

Article

Design Limits of Voltage Unbalance Mitigation in Passive Single-Phase to Three-Phase Converters via Transformer Tap Optimization

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Abstract

Passive single-phase to three-phase conversion represents an attractive alternative for low-power applications, particularly in isolated systems and rural electrification scenarios where simplicity, robustness, and low cost are essential. However, these passive topologies inherently produce voltage unbalance whose magnitude strongly depends on load characteristics. This work analyzes a passive single-phase to three-phase converter based on reactive elements and a transformer, focusing on the limits of voltage unbalance mitigation through discrete transformer tap optimization. The study is conducted under steady-state sinusoidal conditions using phasor modeling and symmetrical component analysis. The voltage unbalance factor (VUF) is adopted as the primary optimization metric, while the current unbalance factor (IUF), neutral current, and converter losses are used as complementary performance indicators. Results indicate that transformer tap optimization can reduce voltage unbalance for specific load conditions, although low residual unbalance is achieved only near the nominal operating point. Higher residual unbalance is observed as the load becomes more inductive within the investigated power-factor range. The findings indicate that passive single-phase to three-phase conversion can be technically viable for low-power applications with relatively stable load conditions. However, applications requiring high power quality or dynamic regulation may benefit from active converter solutions based on power electronics.

Keywords: engineering design; passive converter design; optimization; transformer tap design; voltage unbalance; power quality

1. Introduction

Single-phase to three-phase conversion has received sustained attention due to its relevance in low-power industrial applications, rural environments, and isolated systems where three-phase infrastructure is not available [1–4]. Power electronics-based active converters are capable of synthesizing nearly balanced three-phase voltages from a single-phase source, offering high controllability and good power quality [5–8]. However, these solutions involve increased switching complexity, higher costs, and potential reliability concerns.

A wide range of converter topologies has been proposed in the literature, including matrix converters, multilevel inverters, and reduced-switch configurations, each offering different trade-offs between control complexity, switching losses, and output voltage quality [9–11].

Passive and hybrid approaches based on transformers, inductive coupling, or phase-shifting networks remain attractive when simplicity, robustness, and low cost are the



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main design criteria [4,12–14]. However, their performance is intrinsically limited by the dependence of voltage balance on load impedance and power factor, which limits their ability to maintain acceptable unbalance levels under varying operating conditions and motivates the need for a systematic evaluation of their achievable limits.

Recent developments in power distribution systems have renewed interest in voltage unbalance due to the increasing penetration of distributed energy resources (DERs), particularly single-phase renewable generation and electric-vehicle charging. Consequently, recent studies have investigated voltage-unbalance assessment, the influence of load imbalance on power-quality indicators, and practical mitigation strategies for modern distribution networks [15–17]. Although these studies focus primarily on distribution-system operation rather than converter design, they highlight the continuing importance of minimizing voltage unbalance in practical power systems.

Despite the wide range of conversion strategies and achievable levels of three-phase balance, fewer studies have focused on quantitatively characterizing the limits of unbalance mitigation when only static parametric adjustments are available [3,18,19]. Previous work has primarily addressed converter topologies or drive applications, particularly in the context of motor-drive-oriented implementations [18,19]. In practical implementations, transformer tap selection often constitutes the simplest adjustment mechanism; however, its impact on voltage unbalance under varying load conditions has not been systematically characterized.

Recent optimization methodologies have addressed voltage-unbalance mitigation in active distribution networks by coordinating voltage regulators, capacitor banks, and distributed energy resources [20]. However, these approaches rely on actively controlled network assets and therefore differ fundamentally from passive single-phase to three-phase converters, where transformer tap selection constitutes one of the few available design variables for improving voltage balance.

In this context, this work investigates the achievable limits of voltage unbalance mitigation in passive single-phase to three-phase converters through discrete transformer tap optimization. A steady-state phasor-based model combined with symmetrical component analysis is used to evaluate voltage unbalance as a function of load impedance, power factor, and transformer tap position, treated as a discrete optimization variable. The study provides a quantitative characterization of the minimum achievable unbalance, assesses the robustness of the optimal transformer tap under load variations, and identifies the operating conditions under which passive conversion remains technically viable.

Unlike previous studies focused primarily on converter implementation or motor-drive applications, this work addresses passive single-phase to three-phase conversion from a design optimization perspective, emphasizing the achievable limits of voltage balancing through transformer tap optimization.

The main scientific contributions of this work are summarized as follows:

- (i) Transformer tap optimization substantially reduces voltage unbalance near the nominal operating condition, but its effectiveness decreases as the load departs from the design point.
- (ii) The VUF-optimal transformer setting remains confined to a narrow interval under variations in load impedance and inductor quality factor, quantitatively demonstrating the robustness of the proposed optimization methodology.
- (iii) The achievable operating limits of passive single-phase to three-phase conversion are established, identifying the operating conditions under which passive solutions remain technically viable and those for which active power-electronic converters become preferable.

2. Materials and Methods

This section presents the methodological framework adopted for the analysis of the passive single-phase to three-phase converter. First, the conversion topology and its phasor-based representation are introduced. Then, the electrical model and load conditions are defined, followed by the formulation used to compute phase voltages and currents. Finally, the metrics used to assess voltage and current unbalance are described, together with the optimization procedure applied to the transformer tap position.

The passive converter was initially designed for a nominal operating condition corresponding to a load impedance of $Z = 100 \, \Omega$ and unity power factor ($\text{PF} = 1.00$). This reference operating point was used to determine the reactive compensation network (L_a and C_c). Subsequently, the investigated load impedance and power factor ranges were defined as controlled steady-state deviations around this nominal design condition in order to evaluate the robustness of the proposed transformer tap optimization methodology.

The methodological workflow followed in this study is summarized in Figure 1.

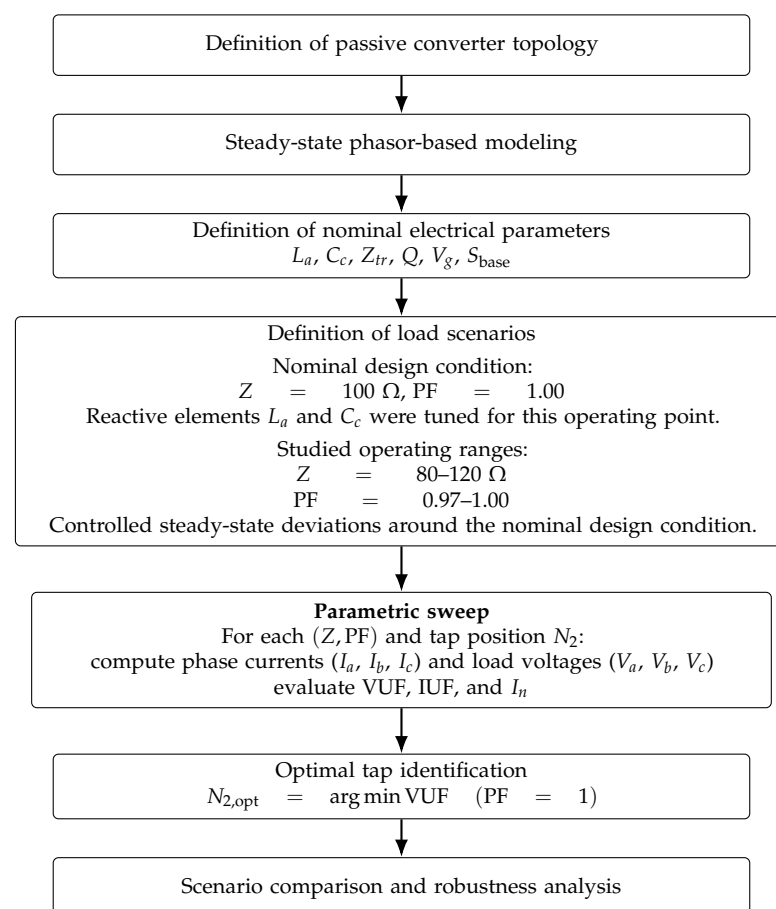


Figure 1. Methodological workflow adopted in this study. The passive converter was designed for the nominal operating condition ($Z = 100 \, \Omega$, $\text{PF} = 1.00$), which was used to determine the reactive compensation network. The investigated impedance and power-factor ranges correspond to controlled steady-state deviations around this design point, allowing the robustness of the proposed transformer tap optimization methodology to be evaluated.

2.1. Conversion Topology

A passive single-phase to three-phase conversion topology based on a reactive network composed of an inductor, a capacitor, and a transformer is analyzed. This type of converter can synthesize a nearly balanced three-phase voltage system from a single-phase source

by means of phase shifts close to $\pm 60^\circ$ produced by reactive elements, a technique widely documented in rural applications and low-power isolated systems [1,2].

