

A COMPARATIVE ANALYSIS OF EUROPEAN AND AMERICAN REGLEMENTATIONS USED IN POWER QUALITY INVESTIGATIONS

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Abstract. *In the realm of electrical engineering, standards play a pivotal role in ensuring the quality and reliability of electrical systems. This paper conducts a comprehensive comparative analysis of the Institute of Electrical and Electronics Engineers (IEEE), International Electrotechnical Commission (IEC), and European Committee for Electrotechnical Standardization (CENELEC) standards, with a particular focus on power quality engineering. Specifically, it focused on key parameters such as the K-factor, the factor K, the Harmonic Loss Factor FHL and the unbalanced factor. By elucidating the differences and similarities between these standards, this study aims to provide insights into their respective impacts on electrical infrastructure, guiding engineering practices, and facilitating global trade. Understanding the regional applicability and industry impact of IEEE, IEC, and CENELEC standards is essential for engineers, manufacturers, and policymakers to navigate the complexities of electrical quality engineering in a diverse and interconnected world.*

Keywords: power quality, standards, IEEE, IEC, CENELEC, international standards, harmonics, distorting regime, asymmetric regime.

1. INTRODUCTION

The global landscape of electrical engineering is shaped by a myriad of standards and regulations aimed at ensuring the efficiency, reliability, and safety of electrical systems. Among these, European and American standards stand as pillars in guiding the design, installation, and operation of electrical infrastructure. However, differences exist between these standards, stemming from historical, cultural, and regulatory contexts.

In the domain of electrical power quality, a multitude of distinct sources of disturbances manifest. They can alter the measured parameters with negative effects. These types of disturbances are categorized as: long-term interruptions, faults (short-term interruptions, voltage gaps, over-voltages, and frequency deviations), and disturbing loads (rapid voltage variations, flicker, unbalance (asymmetry), harmonics, inter-harmonics, transient regimes, and direct current components) [1]. In the analysis of power quality, two of these types of disturbances are thoroughly examined, and both European and American standards have developed their own parameters for them. The two analyzed sources are harmonics corresponding to the distorting regime and

asymmetries corresponding to the asymmetric regime.

European standards, typified by the International Electrotechnical Commission (IEC) [2] and European Committee for Electrotechnical Standardization (CENELEC) [3] framework, emphasize a harmonized approach to electrical quality engineering. The IEC 61000 series [4] delineates comprehensive guidelines for reducing electromagnetic interference (EMI) and addressing harmonic distortions in power systems. By imposing stringent limits on harmonics, European standards prioritize system stability and compatibility with sensitive electronic equipment.

In contrast, American standards, predominantly governed by the Institute of Electrical and Electronics Engineers (IEEE) [5], adopt a more flexible approach towards harmonic reduction. The IEEE 519 standard [6] delineates guidelines for harmonic control in power systems. It reflects a pragmatic stance, accommodating the diverse needs of industrial, commercial, and residential applications while balancing system performance and cost considerations.

2. KEY DISTINCTIONS BETWEEN STANDARDS

The differences between American and European standards in electrical engineering come from various factors including historical background, regulatory frameworks, industrial practices, and cultural influences. Listed below are some key distinctions.

Regulatory Bodies: In the United States, electrical engineering standards are predominantly set by organizations such as the Institute of Electrical and Electronics Engineers (IEEE) and the National Electrical Manufacturers Association (NEMA) [7]. These organizations develop and maintain standards in collaboration with industry stakeholders. In contrast, Europe relies on the International Electrotechnical Commission (IEC) for the development of harmonized standards across member countries. IEC may be an international commission, but European standards are based on those standards. In Europe there are also the European Standards (EN) that are technical standards drafted and maintained by European Committee for Standardization (CEN), European Committee for Electrotechnical Standardization (CENELEC) and European Telecommunications Standards Institute (ETSI)

[8]. EN standards are European adaptations of international standards developed by the IEC. They reflect regional considerations while maintaining alignment with global practices, ensuring interoperability and safety across borders.

Approach to Harmonization: European standards, guided by the principles of the European Union (EU), tend to emphasize harmonization and standardization across member states. This approach facilitates interoperability, promotes cross-border trade, and ensures consistency in technical requirements. In contrast, the United States follows a more decentralized approach, with standards varying across states and industries. While federal agencies such as the National Institute of Standards and Technology (NIST) [9] may set guidelines, compliance is often voluntary or enforced at the state level.

