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Strategies for Harmonic Mitigation in Water Pumping Systems Using Neutrosophic Logic.

Jefferson A. Porras [1], Luis R. Curipoma [2], Byron P. Corrales [3] and Jorge L. Villarroel [4]

[1] Universidad Técnica de Cotopaxi, Latacunga, Faculty of Engineering and Applied Sciences. Ecuador. jefferson.porras0449@utc.edu.ec
[2] Municipal Public Company for Potable Water and Sewerage of Ambato EP-EMAPA-A, Ecuador. luis.curipoma8@utc.edu.ec
[3] Universidad Técnica de Cotopaxi, Latacunga, Faculty of Engineering and Applied Sciences. Ecuador. byron.corrales@utc.edu.ec
[4] Universidad Técnica de Cotopaxi, Latacunga, Faculty of Engineering and Applied Sciences. Ecuador. jorge.villarroel3491@utc.edu.ec

Abstract. This study analyzed harmonic contamination in Quillán 1 and Quillán 2 pumping stations, characterizing the electrical system conditions and proposing solutions that addressed actual operational requirements. High levels of harmonic distortion were identified, particularly in 5th and 7th order harmonics, which exceeded the limits established by national regulations, despite the system presenting adequate energy utilization. To select the most appropriate mitigation strategy, the TOPSIS method under neutrosophic logic was applied, which allowed the integration of expert perception and the inherent indetermination margins of such systems. This logic, which simultaneously considers degrees of truth, falsehood, and uncertainty, enabled the evaluation of solutions without forced simplifications. The highest-rated option was the implementation of tuned passive filters, which were subsequently designed, simulated, and validated through specialized tools. The simulations demonstrated a substantial reduction of critical harmonics and a general improvement in power quality, ensuring regulatory compliance. The study highlighted the importance of using neutrosophic logic in combination with multicriteria decision methods as an effective resource for addressing complex electrical problems in real technical contexts, where absolute precision is not always possible or desirable.

Keywords: Neutrosophic logic, harmonics, water pumping, multicriteria decision-making, TOPSIS, power quality.

1. Introduction

In recent years, the growing presence of electronic devices in industry has profoundly transformed electrical systems. Equipment such as frequency drives, converters, and other nonlinear loads have become indispensable for process optimization [1], but they have also brought with them a problem that is not always addressed with the attention it deserves: harmonic contamination [2]. This distortion of current and voltage waveforms, caused by the nonlinear nature of such devices, has begun to compromise power quality in many industrial installations, affecting not only the equipment that generates them, but also those that simply share the same network [3].

The impact of harmonics is neither an isolated nor local phenomenon. On the contrary, it is a global challenge affecting electrical networks in various productive contexts. The most evident effects include conductor overheating, premature transformer failures, reduced equipment lifespan, and noise presence in communication systems [4]–[6]. In environments where electrical reliability is crucial, such as pumping stations, these consequences can result in considerable economic losses and technical compromises that jeopardize operational continuity.

In response to this problem, international organizations have established regulations that set limits for acceptable harmonic distortion. However, compliance in real contexts often presents difficulties. The complexity of industrial electrical systems, with multiple harmonic sources interacting simultaneously, prevents a simple or universal solution. Furthermore, traditional measures, such as installing reactors or disconnecting sensitive equipment, while useful in certain cases, prove to be unfeasible or insufficient when maintaining energy efficiency and system operability is required.

The search for more effective solutions has led to the development and implementation of filters, as well as transformer reconfiguration and other mitigation strategies. However, the choice among these alternatives cannot be made arbitrarily. Multiple criteria must be considered to obtain the best results. Added to this is an element that is often overlooked: the inherent uncertainty of the data, both technical and subjective, that feeds the decision-making process [7],

In this scenario, traditional analysis methods present certain limitations. Deterministic approaches, for example, tend to assume ideal conditions that rarely occur in practice. Similarly, classical simulation models, although valuable, do not always manage to incorporate the real variability of loads or the differences in expert evaluations. Hence arises the need for more flexible methods that allow not only representing the technical complexity of the system, but also capturing the ambiguity and imprecision of available data [8].