Although these solutions offer advantages in terms of simplicity, robustness, and low cost, their performance strongly depends on load characteristics, particularly load impedance and power factor. The conversion topology considered in this study is shown in Figure 2.

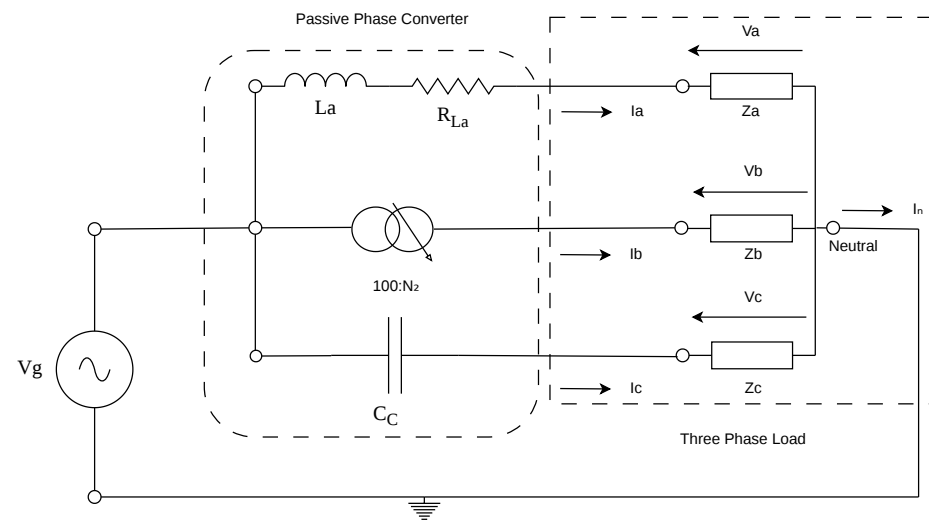


Figure 2. Passive single-phase to three-phase conversion topology based on a reactive phase-shifting network and transformer tap adjustment. Current arrows indicate the adopted positive reference directions for the branch currents.

2.2. Governing Phasor Formulation

The steady-state operation of the converter is based on the phase-shifting properties of the reactive branches and the transformer, as illustrated in Figure 2. The complete derivation of the operating principle was presented in [2]; therefore, a compact formulation is provided here for clarity and reproducibility.

The converter synthesizes a three-phase voltage system from a single-phase source by introducing controlled phase shifts in each branch. In particular, the inductive branch in phase *a* introduces a lagging voltage, while the capacitive branch in phase *c* introduces a leading voltage. Under nominal operating conditions, these phase shifts are set close to $\pm 60^\circ$ relative to the source voltage. In addition, the transformer branch in phase *b* introduces a phase inversion of 180° . As a result, the three output voltages are displaced close to 120° , forming a nearly balanced three-phase system.

In addition to phase shifting, the reactive branches introduce amplitude scaling, which directly affects the attainable voltage balance. For the nominal operating condition, the magnitudes of V_a and V_c are approximately half of the source voltage, which requires adjusting the transformer ratio in phase *b* to achieve comparable voltage magnitudes across the three phases.

The system is described using phasor variables, where V_g denotes the RMS input voltage, and V_a , V_b , and V_c represent the load phase voltages measured with respect to the common neutral node of the Y-connected load. The corresponding phase currents I_a , I_b , and I_c flow through each converter branch and the associated load impedance Z_L .

The transformer tap setting is represented by the number of active secondary turns, N_2 , which is treated as a discrete variable that modifies the effective turns ratio

$$n = \frac{N_2}{N_1}, \quad (1)$$

where N_1 is the fixed number of primary turns. Each admissible value of N_2 corresponds to a discrete transformer tap setting. Variations in N_2 affect the voltage magnitude applied to phase b and, consequently, the balance of the synthesized three-phase system.

For each operating condition, the phase voltages and currents are obtained directly from the equivalent circuit under steady-state sinusoidal conditions. The formulation follows a branch-based phasor analysis, where each phase is described by its corresponding series impedance and source contribution. The scalar equations used in the numerical implementation are presented in Section 2.6.

2.3. Equivalent Circuit Model

The system is modeled under steady-state sinusoidal conditions using phasor analysis. The phasor relationships described in Section 2.2 are implemented through the equivalent circuit defined by the parameters and assumptions introduced in this section. The adopted formulation focuses on the fundamental-frequency behaviour of the passive converter in order to evaluate the theoretical limits of voltage balance achievable through passive parametric adjustments. An ideal purely sinusoidal voltage source, with no internal impedance or harmonic distortion, was assumed in order to isolate the unbalance introduced exclusively by the passive topology under analysis.

The transformer was represented by its equivalent series impedance

$$Z_{tr} = R_{cc} + jX_{cc}, \quad (2)$$

where, in the adopted branch-based phasor model, Z_{tr} denotes the equivalent transformer series impedance referred to the load-side branch representation used for phase b . The magnetizing branch and no-load losses were neglected, which is appropriate for steady-state voltage balance studies.

The transformer parameters were obtained from a relative short-circuit impedance of $Z_{cc} = 0.025$ and an X/R ratio of 1, using a base apparent power equal to the transformer rated apparent power, $S_{base} = S_{rated} = 2000$ VA, and a primary voltage of $V_g = 460$ V.

The reactive network described in Section 2.1 was modeled with an inductance $L_a = 0.4594$ H connected in series with phase a and a capacitor $C_c = 15.315$ μ F connected in phase c . The equivalent series resistance associated with the inductor was modeled through a quality factor $Q = 20$, according to

$$R_s = \frac{\omega L_a}{Q}. \quad (3)$$

The influence of the selected inductor quality factor on the converter performance and the robustness of the transformer tap optimization is further evaluated through the sensitivity analysis presented in Section 3.7.

Model Assumptions and Scope

The adopted formulation intentionally focuses on the fundamental-frequency steady-state behaviour of the passive converter. Consequently, magnetic saturation, nonlinear variations in the reactive components, harmonic distortion, and transient phenomena are neglected. These phenomena may influence the absolute values of the calculated voltage unbalance, current unbalance, neutral current, and converter losses under practical operating conditions. However, the primary objective of the present study is not to predict the exact operating performance of a specific converter but rather to identify the design limits and operating trends governing transformer tap optimization. Therefore, although the adopted simplifications may influence the numerical values of the calculated performance indicators, the optimization trends are expected to remain largely unaffected because the

comparative behaviour among transformer tap positions is primarily governed by the steady-state phasor relationships of the passive network. Consequently, the principal conclusions regarding the achievable limits of passive voltage balancing are not expected to change. Future work will extend the present formulation by incorporating nonlinear magnetic characteristics and harmonic analyses in order to evaluate these effects under practical operating conditions.

Since both the inductive and capacitive reactances are frequency-dependent, deviations from the nominal frequency modify the phase shifts introduced by the reactive network and therefore the optimum tap position. However, the intended applications (utility-fed rural systems) operate at a nearly constant nominal frequency (50/60 Hz), making the expected steady-state frequency deviations considerably smaller than the load variations investigated in this work. Consequently, frequency variations are not expected to alter the principal conclusions of the present study. A dedicated frequency-sensitivity analysis nevertheless constitutes an interesting topic for future work.

2.4. Load Model

The three-phase load was represented by a balanced complex impedance:

$$Z_L = Z(\cos \varphi + j \sin \varphi), \quad (4)$$

where Z is the magnitude of the phase impedance and $\varphi = \arccos(\text{PF})$ is the angle associated with an inductive power factor.

A representative range of impedance magnitudes and power factor conditions was considered in order to represent typical operating conditions of three-phase loads. In particular, inductive conditions with reduced power factor were analyzed due to their greater susceptibility to voltage unbalance.

2.5. Reference Operating Condition

The system under study corresponds to a passive single-phase to three-phase converter supplying a balanced three-phase load under nominal operating conditions. The reference operating point was defined by a phase impedance of $Z = 100 \, \Omega$ operating at unity power factor ($\text{PF} = 1$).

Using the nominal transformer tap (100:50), the converter provides approximately 230 V per phase across the balanced Y-connected load. Under this condition, the three-phase active power is approximately

$$P \approx \frac{3(230)^2}{100} = 1.59 \text{ kW},$$

which remains below the adopted transformer rating of 2 kVA. This operating point was therefore selected as the design condition used to determine the reactive compensation network (L_a and C_c). The subsequent analyses evaluate deviations from this nominal operating point by varying the load impedance magnitude and power factor.

The reactive elements were selected to produce phase shifts close to $\pm 60^\circ$ at the nominal system frequency, allowing the passive topology to approximate a balanced three-phase voltage system.

The selected ranges of load impedance and power factor represent moderate operating variations around the nominal condition typically encountered in low-power rural electrification and isolated off-grid applications, where passive converter solutions are attractive because of their simplicity, robustness, and low implementation cost.

