Advances in Fuzzy Systems

Fuzzy Machine Learning-Based Material Discovery and Design

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Research Article

Semantic Approach for Evaluation of Energy Storage Technologies under Fuzzy Environment

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Energy storage systems are becoming increasingly important, with a growing focus on renewable energy sources that provide highly fluctuating output. Therefore, sound decisions regarding the energy storage systems to be employed need to be made, especially with a systematic and semantic approach. This paper considers the problem of evaluation and selection of energy storage technologies (ESTs). The objective of the proposed research is to decide the best technology for energy storage under the novel idea of hybrid multicriteria decision-making technique under fuzzy environment, that is, fuzzy AHP with fuzzy VIKOR. Electrochemical storage, electrical storage, magnetic storage, mechanical storage, and chemical storage are considered as five alternative energy storage technologies. Energy density, life cycles, cycle efficiency, investment level, suitability to climatic conditions, and required space are considered as six main evaluation criteria. Under each of the main criteria, a set of subcriteria are also considered. The weights of main criteria and subcriteria are determined using fuzzy AHP. With the help of the weights of each set of subcriteria, the weights of alternatives are determined using fuzzy VIKOR. Further, with the help of the main criteria weights and the weights of alternatives determined with respect to each set of subcriteria, the final normalized weights of alternatives are determined. Based on these weights, energy storage technologies are ranked. In addition, the sensitivity analysis is carried out to analyze the variation in ranking pattern of alternatives. From the research findings of this paper, the results are found to be more practical as the evaluation is carried out on an objective basis.

1. Introduction

The energy sector (ES) today is forging its way into uncharted domains with the advent of renewable and alternative energy systems. This brings with it an uncertainty of the viability of such projects [1]. Energy systems engineers and designers do not see eye to eye with the decision-making executives. Engineers' requests and innovations may often get overlooked by the chief financial officer of the company due to various financial jargons.

Working in tandem and fabricating a methodology for analyzing all the aspects, be it technical or commercial, can lead to the effective and successful implementation of a project in the energy sector. Absolute certainty is of essence, and any degree of uncertainty should be avoided at all costs. Energy planners have to consider several criteria while ascertaining the best decision regarding energy projects. The energy sector accounts for large amounts of a nation's economy and is what can make or break a nation's ability for economic growth. Without adequate energy sources, no economy can expect to take giant leaps in terms of development. Therefore, decision analysis can be considered as important as the decision-making procedure itself, if not more.

Moreover, microgrids are becoming state of the art in the domain of energy production and distribution. Microgrids ensure local power reliability, independence, electricity power system, and storage flexibility [2]. Such microgrids attempt to incorporate more sustainable and eco-friendly energy sources in order to emphasize energy independence. Therefore, due to the intermittent nature of renewable energy production, optimum energy storage technology (EST) is mandatory to ensure efficiency and round the clock electrical supply. Energy storage systems serve the role of energy backups or buffers to balance supply and demand [2]. Environment and energy are slated to become the two most complex global challenges shortly [3]. Transmission, distribution, and transport are the three sectors pegged to be the most promising areas where energy storage technologies can be fully utilized. ESTs can also eliminate the need for expensive upgrades and regulate the renewable energy fluctuation that almost definitely occurs according to the climatic conditions [3].

Electrochemical energy storage systems harness the electricity generated by various methods of energy production to drive chemical reactions against the natural flow. This leads to energy generation when the chemicals are allowed to react naturally, leading to the transfer of electrons. Batteries are an example of rechargeable electrochemical ESTs [4]. The battery may consist of one or more cells connected in different combinations according to the application requirement, such as output voltage and capacity [4]. Electrical ESTs employ hardware to separate charges. Therefore, electrical ESTs store energy employing static charge as compared to the electrochemical process used by batteries for energy storage [4]. Supercapacitors are examples of such ESTs. Supercapacitors possess electrolyte layer measuring nanometers to make high surface area capacitors that separate static charges. Once the surfaces come into contact, the usual operating principle of a capacitor applies. Magnetic ESTs store energy in the form of magnetic energy. Superconducting magnetic energy storage (SMES) technologies are considered the sole EST to store flowing electricity [5] as it generates a magnetic field within which the energy is stored. SMES tends to be highly efficient, scalable, eco-friendly, and fast responding, but at the same time, it can be costly as well. There are essentially no losses as superconducting coils are used [5].

Mechanical ESTs use electrical energy to generate kinetic energy [4]. This kinetic energy can then be converted to electrical energy by driving a generator as and when the need arises. A flywheel is one such mechanical EST. It consists of a mass that rotates about a central axis and stores mechanical energy in kinetic energy. Electrical energy is used to accelerate the flywheel and increase the speed of rotation. Therefore, it acts as a mechanical battery in which the energy is stored as moment of inertia of the rotating mass of the flywheel. The energy is then retrieved by attaching the flywheel to a generator, which reduces the speed of rotation, and hence, kinetic energy is thus converted to electrical energy [4]. Chemical ESTs utilize chemical properties of elements such as endotherm and exotherm characteristics to store energy [4]. One such example is that of metal hydrides, where metals readily absorb hydrogen when brought in contact. The absorption is endothermic and, therefore, requires energy in the form of heat. Similarly, the desorption of hydrogen is an exothermic reaction, and hence, heat is evolved during this step, which can harness various forms of energy. There are other hydrogen storage technologies such as liquid hydrogen storage but are in their nascent stages of development and, therefore, experience limited use.

Also, it is a fact that many variables, including economic, technological, social, and environmental, must be considered while choosing energy storage technology. Various methods are used to optimize the selection of energy storage technology by employing cutting-edge techniques such as machine learning and multiobjective optimization methods. Selecting an appropriate energy storage option is an issue with various objectives that cannot all be met by a single technology. Possible trade-offs between the potential benefits and drawbacks of various energy storage systems must be considered. Furthermore, the choice to construct a storage unit frequently involves several stakeholders, each of whom may have different interests and goals in mind. Choosing a storage option that provides the greatest advantage while also meeting all requirements is thus an inherently difficult decision.

From the recent past, the usage of multicriteria decision making (MCDM) methods has been gaining popularity in the field of energy management. To solve complex problems concerning energy planning, MCDM techniques have been turned out to be superior tools. MCDM methods provide amicable solutions to the problems of different projects involved with conflicting objectives. Several techniques have been used for decision analysis in energy sector based weighted means, outranking, different fuzzy principles, and their combinations. Generally, in any project, objectives are conflicting in nature, and therefore, the final preference of the project selection purely depends on the opinion of the decision maker. In several cases of decision-making analysis, more than one group of decision makers are allowed to participate. As the set of criteria considered and viewpoint of each group differs, the problem of biasing in decision making process should be resolved within the context of understanding. Due to the potential application of MCDM methods, the scope of these methods is not confined to only one field. Further, these methods can be used with equal degree of importance in all fields of research.

The remaining work of this paper is classified into four sections. Section 2 presents the detailed review of literature carried out inline to the problem domain. The detailed methodology of the proposed work covering hierarchical structure of alternatives, main criteria, and subcriteria, linguistic scale for main criteria, subcriteria and alternatives, step by step procedure for fuzzy AHP, and fuzzy VIKOR are addressed in Section 3. Numerical illustration of the problem is carried out elaborately in Section 4. In Section 5, conclusions and future scope of the work are addressed. Finally, references are included.

2. Literature Review

In today's landscape, we, humans, cannot thrive without electricity consumption. From using it for daily chores to drive vehicle using it as a fuel, it is omnipresent in every part of land. Hence, electrical energy has indeed become one of the necessities of our lifestyle. Storage of this electrical energy is extremely intricate as complex technology must be utilized. With developments, the sophistication in electrical energy storage technologies have enhanced but also bought with it few drawbacks. These issues must be considered while finalizing the technology and require decision analysis process for that.

Further, in the present era of industrial scenario, the usage of MCDM methods has been proved to be significant in the domain of energy sector. Several methodological approaches and algorithms have developed in order to assess and plan energy structures based on more than one criterion. With ever increasing complexity and multiplicity in the problem of energy sector, the optimization or analysis of single objective is no longer a predominant approach. So, Kumar and Katoch [6] explored in their work that MCDM methods are used to evaluate and solve environmental constraints, socioeconomic issues, technical challenges, and institutional obstructions involved in the power sector.

The usage of MCDM methods has become popular in energy sector as it assists decision makers to keep attention to all available criteria and take appropriate decisions on priority basis. Since a flawless design is administered by various factors, decision makers have to consider several other parameters similar to methodological or economical parameters, which have to be compromised in certain conditions. Fuzzy AHP, fuzzy VIKOR, and a combination of both can be used to evaluate different processes when several stakeholders are involved and when the values may not be quantifiable or discrete [7]. MCDM methods allow a decision maker to quantify particular criteria established on its reputation in the existence of supplementary objectives.

Several possible applications were suggested to streamline the process of decision making by individuals and organizations to maximize gains and minimize efforts. It provides a step-by-step explanation of the utilization method of the AHP [8] process. Another MCDM technique, VIKOR, was developed by Opricovic [9] and served to evaluate alternatives often with conflicting or unrelated criteria [10].

Since then, several MCDM techniques have been formulated with their application niches, such as the PROMETHEE, DEMATEL, TOPSIS, and ANP methods. These methods have been utilized with varying degrees of popularity to provide solutions where numerous evaluation criteria are required to evaluate and find the desired alternative. Technical and nontechnical fields alike have witnessed the benefit of the application of such techniques to business activities. These fields include, but are not limited to, productivity evaluation, operations, optimization, facility and site selection, manufacturing, and robotics.

Duran and Aguilo [11] make use of fuzzy AHP to evaluate advanced manufacturing systems. Duran states that using fuzzy set theory permits the incorporation of information that may not be accurate, complete, or even quantifiable such as the utility of fuzzy MCDM techniques. Augustine et al. [12] present a fuzzy Analytical Hierarchy Process (AHP) framework to determine and rate benchmarks for the service sector. Their approach allows for the involvement of several stakeholders in the business to ensure progressive movement. Finally, Chengl et al. [13] present a novel fuzzy AHP approach for improving worker productivity by setting up the priorities required for the necessary productivity improvement where the unit cost forms a sample criterion for worker productivity.

Rostamzadeh et al. [14] used fuzzy VIKOR to evaluate Green Supply Chain Management (GSCM) indicator among its practitioners. A comparative analysis of the results is then presented. Finally, Sedaghat [15] integrates fuzzy AHP, TOPSIS, VIKOR, and SAW techniques to enable productivity improvement in the industry. The importance and effect of three dimensions, human resources and financial and management performance, were evaluated.

Chatterjee and Stević [16] proposed a two-phase model for supplier selection in a manufacturing environment using fuzzy AHP and fuzzy TOPSIS. They considered several qualitative and quantitative type evaluation criteria and ranked the suppliers. Zavadskas et al. [17] used fuzzy AHP for optimal supplier selection decision towards materials purchasing for the production of preinsulated pipes. They considered five suppliers as alternatives and nine evaluation criteria to ensure the execution of procurement process to be more effective. The other related articles reporting the decision analysis include Gayathri and Nagaraju [18], Varun et al. [19], Hasan et al. [20], and Ali et al. [21].

More recently, Seker and Aydin [22] proposed a novel integrated Fuzzy based SWARA and IVIF-WASPAS method in order to determine the most sustainable method to produce hydrogen energy. They used fuzzy based SWARA method to determine the weights of evaluation criteria, whereas IVIF-WASPAS approach is used to rank the alternatives. Jahangiri et al. [23] addressed the prioritization of solar electricity and hydrogen coproduction stations with the consideration of PV losses and different types of solar trackers using TOPSIS approach. From their research findings, they concluded that the maximum solar electricity yield of 35,276 kWh/yr has been obtained for Zahedan under the scenario of optimal fixed angle mode.

Unlike all the aforementioned articles, in this paper, an attempt is made for the evaluation and selection of the best energy storage technologies under the novel idea of hybrid MCDM techniques under fuzzy environment, that is, fuzzy AHP and fuzzy VIKOR. Electrochemical storage, electrical storage, magnetic storage, mechanical storage, and chemical storage are considered as five alternative energy storage technologies. Energy density, life cycles, cycle efficiency, investment level, suitability to climatic conditions, and required space are considered as six main evaluation criteria. Under each of the main criteria, a set of subcriteria are also considered. In the first phase, the weights of main criteria and subcriteria are determined using fuzzy AHP. With the help of these weights, the final normalized weights of alternatives are determined in the second phase using fuzzy VIKOR, and then, the ranking of energy storage technologies is demonstrated. Also, the sensitivity analysis is carried out to analyze the variation in ranking pattern of alternatives.

3. Methodology

This analysis aims to determine the ideal EST that should be used depending on the opinion of several decision-makers. The different alternatives that are considered are shown in Figure 1. The different criteria, based on which the alternatives are rated, are decided and shown in Figure 2. The final ratings of the alternatives are determined using a single hybrid evaluation scheme of fuzzy AHP and VIKOR [7].

3.1. Fuzzy AHP. AHP is a widely used decision-making tool, which is used to handle multicriteria decision-making statements. Based on pairwise comparisons of different criteria and subcriteria, the alternatives are evaluated [24]. Fuzzy AHP considers the randomness of personal judgements and hence gives a complete result. Linguistic terminologies are utilized to perform pairwise comparisons of criteria and alternatives denoted by triangular numbers [24–29].

Step 1: the criteria are compared following the linguistic distinctions shown in Table 1.

If a decision-maker states that criteria m are fairly important than criteria n, then the TFN scale is (4, 5, 6), and the fuzzy scale for the comparison of criteria m to criteria n would be (1/6, 1/5, 1/4).

Equation (1) shows the pairwise comparison values, where $\tilde{a}_{ij}^{k}$ denotes the k^{th} decision maker's preference of the i^{th} criterion over j^{th} criterion in terms of TFNs.

$$\tilde{P}^{k} = \begin{bmatrix} \tilde{x}_{11}^{k} & \cdots & \tilde{x}_{1n}^{k} \\ \vdots & \ddots & \vdots \\ \tilde{x}_{n1}^{k} & \cdots & \tilde{x}_{nn}^{k} \end{bmatrix}. \tag{1}$$

Step 2: an average value for preferences $\tilde{x}_{ij}$ is taken in case of multiple decision-makers and is calculated using equation (2), where there are n decision-makers.

$$\tilde{x}_{ij} = \frac{\sum_{k=1}^{n} \tilde{x}_{ij}^{k}}{K}. \tag{2}$$

Step 3: thus, the updated pairwise comparison matrix is

$$\tilde{P} = \begin{bmatrix} \tilde{x}_{11} & \cdots & \tilde{x}_{1n} \\ \vdots & \ddots & \vdots \\ \tilde{x}_{n1} & \cdots & \tilde{x}_{nn} \end{bmatrix}. \tag{3}$$

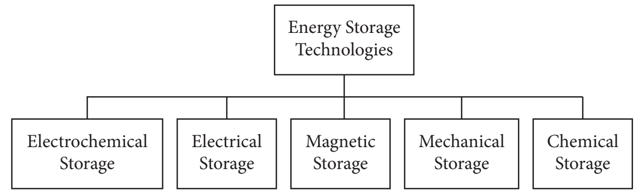

Figure 1: Set of alternative energy storage technologies considered for the analysis.