A promising alternative is offered by the combination of multicriteria decision techniques with neutrosophic logic. This logic, which allows working with simultaneous degrees of truth, falsehood, and indetermination, is especially useful in environments where data are not entirely clear or are influenced by subjective judgments [9]. The integration of models such as TOPSIS within a neutrosophic framework allows evaluating alternatives under a more realistic scheme, where absolute certainty is not required, but rather a more faithful representation of the uncertain and changing nature of industrial electrical systems [10].

Applying this approach, the present research aimed to study the phenomenon of harmonic contamination in two pumping stations of the drinking water system: Quillán 1 and Quillán 2. The objective was to characterize the harmonic conditions of each station and identify the most appropriate strategies to mitigate their effects through the use of neutrosophic logic.

This work not only responds to a specific technical need but also seeks to provide a methodological tool that allows engineers and electrical operation managers to make more informed, transparent, and reality-adapted decisions for their installations. In contexts where technical precision must coexist with adaptability and expert judgment, these types of hybrid approaches present themselves as a solid path toward more sustainable and effective solutions.

2. Methods

The research was developed following a sequential mixed approach, whose purpose was to characterize the presence of harmonic distortion in two pumping stations belonging to the Municipal Public Company for Drinking Water and Sewerage of Ambato: Quillán 1 and Quillán 2. For this purpose, in-situ measurements, computational simulations, and evaluation through neutrosophic logic were integrated in an articulated and staged manner. The methodological decisions responded to the need to understand the behavior of the electrical system against nonlinear loads and to assess possible mitigation strategies.

The two selected stations operated with identical technical configurations: each had two 300 HP pump-motor sets, coupled with six-pulse frequency drives (NIDEC M600 and Schneider ATV930 models), connected to 750 kVA distribution transformers (13,800/440 V ratio). The measurements were concentrated on the low voltage side of the transformers, according to the system's single-line diagram.

With the purpose of capturing the harmonic characteristics of the system, AEMC 3945-B network analyzers were installed in both stations. This equipment remained operational during a continuous period of seven days, with a sampling interval of five minutes. The measured variables included voltage, current, total harmonic distortion of current (THDi), total demand distortion (TDD), and power factor, following the provisions established by regulation ARCERNNR-002/20 [11]. The point of common coupling, located at the transformer output toward the drives, served as reference for the spectral analysis.

In parallel, the perspective of five specialists in electrical engineering was incorporated, selected for their experience in power systems and harmonic distortion mitigation. Their technical criteria were integrated through a structured survey, designed to evaluate the relative importance of various factors: degree of harmonic reduction, implementation cost, maintenance complexity, and regulatory compliance. The interviews were conducted in person, using a five-level ordinal rating scale to facilitate subsequent processing.

Regarding simulations, the electrical system of both stations was modeled in ETAP software. Three load scenarios were considered: nominal (based on field data), increased by 20%, and reduced by 20%. For each scenario, load flow, short circuit, and harmonic analysis modules were executed. These results constituted the basis for evaluating system behavior and estimating operating parameters under different conditions.

With the empirical and simulated data, the neutrosophic TOPSIS method was applied. Each evaluation criterion was assigned neutrosophic triplets (truth, indetermination, and falsehood values) constructed from the judgments issued by the experts. This approach allowed incorporating uncertainty both in performance parameters and in economic and operational implications. To calculate the scores of each alternative and their ranking, a neutrosophic aggregation operator was used. Additionally, a simulation analysis was performed to verify the selected alternatives.