The selected nominal impedance should therefore not be interpreted as a statistical characterization of rural electrical loads. Instead, it defines the reference operating

condition used to synthesize the passive reactive network (L_a and C_c). The subsequent parametric analyses evaluate the robustness of the proposed converter under controlled departures from this design condition through systematic variations in load impedance and power factor.

The main electrical parameters corresponding to this reference condition are summarized in Table 1.

Table 1. Reference electrical parameters adopted for the passive single-phase to three-phase converter model.

Parameter	Symbol	Value
Primary voltage	V_g	460 V
Nominal frequency	f	60 Hz
Base and transformer rated apparent power	$S_{\text{base}} = S_{\text{rated}}$	2000 VA
Transformer primary turns	N_1	100
Nominal transformer secondary turns	$N_{2,\text{nom}}$	50
Transformer short-circuit impedance	Z_{cc}	0.025 p.u.
Transformer reactance-to-resistance ratio	X/R	1
Investigated secondary-turn range	N_2	45–55
Expanded secondary-turn range (verification)	N_2	35–65
Series inductance	L_a	0.4594 H
Capacitance	C_c	15.315 μF
Inductor quality factor	Q	20
Nominal load impedance	Z	100 Ω
Nominal load power factor	PF	1.00

2.6. Phasor Calculation

The scalar equations presented in this section correspond to the direct application of the branch-based phasor formulation described in Section 2.2.

The phase currents, which correspond to the load currents, were obtained from the equivalent circuit as follows:

$$I_a = \frac{V_g}{Z_L + R_s + j\omega L_a}, \quad (5)$$

$$I_b = \frac{V_b}{Z_L + Z_{tr}}, \quad (6)$$

$$I_c = \frac{V_g}{Z_L - j/(\omega C_c)}. \quad (7)$$

The load voltages were then calculated as

$$V_k = I_k Z_L, \quad k = a, b, c. \quad (8)$$

In this representation, phases a and c are directly driven by the source through reactive elements, whereas phase b is modeled from the load-side transformer branch. Accordingly, the current in phase b is expressed in terms of the load-side voltage V_b and the equivalent series impedance Z_{tr} .

2.7. Unbalance Assessment

Voltage unbalance was quantified using symmetrical component analysis.

Any unbalanced three-phase system can be decomposed into positive-, negative-, and zero-sequence components. The positive- and negative-sequence components are used

to calculate the VUF and IUF, whereas the zero-sequence current is quantified through the neutral current.

$$V_1 = \frac{V_a + aV_b + a^2V_c}{3}, \quad (9)$$

$$V_2 = \frac{V_a + a^2V_b + aV_c}{3}, \quad (10)$$

where $a = e^{j2\pi/3}$ and V_a , V_b , and V_c denote the load voltages.

The voltage unbalance factor (VUF) was defined as

$$\text{VUF} = \frac{|V_2|}{|V_1|} \times 100, \quad (11)$$

a widely accepted performance indicator for quantifying voltage unbalance in three-phase systems.

As complementary metrics, the current unbalance factor (IUF) and the neutral current were also evaluated:

The current symmetrical components were obtained using the same transformation applied to the phase voltages, i.e.,

$$I_1 = \frac{I_a + aI_b + a^2I_c}{3}, \quad (12)$$

$$I_2 = \frac{I_a + a^2I_b + aI_c}{3}, \quad (13)$$

where I_a , I_b , and I_c are the phase currents obtained from the equivalent circuit described in Section 2.6.

$$\text{IUF} = \frac{|I_2|}{|I_1|} \times 100, \quad I_n = |I_a + I_b + I_c| = 3|I_0| \quad (14)$$

2.8. Transformer Tap Optimization

The transformer tap setting was represented by the number of active secondary turns, N_2 , which was treated as the discrete optimization variable over the set.

$$N_2 \in \{45, 46, \dots, 55\}. \quad (15)$$

The investigated secondary-turn range was centered on the nominal value $N_{2,\text{nom}} = 50$, corresponding to the nominal transformer ratio 100:50. The selected range ($N_2 = 45$ –55) represents approximately $\pm 10\%$ variations in the number of active secondary turns and corresponds to the available discrete transformer tap settings.

To verify that the selected search interval did not artificially constrain the optimization process, the optimization was repeated using an expanded search range of $N_2 = 35$ –65. For all load-impedance cases investigated in this verification, the VUF-optimal value remained within $N_2 = 46$ –49, confirming that the original interval ($N_2 = 45$ –55) encompasses all identified solutions and is therefore sufficiently wide for the analyses presented.

The optimal tap was defined as the value of N_2 that minimizes the voltage unbalance factor under the nominal unity power factor condition:

$$N_{2,\text{opt}} = \arg \min_{N_2 \in \{45, 46, \dots, 55\}} \text{VUF}(N_2, \text{PF} = 1). \quad (16)$$

In the numerical implementation, this optimization was evaluated over integer tap positions.

Optimization under $PF = 1$ corresponds to the design point of the reactive network, i.e., the condition under which the system is ideally compensated. This criterion makes it possible to identify the transformer turns ratio that provides the best voltage balance at the nominal operating point and to use this value as a reference for analyzing the sensitivity of the system to variations in load impedance and power factor.

The optimal value obtained is indicated in the figures by a vertical dashed line marking the tap position that minimizes the VUF under this nominal condition.

In addition, the figures include a horizontal line at $VUF = 3\%$ as a graphical reference to facilitate comparison among the different operating conditions. This reference is not used as a design criterion or compliance limit but only as a visual benchmark for interpreting the simulated voltage-unbalance levels.

2.9. Computational Implementation

The numerical analysis was carried out using the reference electrical parameters summarized in Table 1. From this reference case, parametric variations in load impedance, power factor, and transformer tap position were evaluated.

The model was implemented in MATLAB R2023b by means of a parametric sweep over load impedance magnitude, power factor, and transformer tap position.

Three load-impedance scenarios were analyzed around a nominal value of $100\ \Omega$, considering representative variations corresponding to lighter and more demanding operating conditions. For each scenario, different power factor values in the range $PF = 1.00$ to $PF = 0.97$ were evaluated in order to represent conditions ranging from purely resistive operation to inductive loads with partial power factor correction.

The transformer turns ratio was evaluated through a discrete tap sweep in the interval $N_2 \in [45, 55]$. For each combination of impedance, power factor, and tap position, the voltage unbalance factor (VUF), current unbalance factor (IUF), and neutral current were calculated.

From these results, the minimum achievable VUF, the corresponding optimal turns ratio, and the behavior of the unbalance indicators under load variations were determined.

3. Results and Discussion

3.1. VUF Behavior with Respect to Transformer Tap Position

Figures 3–5 show the variation in the voltage unbalance factor (VUF) as a function of transformer tap position for the different impedance scenarios considered. In all cases, the curves exhibit a clearly defined minimum, indicating that three-phase balance can be improved through discrete adjustment of the transformer turns ratio. This behavior indicates that transformer tap selection acts as a local balancing mechanism rather than a global compensation strategy, consistent with the persistence of residual unbalance under off-nominal load conditions.

An important observation is that the tap position minimizing the VUF remains within a narrow range for the different impedance and power factor values considered, staying in the vicinity of the nominal tap. This suggests that the optimal transformer adjustment point exhibits a certain degree of robustness against moderate variations in operating conditions. From a practical perspective, this result suggests that the converter may operate satisfactorily with a single tap adjustment over a relatively wide range of operating conditions, which is particularly advantageous in rural or isolated systems where regulation mechanisms are usually limited. In the figures, the optimal tap position obtained from the minimization procedure is indicated by a vertical dashed line.

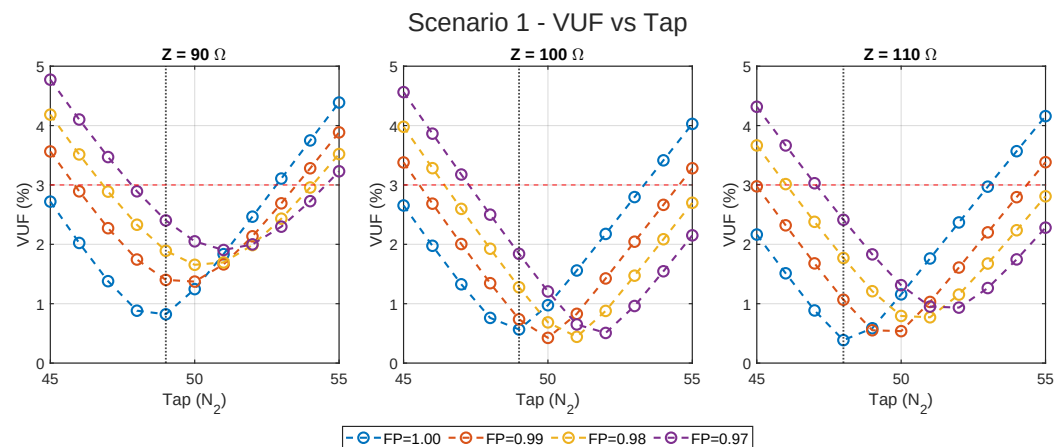


Figure 3. Scenario 1. Voltage unbalance factor (VUF) as a function of transformer tap position for load impedances close to the nominal value ($Z = 90\text{--}110\ \Omega$) and different power factors. Each subplot corresponds to a different impedance value. The vertical dashed line indicates the optimal tap position, while the horizontal line indicates the 3% reference level.