Step 4: the geometric mean of comparison values for each criterion is determined using equation (4); here, $\tilde{t}_i$ represents TFN.

$$\tilde{t}_i = \left(\prod_{j=1}^{n} \tilde{x}_{ij} \right)^{1/n}, \quad i = 1, 2, 3, \ldots, n. \tag{4}$$

Step 5: summation of each $\tilde{r}_l$ is calculated to determine the fuzzy weights for every criterion, and the reciprocal summation is calculated following which the TFNs are arranged in ascending order. The weight of criterion I, $(\tilde{w}_l)$ can be calculated with the help of the following equation:

$$\tilde{w}_i = \tilde{t}_i \otimes \left(\tilde{t}_1 \oplus \tilde{t}_2 \oplus, \ldots, \tilde{t}_n \right)^{-1} = \left(lw_i, mw_i, nw_i \right). \tag{5}$$

Step 6: TFNs must undergo defuzzification using the CoA method proposed by [28] using equation (6). This is followed by the normalization of M_i in equation (7).

$$M_i = \frac{lw_i + mw_i + nw_i}{3}, \tag{6}$$

$$N_i = \frac{M_i}{\sum_{i=1}^{n} M_i}. \tag{7}$$

3.2. Fuzzy VIKOR. The fuzzy VIKOR method is used to solve fuzzy multicriteria problems with conflicting and different units' criteria [26].

Step 1: linguistic terminologies are terms that denote the subjective views of a decision-maker about the subcriterion concerning each alternative being considered [24] from which we obtain TFNs as shown in Table 2.

Step 2: the weight of importance of each criterion is expressed in a vector form by the following equation:

$$\tilde{W}: \tilde{W} = \left[\tilde{a}_1, \tilde{a}_2, \ldots, \tilde{a}_n \right], \quad j = 1, 2, \ldots, n. \tag{8}$$

Here, $\tilde{a}_j$ represents the j^{th} criterion weight based on the linguistic terminology assigned by a decision-maker. In this study, the decision makers' opinions are aggregated. The weight of importance in fuzzy form , $\tilde{w}_2$ for criterion C_j is obtained by utilizing the following equation:

$$\tilde{a}_j^{k} = \left(w_{j1}, w_{j2}, w_{j3} \right). \tag{9}$$

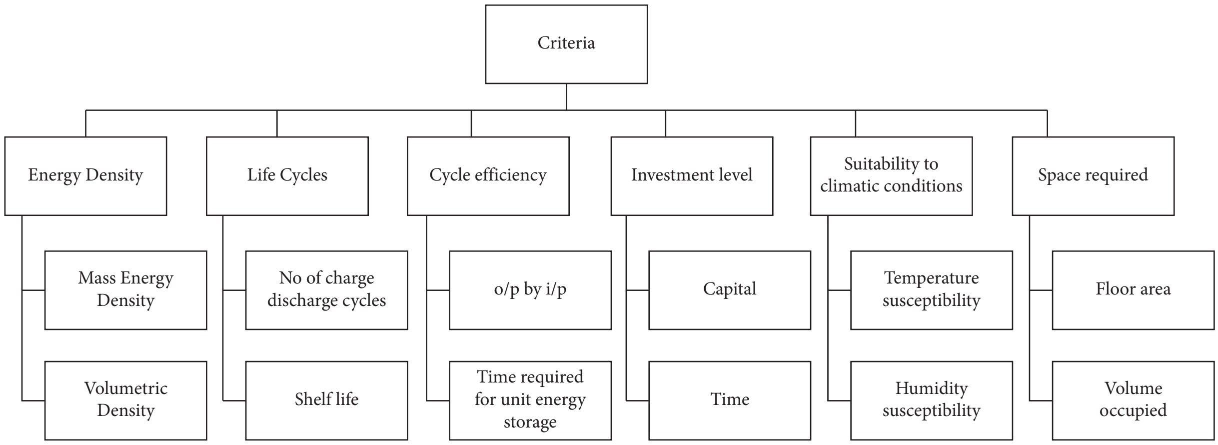

Figure 2: Set of main criteria and subcriteria considered for the analysis.

Table 1: Linguistic variables for main criteria and subcriteria.

Saaty scale	Definition	Fuzzy triangular number
1	Equally important	(1, 1, 1)
3	Weakly important	(2, 3, 4)
5	Fairly important	(4, 5, 6)
7	Strongly important	(6, 7, 8)
9	Absolutely important	(9, 9, 9)
2	The intermittent values between two adjacent scales	(1, 2, 3)
4		(3, 4, 5)
6		(5, 6, 7)
8		(7, 8, 9)

Table 2: Linguistic variables for alternatives.

Linguistic terms	Triangular fuzzy number
Very low (VL)	(0, 0, 0.1)
Medium low (ML)	(0.1, 0.2, 0.3)
Medium (M)	(0.3, 0.4, 0.5)
Medium high (MH)	(0.5, 0.6, 0.7)
Very high (VH)	(0.7, 0.8, 0.9)
Immense (I)	(0.9, 1, 1)

where $w_{j1} = \min_k \{w_{j1}\}$, $w_{j2} = (1/k)\sum_{k=1}^{k} w_{jk2}$, $w_{j3} = \max_k\{w_{jk3}\}w_{jk3}$ for $i = 1$ to m and $j = 1$ to n.

Step 3: a MCDM matrix in fuzzy form is expressed as given in equation (10), with respect to k decision makers ($M_1, M_2, \ldots, M_k$) who were presented with alternatives ($A_1, A_2, \ldots, A_m$) referring to the set of criteria ($C_1, C_2, \ldots, C_n$), where $\tilde{x}_{mn}$ is the rating of alternative A_m with respect to criterion C_j

$$\tilde{D} = \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \ldots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{22} & \ldots & \tilde{x}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \ldots & \tilde{x}_{mn} \end{bmatrix}, \quad (10)$$

where $\tilde{x}_{ij}^k = (p_{ij}^k, q_{ij}^k, r_{ij}^k)$ is a TFN.

Step 4: the fuzzy maximum value $f_i^b = (p_i^b, q_i^b, r_i^b)$ and fuzzy worst vales $f_i^w = (p_i^w, q_i^w, r_i^w)$ are calculated using the following equation:

$$\tilde{f}_i^b = \max_j \tilde{a}_{ij}, \qquad \tilde{f}_i^w = \min_j \tilde{a}_{ij}. \quad (11)$$

Step 5: the fuzzy difference $\tilde{d}_{ij}$ is calculated using the following equation:

$$\tilde{d}_{ij} = \frac{\left(\tilde{f}_i^b - \tilde{x}_{ij}\right)}{\left(r_i^b - p_i^w\right)}. \quad (12)$$

Step 6: we now calculate the separation $\tilde{S}_j$ of A_j from the maximum fuzzy value $\tilde{f}_i^b$ and separation $\tilde{R}_j$ of A_j from the minimum fuzzy value $\tilde{f}_i^w$ using equations (13) and (14). Here, a_j is the weight of importance of the corresponding criterion.

$$\tilde{S}_j = \sum_{i=1}^{n} \left(\tilde{a}_j \otimes \tilde{d}_{ij}\right), \quad (13)$$

$$\tilde{R}_j = \max_i \left(\tilde{a}_j \otimes \tilde{d}_{ij}\right). \quad (14)$$

Step 7: $\tilde{Q}_j = (p_j, q_j, r_j)$ is expressed as TFN and is calculated using the following equation:

$$\tilde{Q}_j = \frac{\nu\left(\tilde{S}_j - \tilde{S}^{\cdot}\right)}{\left(\tilde{S}^{oc} - \tilde{S}^{\cdot a}\right)} \oplus \frac{(1-\nu)\left(\tilde{R}_j - \tilde{R}^{\cdot}\right)}{\left(\tilde{R}^{oc} - \tilde{R}^{\cdot a}\right)}, \quad (15)$$

Table 3: Criteria comparison matrix.

	Energy density	Life cycles	Cycle efficiency	Investment level	Suitability to climatic conditions	Space required
Energy density	(1, 1, 1)	(1/6, 1/5, 1/4)	(1/8, 1/7, 1/6)	(2, 3, 4)	(1/9, 1/9, 1/9)	(6, 7, 8)
Life cycles	(4, 5, 6)	(1, 1, 1)	(1/6, 1/5, 1/4)	(2, 3, 4)	(1/6, 1/5, 1/4)	(5, 6, 7)
Cycle efficiency	(6, 7, 8)	(4, 5, 6)	(1, 1, 1)	(4, 5, 6)	(1/8, 1/7, 1/6)	(7, 8, 9)
Investment level	(1/4, 1/3, 1/2)	(1/4, 1/3, 1/2)	(1/6, 1/5, 1/4)	(1, 1, 1)	(1/8, 1/7, 1/6)	(7, 8, 9)
Suitability to climatic conditions	(9, 9, 9)	(4, 5, 6)	(6, 7, 8)	(6, 7, 8)	(1, 1, 1)	(1/4, 1/3, 1/2)
Space required	(1/8, 1/7, 1/6)	(1/7, 1/6, 1/5)	(1/9, 1/8, 1/7)	(1/9, 1/8, 1/7)	(2, 3, 4)	(1, 1, 1)

where $\widetilde{S}^{\cdot} = \min_j \widetilde{S}_j$, $\widetilde{S}^{oc} = \max_j S_j^c$, $\widetilde{R}^{\cdot} = \min_j \widetilde{R}_j$, $\widetilde{R}^{oc} = \max_j R_j^c$ and $v = ((n+1)/2n)$.

Here, v denotes the strategy weight of maximum criteria, and $(1 - v)$ denotes the weight of the individual regret. Following this calculation, we compute maximum values of S and R, which are $\widetilde{S}^b$ and $\widetilde{R}^b$ respectively.

Step 8: defuzzification involves the conversion of fuzzy numbers into crisp values. The Centre of Area method is used for ranking the fuzzy numbers that result in crisp values for S, R, and Q [27].

4. Numerical Illustration

4.1. Fuzzy AHP. As demonstrated in Table 3, the pairwise comparison matrix is formulated based on decision-makers opinions and linguistic terminologies defined in Table 1.

The Geometric mean of these given values is calculated using equation (4) in the next step as shown in Table 4. Further, the relative fuzzy weights for each criterion are calculated and presented in Table 5. In the 6th step, each criterion's defuzzified weight is calculated from the average of relative weights given in Table 6. The normalized fuzzy weights are calculated using equation (7), further utilized in the hybrid MCDM techniques. Finally, the values of M_i and N_i are calculated and shown in Table 6.

In a similar manner, based on the opinion of decision makers and the linguistic scale defined in Table 1, the initial decision matrix is formulated for all sets of subcriteria, defined with respect to each main criterion. Further, the normalized weights of all sets of subcriteria are calculated and tabulated as shown in Table 7.

4.2. Fuzzy VIKOR. Next, the decision-makers opinions in the form of linguistic terminologies, introduced in Table 2, are shown in Table 8, which are then converted to TFNs for the following steps. In order to keep the paper concise and brief, only one detailed illustration has been shown. The values for the other sets of subcriteria are computed using the methodology, and the numerical illustration is provided. Therefore, Step 2 finds the aggregated fuzzy decision matrix presented in Table 9, giving the aggregated fuzzy weights using equations (8)–(10) to result in Table 10. Maximum and Minimum

Table 4: Fuzzy comparison values.

Criteria description	$\widetilde{t}_i$
Energy density	(0.550320, 0.636770, 0.727415)
Life cycles	(1.017715, 1.237990, 1.479783)
Cycle efficiency	(2.092730, 2.418270, 2.749450)
Investment level	(0.457042, 0.542160, 0.674000)
Sustainability to climatic conditions	(2.620740, 3.004100, 3.464100)
Space required	(0.275880, 0.322069, 0.373643)
Total	(7.014427, 8.161359, 9.468391)
Reciprocal of total	(0.142563, 0.122529, 0.105615)
Increasing value of reciprocal	(0.105615, 0.122529, 0.142563)

Fuzzy Values shown in Table 11 are found in step 4 using

Table 5: Relative weights in fuzzy form.

Criteria description	$\widetilde{w}_i$
Energy density	(0.058122, 0.078023, 0.103702)
Life cycles	(0.107486, 0.151690, 0.210962)
Cycle efficiency	(0.221024, 0.296308, 0.391970)
Investment level	(0.048270, 0.066430, 0.096087)
Sustainability to climatic conditions	(0.276789, 0.368089, 0.493852)
Space required	(0.029137, 0.039463, 0.053268)

Table 6: Average and normalized final weights of criteria.

Criteria description	M_i	N_i
Energy density	0.079949	0.077604
Life cycles	0.156713	0.152115
Cycle efficiency	0.303101	0.294208
Investment level	0.070263	0.068201
Sustainability to climatic conditions	0.379577	0.368441
Space required	0.040623	0.039431

Table 7: Pairwise comparison matrix and normalized weights for subcriteria.

w.r.t energy density	Mass energy density	Volumetric density	Normalized weights
Mass energy density	(1, 1, 1)	(1/6, 1/5, 1/4)	0.16858
Volumetric density	(4, 5, 6)	(1, 1, 1)	0.83142
w.r.t life cycles	No of charge discharge cycles	Shelf life	Normalized weights
No of charge discharge cycles	(1, 1, 1)	(2, 3, 4)	0.74239
Shelf life	(1/4, 1/3, 1/2)	(1, 1, 1)	0.25761
w.r.t cycle efficiency	o/p by i/p	Time required for unit energy storage	Normalized weights
o/p by i/p	(1, 1, 1)	(4, 5, 6)	0.83142
Time required for unit energy storage	(1/6, 1/5, 1/4)	(1, 1, 1)	0.16858
w.r.t investment level	Capital	Time	Normalized weights
Capital	(1, 1, 1)	(6, 7, 8)	0.87424
Time	(1/8, 1/7, 1/6)	(1, 1, 1)	0.12576
w.r.t suitability to climatic conditions	Temperature susceptibility	Humidity susceptibility	Normalized weights
Temperature susceptibility	(1, 1, 1)	(4, 5, 6)	0.83142
Humidity susceptibility	(1/6, 1/5, 1/4)	(1, 1, 1)	0.16858
w.r.t space required	Floor area	Volume occupied	Normalized weights
Floor area	(1, 1, 1)	(1/8, 1/7, 1/6)	0.12576
Volume occupied	(6, 7, 8)	(1, 1, 1)	0.87424

Table 8: Opinions of decision makers.