2.1 Neutrosophy. Fundamentals

Definition 1 [12]. Let X be a universe of discourse. A Neutrosophic Set (NS) is characterized by three membership functions, $u_A(x), r_A(x), v_A(x): X \rightarrow]^{-}0,1^{+}[$, that satisfy the condition $u_A(x), r_A(x), v_A(x): X \rightarrow]^{-}0,1^{+}[$, for every $x \in X$. The function $u_A(x), r_A(x)$ and $v_A(x)$ represent the degrees of truth-membership, indeterminacy-membership, and falsity-membership of x in A, respectively. Their images are standard or non-standard subsets of]-0,1+[. [13]

Definition 2. Let X be a universe of discourse. A Single-Valued Neutrosophic Set (SVNS) A over X is an object of the form:

$$A = \{\langle x, u_A(x), r_A(x), v_A(x)\rangle : x \in X\} \quad (1)$$

Where $u_A, r_A, v_A: X \rightarrow [0,1]$, satisfying the condition $0 \leq u_A(x), r_A(x), v_A(x) \leq 3$ for every $x \in X$. The functions $u_A(x), r_A(x)$, and $v_A(x)$ represent the degrees of truth-membership, indeterminacy-membership, and falsity-membership of x in A, respectively. For convenience, a Single-Valued Neutrosophic Number (SVNN) is expressed as A = (a, b, c), where a, b, c ∈ [0,1] and satisfy $0 \leq a + b + c \leq 3$.

SVNSs emerged with the purpose of applying neutrosophic sets to practical contexts. Some operations between SVNNs are expressed below:

1. Let $A_1 = (a_1, b_1, c_1)$ and $A_2 = (a_2, b_2, c_2)$ be two SVNNs. The sum of A_1 and A_2 is defined as:

$$A_1 \ A_2 = (a_1 + a_2 - a_1a_2, b_1b_2, c_1c_2) \quad (2)$$

2. Let $A_1 = (a_1, b_1, c_1)$ and $A_2 = (a_2, b_2, c_2)$ be two SVNNs. The multiplication of A_1 and A_2 is defined as:

$$A_1 \ A_2 = (a_1a_2, b_1+b_2 - b_1b_2, c_1 + c_2 - c_1c_2) \quad (3)$$

3. The product of a SVNN, $A = (a, b, c)$, by a positive scalar is defined as:

$$\lambda A = \left(1 - (1 - a)^{\lambda}, b^{\lambda}, c^{\lambda}\right) \quad (4)$$

4. Let $\{A_1, A_2, \dots, A_n\}$ be a set of n SVNNs, where $Aj = (a_j, b_j, c_j)$ $(j = 1, 2, \dots, n)$, Then, the *Single-Valued Neutrosophic Weighted Average Operator* (SVNWAO) over the set is calculated using the following equation:

$$\sum_{j=1}^{n} \lambda_j A_j = \left(1 - \prod_{j=1}^{n} (1 - a_j)^{\lambda_j}, \prod_{j=1}^{n} b_j^{\lambda_j}, \prod_{j=1}^{n} c_j^{\lambda_j}, \right) \quad (5)$$

Where λ_j is the weight of Aj, with $\lambda_j \in [0, 1]$ and $\sum_{j=1}^{n} = 1$.

Definition 3. Let $A^* = (A_1^*, A_2^*, \dots, A_n^*)$ be a vector of SVNNs, such that $A_j^* = (a_1^*, b_2^*, c_j^*)(j = 1,2, \dots, n)$ and $B_i = (B_{i1}, B_{i2}, \dots, B_{im})(i = 1,2, \dots, m)$ be m vectors of n SVNNs, where $B_{ij} = (a_{ij}, b_{ij}, c_{ij})(i = 1,2, \dots, m)(j = 1,2, \dots, n)$. Then, the Separation Measure between B_i and A^* is calculated using the following equation:

$$s_i = \left(\frac{1}{3}\sum_{j=1}^{n}\left\{(a_{ij} - a_j^*)^2 + (b_{ij} - b_j^*)^2 + (c_{ij} - c_j^*)^2\right\}\right)^{\frac{1}{2}} \quad (6)$$

Where $i = (1,2, \dots, m)$

Definition 4. Let $A = (a, b, c)$ be a SVNN. The score function S of an SVNN, based on the degree of truth-membership, the degree of indeterminacy-membership, and the degree of falsity-membership, is defined by the following equation:

$$S(A) = \frac{1 + a - 2b - c}{2} \quad (7)$$

Where $S(A) \in [-1,1]$

In this article, linguistic terms will be associated with SVNNs, allowing experts to carry out their evaluations using linguistic expressions, which is more natural. Therefore, the scales presented in Table 1 will be considered.