Flexibility in Industries: IEEE standards often offer flexibility to accommodate the dynamic nature of technological advancements and industry practices, allowing for customization based on specific applications. They are heavily influenced by industry stakeholders, with active participation from engineers, manufacturers, researchers, and policymakers in their development and revision processes. The result of industry influence is the frequent prioritization of innovation and new emerging technologies, fostering advancements in areas such as power systems, telecommunications, and electronics. IEC standards aim for global harmonization, providing a common framework for electrical engineering practices and regulations across different countries and regions. They are adopted by national standards bodies worldwide, providing a foundation for regulatory compliance and facilitating international trade and cooperation. EN standards are tailored for the European market, reflecting the specific needs and regulatory requirements of European Union (EU) member states and European Economic Area (EEA) countries. They align closely with EU directives and regulations, ensuring conformity with European legislation on safety, environmental protection, and market access. EN standards promote interoperability and compatibility of electrical products and systems within the European Single Market, facilitating trade and harmonization across borders. One can say that this need for international compatibility between electrical systems regulations may decrease flexibility in specific limits for special applications, but it makes standard easier to enact and follow.

Voltage and Frequency: One of the fundamental differences between American and European electrical systems is the standard voltage and frequency. In Europe, the standard voltage is typically 230 volts at 50 Hz, whereas in the United States, it is 120 volts at 60 Hz. These variations necessitate different standards for equipment design, installation, and safety considerations. Safety Regulations: Both American and European standards prioritize safety in electrical engineering, but the specific regulations and testing procedures may differ. For example, European standards may adhere to the Low Voltage Directive (LVD) [10] and the Electromagnetic

Compatibility (EMC) Directive [11], which mandate safety and compatibility requirements for electrical products sold in the EU market. In the United States, safety standards are enforced by organizations such as the Occupational Safety and Health Administration (OSHA) [12] and the Consumer Product Safety Commission (CPSC) [13].

Adoption and Enforcement: IEEE standards are often adopted voluntarily by industries and may be referenced in regulatory frameworks or contractual agreements. In Europe IEC standards are widely adopted internationally and may be incorporated into national or regional regulations in many countries. EN standards are mandatory for compliance within the European Union (EU) market and are often referenced in EU directives and regulations.

Terminology and Units: Differences in terminology and units of measurement also exist between American and European standards. For instance, European standards often use the metric system (e.g., millimeters, kilograms) and adhere to the International System of Units (SI). In contrast, American standards may incorporate both metric and imperial units (e.g., inches, pounds) depending on industry conventions and historical practices.

Focused Specific Standards: In American standards IEEE 519 [6] is a notable standard focusing on harmonic control in electric power systems, addressing issues related to power quality. The standard specifies limits for harmonic distortion based on the system voltage and the type of electrical load. These limits are expressed in terms of voltage or current distortion at various harmonic frequencies. Different categories of electrical systems (e.g., residential, commercial, industrial) may have different harmonic limits to reflect their unique characteristics and requirements. In Europe the IEC 61000 [4] series is composed of standards related to electromagnetic compatibility (EMC), including measures to diminish harmonics and ensure power quality. The standards within the IEC 61000 series are intended to be globally applicable, providing a common framework for addressing EMC issues across different countries and industries.

Overall, while American and European standards share common objectives of ensuring the safety, reliability, and efficiency of electrical systems, their different approaches reflect the unique regulatory environments and industrial landscapes of each region. Understanding these differences is essential for engineers, manufacturers, and policymakers involved in the design, implementation, and regulation of electrical infrastructure.

In this chapter there were presented general key distinctions between American and European standards in electrical engineering that are applied to the domain of power quality. In the next chapter, the differences concerning parameters, indicators, and outcomes will be analyzed. This will give a more specific point of view between the differences in standards.

3. SPECIFIC DISTINCTIONS BETWEEN STANDARDS

In this chapter, various indicators of electrical power quality will be analyzed for different operating regimes, thereby considering different sources of disturbances. Both the equations of the indicators and the results and parameters they entail will be studied.