Main criterion	Subcriterion	D.M. 1	D.M. 2	D.M. 3
Energy density	Mass energy density	MH	VH	MH
	Volumetric density	M	ML	M
Life cycle	No of charge/discharge cycles	ML	M	MH
	Shelf life	MH	M	M
Cycle efficiency	o/p by i/p	VH	MH	MH
	Time required for unit energy storage	M	ML	M
Investment level	Capital	MH	VH	VH
	Time	M	MH	MH
Suitability to climatic conditions	Temperature susceptibility	M	MH	VH
	Humidity susceptibility	MH	VH	M
Space required	Floor area	ML	VL	ML
	Volume occupied	MH	M	MH

Table 9: Aggregated fuzzy decision matrix.

Subcriteria for energy density	Mass energy density	Volumetric density
Electrochemical storage	(6, 7, 8)	(7, 8, 9)
Electrical storage	(2, 3, 4)	(7, 8, 9)
Magnetic storage	(7, 8, 9)	(9, 9, 9)
Mechanical storage	(1, 1, 1)	(2, 3, 4)
Chemical storage	(5, 6, 7)	(6, 7, 8)

Table 10: Aggregated fuzzy weights for each criterion.

Subcriterion for energy density	Triangular fuzzy number		
Mass energy density	0.5000	0.6667	0.9000
Volumetric density	0.1000	0.3333	0.5000

equation (11).

Table 11: Maximum and minimum fuzzy values.

Subcriterion for energy density	$\tilde{f}_i^b$	$\tilde{f}_i^w$
Mass energy density	(7, 8, 9)	(1, 1, 1)
Volumetric density	(9, 9, 9)	(2, 3, 4)

Table 12: S_j and R_j.

Alternatives	S_j values	R_j values
Electrochemical storage	(−0.0625, 0.1310, 0.4804)	(0.0000, 0.0833, 0.3375)
Electrical storage	(0.1875, 0.4643, 0.9304)	(0.1875, 0.4167, 0.7875)
Magnetic storage	(−0.1250, 0.0000, 0.2250)	(0.0000, 0.0000, 0.2250)
Mechanical storage	(0.4464, 0.8690, 1.4000)	(0.3750, 0.5833, 0.9000)
Chemical storage	(0.0143, 0.2619, 0.6643)	(0.0143, 0.1667, 0.4500)

Table 13: Final Q_j values of alternatives.

	Electrochemical storage	Electrical storage	Magnetic storage	Mechanical storage	Chemical storage
Q_j	1.0047	0.9333	1.0000	0.9721	1.0050

Normalized Fuzzy Differences are calculated using equation (12) in step 5. The S_j and R_j values are calculated using equations (13) and (14) in step 6, and the results are tabulated as shown in Table 12.

In step 7, equation (15) is used to find the value of Q. Defuzzification is carried out using the Centre of Area Method to return crisp values for each of the 6 alternatives in step 8. The final values of Q for the set of subcriteria defined with respect to energy density are tabulated in Table 13.

Thus, the same procedure is repeated for the other sets of subcriteria groups, and Q values are obtained and tabulated as shown in Table 14. Now, we integrate the AHP and VIKOR techniques by taking the product of the Q values and the normalized weights of each of the criteria to obtain the ranks of the alternatives by ranking the highest resulting product first and moving to the lower products. Therefore, we obtain the final ranks given in Table 14. Further, the sensitivity analysis is carried out to analyze the effect of variation in the main criteria weights on the final ranking of alternatives.

4.3. Sensitivity Analysis. This section deeply examines the influence of main criteria weights on the ranking of alternatives. The scenarios are produced by varying the most important main criterion weight obtained by Fuzzy AHP method. At the same time, the weights of the other criteria are adjusted using the following equation [30, 31]:

$$w_i' = (1 - w_m')\left(\frac{w_i}{1 - w_m}\right), i = 1, 2, \ldots, n | i \neq m, \quad (16)$$

where w_i is the original weight of the main criterion C_i, w_i' represents the adjusted weight of the main criterion C_i, w_m is the original weight of the most important main criterion C_m, and w_m' is the adjusted weight of the most important main criterion C_m.

In the initial scenario (S_0), the main criteria weights are calculated using Fuzzy AHP method; that is, the weights of energy density, life cycle, cycle efficiency, investment level, suitability to climatic conditions, and space required are $w_1 = 0.077604$, $w_2 = 0.152115$, $w_3 = 0.294208$, $w_4 = 0.068201$, $w_5 = 0.368441$, and $w_6 = 0.039431$, respectively. From the obtained weights, the suitability to climatic conditions criterion has the highest value. Therefore, it (C_5) is the preeminent criterion. Now, for scenario 1 (S_1), the weight of C_5 is reduced by 10%, and the weights of other main criteria are adjusted using equation (16). Fuzzy VIKOR methodology is now applied to obtain the ranking of the alternatives. A similar procedure is followed for S2–S10. All scenarios are summarized in Figure 3.

In all the scenarios, the ranks of the two alternatives, that is, magnetic (A_3) and electrochemical (A_1) storage, remain unchanged. For the remaining three alternatives, that is, electrical storage (A_2), mechanical storage (A_4), and chemical storage (A_5), there are slight changes in the rank. For scenarios 1–3, the initial rank of the alternatives (i.e., $A_3 > A_1 > A_5 > A_4 > A_2$) is retained. The ranks of the alternatives for scenarios 4-5 are obtained as $A_3 > A_1 > A_5 > A_2 > A_4$, for scenarios 6-7, they are obtained as $A_3 > A_1 > A_2 > A_5 > A_4$, and for scenarios 8–10, they are obtained as $A_3 > A_1 > A_2 > A_4 > A_5$.

According to the sensitivity analysis results, it can be outlined that the utilized hybrid approach of fuzzy AHP and fuzzy VIKOR for energy storage technology selection is stable. Here, the magnetic storage alternative is the prominent solution among all other energy storage technologies.

Table 14: Overall Ranking of Energy storage technologies.

Alternatives	Overall priority weights of main criteria						Overall priority weights of alternatives	Normalized priority weights of alternatives	Overall ranking of alternatives
	Energy density 0.077604	Life cycle 0.152115	Cycle efficiency 0.294208	Investment level 0.068201	Suitability to climatic conditions 0.368441	Space required 0.039431			
	Priority weights of alternatives								
	w.r.t energy density	w.r.t life cycle	w.r.t cycle efficiency	w.r.t investment level	w.r.t suitability to climatic conditions	w.r.t space required			
Electrochemical storage	1.0047	1.0341	1	0.9039	0.9914	0.9996	0.995813	0.201454997	**2**
Electrical storage	0.9333	1.0000	1.0063	1.0219	0.9377	0.9963	0.975071	0.197258848	**5**
Magnetic storage	1.0000	1.0684	0.9857	1.0000	1.0000	1.0000	1.006197	0.203555701	**1**
Mechanical storage	0.9721	0.9839	1.0000	0.9818	0.9636	0.9631	0.979278	0.198109933	**4**
Chemical storage	1.0050	0.9817	0.9857	0.9712	0.9881	0.9923	0.986745	0.199620522	**3**

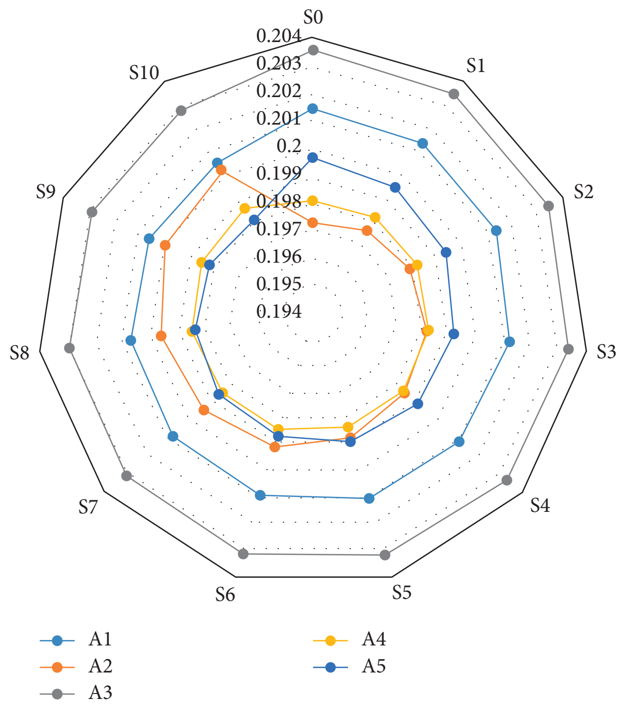

FIGURE 3: Sensitivity analysis.

5. Conclusion

The importance of employing energy storage techniques (EST) for power evacuation and their respective advantages has been emphasized. ESTs such as electrochemical storage, electrical storage, magnetic storage, mechanical storage, and chemical storage have been selected as the alternatives. The final decision was made to decide the best storage technology. The criteria being considered were energy density, life cycles, cycle efficiency, investment level, suitability to climatic conditions, and storage space required. The alternatives have been evaluated using the novel idea of hybrid multicriteria decision-making technique under fuzzy environment prioritizing different ESTs. A numerical illustration for a sample scenario was provided with detailed descriptions linked to the various mathematical procedures, alternatives, and criteria.

The sample scenario evaluated using the set of criteria, subcriteria, and alternatives resulted in magnetic storage being the most effective EST based on the opinion of the decision-makers and the subsequent fuzzy techniques used. The final weight of magnetic storage was the highest, and it decreased with subsequent alternatives. Other alternative EST followed hierarchical ranking order as electrochemical storage, chemical storage, mechanical storage, and electrical storage following most effective to least effective. Hence, fuzzy AHP and fuzzy VIKOR have thus been integrated into a hybrid multiple-criteria decision-making methodology to find the best storage technology.

From the sensitivity analysis, it is concluded that utilized hybrid approach of fuzzy AHP and fuzzy VIKOR for energy storage technology selection is stable. The magnetic storage alternative is the most prominent solution among all other energy storage technologies.

Data Availability

All data are included inside in the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Research Article

Experimental Harmonics Analysis of UPS (Uninterrupted Power Supply) System and Mitigation Using Single-Phase Half-Bridge HAPF (Hybrid Active Power Filter) Based on Novel Fuzzy Logic Current Controller (FLCC) for Reference Current Extraction (RCE)

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UPS Uninterruptible power supply) is used as backup when the input source, usually the national grid, fails to give power to a load. In addition to the growing use of electronic power devices in industrial and residential systems, such as UPS, controlled rectifiers, SMPS (Switch Mode Power Supplies), and DC Converters, there is a serious problem caused by harmonics in AC mains, which lowers the power quality. Harmonics can cause a variety of problems, including sensitive equipment failure, resonance issues, heated wires, power loss, and inefficient distribution systems. A passive or active power filter could be used to reduce harmonics. However, passive filters are more difficult to design and are bulkier. With the advancement of power electronics, active power filters were developed, and the best combination of both was supplied in the form of hybrid active power filters (HAPF). This study shows an approach to minimizing the harmonics contained in the output of a UPS connected to a nonlinear load. Experiments with several UPS types have been conducted under various nonlinear loads, as well as charging and discharging of batteries, and the proposed technique significantly reduces harmonics in a system with a HAPFs (hybrid active power filter) based on a unique FLCC (fuzzy logic current controller). In this paper, we use a fuzzy logic controller to generate pulse width modulation (PWM) switching signals in a single-phase half-bridge HAPF. The operation of the proposed PWM-FLCC will be studied in a steady and transient state. Based on a connection between the uninterrupted power supply (UPS) supplying a single-phase power to a nonlinear load, different power filter topologies and a brief review of reference current extraction (RCE) methods used in this study were also included and the most common configurations have been compared with their advantages and disadvantages to ensure the right selection of the power filter for UPS connected with the nonlinear load. The results of the investigation demonstrate that the HAPF with the fuzzy logic current controller has reasonable performance, with a significant reduction in current THD down to 1.09%, as per IEEE-519 standard.

1. Introduction

In today's world, improving power quality (PQ) is a major challenge in the field of power distribution. In general, the devices used in the power system such as Switched-mode power supplies (SMPS), arc furnaces, uninterruptible power supplies (UPS), variable speed drives (VSDs), and other power electronic devices are nonlinear in nature. The increase in nonlinear load has exponentially caused power quality problems such as high harmonics of current and voltage and low power factor, especially when connected to the grid in a distributed generation system. These loads generate a variety of PQ issues, including harmonics in source/load voltages and currents, which have a negative impact on system security, efficiency, and dependability [1]. As a result, many studies have been conducted employing various custom power devices (CPD) to improve the system's PQ.

Decentralized grids in modern times have also made complex electricity networks. In such a system, power interruption can be a serious problem for sensitive equipment. In 2005, conventional uninterruptible power supply (UPS) systems were summarized [1]. In the case of an input power failure from the national grid, the UPS is employed as a backup power supply for the load (usually mains). These conventional UPS systems are still available commercially with reasonable performance capabilities. However, many problems have remained unsolved as yet. In [2], a hybrid energy storage system (ESS) integrated with UPS was proposed for online operation. The authors insisted that the system cost is minimized and that the battery usage factor is improved by using the system for demand management as well as emergency power supply. In [3], a new solution for adopting line-interactive UPS as a shunt active power filter (SAPF) was designed and investigated. The exponential development in nonlinear loads in the previous decade worsened power quality problems such as excessive current and voltage harmonics, as well as low power factor, especially when connected to the power grid with distributed generation systems [4, 5]. Hence, as an effort to improve the power quality conventionally, passive filters were used, leading to emerging new topologies [5]. However, these traditional filter topologies did not live up to the expectations of modern diversity of the types of loads. APFs (active power filters) have been studied for decades and have been improved to suit the modern load requirements. In [6], APF topologies have been summarized and were available around 1999. Two decades have passed since this research was published and many improvements have been observed in APF topologies. In the last few years, HAPFs (hybrid active power filters) have been developed for specific types of loads mentioned in the respective research [7–15]. In this paper, the UPS system experimental harmonics analysis has been performed with harmonics mitigation by hysteresis-based HAPF. A fundamental 50-Hz sinusoidal waveform, 3rd harmonic, 5th harmonic, and the deformed waveform are shown in Figure 1. The Fourier series can be used to decompose this distorted waveform into its fundamental and harmonic components. Total harmonic distortion (THD) in voltage or current can be determined using the following formula.

$$\text{THD} = \frac{\sqrt{\sum_{h>1}^{h_{\max}} {M_h}^2}}{M_1} \times 100, \quad (1)$$

where $h_{\max}$ is the highest order harmonic in the calculation, M_h is the effective value of h^{th} harmonic, and M_1 is the effective value of the fundamental component. Nonlinear loads such as electric traction systems, PE Devices, VFD/VSD, SMPS, CVCF, UPS, power converters, and domestic appliances of all types cause harmonics in power distribution systems.