Table 1: Linguistic terms used. Source: [10]

Linguistic Term	SVNN
Very Very Good (VVG)	(0.9, 0.1, 0.1)
Good (G)	(0.70,0.25,0.30)
Medium (M)	(0.50,0.50,0.50)
Bad (b)	(0.30,0.75,0.70)
Very Very Bad (VVB)	(0.10,0.90,0.90)

2.2. TOPSIS Method for SVNS [14]

Let A $= \{\rho_1, \rho_2, \dots, \rho_m\}$ be a set of alternatives and G $= \{\beta_1, \beta_2, \dots, \beta_n\}$ be a set of criteria. The following steps are carried out:

Step 1: Establish the relative importance of the experts. For this purpose, specialists evaluate according to the linguistic scale shown in Table 1, and calculations are performed with the associated SVNS. Let $A_t = (a_t, b_t, c_t)$ denote the SVNS corresponding to the t-th decision-maker $(t = 1,2, \dots, k)$. The weight is calculated by the following formula:

$$\delta_t = \frac{a_t + b_t\left(\frac{a_t}{a_t + c_t}\right)}{\sum_{t=1}^{k} a_t + b_t\left(\frac{a_t}{a_t + c_t}\right)} \tag{8}$$

$\delta_t \geq 0$ *and* $\sum_{t=1}^{k} \delta_t = 1$

Step 2: Construction of the aggregated single-valued neutrosophic decision matrix. This matrix is formed as $D = \sum_{t=1}^{k} \lambda_t D^t$, where $d_{ij} = \left(u_{ij}, r_{ij}, v_{ij}\right)$, and is used to aggregate all individual evaluations. Each d_{ij} is calculated as the aggregation of the evaluations given by each expert $(u_{ij}^t, r_{ij}^t, v_{ij}^t)$, using the weights λ_t of each expert with the use of Equation 5. In this way, a matrix $D = \left(d_{ij}\right)_{ij}$ is obtained, where each d_{ij} is an SVNS $(i = 1,2, \dots, m; j = 1,2, \dots, n)$.

Step 3: Determination of the weights of the criteria. Suppose the weight of each criterion is given by $W = (w_1, w_2, \dots, w_n)$, where w_j indicates the relative importance of criterion β_j. Let $\lambda_t w_j^t = \left(a_j^t, b_j^t, c_j^t\right)$ be the evaluation of criterion β_j by the t-th expert. Then, Equation 5 is used to aggregate the w_j^t values with the weights λ_t.

Step 4: Construction of the weighted average single-valued neutrosophic decision matrix with respect to the criteria.

$$D^* = D * W, \tag{9}$$

$Where\ d_{ij} = (a_{ij}, b_{ij}, c_{ij})$

Step 5: Calculation of the positive and negative ideal SVNS solutions. The criteria can be classified as either benefit-type or cost-type. Let G_1 be the set of benefit-type criteria and G_2 the set of cost-type criteria. The ideal alternatives are determined as follows:

The positive ideal solution, corresponding to G_1.

$$\rho^+ = a_{\rho+w}(\beta_j), b_{\rho+w}(\beta_j), c_{\rho+w}(\beta_j) \tag{10}$$

The negative ideal solution, corresponding to G_2.

$$\rho^- = (a_{\rho-w}(\beta_j), b_{\rho-w}(\beta_j), c_{\rho-w}(\beta_j)) \tag{11}$$