As can be seen in Figures 3–5, a horizontal line at $\text{VUF} = 3\%$ is included only as a visual reference to facilitate comparison among the different operating conditions. It is not intended to represent a prescribed design limit or compliance threshold.

The minimum achievable VUF depends on both load impedance magnitude and power factor, reflecting the interaction between the passive network parameters and the load conditions.

Although the underlying mitigation mechanisms differ, this behavior is consistent with recent studies showing that voltage unbalance is strongly influenced by operating conditions and load characteristics in three-phase power systems [15,16].

When the impedance deviates from the nominal operating condition, the currents in the reactive branches are modified, which alters the associated voltage drops and, consequently, the phasor relationships among the three-phase voltages.

Consistently, operating conditions close to unity power factor exhibit lower residual unbalance levels, whereas more inductive operating conditions increase the minimum achievable VUF even after tap optimization. This effect can be explained by the fact that the reactive network introduces phase shifts that depend on the interaction between the converter impedances and the load, so that higher load reactance tends to alter the voltage balance synthesized by the passive converter [21–23].

This behavior can be observed by comparing the cases $Z = 90\ \Omega$ and $Z = 110\ \Omega$, where the minimum VUF increases slightly with respect to the nominal case ($Z = 100\ \Omega$), while the optimal tap position remains nearly unchanged. However, the VUF degradation is not strictly symmetric with respect to the nominal impedance value. In particular, deviations toward lower impedance values tend to produce slightly larger increases in the minimum VUF, which is consistent with the increase in system currents and the corresponding voltage drops across the reactive branches of the converter.

A similar trend is observed in Scenarios 2 and 3 (Figures 4 and 5), where progressively wider impedance ranges around the nominal value are considered. In particular, Scenario 3 includes deviations of approximately $\pm 30\%$ with respect to $Z = 100\ \Omega$, thus illustrating the behavior of the passive converter when the load departs significantly from the design point. Under these conditions, the minimum achievable VUF increases progressively, and slight variations in the optimal tap position can also be observed in some cases. This indicates that, as the load impedance moves away from the nominal point, voltage balance becomes increasingly dependent on the interaction between the reactive network and the load, which may slightly modify the optimal transformer adjustment condition.

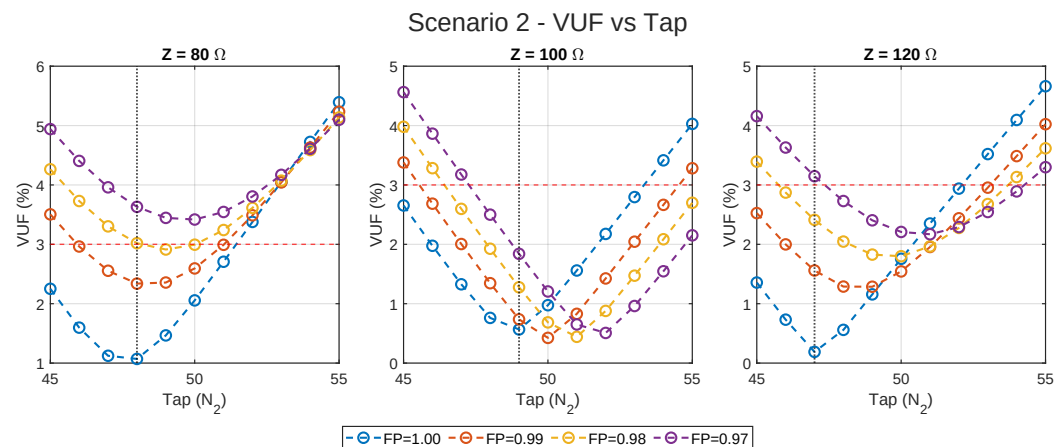


Figure 4. Scenario 2. VUF behavior for a wider range of load impedances ($Z = 80\text{--}120 \Omega$) under different power factor conditions. The vertical dashed line indicates the optimal tap position, while the horizontal line indicates the 3% reference level.

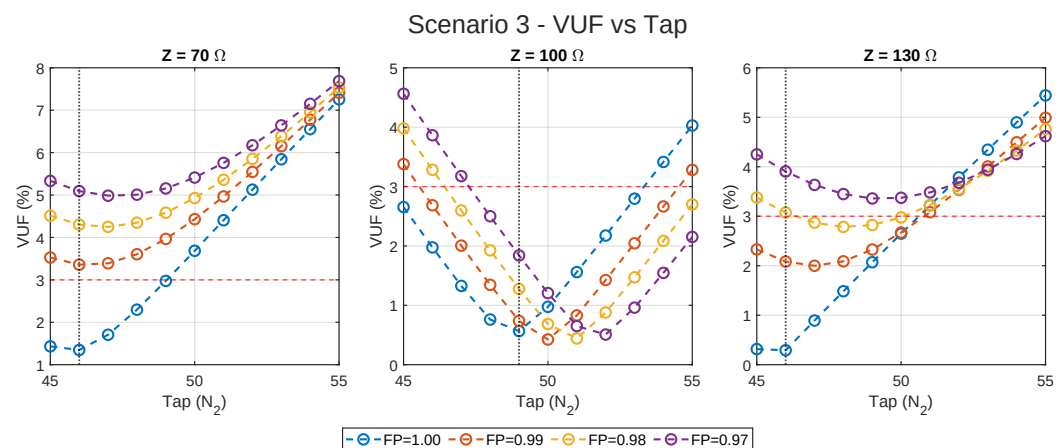


Figure 5. Scenario 3. VUF behavior for the largest deviation from the nominal load impedance ($Z = 70\text{--}130 \Omega$). The vertical dashed line indicates the optimal tap position, while the horizontal line indicates the 3% reference level.

Comparison with the 3% graphical reference facilitates the interpretation of the converter performance under the analyzed operating conditions. In Scenario 1, the residual VUF generally remains below this reference in the vicinity of the minimum, whereas in Scenarios 2 and 3 higher VUF values are observed for operating conditions far from the nominal load. These results highlight the limited adaptability of passive converters under wide load variations.

The relatively flat shape of the curves in the vicinity of the minimum indicates that the VUF exhibits moderate sensitivity to small deviations in tap position. In practical terms, this means that slight variations in transformer adjustment do not produce significant increases in voltage unbalance, which facilitates implementation in real applications.

The voltage unbalance analysed in this section has a direct effect on current distribution in the three-phase load. The presence of negative-sequence components in the voltages leads to unbalanced phase currents. It is therefore also relevant to analyse the behavior of the current unbalance factor (IUF) in order to assess how the operating conditions and the transformer tap setting influence current balance in the system.

3.2. IUF Behavior with Respect to Transformer Tap Position

Figures 6–8 present the current unbalance factor (IUF) as a function of transformer tap position for the impedance scenarios considered. In general terms, the IUF follows the

same overall trends observed for the VUF, also exhibiting a minimum in the vicinity of the nominal tap.

Relevant quantitative differences appear when the load impedance departs from the nominal value. The IUF tends to be more sensitive to load variations, which becomes more evident in Scenarios 2 and 3 (Figures 7 and 8), where the impedance range is broader. Under such conditions, small deviations in voltage balance translate into more pronounced increases in current unbalance.

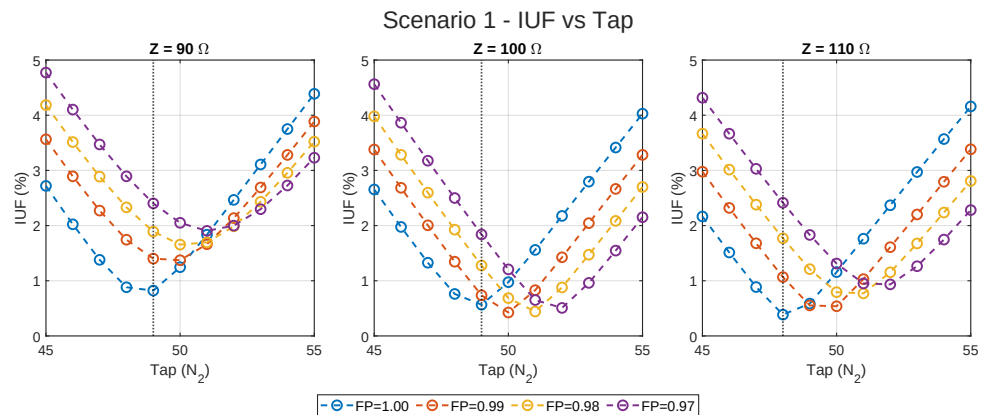


Figure 6. Scenario 1. Current unbalance factor (IUF) as a function of transformer tap position for load impedances close to the nominal value ($Z = 90\text{--}110 \Omega$) and different power factors. Each subplot corresponds to a different impedance value. The vertical dashed line indicates the tap position corresponding to the minimum VUF.