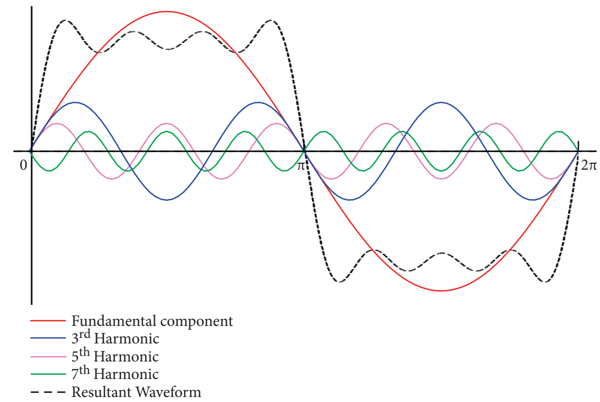


Figure 1: Distorted waveform and its constituent Fourier series.

These harmonics, in turn, will cause many power utilization problems.

(i) Higher harmonic frequencies cause voltage flickers, which is harmful to human eyes.

(ii) Increase inaudible sound as higher harmonics start vibrations

(iii) Magnetic losses increased due to higher harmonics, leading to raised temperatures, eventually decreasing the life and efficiency of the electrical machines and transformers.

(iv) Created Resonant, which can shorten the life of capacitors and cause metering and instrumentation systems to malfunction. The fifth and seventh harmonics generate torque ripple in the electrical machines.

(v) Magnetic and electric fields are also produced by harmonics, which affect telephone wires and other communication systems near the transmission system.

To address the aforementioned problems associated with harmonics, harmonic filters can be used. In [16], harmonic suppression technologies in power distribution that have been used in the past have been classified. In a conventional context, passive power filters (PPFs) are the simplest solution for mitigating harmonic distortion [17, 18]. Recent investigation on different applications of passive power filters has shown the potential advantages of their use [19–22]. Figure 2 depicts some of the most common passive filter types and configurations, which are essentially inductors, capacitors, and resistors configured in a way to control harmonics.

Even though it is affordable, the most widely used passive filter is a simple LC series single tuned filter. This filter is adjusted to offer low impedance to a specific harmonic frequency and is coupled in shunt with the main distribution system. Hence, that particular frequency current is provided an alternative flow path that passes through the filter. A high-pass filter (HPF) eliminates the harmonic frequencies

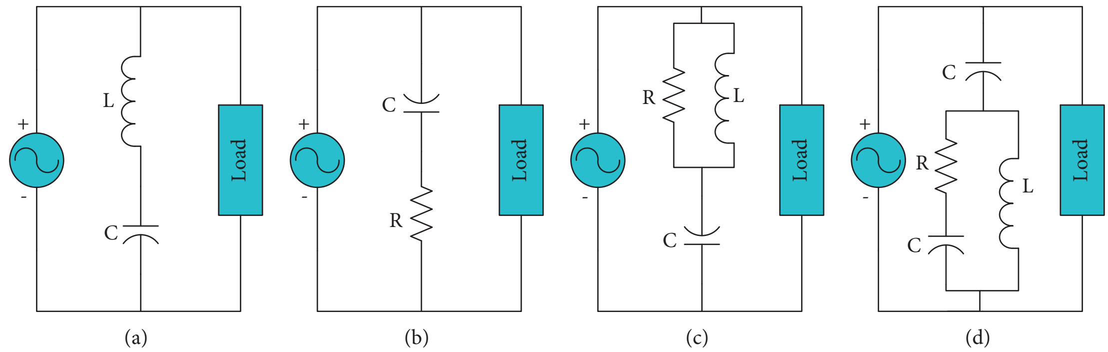


FIGURE 2: Configurations of passive power filters (a) single tuned (b) 1st order high-pass (c) 2nd order high-pass (d) 3rd order high-pass.

above a certain frequency value. Typically, HPF is formed into three types of configurations as shown in Figure 2. Due to the relatively higher losses created at the fundamental frequency, the 1st-order HPF is still not widely used. Unlike the 1st-order HPF, the 2nd-order HPF creates fewer power losses and its harmonic frequency filtration ability is adequate. Comparatively, the 3rd-order HPF's filtering capabilities are superior to 2nd-order HPF. However, due to its stability and expense, it is rarely employed in low- and medium-voltage applications [17, 18]. In general, PPFs mitigate harmonics and provide the necessary reactive power for converters in distribution systems with pre-defined standards as a conventional inexpensive solution. However, as the performance of these filters depends on the constantly shifting source impedance, under low load conditions, they cannot be used to control reactive power. Additionally, they cause resonance and hence potentially destabilize the power distribution systems.

Moreover, component value changes due to frequency variation or prolonged use of the filter can determine it. These problems are addressed by using active power filters (APFs) [3, 6]. In [3], UPS is used as an active filter and the design and analysis is presented in detail. In [23], to reduce the magnitude of external disturbances and modelling uncertainties, an APF current controller is presented that uses non-singular terminal sliding mode control based on an adaptive fuzzy neural network. In [24], to improve power quality, based on a self-regulated double hidden layer output feedback neural network, an APF current controller has been investigated. In [25], for digitally controlled LCL-type SAPFs, a dual-loop current control approach is explored.

The principle of APF is injecting equal magnitude current or voltage 180° phase-shifted to the harmonics in the system. Figure 3 depicts the fundamental block diagram of a typical APF constituent. The reference signal estimator gathers data on all system variables, including harmonic currents, and generates reference current and voltage signals. These signals are processed by the PWM control unit to send switching pulse sequences to the voltage source converter to produce the compensating current. Comparatively, APFs are more beneficial than passive filters, and are unique in that they suppress both supply and reactive current harmonics.

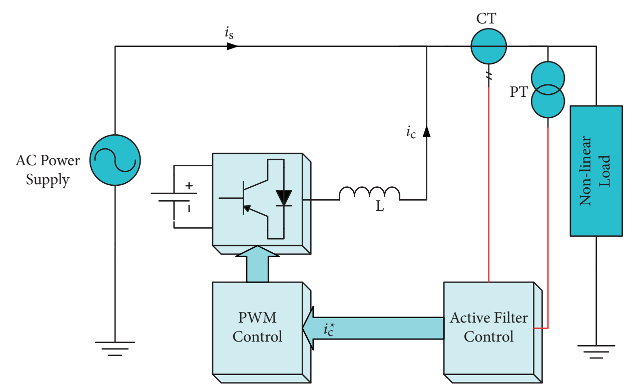


FIGURE 3: Basic block diagram of a shunt active power filter.

Additionally, since they do not create resonance with the distribution system, their performance does not depend on system properties. However, APFs have some disadvantages, such as the fast switching devices implemented for control which create high-frequency noise. Consequently, it creates electromagnetic interference (EMI). Figure 4 shows how APF can be classified with reference to the power circuit configuration. In general, the following are the categories of APFs [26].

(1) SAPFs (Shunt Active Power Filters)
(2) SeAPFs (Series Active Power Filters)
(3) HAPFs (Hybrid Active Power Filters)

For the SAPFs, either a current or voltage source converter can be connected to an APF circuit. However, voltage source converters (VSC) are commonly selected for their distinguished topology and simple installation method [27]. A VSC-based general configuration of SAPF has been shown in Figure 5.

It is fundamentally a current source that has a primary function to correct for harmonic current caused by non-linear loads. The principle of APF is injecting an equal magnitude current 180° phase-shifted to the harmonics generated by load, eventually canceling out the original distortion of the supply current.

A common configuration of the SAPF is using a rectifier and a dc link inductor that effectively dampens the harmonic resonance between the passive filter and the system impedance.

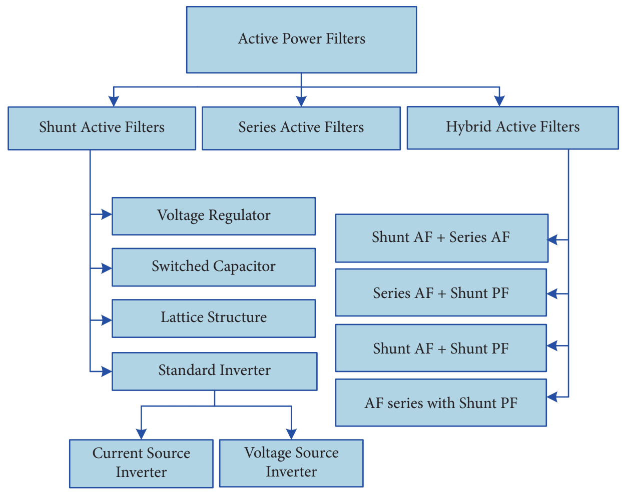


Figure 4: APF classification on the basis of circuit configurations.

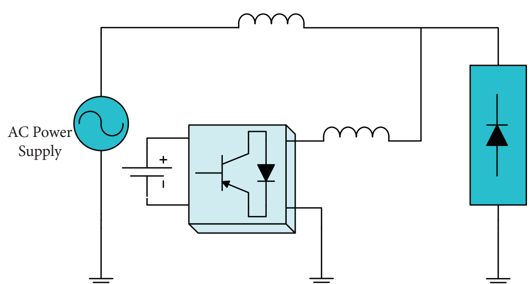


Figure 5: VSC-based SAPF.

SeAPF and SAPF basically have the same configuration except that the matching inductor of SAPF is displaced by the matching transformer whose one winding is connected in series with a distribution bus [28]. The basic scheme of SeAPF is shown in Figure 6.

Generally, SeAPF acts as a component that provides a very high impedance path for unwanted harmonic frequencies and hence isolates them from entering the source. The SeAPF acts like a CVS, providing an offset voltage equal to the harmonics of the source voltage. A high rating isolating transformer is to be used as the system's current magnitude (50-Hz) goes higher, since the power losses scale up according to the system ratings. Eventually, SeAPF has become more expensive than the SAPF scheme. Therefore, SeAPFs are generally used when the system is connected with voltage-sensitive equipment which requires the supply voltage to be precisely sinusoidal for accurate operation of the equipment. As shown in Figure 6, the SeAPF arrangement is such that it acts as a component that provides a very high impedance path for unwanted harmonic frequencies and hence isolates them from entering the source. Hence, the unwanted harmonic currents cannot flow between the source and the load.

However, pure APFs have limited capabilities. Instead, HAPFs are used to combine the advantages of PPFs and APFs in order to reduce harmonic content. In this combination, PPFs are designed to provide low impedance routes for harmonic frequency currents, and APF increases the PPFs' performance. Thus, HAPF gives only the advantages of APFs and PPFs while removing the disadvantages. Advancements in HAPF topologies implemented in various types of power systems have brought a range of HAPFs which are investigated for general or specific power systems [7–15]. However, PFFs combined with SeAPF or SAPF make two general configurations for HAPFs. HAPF as a combination of SeAPF and SPPF is shown in Figure 7(a) filter, while a combination of the SPPF (shunt passive power filter) and SAPF (shunt active power filter) is shown in Figure 7(b). [29].

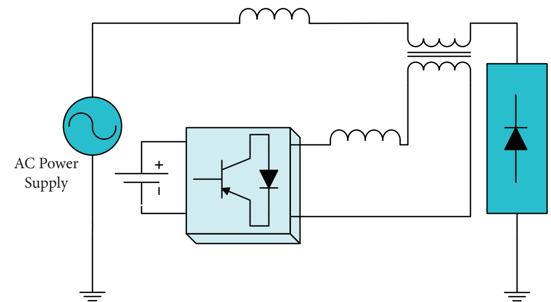


Figure 6: VSC-based SeAPF.

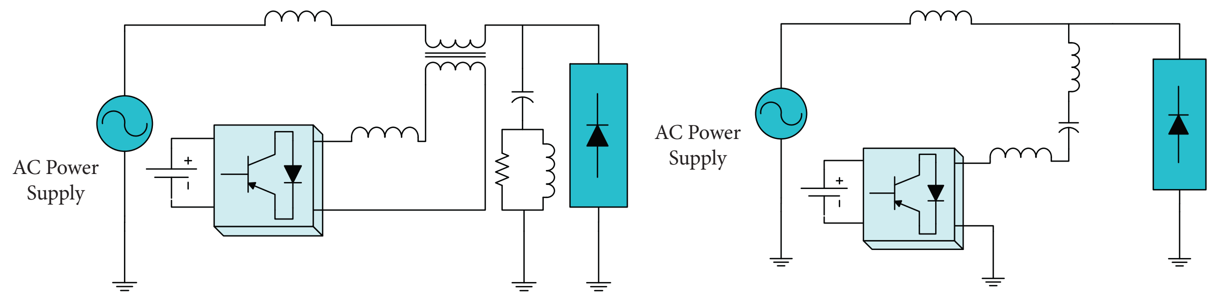
SeAPF redirects high-frequency currents from the load to the low impedance route of SPPF, as shown in Figure 7(a). The SeAPF's safety, on the other hand, is essential because this topology requires the transfer of the sum of the fundamental and harmonic currents. In this case, no matching transformer is used for the daisy chain SAPF and SPPF. Therefore, it is known as a transformer with less topology.

SPPFs are developed to provide a path with no impedance to the current of the most dominant load frequency, but their filtering efficiency is unacceptable. In this way, SAPF helps PPF to improve filtering efficiency and avoid the risk of resonance.

2. Experimental Analysis Setup and Results

For reliable, uninterrupted, and fast backup power, UPS systems are employed in various sectors, including residential, commercial, industrial, healthcare, and communication. In some countries, the use of the UPS System is very common due to load shedding, as power generation is not sufficient. Experimental Analysis Setup, Design, and development of a hybrid interface use an optical USB port and a power quality meter as illustrated in Figure 8 for UPS system harmonic analysis linked to a linear and nonlinear load.

Harmonic distortion from UPS systems, inverters, and nonlinear loads has become an issue with the explosive growth of UPS systems [30–32]. This work proposes a generic model modified from the usual control structure scheme to evaluate the harmonized generating process. Figure 9 (a-c) shows the Power Quality (PQ) and Energy Analyzer (EA) fluke with Optical USB Interface Cable (OC4-USB) utilized for Experimental Setup to obtain THD Analysis of the UPS System linked with linear and nonlinear load results of these, and a new HAPF with novel fuzzy logic control has been proposed to reduce THD.



(a) (b)

Figure 7: HAPFs (a) Configurations of SeAPF and SAPF and (b) Configurations of SAPF and SPPF.