Where:

$$a_{\rho+w}(\beta_j) = \begin{cases} max_i a_{\rho iw}(\beta_j), if\ j \epsilon G_1 \\ min_i a_{\rho iw}(\beta_j), if\ j \epsilon G_2, \end{cases} \quad a_{\rho-w}(\beta_j) = \begin{cases} min_i a_{\rho iw}(\beta_j), if\ j \epsilon G_1 \\ max_i a_{\rho iw}(\beta_j), if\ j \epsilon G_2, \end{cases}$$

$$b_{\rho+w}(\beta_j) = \begin{cases} min_i b_{\rho iw}(\beta_j), if\ j \epsilon G_1 \\ max_i b_{\rho iw}(\beta_j), if\ j \epsilon G_2, \end{cases} \quad b_{\rho-w}(\beta_j) = \begin{cases} max_i b_{\rho iw}(\beta_j), if\ j \epsilon G_1 \\ min_i b_{\rho iw}(\beta_j), if\ j \epsilon G_2, \end{cases}$$

$$c_{\rho+w}(\beta_j) = \begin{cases} min_i c_{\rho iw}(\beta_j), if\ j \epsilon G_1 \\ max_i c_{\rho iw}(\beta_j), if\ j \epsilon G_2, \end{cases} \quad c_{\rho-w}(\beta_j) = \begin{cases} max_i c_{\rho iw}(\beta_j), if\ j \epsilon G_1 \\ min_i c_{\rho iw}(\beta_j), if\ j \epsilon G_2, \end{cases}$$

Step 6: Calculation of the distances to the positive and negative ideal SVNS solutions. Using Equation 6, the following expressions are computed:

$$d_i^+ = \left(\frac{1}{3n} \sum_{j=1}^{n} \left\{\left(a_{ij} - a_j^+\right)^2 + \left(b_{ij} - b_j^+\right)^2 + \left(c_{ij} - c_j^+\right)^2\right\}\right)^{\frac{1}{2}} \tag{12}$$

$$d_i^- = \left(\frac{1}{3n} \sum_{j=1}^{n} \left\{\left(a_{ij} - a_j^-\right)^2 + \left(b_{ij} - b_j^-\right)^2 + \left(c_{ij} - c_j^-\right)^2\right\}\right)^{\frac{1}{2}} \tag{13}$$

Step 7: Calculation of the Coefficient of Proximity (CC). The CP of the alternatives is calculated with respect to the positive and negative ideal solutions.

$$\widetilde{\rho_J} = \frac{d_i^-}{d_i^+ + d_i^-} \quad (14)$$

Where $0 \leq \widetilde{\rho_J} \leq 1$.

Step 8: Determination of the ranking of the alternatives. The alternatives are ranked according to the values obtained by $\widetilde{\rho_J}$. They are ordered from highest to lowest, with the condition that $\widetilde{\rho_J}$ approaching 1 represents the optimal solution.

3. Results

Initially, the measurements performed provided detailed information about the operational conditions of the electrical system and served as the basis for evaluating its compliance with current technical regulations. As observed in Table 2, in Quillán 1 station an average voltage of 451.0 V and a line current of 474.23 A were observed, while the apparent power reached 374.8 kVA, with a power factor of 0.935. On the other hand, in Quillán 2, the voltage was 454.5 V, the current was 462.03 A, and the apparent power was 367 kVA, with a power factor of 0.932 being recorded. These values indicated acceptable behavior from the energy utilization standpoint, as both cases exceeded the minimum threshold of 0.92 required by Empresa Eléctrica Ambato S.A. However, the current harmonic distortion indices (THDi) evidenced a different situation. In Quillán 1, a THDi of 27.89% was recorded, and in Quillán 2, 29.70%, levels that widely exceeded the permissible limits, reflecting a clear affectation by harmonics, particularly attributable to electronic converters.

Table 2: Pumping stations demand data. Source: Authors.

Description	Quillán 1	Quillán 2
System Voltage (V)	451.0	454.5
Current (A)	474.23	462.03
Current THD (%)	27.89	29.70
Apparent Power (kVA)	374.8	367
Power Factor	0.935	0.932

Total demand distortion (TDD) was also estimated based on the measurements and, like THDi, widely exceeded the maximum value of 8% established by national regulation. In Quillán 1, a TDD of 27.77% was obtained, while in Quillán 2 the value reached 28.66%. These results confirmed the magnitude of harmonic distortion present in the system.