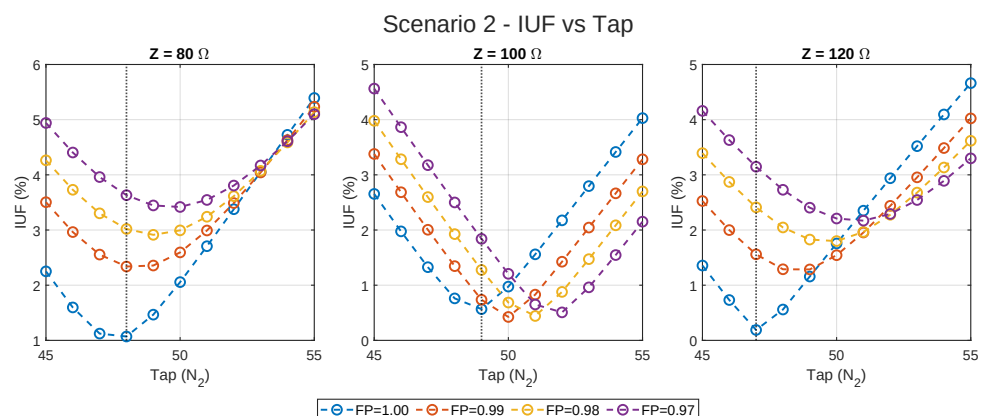


Figure 7. Scenario 2. IUF behavior for a wider range of load impedances ($Z = 80\text{--}120 \Omega$) under different power factor conditions.

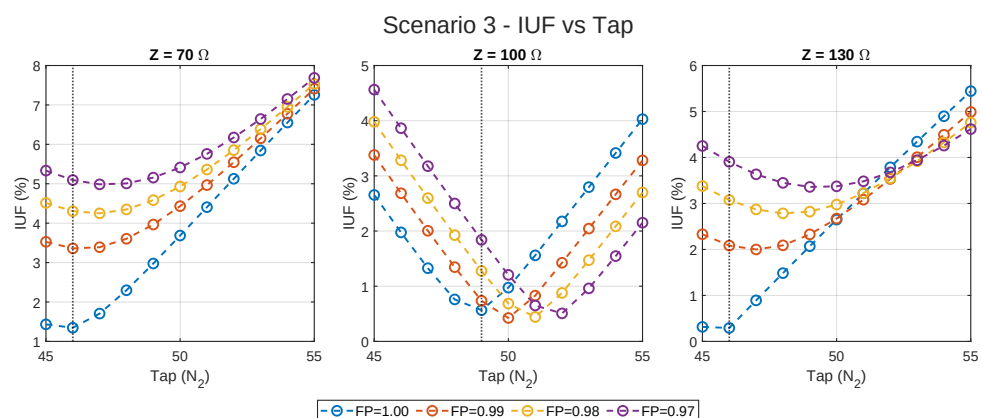


Figure 8. Scenario 3. IUF behavior for the largest deviation from the nominal load impedance ($Z = 70\text{--}130 \Omega$) under different power factor conditions.

Current balance does not depend exclusively on voltage balance, but also on the interaction between the phase-shifted voltages generated by the converter and the load impedance. Under more inductive conditions, the interaction between phase-shifted voltages and load impedance may amplify negative-sequence currents, a phenomenon also reported in comparative analyses between passive and active conversion systems [8,23,24].

Although both metrics exhibit similar trends, the IUF values differ slightly from the VUF values due to the influence of load impedance on current distribution. Nevertheless, the minimum of both quantities occurs at the same tap position in all scenarios analysed.

3.3. Neutral Current and Model Consistency

Figures 9–11 show the evolution of the neutral current I_n . In general, the transformer setting that minimizes the VUF also reduces the neutral current, indicating a simultaneous reduction in the zero-sequence current.

The neutral current is, in addition, more sensitive to impedance variations. This suggests that the voltage-optimal operating point does not necessarily guarantee minimization of residual currents under all operating conditions.

This behavior indicates the physical consistency of the model and shows that the three metrics (VUF, IUF, and I_n) must be analysed jointly in order to assess the overall balance of the system.

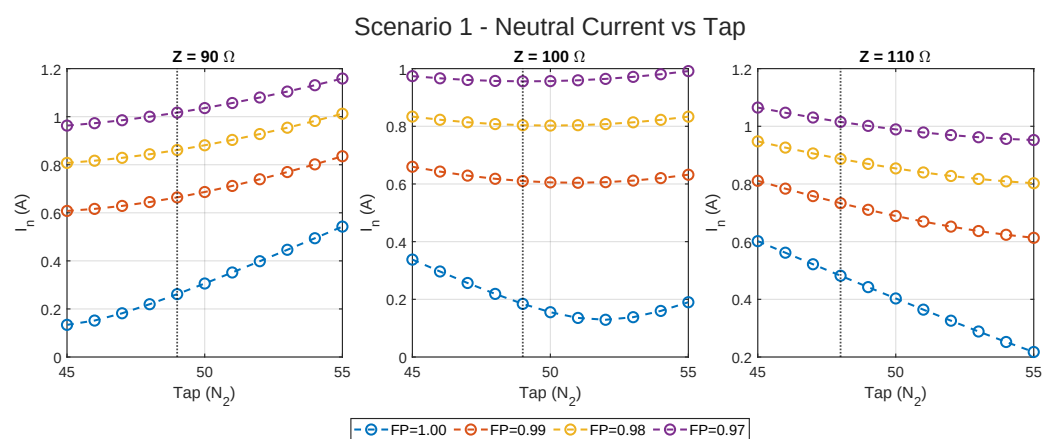


Figure 9. Scenario 1. Neutral current magnitude I_n as a function of transformer tap position for load impedances close to the nominal value ($Z = 90$ – 110Ω) and different power factors.

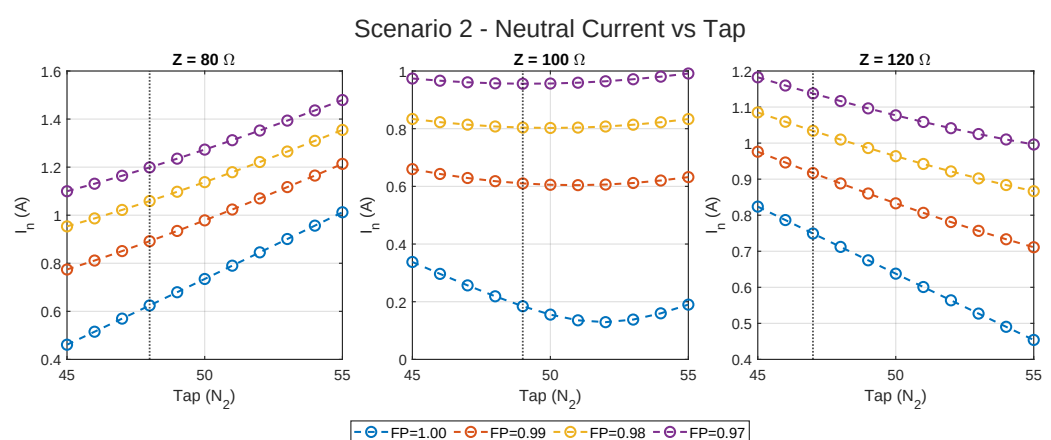


Figure 10. Scenario 2. Neutral current magnitude I_n as a function of transformer tap position for a wider range of load impedances ($Z = 80$ – 120Ω).