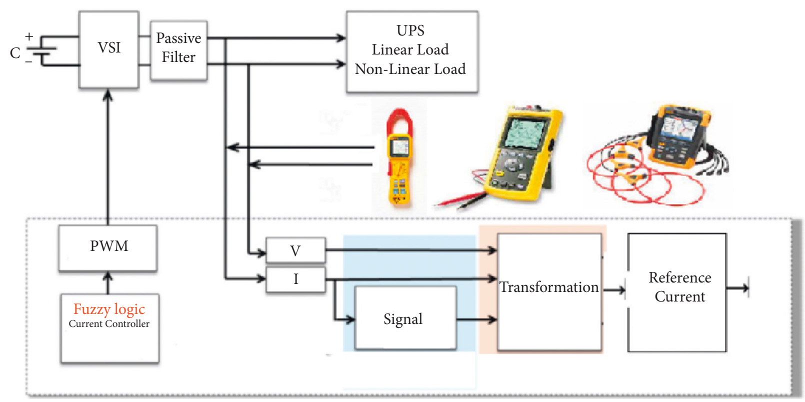


Figure 8: Experimental Setup, design, and development for harmonic analysis for UPS systems connected to linear & non-linear load.

(a) (b) (c)

Figure 9: (a-c) PQ & EA fluke Analyzer 435-43b and Optical USB Interface Cable (OC4-USB) for Experimental Harmonic Analysis.

Experimental tests of various UPS Types have been performed at different nonlinear loads as well as on charging and discharging of batteries, on basis of these experimental results as given in Table.1, proposed fuzzy logic PWM technology which reduces harmonics and compensates for reactive power.

Various types of different rating UPS systems were taken for experimental analyses and tests, with the findings presented in Figure 10. UPS System THD Analysis connected with different types of loads is shown (Figure 11).

Other experimental tests of UPS/CVCF System (Control Voltage Control Frequency) were performed with higher ratings having maximum THD and results are shown in Figure 12.

It examines the relationship between current harmonics and output power and outlines the causes of current harmonics. Both modelling and experimental evaluation support theoretical conclusions and analysis [1, 2]. A general model, adapted from the classic control block diagram, was developed to investigate the harmonic production process induced by a single-phase UPS system. Table 1 shows that locally built UPS without a filter has higher THD losses and very low efficiency.

Table 1: Different UPS System Efficiency and THD Result from experimental analysis

UPS system			Efficiency		THD
U.P.S	Battery Voltage V	Power Watt	Charging (%)	Discharging (%)	Charging
U.P.S#1	12	800	79	63.5.0	30.6
U.P.S#2	12	550	80	70	70.5
U.P.S#3	24	650	76	86	15.5
U.P.S#4	24	1600	84.7	77.5	25.1
U.P.S#5	24	1200	78	86.5	21.5
U.P.S	Average THD				32.63%

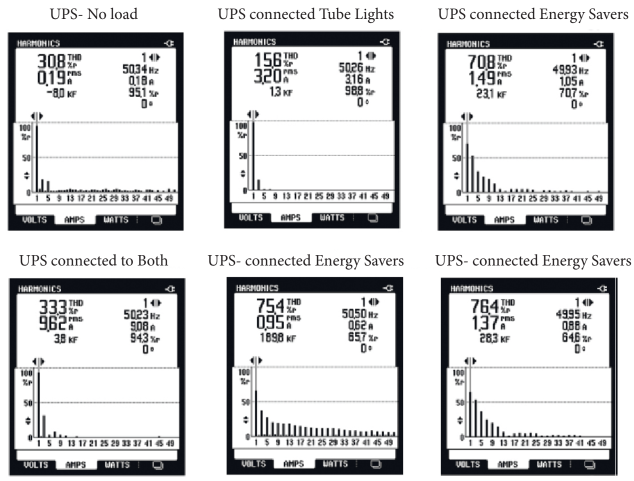


Figure 10: Experimental THD Analysis of UPS system connected with different types of linear and non-linear loads.

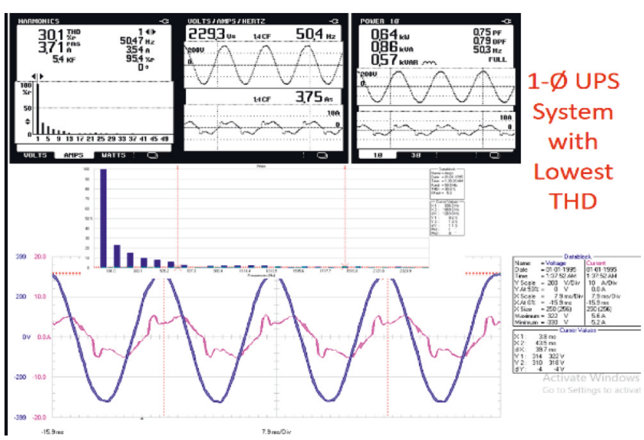


Figure 11: Experimental single-phase UPS system waveforms of voltage, current, and the frequency spectrum of harmonics with the lowest THD.

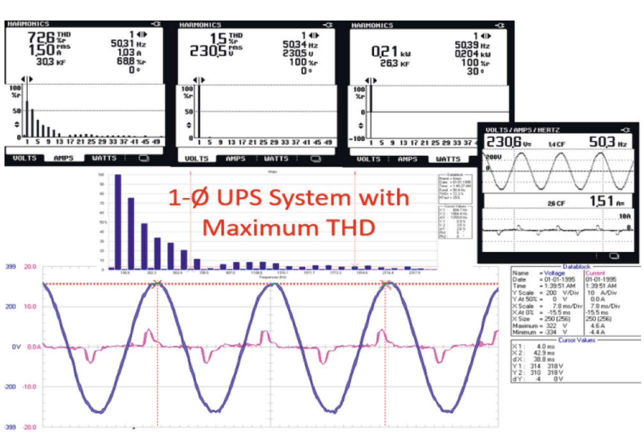


Figure 12: Experimental single-phase UPS system waveforms of voltage, current, and the frequency spectrum of harmonics with maximum THD.

Based on these results, Single-phase half-bridge HAPF with fuzzy logic controller-based PWM has been investigated particularly for UPS-connected nonlinear loads. During battery charging and discharging, Table 1 shows UPS efficiency and THD data for various types of loads. Furthermore, according to the results of the experiments, the average harmonic distortion of the UPS system is equal to or greater than 32.63%, and dire need to develop HAPF, to reduce the THD at large compared to other passive and APFs (active power filters) with most efficient and effective method.

3. Conventional HAPF Topology and Reference Current Extraction RCE Technique

The generation of compensation or reference current extraction (RCE) is one of the primary components of the HAPF. The exact measurement and estimation of the reference current for the controller are significant for the proper function of the APF. As it is illustrated in Figure 13, the APF evaluates the RCE (reference current extraction) signal by detecting the voltage/current signal along with system variable data. The supply voltage, D.C Bus voltage, and corresponding transformer voltage detected by the APF are called voltages variables while currents variables detected by APF are supply current, load current, compensation, and D.C link current. The APFs extract voltage or current as a frequency or time domain reference signal based on both variables. An important part of detection and measurement of the system variables has been widely investigated with many improvements and advancements made in the literature to estimate the reference signal for APF [33, 34]. Figure 8 shows the various techniques of the estimation of the reference signal with two main techniques, namely, frequency domain, and time domain. In the frequency domain technique, when reference signal estimate is appropriate for single- or three-phase supply systems based on Fourier analysis, the Fourier transforms method (FTT) is applied.

Firstly, FTT is utilized to achieve the amplitude and phase of harmonics; then time-domain compensation reference signal is then calculated using an inverse Fourier transform (IFT). [35–37]. The main disadvantage of the above technique is the time delay in calculating Fourier coefficients and sampling system variables in which, eventually, the response time of the filter will be longer. Consequently, it cannot be used in fluctuating load conditions and is only utilized under fluctuating load scenarios where a quick response time is not necessary. In time-domain approaches, reference signal estimation is performed instantly from the distorted signal. Except for the synchronous-reference-frame theorem, which is only relevant to three-phase systems, these strategies apply to single- and three-phase systems [38]. Following is a brief explanation of each technique.

3.1. Instantaneous (p-q) Theory. The reference compensating currents are calculated using the $\alpha\beta$ Clarke transformation of the recorded three-phase voltages and currents in this method. Based on these $\alpha\beta$ transformations, the instantaneous reactive and active powers are calculated, and the

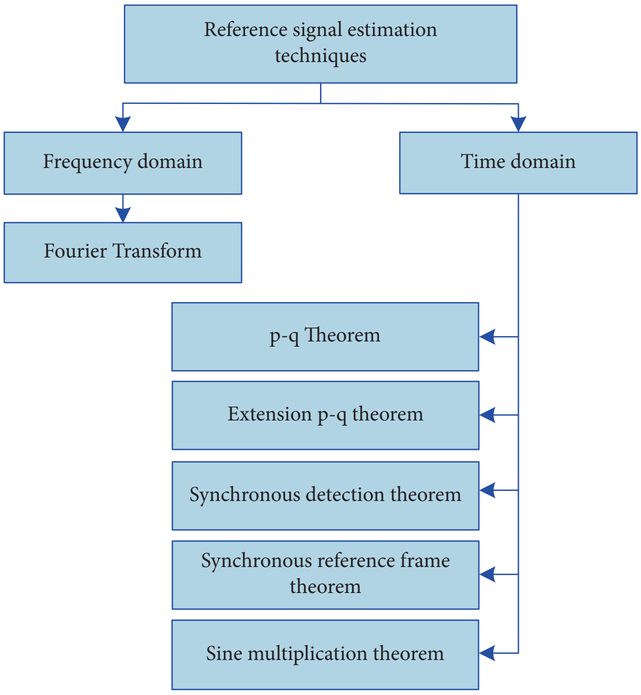


Figure 13: Classification of reference signal estimation techniques.

oscillating parts, which, with the help of the HPF, really contribute to the formation of harmonics in the system. The filter is fine-tuned to provide the desired results while reducing cut-off frequencies as required by the AF. The exerted part is transformed back to three-phase quantities to achieve reference compensation signals. However, this method can only be used with three-phase sinusoidal voltage systems. Some adjustments to the original p-q theorem were proposed and executed to make it suitable for single-phase systems [39].

3.2. Extension Instantaneous (p-q) Technique. For unsymmetrical and non-sinusoidal voltage systems, the extension of the instantaneous (p-q) theory has been used. In this technique, computation of the instantaneous reactive power is done by displacing the supply voltages by 90°. Unlike the instantaneous (p-q) technique, in this technique, DC components are exerted from LPFs, and then a reference compensating signal can be obtained using inverse transformation. This technique is relatively advantageous in that it is simpler in the calculation of the three-phase reactive and active power quantities [40] and of the fundamentals of the p-q theorem for a single-phase system [41].

3.3. Synchronous-Detection Theorem (S.D.T). It is similar to the instantaneous (p-q) method, but it is only applicable to three-phase systems. In this technique, despite the load conditions, it is necessary to assume that the APF maintains the source current and voltage as sinusoidal without phase difference. The actual power (W) of the connected load is computed, evenly distributed over the three phases, and then the calculated compensation current is obtained using simple mathematical calculations [42]. Although this technique is simple, it is generally used for supply voltage harmonics only.

3.4. Synchronous-Reference-Frame Theorem (S.R.F.T). For calculating the instantaneous active and reactive current components, reference compensating currents are calculated by converting the voltage and current variables from three-phase sources into a synchronous rotating frame (DQ co-ordinates). In this method, an amount of DC is applied from the main component using a filtration process. It is only used for three-phase systems and its control must be able to interface with DC quantities [43].

3.5. Sine Multiplication Theorem (S.M.T). The fundamental component of the distorted load current is estimated using this method by integrating the response obtained by multiplying the distorted load current by the fundamental frequency's sine wave. The APF drive current is the difference between this fundamental component and the instantaneous distortion in the connected load current. It can be utilized in single-phase and three-phase systems. Although LPFs and HPFs are used for reducing time delay, it is a slow technique to estimate the reference compensation currents mainly caused by integration and sampling [44].

4. Proposed Harmonic Reference Current Extraction (RCE) Technique Based on DQ with Fuzzy Logic Current Controller (FLCC) for Half-Bridge Single-Phase HAPF

The proposed FLCC single line diagram for single-phase half-bridge HAPF is depicted in Figure 14. The controller is made up of two primary components. The first is an RCE (reference current extraction) from a distorted line current, while the second is a PWM current controller for inverter switching. Whereas, traditional controllers, on the other hand, necessitate an accurate linear mathematical model of the system.

With parameter changes and nonlinear load disturbances, this is challenging to implement. Fuzzy logic controllers (FLCs) have recently been used in a variety of power electronics and active power filter applications [45]. Figure 15 shows a complete simulation of active and ineffective current components with proposed single-phase half-bridge HAPF based on FLCC with Reference current estimators (RCE) and PI controller.

The proposed HAPF's power supply circuit is a half-bridge VSI, as depicted in Figure 16. The voltage source inverter VSI involves two MOSFETs, each linked to an antiparallel diode. Selected MOSFETs on their superior performance such as fast switching times, low forward voltage drops, and high power handling. The presented HAPF combines the benefits of dynamic and latent filters, removing the drawbacks of entirely dynamic and inactive filters.

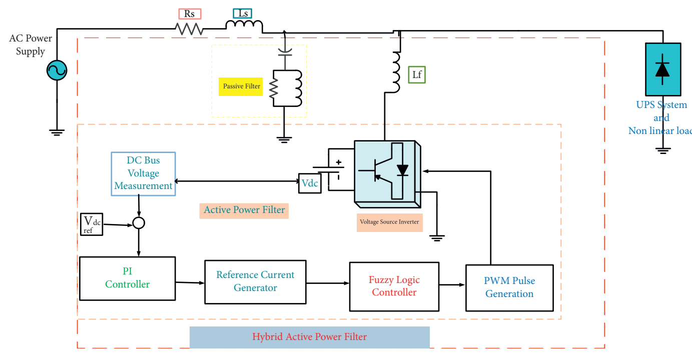


FIGURE 14: Proposed FLCC for single-phase half-bridge HAPF.