The electrical system characterization, supported by the technical field survey, facilitated modeling in the ETAP environment. The stations shared similar structural characteristics: 750 kVA transformers fed from the same feeder, service connections with XLPE 1/0 AWG cable and distances of 25 meters in Quillán 1 and 350 meters in Quillán 2. The short-circuit parameters estimated at the transformer secondary were consistent with the physical configuration of the system. In Quillán 1, currents of 15,988 A for the three-phase case and 18,640 A for the single-phase case were calculated, while in Quillán 2, 15,552 A and 18,129 A were obtained, respectively. The ratio between short-circuit current and load current (Icc/IL) remained within the range established by regulations, with values of 39.31 in Quillán 1 and 39.23 in Quillán 2, as shown in Table 3. This justified the application of harmonic distortion limits for medium stiffness installations.

Table 3: Short-circuit ratio for each transformer. Source: Authors.

Transformer	Load Current (IL)	Maximum Short-circuit Current (Icc)	Icc/IL Ratio
Quillán 1	474.23 A	18,640 A	39.31
Quillán 2	462.03 A	18,129 A	39.23

The model simulated in ETAP was validated through comparison with real data. In the load flow analysis, discrepancies between measured and simulated values were minimal, which reaffirmed the model's fidelity to real conditions. For example, in Quillán 1, the simulated current was 475 A versus 473.23 A measured, with a simulated power factor of 0.933 and measured 0.935. In Quillán 2, the simulated current was 462.5 A versus 462.03 A measured, with an equally marginal difference. This correspondence strengthened the validity of subsequent analyses performed in the virtual environment.

The harmonic analysis allowed quantifying in greater detail the magnitude of individual components. The fifth-order harmonic reached values of 26.2% in Quillán 1 and 27.8% in Quillán 2, while the seventh order was situated around 7.8% and 7.9%, respectively. Both measurements and simulations (see Table 4) reflected substantial coherence, with deviations below 0.1%, which reinforced the model's validity for predictive analysis purposes and solution design.

Table 4: Pumping stations demand data. Source: Authors.

Transformer	Quillán 1		Quillán 2	
	Simulation	**Measurement**	**Simulation**	**Measurement**
Current (A)	475	473.23	462.5	462.03
Power factor	0.933	0.935	0.934	0.932
Apparent Power (kVA)	370.9	374.8	363.5	367

The results indicated that the system operated efficiently in terms of power and load factor but faced a critical harmonic distortion problem. The repeated presence of low-order harmonics and the elevated TDD values served as a technical basis for advancing toward the proposal of strategies that help mitigate this situation.

In this regard, the strategies to be evaluated included the use of tuned passive filters, use of power electronics active filters, and reconfiguration of supply transformers. Each of these options responded to different approaches to reduce the previously diagnosed harmonic distortion. The evaluation of strategies aimed at mitigating harmonic contamination in the pumping stations was developed through the neutrosophic TOPSIS method, which proved especially pertinent given the uncertainty conditions inherent to the operational environment and to the experts' own judgments.

A structured survey was applied to the previously selected expert panel, who assessed four essential evaluation criteria: harmonic reduction capacity, implementation cost, required maintenance complexity, and degree of compliance with regulations. The values from Table 1 were employed to evaluate these criteria, obtaining the weight vector shown in Table 5.

Table 5: Criteria weight vector. Source: Authors.

Criterion	Criterion Weight
Harmonic reduction	(0.88,0.12,0.115)
Implementation cost	(0.713,0.287,0.24)
Maintenance complexity	(0.856,0.144,0.132)
Regulatory compliance	(0.713,0.287,0.24)

Based on the evaluations provided by the experts, the initial decision matrix was constructed, integrating the neutrosophic values corresponding to each technological alternative in relation to the established criteria. Using this data, the weighted decision matrix was developed, incorporating the evaluations of the alternatives while considering the weights of each criterion. This matrix constitutes a key element for applying the neutrosophic TOPSIS method, as it enables the calculation of distances to the ideal solutions. Table 6 presents the resulting matrix.