Regarding the analysis of the distorting regime, this corresponds to harmonic disturbances. Currently, the proportion of nonlinear equipment (such as photovoltaic systems for energy production, high-efficiency lighting fixtures, electric vehicle charging stations) exceeds that of linear equipment [14-17].

Electric distribution transformers represent one of the most important classes of equipment analyzed in the field of electrical power quality. Their malfunction can lead to waveform distortion of the current flowing through the transformer windings. To minimize undesired negative effects, limitation of the maximum overload is conditioned, a procedure known as derating of the transformer parameters [18-20].

For the analysis of electrical power quality, the most used factors are total harmonic distortion (THD), distortion factor (DF), crest factor (CF), and harmonic loss factor (F_{HL} , sometimes denoted as KF) [21]. To numerically assess the additional losses generated by harmonic currents in transformers, two specific parameters of power quality have been defined [22-24]: the harmonic loss factor (F_{HL} or KF), and the harmonic loss factor for other stray losses (F_{HL-STR}). The F_{HL} factor is a measure of losses due to eddy currents generated in windings by higher harmonics, while the F_{HL-STR} factor quantifies losses in other transformer components (tank, stiffening elements, etc.) due to the same higher harmonics. The F_{HL-STR} indicator is exclusively used for oil-filled transformers [21].

The difference between American and European standards lies in the definition of the derating factor for nonlinear distribution transformers. The American standard [25] defines the harmonic loss factor (F_{HL}). An additional derating factor is described by the company Underwriters Laboratory, known as UL K -factor or simply K -factor [26,27]. This factor is generally adopted for dry-type transformers of lower powers and depends on both the harmonic current spectrum at the secondary and its nominal value I_{R2} [21]:

$$F_{HL} = \frac{\sum_{k=0}^N k^2 I_k^2}{\sum_{k=0}^N I_k^2} = \frac{1}{I^2} \sum_{k=0}^N k^2 I_k^2, \quad (1)$$

$$F_{HL-STR} = \frac{\sum_{k=0}^N k^{0.8} I_k^2}{\sum_{k=0}^N I_k^2} = \frac{1}{I^2} \sum_{k=0}^N k^{0.8} I_k^2, \quad (2)$$

$$\begin{aligned} K - factor &= \frac{1}{I_{R2}^2} \sum_{k=0}^N k^2 I_k^2 = \frac{F_{HL}}{I_{R2}^2} \sum_{k=0}^N I_k^2 = \\ &= F_{HL} \left(\frac{I}{I_{R2}} \right)^2 = F_{HL} \beta^2. \end{aligned} \quad (3)$$

As it can be observed from the equation above, the American-origin factor known as K -factor is proportional to the transformer harmonic loss factor F_{HL} and the square of its loading β . The loading β is represented by the ratio of the effective value of the non-sinusoidal current at the secondary to its nominal value.

Using American standards for calculating the maximum permissible current, it can be expressed as a function of loading β with the following formula. In this case the additional losses compared to those due to eddy currents are considered negligible [21]:

$$\begin{aligned} I_{MPC}^K (\text{p.u.}) &= \beta_{\max}^K = \sqrt{\frac{P_{LL-R}}{P_{DC-R} + P_{EC-R} F_{HL}}} = \\ &= \sqrt{\frac{1 + P_{EC-R} (\text{p.u.})}{1 + P_{EC-R} (\text{p.u.}) F_{HL}}}, \end{aligned} \quad (4)$$

It can be observed that ultimately the maximum permissible current will depend on the nominal losses due to eddy currents (P_{EC-R}) and the transformer harmonic loss factor (F_{HL}).

In European standardization (EN/CENELEC), the derating of transformers is characterized by the derating factor K . This factor considers the harmonic spectrum of the current at the secondary, its fundamental harmonic I_1 , as well as the constructive peculiarities of the secondary winding conductor [21].

$$Factor K = \sqrt{1 + \frac{e}{1+e} \left(\frac{I_1}{I} \right)^2 \sum_{k=2}^N k^q \left(\frac{I_k}{I_1} \right)^2}, \quad (5)$$

Where:

- e represents the ratio of losses due to eddy currents in the transformer at the fundamental frequency to losses in windings supplied with direct current at a value equal to the effective value of the nominal current (a constant that must be entered by the user of the measuring device).
- q is a constant depending on the type of winding and the nominal frequency of the transformer. Typical values are 1.7 for transformers with windings made of round or rectangular section conductors and 1.5 for those with windings in conductor foils (a constant that must also be entered by the user of the measuring device).
- I is the effective (true RMS) value of the non-sinusoidal current.
- I_k is the effective value of the harmonic current of order k .
- I_1 is the effective value of the fundamental current [28].