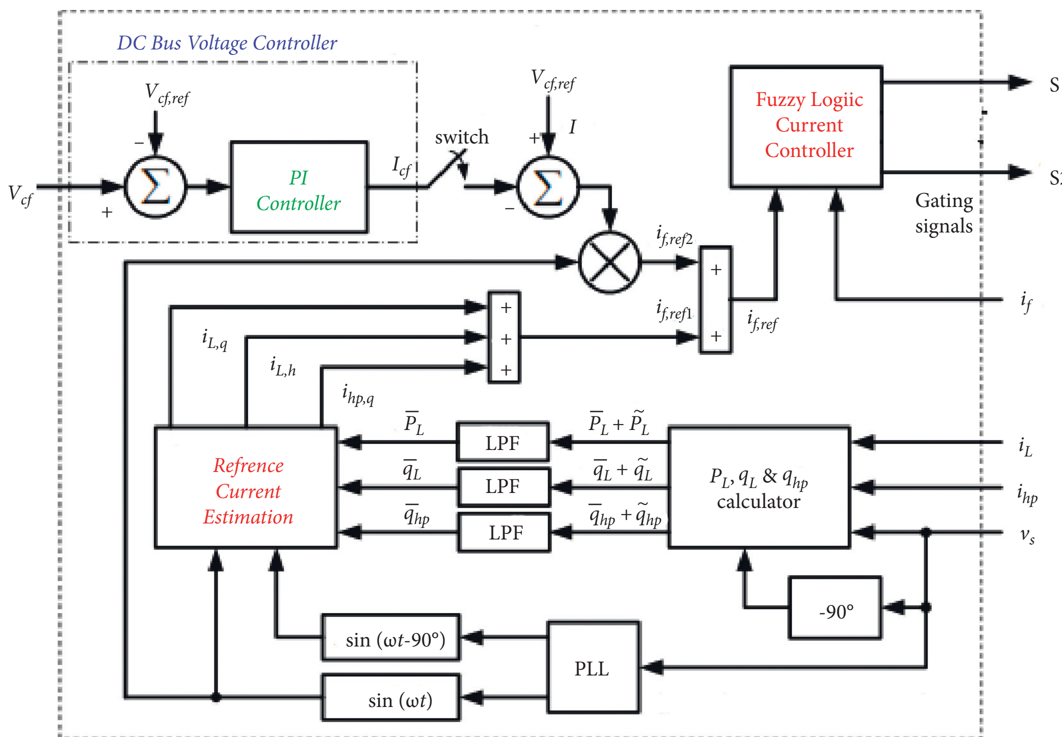


FIGURE 15: Proposed single-phase half-bridge HAPF based on FLCC with Reference current estimators (RCE) and PI controller for DC Bus-Voltage.

FLC (Fuzzy logic controller) has an advantage over traditional controllers in that it does not necessitate an exact mathematical model. It is more reliable than typical controllers and can manage nonlinearity. The distribution system is unbalanced because the distribution lines do not move and the loads are unbalanced. As a result, a hybrid active power filter must be designed that can maintain the THD limit in compliance with the IEEE standard under varied load situations. Figure 17 single-phase half-bridge HAPF based on FLCC for UPS System control block diagram.

In this article, a single-phase synchronous reference frame in equilibrium is simulated in MATLAB to generate the harmonic current reference for the HAPF filter. To achieve the desired reference current, however, just one phase was chosen. Synchronous reference systems transform distorted current caused by a nonlinear load from a static reference system a-b-c to a dynamic reference system d-q [46, 47]. The synchronization reference frame for the isolation of harmonic signals is shown in Figure 18.

Current control uses fuzzy logic because the controller does not require an exact mathematical model; the FLCC-based PWM technique is used and works effectively under imbalanced and fluctuating load conditions. It works with inaccurate inputs and could manage nonlinearity. The controller is tested for unbalanced voltage and varying load conditions. Fuzzy logic controllers have also been developed to control constant voltage capacitors. The compensation current reference signal is compared with the predefined hysteresis band around the reference compensating signal in three-phase, and single-phase HAPF/APF is widely used with the hysteresis controller [39–43]. There is no switching if the compensation reference signal falls within this predefined band as shown in Figure 19.

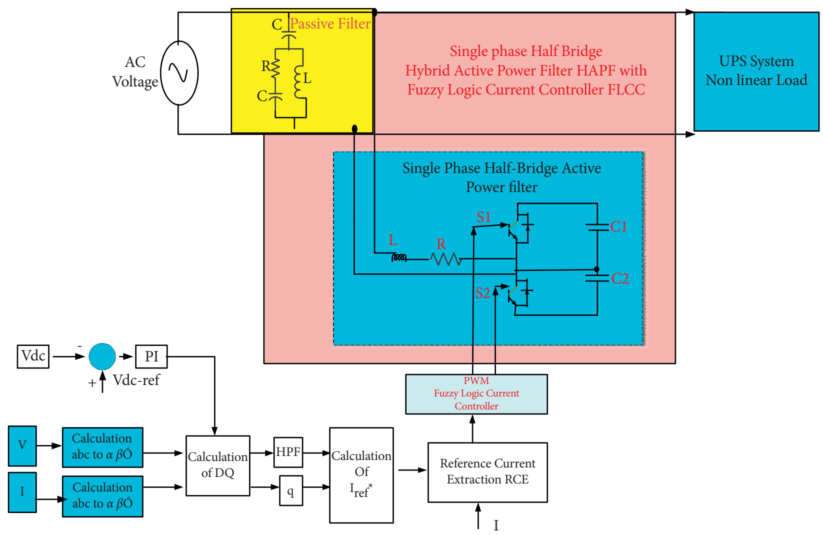


FIGURE 16: Power Supply Circuit for VSI and single-phase half-bridge HAPF with FLCC.

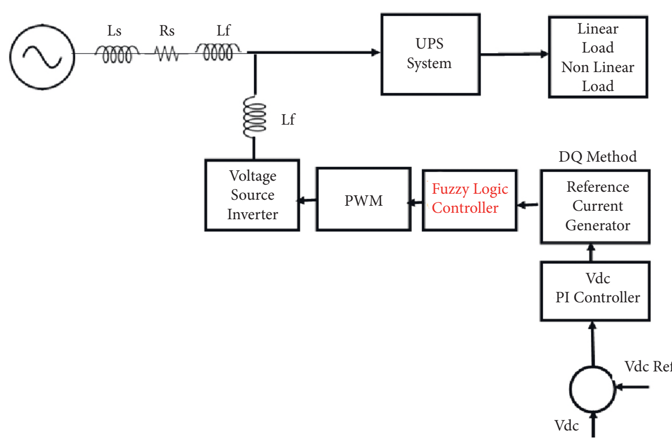


FIGURE 17: Single-phase half-bridge HAPF based on FLCC for UPS System control block diagram.

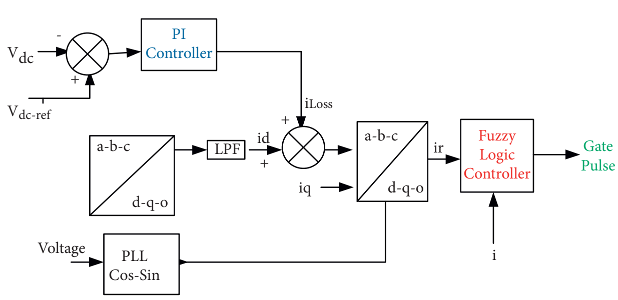


FIGURE 18: Synchronous reference frame SRF-DQ for reference current extraction RCE of harmonic to FLCC-based gate pulse for single-phase half-bridge HAPF.

Consequently, the switching takes place if the reference signal falls out of the band. The performance of the hysteresis current controller has been proven to be exceptional [44, 48]. Apart from its exceptionally dynamic performance, it is simple to apply. On the contrary, the generation of non-uniform switching frequencies is the main disadvantage of this controller, which affects the filter's ability to suppress circuit resonance. [49]. Conventionally, linear and hysteresis controllers were adopted to create and obtain the switching pulse for VSC (voltage source converter) by constructing a system model to obtain control laws with model analysis. With conventional techniques, the model needs to be linearized to handle a nonlinear system. To address these problems, new research is carried out for the application of HAPF.

5. Proposed Fuzzy Logic Current Control FLCC Technique

5.1. Fuzzy Logic Controller Review. Professor Zadeh Lotfi of the University of California, Berkeley, initially proposed the fuzzy logic controller (FLC) in 1965. He provided a strategy for dealing with complex and complicated input data and handling inaccurate input data. Many researchers and system engineers are beginning to recognize the value of fuzzy logic controllers in control algorithms for control analysis and active power filter applications. Fuzzy controllers offer the advantage of simple design techniques that do not necessitate perfect mathematical modelling, the

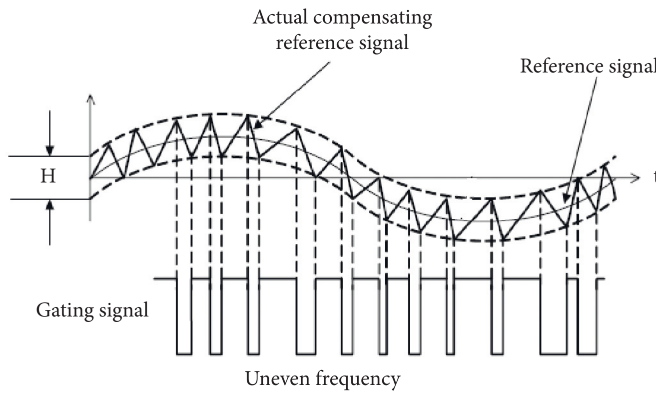


Figure 19: Gating pulse for FLCC.

ability to manage erroneous system inputs, and the ability to handle nonlinearity, making them far more reliable than conventional controllers.

Fuzzy set theory is utilized for developing fuzzy logic, in that a variable is a member of one or more sets to some degree of membership. [46, 47, 49, 50]. Fuzzy logic allows a machine to replicate human reasoning by quantifying inaccurate input and make inferences based on ambiguous and complete facts, but apply a "defuzzification" process, to obtain a clear response. In [51], PQ improvement using fuzzy sliding mode based PWM control control for UPQC is presented in detail as well harmonic distortion is addressed by using three-phase half-bridge HAPF with fuzzy logic control [52]. A block schematic of a fuzzy logic controller (FLC) is shown in Figure 20.

The fuzzy logic controller FLC is made up of three main blocks, each of which has its own working processes and control operation, the specifics of which are listed below:

(i) Fuzzification
(ii) Inference
(iii) Defuzzification

5.1.1. Fuzzification. FLC requires that each input/output (I/O) variable that defines a control surface be represented in fuzzy notation using the language layer. The linguistic values of each I/O variable divide the complete system into contiguous intervals to produce a membership function. The element member values indicate the range in which the variable belongs to a given level. The process of converting I/O variables at the language level is called "fuzzification."

5.1.2. Inference. The control surface performance is directly linked and associated with the system's I/O variables, which are completely controlled by a set of rules. A complex rule of thumb is as under:

If p is M then q is N; If p is M then q is N.

Each rule is implemented with any degree of truth when reading a collection of input variables, assuming that the assumption is correct and that the changes contribute nearly perfectly to the development of the control surface. When all of the rules are met, the control surface is represented as a fuzzy set to represent the constraint's output. This entire procedure is called inference.

The fuzzy inference system (FIS) is consisting of three editors for editing purposes and two viewers which can be termed read-only tools.

(1) FIS- Editor

(i) FIS
(ii) Membership function
(iii) Rule

The FIS fuzzy inference system editor solves high-level problems in the system, with the total number of input and output variables AND their names. The MFE (Membership Function Editor) is used to specify the shape of all membership functions associated with a variable. The RE (rule editor) can be utilized to change or rewrite the set of rules that determine the system's operation.

(2) FIS-Viewer

(i) Rule
(ii) Surface

The rule and surface viewers are both read-only options and used for the look-in to system only and opposite to FIS Editor and cannot be used for editing limited to a diagnostic to show how active rules and the shape of individual membership functions affect the results. One of the outputs is dependent on one or two inputs, as indicated by the surface display. That is, it creates and builds a plot of the output surface of the system.

Control rules designing is the definition of rules that associate the input variables with the properties of the output model and is part of the design of fuzzy control rules. Because the fuzzy logic controller is independent of the system model, the design is essentially intuitive.

5.1.3. Rule Base Table. Variables for linguistic rules are provided. Table 2 demonstrates "if-then" rules for five membership functions chosen for each of the input errors (e) and error variation (Δe) variables as defined in the language rule variables. For two inputs, only 15 possible rules are possible, based on the combination "if, then" $(5 * 3) = 15$.

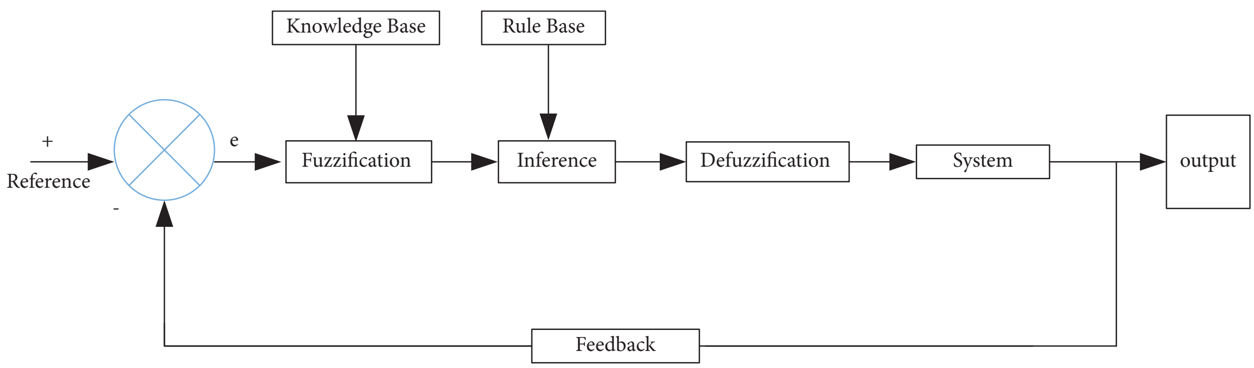


FIGURE 20: FLC's (Fuzzy Logic Controller) block diagram.

TABLE 2: Fuzzy control rules.

Δe e	Small	Zero	Large
Very low	Very increase	Very increase	Very increase
Low	Very increase	Increase	Increase
Zero	Increase	Constant	Decrease
High	Decrease	Decrease	Very decrease
Very high	Very decrease	Very decrease	Very decrease

(3) Mamdani Type Inference. The most widely used fuzzy method is Mamdani's fuzzy inference method. Ebrahim Mamdani introduced the Mamdani technique in 1975, and it was one of the earliest fuzzy set theory inference methods. Mamdani Type inference assumes that the membership function in the output is a fuzzy set. After the aggregation procedure, each output variable has a fuzzy set that should be defuzzified. It is feasible to use a single burst as an output membership function instead of using a single burst, which is often much more efficient. With the linguistic concept "if-then," a Mamdani fuzzy controller was chosen and constructed. The following language variables were chosen for the rule base, increase, Very Increase, Constant, Decrease, Very Decrease and due to their simplicity, triangular, and trapezoidal membership functions are utilized.

Distributed set is sometimes called the singleton inference membership function and it may be thought of as a pre-fuzzy collection of fuzzy sets that have been defuzzified. The Mamdani approach, which calculates the center of gravity of a two-dimensional function, is more often used and greatly simplifies the necessary calculations, making the fuzzy process more efficient. Instead of integrating the entire 2D function, use a weighted average of many data points to get the centroid. Sugeno-type system supports this type of model; in general, the system may be used to simulate an inference system with a linear or constant membership function on the output.