Table 6: Aggregated weighted decision matrix. Source: Authors.

Alternatives	Criterion 1	Criterion 2	Criterion 3	Criterion 4
Alt 1	(0.774,0.226,0.217)	(0.571,0.429,0.378)	(0.708,0.292,0.264)	(0.61,0.39,0.34)
Alt 2	(0.734,0.266,0.255)	(0.571,0.429,0.378)	(0.733,0.267,0.247)	(0.59,0.41,0.356)
Alt 3	(0.269,0.805,0.84)	(0.642,0.358,0.316)	(0.693,0.307,0.297)	(0.61,0.39,0.34)
Ideal (+)	(0.774,0.226,0.217)	(0.571,0.429,0.378)	(0.693,0.307,0.297)	(0.61,0.39,0.34)
Ideal (–)	(0.269,0.805,0.84)	(0.642,0.358,0.316)	(0.733,0.267,0.247)	(0.59,0.41,0.356)

From this matrix, the distances to the positive ideal (d^+) and the negative ideal (d^-) were calculated, as well as the coefficient of proximity (CP) for each alternative. These values, presented in Table 7, made it possible to establish a preference ranking among the evaluated alternatives.

Table 7: Ideal distances and coefficients of proximity. Source: Authors.

Alternatives	d^+	d^-	CP	Orden
Passive Filters	0.0113	0.2879	0.962	1
Active Filters	0.0308	0.2682	0.897	2
Transformer Reconfiguration	0.2876	0.0237	0.076	3

The analysis indicated that the alternative with the greatest proximity to the positive ideal solution is passive filters, which obtained a closeness coefficient of 0.962, standing out as the most suitable option for harmonic mitigation in pumping systems. This strategy demonstrated a notable balance between technical effectiveness, moderate implementation cost, and regulatory compliance, positioning it as the most robust solution.

In second place were active filters, with a very similar coefficient (0.897), reflecting their high technical performance, although with slightly higher maintenance complexity. This alternative can be considered highly competitive, especially in environments that support sustained technological investments.

After identifying passive filters as the most suitable alternative for mitigating harmonic distortion in pumping stations, the design and technical validation of these devices were carried out. The process began with the load flow analysis and the harmonic spectrum recorded at the Quillán 1 station, whose initial values showed distortion levels above the limits established by Ecuadorian regulations.

The sizing of the tuned filters initially focused on the attenuation of the 5th harmonic, as this represented the most significant component within the measured harmonic spectrum. Based on the station's operating data — an apparent power of 370.9 kVA, line voltage of 451 V, and a power factor of 0.9332 — it was determined that a correction was needed to achieve a power factor close to 0.98. The design yielded an effective reactive power of 63 kVAR, which allowed the determination of the filter parameters: a capacitance of 786.69 μF, an inductance of 0.3802 mH, and a resistance of 0.023 Ω, configured with a quality factor Q equal to 30.

The ETAP simulation revealed that the fundamental current of the filter reached 80.65 A, while the current corresponding to the 5th harmonic was 21.05 A. The total RMS current recorded in the filter was 83.73 A, representing 103.8% of the fundamental current, thus complying with the established limit of

135%. Regarding the capacitor's behavior, an RMS voltage of 108.425% with respect to the system's nominal voltage was observed, within the permissible margin of 110%. It was also verified that the recalculated reactive power (112.56%) and the associated dielectric heating (70.917 kVAR) remained within acceptable regulatory values, validating the technical feasibility of the design.

The results obtained for the Quillán 2 station were similar, with a passive filter sizing that yielded a power of 20.31 kVAR. Subsequently, the simulation results showed effective reduction of the 5th harmonic, reaching 4.58% for Quillán 1 and 4.61% for Quillán 2, both below the 7% threshold established by current regulations. However, it was found that the Total Demand Distortion (TDD) remained high, with values of 9.14% and 10.42% respectively, indicating the need to adjust the system by incorporating filters tuned to the 7th harmonic.