Using European standards for calculating the maximum permissible current, it will depend solely on the derating factor K , being inversely proportional to it.

$$I_{MPC}^{Factor K} (\text{p.u.}) = \beta_{\max}^{Factor K} = \frac{1}{Factor K}. \quad (6)$$

The values of these derating factors, calculated using each method separately (using either American or European standards), are numerically different. "*Factor K*" is a "total" derating factor (allowing for direct assessment of maximum power), whereas "*K-factor*", F_{HL} or F_{HL-OSL} , are different for any harmonic (the derating level of the transformer can be determined using their value indirectly). The fact that both methods use the notation K as a name can lead to confusion. Consequently, to be used correctly, the value of a derating factor must be accompanied by an indication of the calculation method used or the standard used [21]. In addition to the derating factor, another difference between standards is the determination of reactive power. Most measuring instruments analyze reactive power according to the definition given by Budeanu, a definition specific to European standards. It is not a unique definition but serves as the basis for other definitions in non-sinusoidal regimes. There is also a definition provided by Fryze [29,30], by American origin, in which reactive power coincides with non-active power.

$$Q = \sum_{k=1}^{\infty} U_k I_k \sin \varphi_k = \sum_{k=1}^{\infty} Q_k = Q_1 + Q_H, \quad (7)$$

$$Q = N = \sqrt{S^2 - P^2}.$$

Next, a real technical scenario will be analyzed, focusing on a comparison between the derating parameters of American and European standards. In [21], a distribution transformer with a nominal power of 160 kVA that supplies a pumping station with induction motors is analyzed [31]. The results are presented in Table 1.

Table 1. Transformer derating reports according to various standards [21].

International standards	American Standard	European Standards
Derating factors	$F_{HL} = 20.308$ $F_{HL-STR} = 2.512$	$Factor K = 1.576$
β	0.542	0.634
S_m [kVA]	86.829	101.493

It is notable that the derating factor analyzed according to the American standard has a much higher value than that analyzed according to the European standard. This detail occurs from the fact that IEEE standards do not require knowledge of the transformer's constructional data, resulting in a more general value that allows for a certain margin of safety deviation, a small error. Under the European standard, we observe a lower and more precise value of the derating factor. In calculating power [21], both powers are diminished, with a greater reduction being observed in the case of the American standard, at 45%, compared to the European standard's 36%. This substantial reduction in available power

indicated by both standards underscores the significance of losses due to eddy currents [21]. Currently, electrical power quality analyzers can determine parameters according to both American and European standards, the user being the one who selects which standard to use.

The next step in this article involves analyzing the differences between parameters of American and European standards regarding the asymmetrical regime of electrical installations. This analysis exclusively relates to three-phase systems of sinusoidal magnitudes with unequal effective values or unequal phase angles between successive phases. A symmetric system has a phase angle of $2\pi/3$ between any two successive phases.

To approximate the degree of asymmetry of the system, certain quantitative indicators have been defined. Currently, two different methods of defining these parameters are being pursued, according to the European standard [32] or the American standard [33]. It is crucial to know the standard used in calculations to avoid misuse of measurement devices (electrical energy quality analyzers). The indicators defined for both standards can target both voltage and current, and in the following equations, it will be used the notation for current.