5.1.4. Defuzzification. It is the method of transforming a fuzzy sum into a crisp sum. Defuzzification can be done in many methods. The centroid approach, which employs the formula (2), is the most commonly used method:

Here, λ is the affiliation degree of the output.

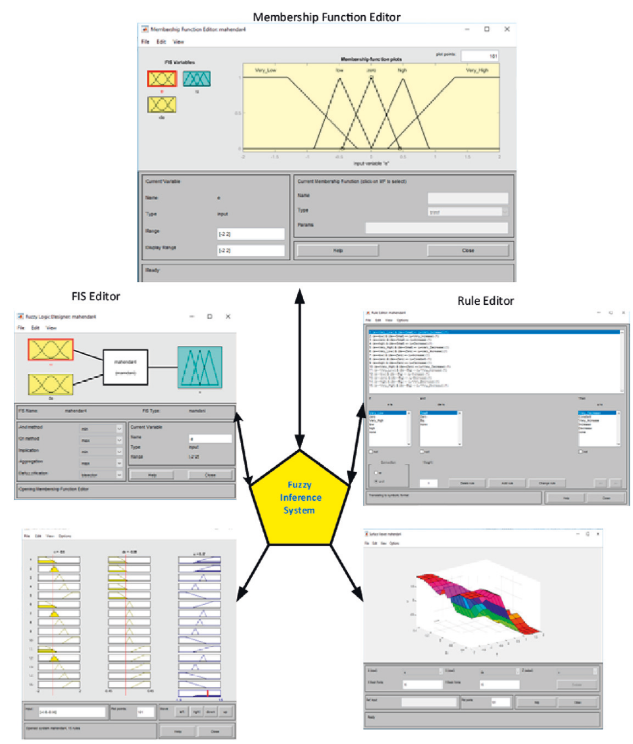


FIGURE 21: Fuzzy inference system with membership function.

$$\frac{\int (\lambda(y)y)\mathrm{d}x}{\int \lambda(y)\mathrm{d}x}, \quad (2)$$

where λ = output y "degree of membership."

The technique of the centroid of area (COA) was considered: For the purpose of defuzzification, HA(y) = defuzz(y, mf, type), Here defuzz (y, mf, type) is the membership function mf, a defuzzified value placed in the corresponding value of the using one of many defuzzification methods on variable y [12], depending on the type of argument. Variables can originate from any of the following categories:

(i) lom: largest (absolute) value of maximum

(ii) som: smallest (absolute) value of maximum

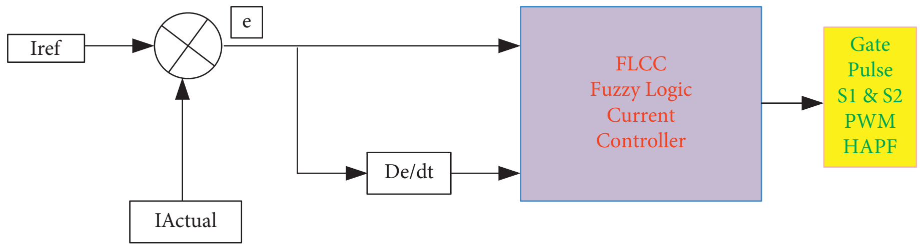


Figure 22: FLC (Fuzzy Logic Controller) based PWM (Pulse Width Modulation) for switching signals (S1 & S2) generation to trigger single-phase half-bridge HAPF.

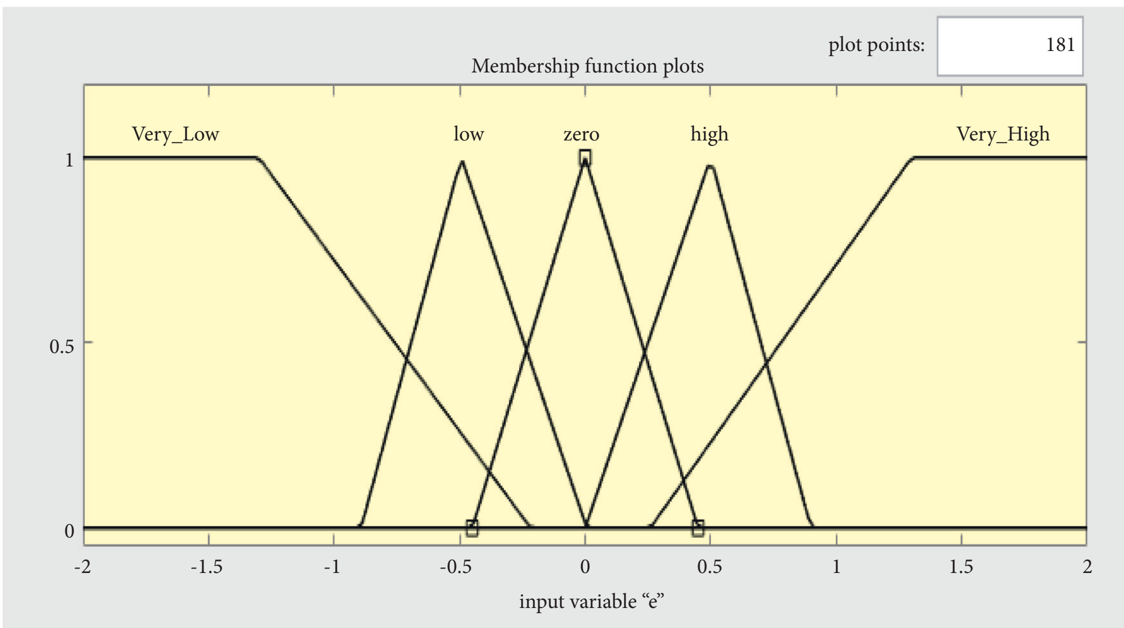


Figure 23: The 1st input (e) Membership Functions.

(iii) mom: mean value of maximum,

(iv) bisector: bisector of area,

(v) centroid: centroid of area,

Membership features are available in a variety of shapes, including trapezoids, triangles, Gaussians, bells, dashed lines, and shapes. Figure 21 shows the membership function in a fuzzy inference system.

The proposed FLCC generates a gate signal obtained by using fuzzy logic technology after the correct gain is applied to the PWM switching and a PI controller has also been used which maintains the DC link capacitor voltage. Figure 22 shows the fuzzy logic based (FLC) Pulse Width Modulation (PWM) for switching signals generation [30–32, 45, 50].

The five linguistic variables for the first input variable error (e) are named as very low, low, zero, high, and very high, and three subsets have been specified for the second input variable (Δe) called: small, zero, and large. Its derivative (e), which is based on a triangular membership function, the Matlab is used for simulation, in contrast to the usual fuzzy inference model that can be found. MFs for the first input (e) are shown in Figure 23(e); MFs for the second input are shown in Figures 24 and MFs for the output (u) below show two input errors and their derivatives are shown in 25. The triangular membership function was originally chosen as easy to implement.

6. DC-Bus Voltage Control

The HAPF does not need to supply active power to compensate for the load's harmonic and reactive currents, as well as the HPF's reactive currents, under lossless conditions. As a result, the DC bus capacitor is more than capable of supplying the reactive power required by the proposed HAPFs (hybrid APF).

The DC bus capacitor provides reactive energy, which is transmitted between the charge and the DC bus capacitor (DC bus capacitor charging and discharging) to keep the average DC bus voltage at a predetermined level.

Due to switching losses, capacitor leakage, and other factors, the distribution power supply must provide not only the actual power required by the load but also the additional power required by the VSI to maintain the DC bus voltage constant. The DC bus voltage will continue to decline if these losses are not addressed. The PI regulator used to control the

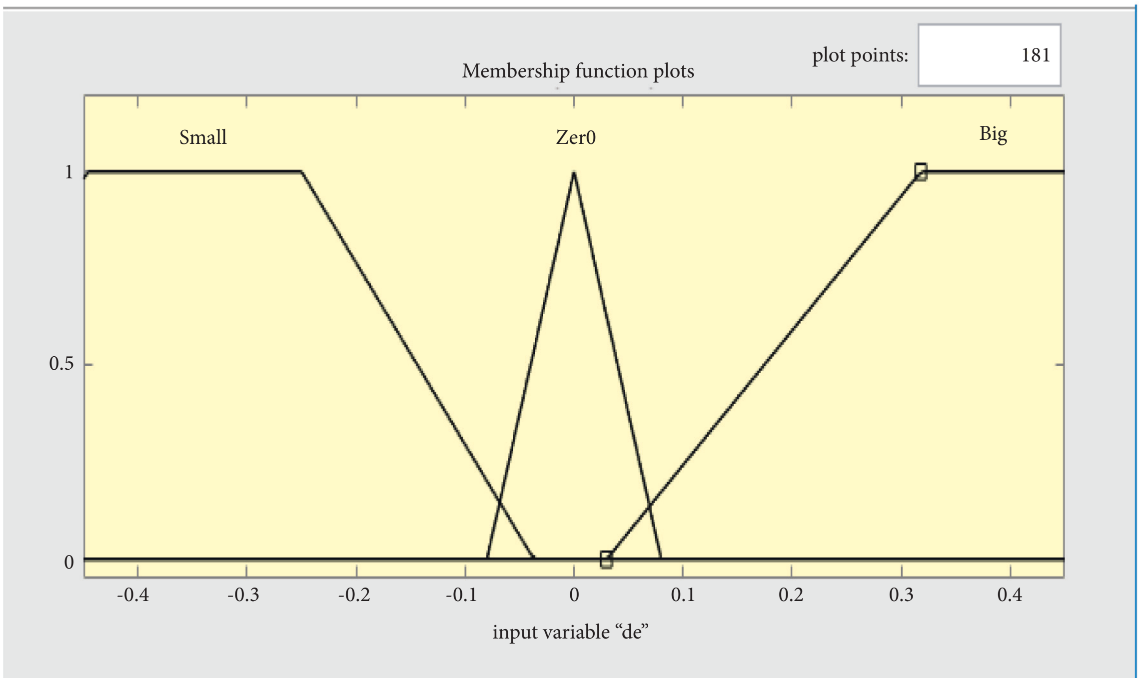


FIGURE 24: The 2nd input (Δe) Membership Functions.

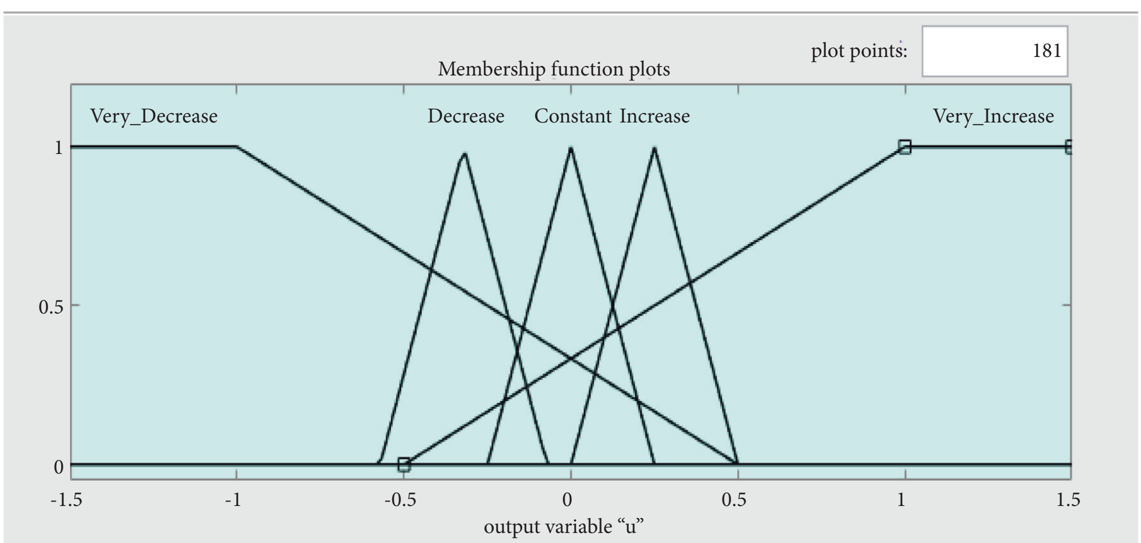


FIGURE 25: The output (u) Membership Functions.

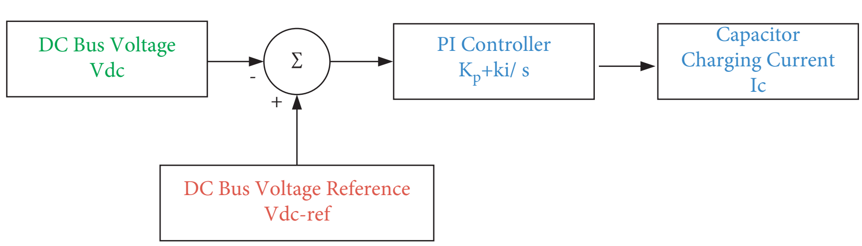


FIGURE 26: PI-Controller to maintain DC Bus Voltage.

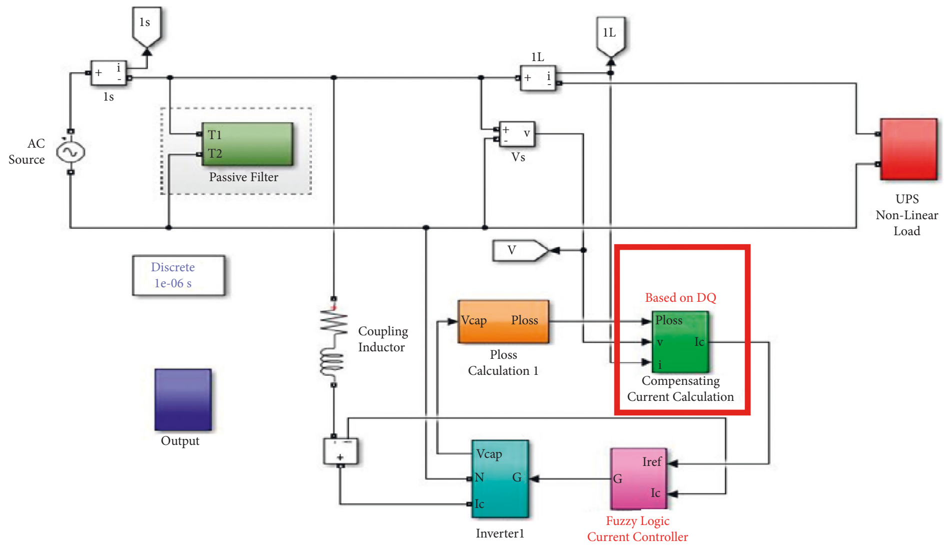


Figure 27: Simulation model of Single-phase Half-Bridge HAPF based on DQ Theory Reference Current Extraction (RCE) with Fuzzy Logic Current controller (FLCC) for the UPS System connected with nonlinear load.