The design of these additional filters included parameters similar to the previous ones, with capacities of 21 kVAR and 0.189 mH for Quillán 1, and 20.31 kVAR and 0.199 mH for Quillán 2. The final simulation, the results of which are presented in Table 8, reflected a substantial improvement in the system's harmonic behavior. The 5th harmonic remained stable at 4.49% and 4.55%, while the 7th harmonic was significantly reduced to 1.48% and 1.10%. As for the TDD, values of 5.98% for Quillán 1 and 7.34% for Quillán 2 were recorded, both within the margins accepted by the regulation.

Table 8: Simulation results with filters tuned to the 5th and 7th harmonics. Source: Authors.

Harmonic	Limit	Quillán 1	Quillán 2
5º	7%	4.49%	4.55%
7º	7%	1.48%	1.10%
TDD	8%	5.98%	7.34%

The combined implementation of passive filters tuned to the 5th and 7th harmonics proved to be an effective technical strategy, not only due to their capacity to reduce individual harmonics but also for ensuring comprehensive compliance with regulatory energy quality parameters. These findings not only supported the prior selection made through the neutrosophic multicriteria evaluation but also demonstrated that a well-designed passive solution can satisfactorily meet the operational demands of complex electrical systems such as water pumping stations.

4. Discusion

The results obtained prompted reflection on the practical value of integrating neutrosophic logic into the decision-making process. The use of this logical framework, which simultaneously accommodates degrees of truth, falsity, and indeterminacy, facilitated a reading closer to the reality of electrical systems, where operational conditions are seldom defined with absolute precision.

The application of the TOPSIS method, combined with the principles of neutrosophic logic, enabled the selection of the most suitable alternative without imposing a false dichotomy between supposedly mutually exclusive options. Instead of working with idealized criteria and binary decisions, an evaluation was prioritized that recognized nuances, contradictions, and areas of uncertainty. This approach proved especially useful when comparing different solutions for the study's problem, where the benefits of each alternative depended on multiple technical, economic, and regulatory factors that were not always directly comparable.

The values obtained after implementing the filters confirmed that the option selected through this integrative process was not only viable but also compatible with the standards required by national regulations. The reduction of the 5th and 7th order harmonics, as well as compliance with the TDD and THDi limits, validated the appropriateness of decisions made based on a more flexible and adaptive logic. This was essential for addressing operational contexts with narrow margins, where a traditional evaluation might have dismissed functional alternatives for failing to strictly meet certain parameters.

Furthermore, the use of neutrosophic logic provided a useful tool for addressing the inherent uncertainty of real systems. This capacity to manage ambiguity without oversimplifying it allowed for the construction of a decision-making process closer to practical conditions. Consequently, the findings of this work not only offered a functional solution to the technical problem addressed but also contributed evidence regarding the utility of adopting conceptual frameworks that acknowledge the inherent complexity of real-world application environments.

5. Conclusion

An energy quality characterization was conducted at two pumping stations, enabling the identification of elevated harmonic distortion levels generated by variable frequency drives. This initial diagnosis served as the basis for designing a technical solution focused on the application of passive tuned filters aimed at mitigating the 5th and 7th order harmonics. The design and simulation of these devices achieved values within the margins established by national regulations, demonstrating a significant improvement in total demand distortion indices and a substantial reduction of predominant harmonics. Validation of the results through the ETAP environment confirmed that the proposed solution was technically feasible and applicable to electrical systems with similar conditions.

The selection of the most suitable strategy was made possible by integrating neutrosophic logic with the multicriteria decision-making method TOPSIS, which allowed addressing the uncertainty inherent in expert judgment and electrical system behavior. This approach evaluated technical, economic, and regulatory criteria, enabling a clear determination that the alternative based on passive filters offered the best balance. The application of neutrosophic analysis provided a framework capable of capturing not only expected values but also the zones of indeterminacy associated with each option, enriching the quality of the decision-making process. This methodological integration represented a substantial contribution to the analysis of complex electrical problems and opens a future line of work in optimizing technical solutions through approaches based on neutrosophic logic and its articulation with multicriteria tools.

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