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Power Quality Improvement using Modified DVR with integration of Coati Optimization Algorithm and Fuzzy Logic

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Abstract:

Power quality is a pressing concern, particularly for power-sensitive devices impacted by supply irregularities, leading to equipment failure for end users. Voltage sags and swells are the predominant issues in medium and low voltage distribution grids, causing significant disruptions and financial losses. The Dynamic Voltage Restorer (DVR) is the most efficient solution, known for its affordability, compactness, and swift response to disturbances. This study focuses on DVR principles and techniques for restoring voltage during sag and swell events. Simulations demonstrate the DVR's capabilities using pulse width modulation (PWM). Coati optimization coupled with fuzzy logic optimizes membership functions, achieving notable reductions in total harmonic distortion (THD) when compared to a PI controller.

1. Introduction:

Power quality is a crucial consideration for energy-related initiatives. Any power delivery issues can negatively impact customer satisfaction. The issue encompasses transients, harmonics, interruptions, sags, and swells. These occurrences can lead to a decline in service quality, resulting in significant costs for both customers and utility firms. Power quality problems often stem from incorrect load flow and frequent power cycling at customer sites. With the rise of voltage-sensitive machinery in the manufacturing industry, factories are more vulnerable to voltage fluctuations. The Dynamic Voltage Restorer (DVR) is designed to protect sensitive loads from voltage variations and reduce harmonic distortion. The DVR offers an effective and efficient solution, characterized by its compact size and rapid response to shocks.

Poor power quality can have a considerable economic impact on major factories and stores due to damage to machinery and inventory. The costs involve equipment downtime, repairs or replacements, rework, lost productivity, and hidden expenses resulting from harmonic distortion. Power quality issues can occur at various stages of the system's lifecycle, from transmission to distribution to end use. Primary challenges related to power quality include the widespread usage of microprocessors in consumer electronics, the sensitivity of power electronics hardware to poor power quality, interconnections between systems with cascading effects, increased vulnerability of high-performance devices to power fluctuations, and the impact of deregulation in the power industry. Power quality concerns can be categorized as follows:

- Voltage Sag: Temporary drop in voltage, lasting from half a cycle to one minute, with subcategories of momentary, temporary, and instantaneous voltage sags. Common causes include power system problems, electrical network overload, and high starting currents of appliances. Voltage sags result in relay, contactor, and lighting failures.
- Voltage Swell: Temporary increase in voltage, lasting from half a cycle to one minute, with subcategories of momentary, temporary, and instantaneous voltage swells. Sustained high voltage is referred to as over-voltage. Causes include significant load disconnection or single line to ground faults. Voltage swells can cause insulation failure, overheating, and damage to electronic devices.
- Voltage Spike: Rapid shift in voltage lasting microseconds to milliseconds, often reaching high magnitudes. Causes include lightning storms, resetting of power lines or capacitors, and disconnection of large electrical equipment.
- Harmonic Distortion: Harmonics are integral multiples of the fundamental frequency. Non-linear loads in the system can cause overheating of electrical components. Reducing overall harmonic distortion is crucial to mitigate this issue.

- Voltage Unbalance: Discrepancy in magnitudes of the three voltages or phase angle variations in a three-phase system. Large single-phase loads or improper distribution of single-phase loads can exacerbate voltage unbalance.
- Noise: Undesired signals causing fluctuations in voltage and current signals. Sources include parallel running of electricity and communication lines, electronic equipment, welding machines, and arc furnaces generating electromagnetic radiation or interference. Incorrect grounding can also contribute to noise.
- Voltage Interruptions: Drop in rms voltage below 0.1 percent of nominal value or sudden power loss. Categorized into short interruptions lasting milliseconds, risking confidentiality of stored information, and long interruptions lasting seconds, primarily caused by network equipment failure, storms, coordination issues, or security protocol failures.

Ensuring high power quality is essential for the security and effectiveness of electrical power systems. Power quality issues, including voltage swells, sags, and interruptions, can cause severe damage to sensitive electronic devices and result in significant economic losses. To address power quality concerns, Dynamic Voltage Restorers (DVRs) are being installed. However, the successful integration of DVRs into power distribution networks faces substantial challenges. This thesis focuses on the integration of DVRs into the power distribution network to enhance power quality. Key challenges to address include identifying optimal DVR installation locations, selecting suitable control strategies, and developing a reliable and efficient control algorithm capable of quickly responding to voltage disturbances. Cost is a significant consideration for DVRs, as they are relatively expensive compared to alternative power quality options. Therefore, it is crucial to assess the financial benefits of installing DVRs in the grid. This thesis aims to propose solutions to make DVRs a more viable and cost-effective option for improving power quality.

The objective of this thesis is threefold. Firstly, it aims to conduct a comprehensive analysis of Dynamic Voltage Restorers (DVRs), encompassing all possible power circuit configurations and control strategies. Secondly, it focuses on the design and implementation of a DVR using a novel hybrid control strategy called Coati Optimization Algorithm (COA)-Fuzzy. Lastly, the thesis adopts a simulation-based approach to compare and evaluate the performance of the proposed DVR with other existing solutions.