Table 3: Circuit parameters.

RMS voltage (L-N)	220 V
Frequency	50 Hz
Source inductance	$1e-4$H
Source resistance	1Ω
Coupling inductance	0.0035 H
Coupling resistance	1Ω

D.C bus voltage is shown in Figure 26. It is observed that when Kp and ki are high, bus voltage regulation dominates, and the steady-state DC bus voltage error is low. The actual power imbalance has little effect on the transient reaction if Kp and Ki are minor. To satisfy the above two control features, the proper selection of Kp and Ki is required. [48].

$$H(s) = K_p + \frac{K_i}{S}. \quad (3)$$

7. Simulation Analysis

The simulation model is illustrated in Figure 27 of the proposed single-phase half-bridge hybrid active power filter and circuit parameters are given in Table 3. As UPS load, a parallel nonlinear load with a complete bridge rectifier is used, which is the main source of harmonic generating load.

Simulation Analysis on the proposed HAPF fuzzy logic current controller FLCC has been carried out by simulating a single-phase half-bridge inverter connected to the main ac source and another end with UPS System having nonlinear load generating unwanted harmonics in the system. Figure 28 depicts the internal Simulink model of fuzzy logic current controller FLCC for PWM.

Source voltage waveform is shown in Figure 29. Figure 30(a) and 30(b) shows distorted waveform and frequency spectrum of the source current, respectively. Overall, 32.63% is THD with a supply current.

The source current waveform is significantly distorted, as seen in Figure 30, with a total harmonic distortion of 32.63 percent. The uncontrolled rectifier UPS type load generates a combined harmonic current with 5^{th}, 7^{th}, and 11^{th} order harmonics mainly with the most prevailing harmonic current from 5^{th} harmonic of the fundamental current. The proposed HAPF can reduce harmonic content to 5%, which is the limit set by IEEE harmonic standards. After adjustment with the use of a current controller, simulation results were produced. Figure 30 depicts the waveforms and frequency spectrum of the current drawn by the load. Figure 31 depicts the waveform and frequency spectrum of the compensating current entering the HAPF PCC.

PI Controller is used to maintaining Vdc Bus Voltage and its waveform is shown in Figure 32.

The source current's 5^{th}, 7^{th}, and 11^{th} harmonic components are greatly reduced after compensation, resulting in a sinusoidal source as illustrated in Figure 33(a). After compensation, the frequency spectrum of the source currents is shown, respectively, in Figure 31(b).

Table 4 shows the harmonics of the load current, HAPF output current, and source current when using a proposed FLC controller for HAPF.

The current drawn by the load before HAPF has a THD of 32.63%; however, the source current using the HAPF based on the fuzzy logic current controller has reduced THD up to 1.09%. Thus, it is evident that the filtration efficiency of a HAPF designed using a fuzzy logic current

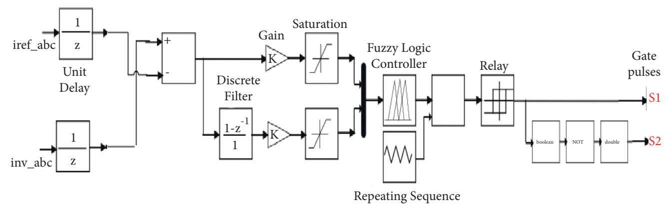


Figure 28: Simulink model of Fuzzy Logic current controller FLCC for PWM Gate Pulse to HAPF.

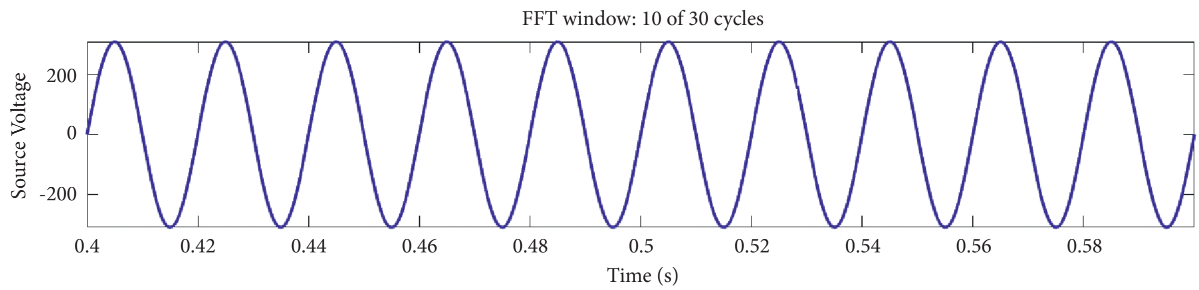


Figure 29: The source voltage (Vs) waveform.

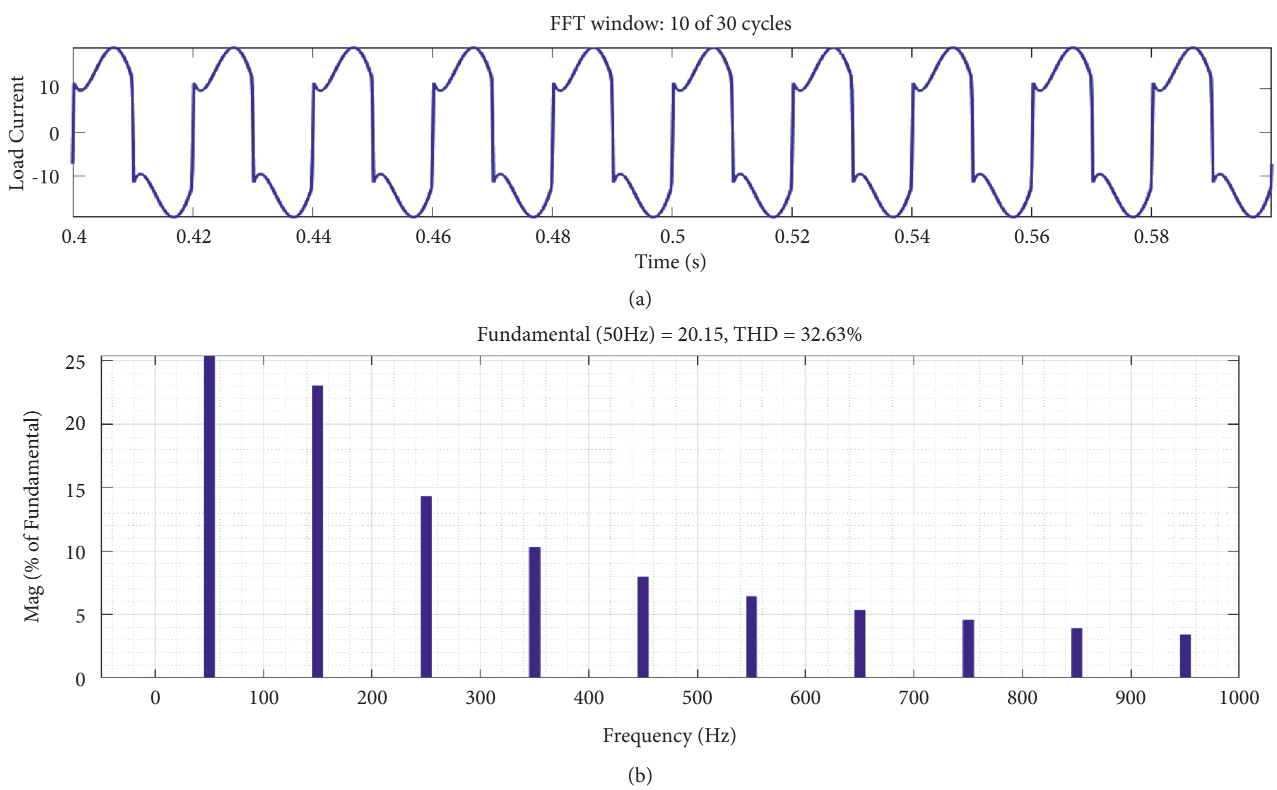


Figure 30: Source current before compensation (a) distorted waveform (b) frequency spectrum with THD 32.63%.

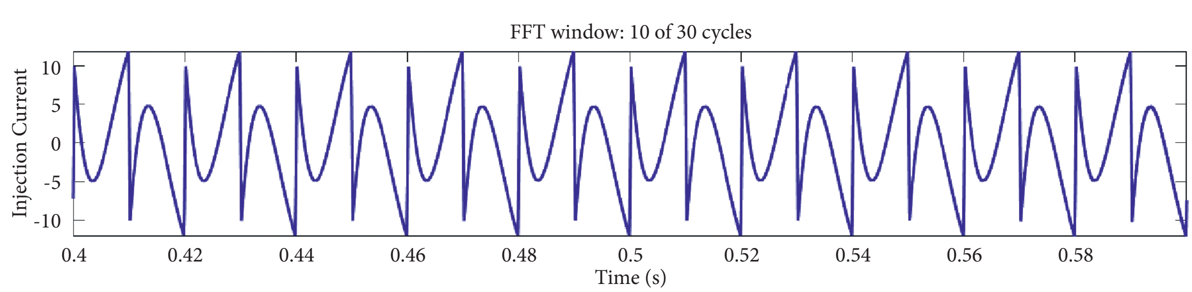


Figure 31: Waveform of the output current of HAPF with the implementation of fuzzy logic controller.

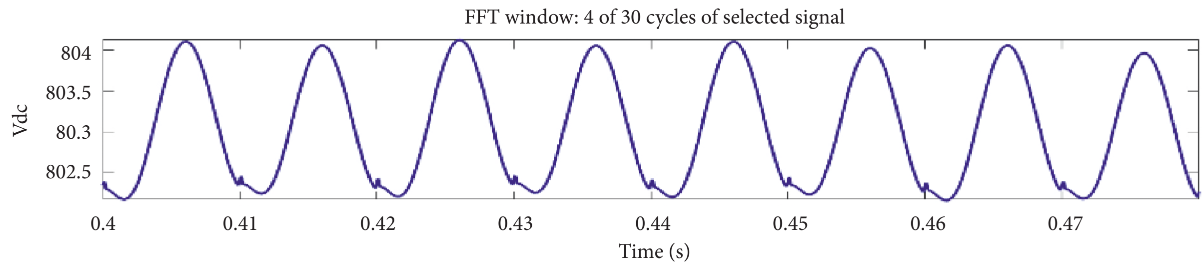
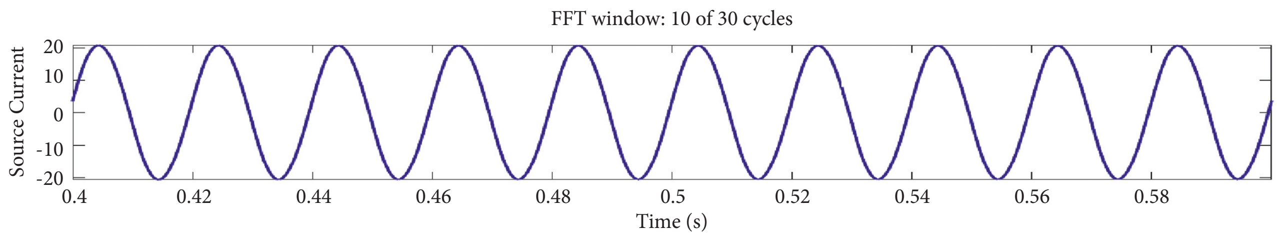
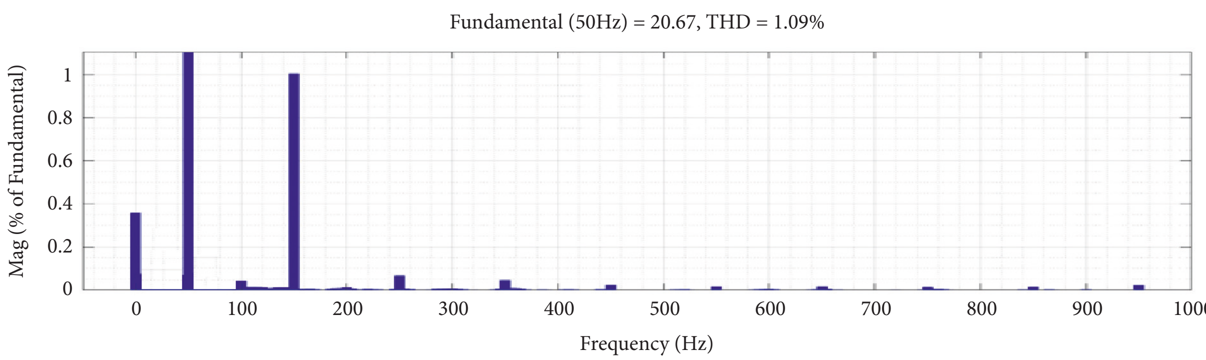


Figure 32: Waveform of the Vdc DC-Bus voltage.



(a)



(b)

Figure 33: (a) Waveform of the source current with the implementation of fuzzy logic current controller FLCC (b) Frequency spectrum of the source current with the implementation of fuzzy logic current controller FLCC.

Table 4: System Harmonic (THD %) contents comparison with and without HAPF based on FLCC.

S.No	System	THD% (%)
1.	Harmonics without HAPF	32.63
2.	Harmonics with proposed HAPF based on fuzzy logic current controller (FLCC)	1.09

controller is well below the standard 5% THD IEEE-519 standard limit.

8. Conclusion

In this study, an experimental harmonic analysis of a UPS system is performed and a Single-Phase Half-Bridge HAPF based on the fuzzy logic current controller (FLCC) for Reference Current Extraction (RCE) is proposed. Different power filter topologies have been studied in this research. To ensure proper power filter selection for UPS linked with single-phase nonlinear load, the most prevalent designs have been compared with their benefits and drawbacks. In MATLAB/Simulink, the HAPF with the fuzzy controller was investigated. Higher harmonic frequencies induce voltage flicker, sag, and swell as a result of harmonic vibrations, magnetic losses as a result of increased temperatures, and reduced life and efficiency of electrical devices and transformers. Furthermore, they reduce the life of capacitors and increase the probability of metering and instrumentation devices operating incorrectly. Power filters, both passive and active, can be utilized to solve such issues. Much advancement has been made in APF topologies, which have surpassed passive filters in many ways. HAPFs, on the other hand, were designed for specific types of loads and combined the benefits of passive and active filters for specific applications. This demonstrates that the proposed FLCC controller has a good response and can fix the harmonics present in the source since the THD of the system was decreased from 32.63% to 1.09% using the proposed novel approach.

The system is intended to evaluate the HAPF's fuzzy logic controller's efficiency and effectiveness in terms of HAPF operation connected with UPS system and nonlinear Load.

Data Availability

There is no dataset involved in the research.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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