According to the European standard, based on Fortescue's decomposition theory, the symmetrical sinusoidal three-phase system $\underline{I}_A, \underline{I}_B, \underline{I}_C$ is decomposed into three independent single-phase systems: the positive sequence (direct) $\underline{I}^+$, the negative sequence (inverse) $\underline{I}^-$, and the zero sequence (homopolar) $\underline{I}^0$. This decomposition considers both magnitude asymmetry and phase angle asymmetry [28].

$$\begin{bmatrix} \underline{I}^0 \\ \underline{I}^+ \\ \underline{I}^- \end{bmatrix} = \frac{1}{3} \cdot \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \cdot \begin{bmatrix} \underline{I}_A \\ \underline{I}_B \\ \underline{I}_C \end{bmatrix}, \quad (8)$$

$$a = e^{j\frac{2\pi}{3}} = -\frac{1}{2} + j\frac{\sqrt{3}}{2}.$$

Based on the sequence components defined above, asymmetry regime indicators can be determined according to the European standard. The indicators are as follows:

- The negative sequence asymmetry factor k^- (unbalance factor) is defined as the ratio between the effective value of the negative sequence component $\underline{I}^-$ and the effective value of the positive sequence component $\underline{I}^+$.
- The zero-sequence asymmetry factor k^0 is defined as the ratio between the effective value of the zero-sequence component $\underline{I}^0$ and the effective value of the positive sequence component $\underline{I}^+$. This indicator appears only in systems where the value of the homopolar sequence is non-zero, namely those in star configuration with a neutral conductor. In other situations, the homopolar component will be zero.

$$k_I^- = \frac{\left| \frac{I^-}{I^+} \right|}{\left| \frac{I^-}{I^+} \right|} \cdot 100\% = \frac{I^-}{I^+} \cdot 100\%, \quad (9)$$

$$k_I^0 = \frac{\left| \frac{I^0}{I^+} \right|}{\left| \frac{I^-}{I^+} \right|} \cdot 100\% = \frac{I^0}{I^+} \cdot 100\%.$$

The negative sequence asymmetry factor is the most important indicator in evaluating asymmetry. For this reason, there are various regulations that establish maximum limits for this parameter beyond which the system is unsymmetrical [30]: for voltage, typically around a maximum of 4-5%, and for current, 20-30%.

The use of these factors defined by European standards unfortunately involves a crucial issue. In defining the terms Fortescue's theorem is utilized, a theorem that involves purely sinusoidal quantities, which is not applicable to modern electrical installations. As a result, it has been established [29, 30, 34, 35] that the assessment of asymmetry can only be associated with fundamental quantities. This initially requires a Fourier decomposition of the quantities before applying Fortescue's theorem. By extension, positive, negative, and zero components have been associated with the other harmonics resulting from the decomposition of sinusoidal quantities [28].

Unlike the European standard, which relies on the sequence components of the quantities, the American standard [33] is based on the measured effective values of the quantities analyzed across the three phases (I_A , I_B , I_C). This mode of analysis does not consider the presence of distorting regimes or phase shifts between the phase quantities. The indicator defined by American standards is the asymmetry factor, k_s , and it has the following formula:

$$k_{sI} = \max_{k \in A, B, C} (k_{sIk}) \cdot 100\%,$$

$$k_{sIA} = \frac{I_A - I_{med}}{I_{med}}, \quad k_{sIB} = \frac{I_B - I_{med}}{I_{med}}, \quad (10)$$

$$k_{sIC} = \frac{I_C - I_{med}}{I_{med}}, \quad I_{med} = \frac{I_A + I_B + I_C}{3}.$$

In assessing asymmetry using American standards, valuable information can be provided regarding the three-phase voltage system, which in most modern electrical systems is sinusoidal. However, when analyzing current systems, American standards do not provide accurate and conclusive information due to the excessively high harmonic distortion they exhibit [28].

In practice, a significant difference has been observed between the asymmetry indicators defined by the two standards. Differences of up to 20% have been noted between the indicators established by European standards and those by American standards.

A particular situation that presents standardized differences between European and American standards is the quality of electrical energy in the field of renewable energy production using photovoltaic panels. American standards are guided by IEEE 1547, which had its latest

comprehensive revision in 2018 [36]. European standards are represented by the German standards, which are part of the VDE-AR-N series. A first comparison between standards is made by analyzing the voltage amplitude at the connection point. In German standards the voltage amplitude change of common connection points should not exceed 2% and the low voltage should not exceed 3% compared with that of no distributed photovoltaic connection. American standards had a slightly different approach: the voltage of the grid-connected access point of distributed power supply with capacity less than 10MVA is less than $\pm 5\%$ [36, 37].