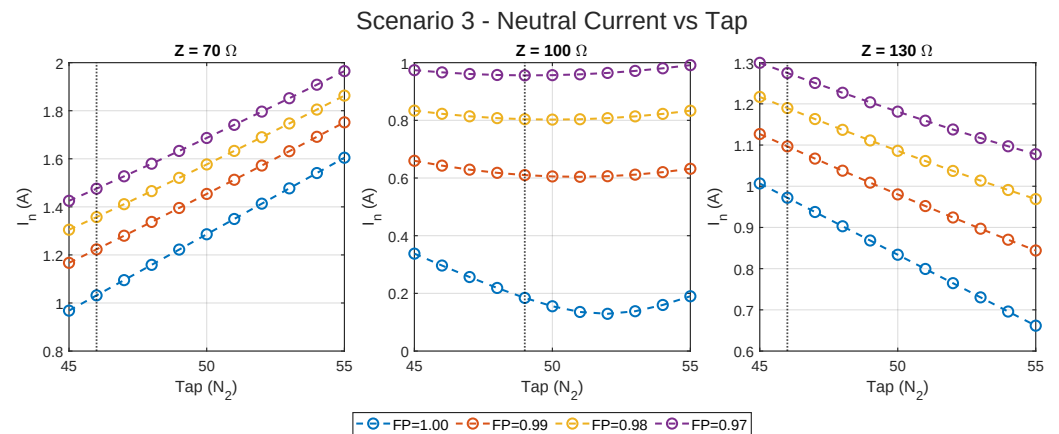


Figure 11. Scenario 3. Neutral current magnitude I_n as a function of transformer tap position for the largest deviation from the nominal load impedance ($Z = 70\text{--}130\ \Omega$).

3.4. Optimal Tap Position and Operational Robustness

Table 2 summarizes the optimal tap position N_2^* obtained by discrete VUF minimization. In general, the optimal value remains close to the nominal tap for impedances near the design condition, while larger load deviations produce slight shifts in the optimal position.

To verify that the selected search interval did not artificially constrain the optimization process, the transformer tap optimization was repeated using an expanded search interval ($N_2 = 35\text{--}65$). The verification results are summarized in Table 3. The expanded search showed that the VUF-optimal transformer tap remained within the interval $N_2 = 46\text{--}49$ for all investigated load-impedance cases, which is entirely contained within the original search interval ($N_2 = 45\text{--}55$).

Table 2. Optimal transformer tap position corresponding to the minimum VUF condition under unity power factor ($\text{PF} = 1$).

Scenario	Z_{low}	Z_{nom}	Z_{high}
1	49	49	48
2	48	49	47
3	46	49	46

Table 3. Verification of the adopted transformer tap search interval using an expanded optimization range ($N_2 = 35\text{--}65$).

Verification Item	Result
Expanded search interval	$N_2 = 35\text{--}65$
Observed VUF-optimal tap interval	$N_2 = 46\text{--}49$
Any VUF-optimal tap outside the original interval (45–55)?	No

The expanded-search verification confirms that the adopted search interval is sufficiently wide to contain all reported VUF-optimal solutions and therefore does not constrain the optimization process. However, the increase in residual unbalance under inductive scenarios highlights a limitation of the passive approach: when fixed reactive compensation is employed, the system cannot dynamically adapt to significant variations in load impedance.

From a practical perspective, these results suggest that passive single-phase to three-phase conversion is particularly suitable for low-power applications with relatively stable loads, as commonly encountered in isolated systems and rural electrification schemes [25]. In applications requiring higher levels of power quality or dynamic regulation capability,

active solutions based on power electronics provide greater flexibility and compensation capability [26].

3.5. Converter Losses and Trade-Off with Voltage Balance

In addition to voltage and current unbalance metrics, it is also relevant to evaluate the energetic performance of the converter, particularly the resistive losses associated with the passive elements and transformer equivalent series resistance. Figures 12–14 present the converter resistive losses using a bar-based representation, allowing a direct comparison across transformer tap positions and operating conditions. These results complement the VUF and IUF analysis.

An additional aspect revealed by the loss results is that the tap position that minimizes the voltage unbalance factor does not coincide with the tap yielding minimum converter losses. In all three scenarios, the converter resistive losses generally increase with transformer tap position, whereas the minimum VUF is obtained near the nominal tap region. This indicates that improving voltage balance through tap adjustment is achieved at the expense of higher internal dissipation in the passive elements and transformer equivalent resistance. Therefore, transformer tap selection should not be interpreted as a purely voltage-quality optimization variable, but rather as a parameter that introduces a trade-off between phase balance and energetic efficiency.

This trade-off becomes more evident when comparing the different impedance scenarios shown in Figures 12–14. Lower-impedance cases exhibit higher losses over the full tap range, which is consistent with the larger branch currents circulating through the passive network. By contrast, higher-impedance cases present lower overall dissipation, although the same increasing trend with tap position is preserved. From a practical viewpoint, these results suggest that the VUF-optimal tap remains attractive when voltage symmetry is the primary requirement, but the associated efficiency penalty should also be considered in real implementations. Consequently, these results suggest that transformer tap selection involves a practical trade-off between voltage balance and converter losses, motivating the additional quantitative analysis presented in the following subsection.

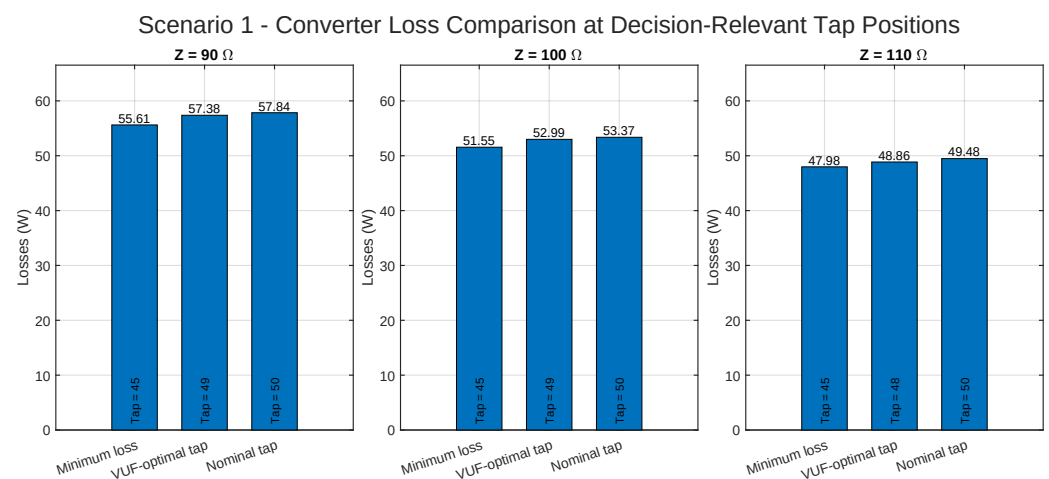


Figure 12. Bar representation of converter resistive losses for Scenario 1 as a function of transformer tap position and power factor. Each bar corresponds to a specific operating condition. A relatively narrow variation in losses is observed, indicating stable behavior across the evaluated range.

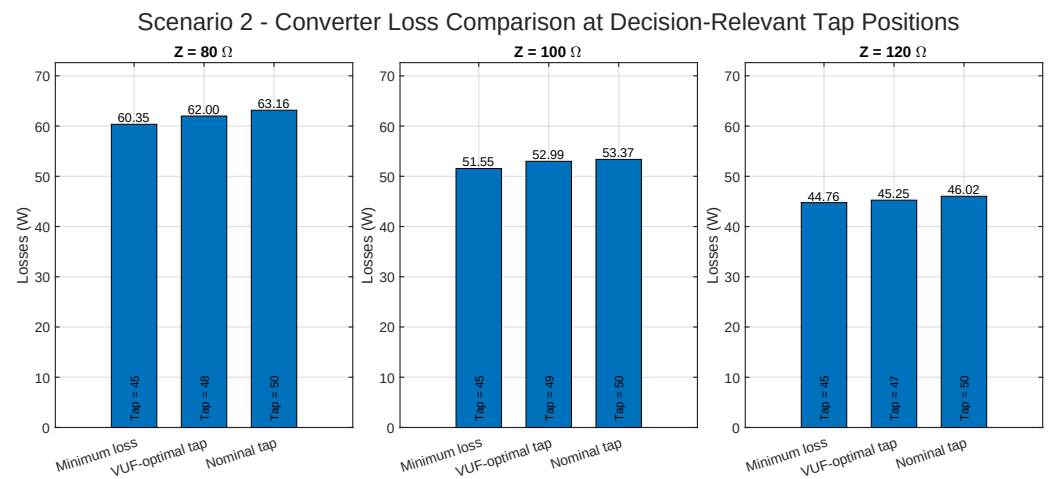


Figure 13. Bar representation of converter resistive losses for Scenario 2 under different operating conditions. Compared to Scenario 1, a wider dispersion of losses is observed, indicating increased sensitivity to variations in tap position and load conditions.