2. Literature Review:

Power quality issues have gained significant attention from utilities and large-scale electricity users in the commercial and industrial sectors. Maintaining a sinusoidal waveform with prescribed amplitude is crucial for acceptable power quality, enabling smooth operation of sensitive loads, automation, and improved product quality. Power quality is characterized by parameters such as mean value, frequency, three-phase symmetry, pure sinusoidal waveform, and total harmonic distortion (THD), with established limitations to ensure desired power quality.

Indirect and direct voltage control, voltage sag mitigation, voltage swell mitigation, harmonic mitigation, renewable energy integration, power mitigation, reactive power mitigation, and voltage disturbance compensation are all ways in which DVR can be used to enhance power quality. To improve power quality, authors in papers [6] and [7] manipulate the DVR's voltage output either directly or indirectly. Using an ant lion optimizer-optimized artificial neural network (ALO-ANN), a DVR is used to correct for voltage sags and surges, as well as disturbances on the load side, in [6]. Voltage sags and swells, which are short-term voltage changes, are a common source of interference for sensitive electronics and other loads. As shown in [8], a transformerless single-phase DVR based on a qZS can be utilized to dampen grid voltage disturbances. Power mitigation is used to ensure that consumers continue to receive a consistent and well-regulated supply of electricity in the works [9], [10], [11], [12], and [13]. The study referenced in [10] uses an adaptive NeuroFuzz controller as an example of a soft computing-based control technique to enhance power quality. Harmonics mitigation is utilized to improve power quality in papers 14, 15, 16 and 17. The quick dynamic responsiveness of an ECVB-based TCHB and the suppression of ASD voltage harmonics are explored in the highlighted study [14].

An adaptive noise canceling (ANC) technique is described in the paper [18] as the basis for a dynamic voltage restorer (DVR) architecture. Both voltage correction and harmonic reduction are possible with this topology. The DVR was developed to mitigate the negative impacts of voltage sag, which is recognized as a significant contributor to poor power quality (PQ) for a variety of loads. In manufacturing facilities that make use of variable speed drives (ASD), a typical power quality concern is voltage sag. A Dynamic Voltage Restorer (DVR) operated by a Battery Energy Storage (BES) and Photovoltaic (PV) system reduces voltage sag/swell and harmonics in a low voltage distribution network [26]. Power quality can be improved by incorporating renewable energy sources into the dynamic voltage restorer, as mentioned in works [2], [3], [5], and [29–34]. Three-phase MV networks coupled to hybrid distribution generators can improve power quality and low voltage ride-through (LVRT) capacity with the use of a DVR, as described in publications [29] and [32]. As described in [30], the distribution system has been improved thanks to the installation of solar panels and subsequent study of the DVR's performance in terms of electricity quality. In paper [33], the authors discuss the efficiency of HRGSs. Solar photovoltaics (PV), a battery storage unit (BSU), and an auxiliary unit made comprised the core of HRGS (AU). The backup power system at AU relied on a diesel generator (DG) and a fuel cell.

3. Problem Formulation:

For the safety and efficiency of all electrical power systems, high power quality is indispensable. Power quality issues, such as voltage spikes, dips, and interruptions, can result in calamitous harm to sensitive electronic equipment and substantial economic losses. The installation of Dynamic Voltage Restorers (DVRs) is addressing power quality issues. Integration of DVRs into electrical systems confronts substantial obstacles, however.

This thesis addresses the fundamental problem of successfully integrating a DVR into the power distribution network to improve the power quality of the system. To be addressed are the identification of the optimal location for the installation of DVRs, the selection of appropriate control strategies for the DVRs, and the development of a reliable and efficient control algorithm that can respond rapidly to voltage disturbances.

Additionally, the price of DVRs is a major concern, as they are relatively expensive compared to other power quality options. Therefore, it is essential to determine the financial benefits of installing DVRs in the infrastructure. In order to make DVRs a more viable and cost-effective option for increasing power quality, this thesis addresses and proposes solutions to these problems.

4. Proposed Methodology:

DVR is used to manage the voltage in transmission lines to address voltage sag or swell issues. To achieve this, an IGBT operated by a pulse width modulator (PWM) is employed. The pulse width of the PWM can be adjusted, and various controllers such as PI, fuzzy logic, and Coati-optimized fuzzy logic are utilized. The performance of fuzzy logic algorithms depends on membership functions and rule sets. Membership functions and rules are typically fixed when created for a specific objective. However, as system conditions change, steady-state error may also change. To reduce steady-state errors, membership functions should be continuously updated when there are changes in initial conditions, ensuring optimal placement of membership functions. In our research, we utilize the Coati Optimization Algorithm (COA) to achieve this. The number of iterations considered determines the time required to decrease steady-state inaccuracy, while the total number of membership positions affects the size of the search space. In this study, seven membership functions are used for each input and output, as shown in Figure 4.1. Initially, these functions are in fixed positions, employing trapezoidal and triangular membership functions. By having one or two location vectors that coincide in the error input, the size of the search space can be greatly minimized. For example, the triangular function satisfies the criterion x1 x2 x3 and has three positions [x1, x2, x3]. Figure 4.1 demonstrates that only four places need to be optimized to minimize the steady-state error for a single input, as the middle position of NM is the same as the starting position of NS, and similar positions are shared among other membership functions. Since there are two inputs and one output, the COA method needs to adjust a total of 12 points for the membership functions. Therefore, each iguana in the COA algorithm searches for food in one of the twelve search spaces. An objective function is chosen to minimize the steady-state error during optimization. For each iguana, twelve membership function positions are modified, and the new fuzzy logic is evaluated based on the supplied error. In this study, the integral square error (ISE) is used as the objective function and as an input for assessing the fuzzy logic. After completing all iterations, the error is reduced, and new positions in the fuzzy logic are created using the instantaneous locations of the membership functions.