Another difference that these standards have is the power factor requirements. The European standard mandates that the apparent power factor above 4.6kVA should be in 0.9 (leading) to 0.9 (lagging) and less than 4.6kVA power factor should be 0.95 (leading) to 0.95 (lagging). On the other hand, the American standards doesn't have a standardized value for its power factor. Analyzing the active power control requirements, the American standards requires that the distributed photovoltaic system has active power control capability and can respond to power grid dispatching instructions within 30s. The German standards requires that all distributed photovoltaic systems have active power control capability and can be adjusted to 100%, 60%, 30% or 0% of the maximum power according to the power command of the grid common connection point [36].

Another numeric difference between standards is the percentage limits to voltage unbalance, a more general consideration of the waveform. This limit is considered 3% by ANSI standards and 2% by IEC and IEEE standards [38]. As it can be seen American and European standards agree on the limit of 2%, but, with some American standards being more diverse through purpose the limit is still acceptable at 3%. The difference between standards can also be observed in the voltage unbalance equation. The NEMA standard proposes an equation where it uses only the line voltages. Phase voltages are not used because the phase voltage unbalance does not influence the unbalance percentage, so, they can be neglected [38].

$$\%V_{UNB} = \frac{\text{Max Deviation from Average}}{\text{Average of Three L-L Voltage}} \cdot 100\%. \quad (11)$$

On the other hand, the IEEE standards consider only the phase voltage, this equation being known as the phase voltage unbalanced rate [38]. The IEC standards consider the symmetric components of the voltage unbalance, the equation being a ratio of the amplitude of the negative sequence component of the voltage V^- to the amplitude on the positive V^+ sequence [38].

$$\%V_{UNB} = \frac{\text{Max Deviation from Average}}{\text{Average of Three Line Voltage}} \cdot 100\%, \quad (12)$$

$$\%V_{UNB} = \frac{V^-}{V^+} \cdot 100\%.$$

These three formulas based on different standards were tested [38] with the purpose of evaluating the power

quality of a MV grid with the help of a IEC61000-4-30 Class A power quality analyzer. The study has concluded that the IEC standard focuses on the unbalance between the voltage magnitude and phase angles. Unfortunately, this formula has some disadvantages such as: it can detect false unbalances that do not exist, it can determine lower values than the real ones and it can cause difficulties in calculating the parameters. On the other hand, the definitions provided by NEMA and IEEE are more accurate because they evaluate the voltage difference between voltage values in three phases.

In addition to these two types of analyzed regimes, namely the distorting and asymmetrical regimes, there are many other power quality indicators defined according to either European or American standards that may correspond to other sources of disturbances [34, 39, 40].

4. CONCLUSIONS

In conclusion, this comparative analysis of European and American standards in power quality engineering reveals significant differences in approaches, methodologies, and outcomes. European standards, exemplified by the International Electrotechnical Commission (IEC) and European Committee for Electrotechnical Standardization (CENELEC), prioritize harmonization and standardization across member states, promoting system stability and compatibility with sensitive electronic equipment. In contrast, American standards, predominantly governed by the Institute of Electrical and Electronics Engineers (IEEE), adopt a more flexible approach that accommodates the diverse needs of industrial, commercial, and residential applications.

Differences in terminology, flexibility, and safety regulations underscore the divergent approaches between American and European standards. While both prioritize safety and reliability, the specific regulations and testing procedures may vary, leading to differences in compliance requirements and enforcement mechanisms.

Moreover, the analysis highlights specific differences in parameters such as derating factors for transformers, asymmetry indicators, and power factor requirements. These variations can have significant implications for the design, operation, and maintenance of electrical systems, particularly in the context of renewable energy production and distributed generation.

The derating factor in American standards significantly exceeds that of European standards due to less stringent construction requirements. This discrepancy underscores the importance of considering eddy current losses in power calculations. Power quality analyzers now support both American and European standards, giving users flexibility in their choice. As far as asymmetry indicators go, the gap between the parameters defined by European standards and American standards is even bigger, for up to 20%.

Overall, understanding these differences is crucial for engineers, manufacturers, and policymakers involved in

the design, implementation, and regulation of electrical infrastructure. By recognizing the distinct regional approaches and standards, stakeholders can navigate the complexities of power quality engineering more effectively, ensuring the safety, reliability, and efficiency of electrical systems in a diverse and interconnected world.

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