_{eH}	Equivalent harmonic voltage RMS (V)
I	Current RMS (A)
I_1	Fundamental current RMS (A)
I_1^+	Fundamental positive sequence current RMS (A)
I_1^-	Fundamental negative sequence current RMS (A)
I_H	Harmonic current RMS (A)
I_e	Equivalent current RMS (A)
I_{e1}	Fundamental equivalent current RMS (A)
I_{eH}	Equivalent harmonic current RMS (A)
φ_1	Fundamental phase angle (°)
φ_1^+	Fundamental positive sequence phase angle (°)
S	Apparent power (VA)
S_1	Fundamental apparent power (VA)
S_N	Non-fundamental apparent power, (VA)
S_H	Single-phase harmonic apparent power (VA)
S_e	Equivalent apparent power (VA)
S_{e1}	Fundamental equivalent apparent power (VA)
S_1^+	Fundamental positive sequence apparent power (VA)
S_{U1}	Unbalanced apparent power (VA)
S_{eN}	Non-fundamental equivalent apparent power (VA)
S_{eH}	Three-phase harmonic apparent power (VA)
S_{Loss}	Single-phase total line loss apparent power (VA)
S_{PH}	Single-phase harmonic line loss apparent power (VA)
S_{eLoss}	Three-phase total line loss apparent power (VA)
S_{ePU}	Three-phase unbalanced line loss apparent power (VA)
S_{ePH}	Three--phase harmonic line loss apparent power (VA)
P	Active power (W)
P_1	Fundamental active power (W)
P_H	Harmonic active power (W)
P_1^+	Fundamental positive sequence active power (W)
ΔP_{Loss}	Total line loss (W)
$\Delta P_{Loss\text{-}min}$	The minimum line loss (W)
$\Delta P_{P\text{-}min}$	Single-phase fundamental active line loss (W)
ΔP_Q	Single-phase reactive additional line loss (W)
ΔP_H	Single-phase harmonic additional line loss (W)
ΔP_{eLoss}	Three-phase total line loss (W)
$\Delta P_{eP\text{-}min}$	Three-phase fundamental positive sequence active line loss (W)
ΔP_{eQ}	Three-phase fundamental positive sequence reactive additional line loss (W)
ΔP_{eU}	Three-phase unbalanced additional line loss (W)
ΔP_{eH}	Three-phase harmonic additional line loss (W)
N	Non-active power (VAR)
Q_1	Fundamental reactive power (VAR)
D_I	Current distortion power (VAR)
D_U	Voltage distortion power (VAR)
Q_1^+	Fundamental positive sequence reactive power (VAR)
D_{eI}	Three-phase current distortion power (VAR)

D_{eU}	Three-phase voltage distortion power (VAR)
R	Line equivalent resistance (Ω)
X	Line equivalent reactance (Ω)
Y	Line equivalent admittance (S)
PF_P	Single-phase active line loss power factor
PF_Q	Single-phase reactive line loss power factor
PF_H	Single-phase harmonic line loss power factor
PF_{eP}	Three-phase fundamental positive sequence active line loss power factor
PF_{eQ}	Three-phase reactive line loss power factor
PF_{eU}	Three-phase unbalanced line loss power factor
PF_{eH}	Three-phase harmonic line loss power factor
Φ	Power Factor
ζ	THD_I
ε	The degree of negative-sequence imbalance
U	Voltage RMS (V)

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