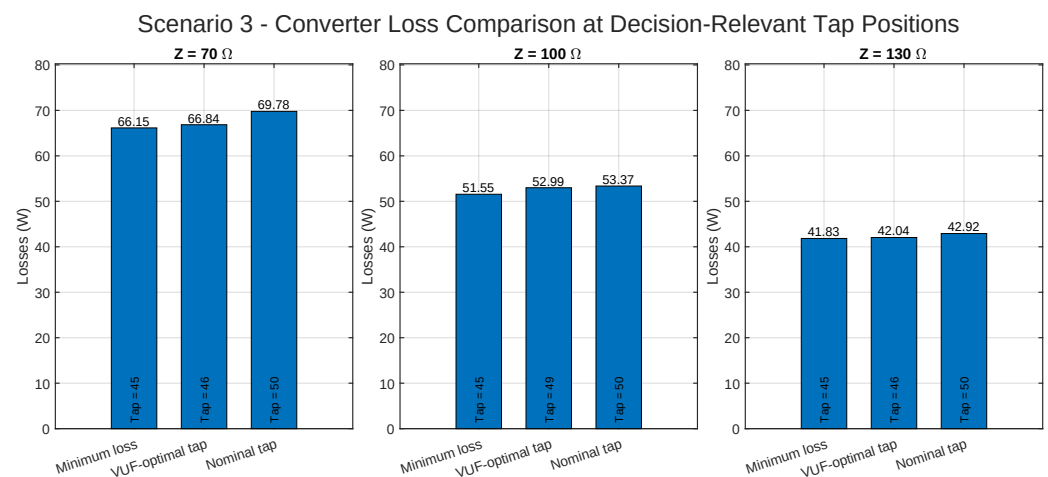


Figure 14. Bar representation of converter resistive losses for Scenario 3. A significantly wider variation in losses is observed, highlighting the strong dependence of converter performance on operating conditions and reinforcing the trade-off between loss minimization and voltage unbalance mitigation.

3.6. Combined VUF–Loss Trade-Off Analysis

Although the proposed optimization is based exclusively on the voltage unbalance factor (VUF), converter losses also constitute an important practical performance indicator. To illustrate the relationship between both criteria, a combined VUF–loss analysis was performed for the representative nominal operating condition ($Z = 100 \Omega$, $PF = 1$). Figure 15 compares the evolution of the VUF and converter resistive losses as functions of the transformer tap.

The minimum-loss operating point occurs at $N_2 = 45$, resulting in converter losses of 51.554 W and a VUF of 2.654%. In contrast, the VUF-optimal tap occurs at $N_2 = 49$, where the VUF decreases to 0.566% while the converter losses increase slightly to 52.988 W.

As summarized in Figure 15, moving from the minimum-loss operating point ($N_2 = 45$) to the VUF-optimal operating point ($N_2 = 49$) reduces the VUF by approximately 78.7% while increasing converter resistive losses by only 2.78%. These results quantitatively demonstrate that a substantial improvement in voltage balance can be achieved at the expense of only a marginal increase in converter losses, confirming the practical significance of the proposed optimization criterion without requiring a formal multi-objective optimization framework.

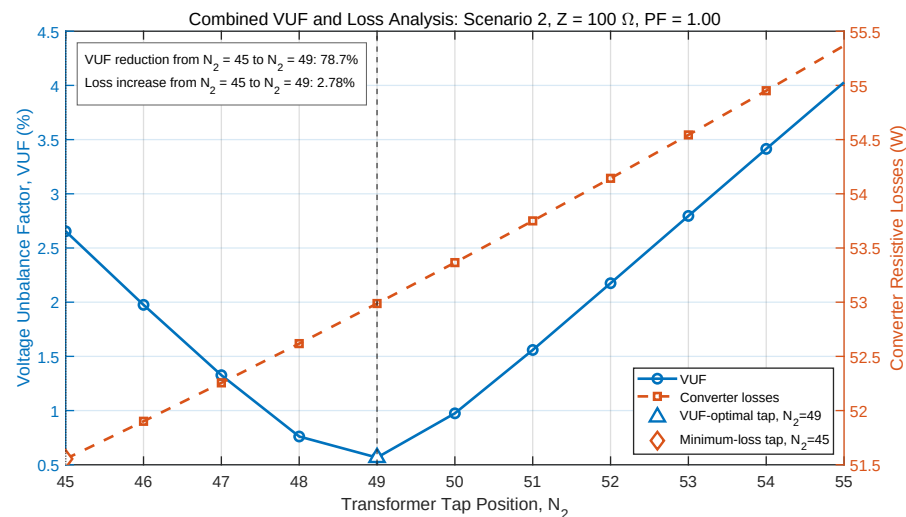


Figure 15. Combined VUF and converter-loss analysis for the representative nominal operating condition ($Z = 100 \Omega$, $PF = 1$). The VUF-optimal tap substantially improves voltage balance while introducing a comparatively small increase in converter resistive losses.

3.7. Sensitivity Analysis with Respect to the Inductor Quality Factor

The previous analyses were performed using an inductor quality factor of $Q = 20$, which was selected as a representative value for power inductors operating under nominal conditions. Since the quality factor may vary considerably depending on the winding resistance, magnetic core characteristics, manufacturing tolerances, and operating temperature, an additional sensitivity analysis was carried out to evaluate its influence on the converter performance and on the robustness of the transformer tap optimization. The analysis considers values ranging from $Q = 10$ to $Q = 80$ under the nominal operating condition ($Z = 100 \Omega$, $PF = 1$), while maintaining the same transformer tap optimization procedure adopted throughout this work.

Figure 16 presents the evolution of the transformer tap that minimizes the voltage unbalance factor as the inductor quality factor varies. Although the inductor quality factor changes by a factor of eight, the optimum transformer tap remains confined within only four adjacent discrete tap positions (47–50), corresponding to a variation of only three tap increments over the analyzed interval. Moreover, for $Q \geq 35$, the optimal solution stabilizes at tap position 50, indicating that further improvements in the inductor quality factor have virtually no influence on the optimum transformer tap. This limited variation confirms that the optimum transformer tap is only weakly sensitive to practical variations in the inductor quality factor, thereby providing quantitative evidence supporting the robustness of the proposed transformer tap optimization methodology.

The corresponding minimum voltage and current unbalance factors are shown in Figure 17. Both indicators exhibit nearly identical behaviour because, under the balanced load model adopted in this work, the voltage and current symmetrical components remain proportional. Although the minimum VUF and IUF vary moderately with the quality factor, both indicators remain below 0.7% throughout the analyzed range, which is well below the 3% graphical reference. These results indicate that variations in the inductor quality factor have only a limited influence on the voltage balancing capability of the proposed converter. This is because the transformer tap optimization is primarily governed by the phasor relationships established by the reactive network, whereas the inductor quality factor mainly affects the converter resistive losses. Therefore, the proposed optimization maintains low residual voltage-unbalance levels over a wide range of practical inductor quality factors.

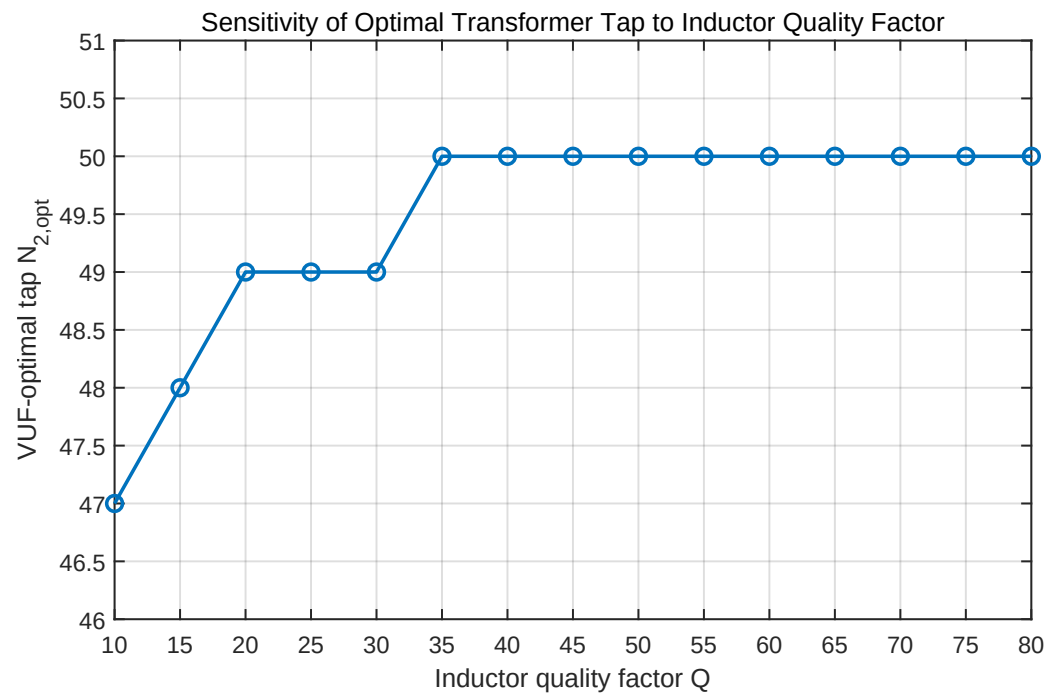


Figure 16. Sensitivity of the VUF-optimal transformer tap to variations in the inductor quality factor.

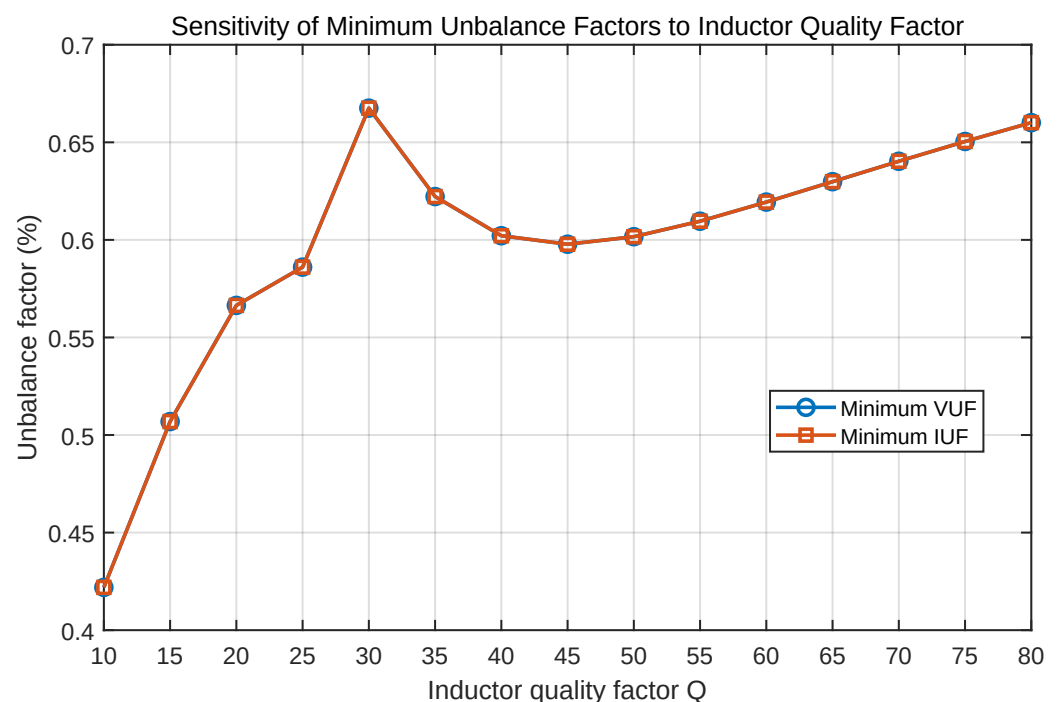


Figure 17. Minimum voltage and current unbalance factors obtained after transformer tap optimization for different inductor quality factors.

Figure 18 illustrates the influence of the inductor quality factor on two practical performance indicators evaluated at the VUF-optimal transformer tap. As expected, increasing the quality factor reduces the equivalent series resistance of the inductor, leading to a substantial reduction in converter losses. Simultaneously, the neutral current decreases monotonically as Q increases, indicating an improvement in phase current balance. These results show that, although the voltage balancing capability is only moderately affected by the quality factor, the use of higher-quality inductors provides significant benefits in terms of converter efficiency and neutral current reduction.

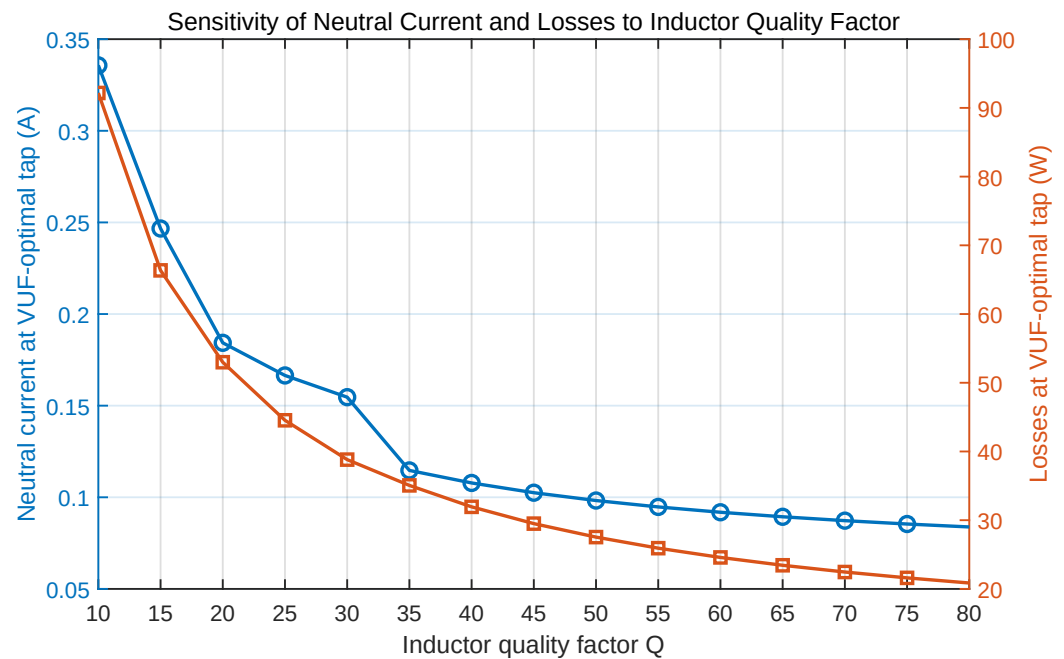


Figure 18. Neutral current and converter losses evaluated at the VUF-optimal transformer tap as functions of the inductor quality factor.

Finally, the quantitative results summarized in Table 4 confirm the trends observed in Figures 16–18. The optimum transformer tap varies only over four adjacent discrete tap positions throughout the analyzed interval, whereas converter losses decrease by more than a factor of four as the quality factor increases. Consequently, the originally selected value of $Q = 20$ can be regarded as a representative design value for the proposed converter while maintaining the general validity of the transformer tap optimization methodology over a broad range of practical inductor quality factors. These results quantitatively confirm the robustness and practical applicability of the proposed transformer tap optimization methodology.

Table 4. Sensitivity of converter performance indicators to the inductor quality factor under nominal operating conditions ($Z = 100 \Omega$, $\text{PF} = 1$).

Q	$N_{2,\text{opt}}$	Min. VUF (%)	IUF at Opt. Tap (%)	I_n at Opt. Tap (A)	Loss at Opt. Tap (W)
10	47	0.422	0.422	0.336	92.170
15	48	0.507	0.507	0.247	66.354
20	49	0.566	0.566	0.184	52.988
25	49	0.586	0.586	0.166	44.537
30	49	0.668	0.668	0.155	38.815
35	50	0.622	0.622	0.115	35.063
40	50	0.602	0.602	0.108	31.942
45	50	0.598	0.598	0.102	29.501
50	50	0.602	0.602	0.098	27.539
55	50	0.610	0.610	0.095	25.928
60	50	0.619	0.619	0.092	24.582
65	50	0.630	0.630	0.089	23.440
70	50	0.640	0.640	0.087	22.459
75	50	0.650	0.650	0.085	21.607
80	50	0.660	0.660	0.084	20.860

4. Conclusions

This work presented a steady-state phasor-based methodology for evaluating transformer tap optimization in a passive single-phase to three-phase converter employing a reactive phase-shifting network. The transformer tap was treated as a discrete optimization variable, and its influence on voltage unbalance was systematically evaluated under variations in load impedance, power factor, and inductor quality factor.

The results demonstrated that transformer tap optimization substantially reduced the voltage unbalance factor (VUF) around the nominal design condition, while quantitatively establishing the achievable operating limits of passive voltage balancing based exclusively on transformer tap adjustment.

The parametric analyses further demonstrated that the VUF-optimal transformer setting remained confined to a narrow interval under variations in load impedance and inductor quality factor, quantitatively confirming the robustness of the proposed optimization methodology. In particular, the sensitivity analysis showed that the optimum tap varied only between positions 47 and 50 over an eightfold variation in the inductor quality factor, while the minimum voltage and current unbalance factors remained below 0.7% throughout the analyzed range.

The complementary VUF–loss analysis demonstrated that improving voltage balance is accompanied by a small increase in converter losses, quantitatively confirming the practical trade-off between power quality and energetic efficiency. Consequently, future developments of the proposed methodology may consider multi-objective optimization strategies that simultaneously account for voltage unbalance and converter losses. Such an extension would be consistent with recent optimization trends in power systems aimed at simultaneously improving voltage quality and operational performance, although adapted here to the design of passive single-phase to three-phase converters rather than actively controlled distribution networks [17,20].

The proposed methodology is limited to steady-state sinusoidal operation and idealized component models. Future work should incorporate nonlinear magnetic effects, harmonic distortion, transient phenomena, and experimental validation in order to evaluate the proposed approach under practical operating conditions.

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