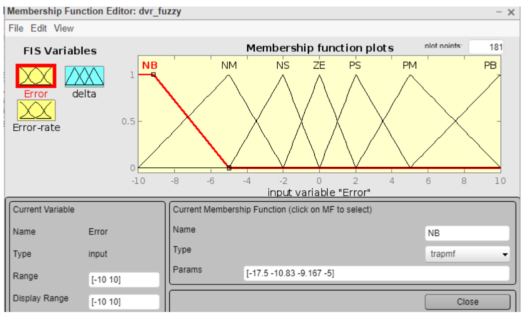

Figure 4.1: Membership function of input 'error'

Coati Optimization Algorithm (COA) is crucial for Dynamic Voltage Regulation (DVR). It offers several benefits, such as eliminating the need for manual control parameters and effectively solving complex optimization problems. COA's search process balancing abilities enable fast convergence and accurate decision variable values, especially in challenging scenarios. With its strong performance in real-world applications, COA enhances DVR functionality and ensures efficient voltage management.

The COA method, which is a population-based metaheuristic, views the coatis as population members. The values of the decision factors are determined by the location of each coati within the search space. The viewpoint of Coatis thus suggests a potential solution to the COA issue. At the outset of the COA implementation, the initial position of the coatis in the search space is initialized randomly using **Eq. (4.1).**

$$X_i : x_{i,j} = lb_j + r\left(ub_j - lb_j\right), \mathrm{i} = 1, 2, \ldots, \mathrm{N}, \mathrm{j} = 1, 2, \ldots, \mathrm{m}, \quad \textbf{(4.1)}$$

where X_i is the position of the ith coati in search space, $x_{i,j}$ is the value of the jth decision variable, N is the number of coatis, m is the number of decision variables, r is a random real number in the interval [0, 1], and lb_j and ub_j are the lower bound and upper bound of the j^{th} decision variable, respectively. The population of coatis in the COA is mathematically represented using the following matrix X, called the population matrix,

$$X = \begin{bmatrix} X_1 \\ \vdots \\ \vdots \\ X_i \\ \vdots \\ X_N \end{bmatrix}_{N \times m} = \begin{bmatrix} x_{1,1} & \cdots & \cdots & x_{1,j} & \cdots & x_{1,m} \\ x_{2,1} & \cdots & \cdots & x_{2,j} & \cdots & x_{2,n} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ x_{i,1} & \cdots & \cdots & x_{i,j} & \cdots & x_{i,m} \\ x_{N,1} & \cdots & \cdots & x_{N,j} & \cdots & x_{N,m} \end{bmatrix}_{N \times m}$$

(4.2)

The positioning of potential solutions in choice variables results in the evaluation of various values for the problem's objective function. Eq. (3) is used to display these values.

$$F = \begin{bmatrix} F_1 \\ \vdots \\ F_i \\ \vdots \\ F_N \end{bmatrix}_{N \times 1} = \begin{bmatrix} F\ (X_1) \\ \vdots \\ F\ (X_i) \\ \vdots \\ F\ (X_N) \end{bmatrix}_{\boldsymbol{N \times 1}} \quad \textbf{(4.3)}$$

where F is the value of the objective function derived from the i^{th} coati and F is the objective function's vector. In metaheuristic algorithms such as the one presented for COA, the value of the objective function serves as the benchmark for candidate solution quality. The member of the population whose evaluation yields the highest value for the objective function is referred to as the finest member of the population. Since the candidate solutions are updated during each iteration of the algorithm, the highest member of the population is updated with each iteration. The premise for altering the position of coatis (candidate solutions) in the COA is the modeling of two of their natural behaviors. These actions include the strategies coatis use to assault iguanas and how they escape from predators.

As a consequence, revising the COA population occurs in two distinct phases. The initial phase of updating the coati population in the search area is represented by a simulation of the coatis' attack strategy against iguanas. Several coatis scale the tree to approach an iguana and startle it using this method. Other coatis wait beneath a tree until the iguana falls to the ground, at which point they ascend a tree. After the iguana strikes the ground, the coatis attack and hunt it. This method demonstrates the COA's capacity for global search within the problem-solving domain by allowing coatis to migrate to different locations within the search area.

The COA design implies that the iguana is the most valuable member of the population. In addition, it is believed that half of the coatis climb the tree while the other half waits for the iguana to descend. Therefore, equation (4.4) is used to replicate the position of the coati when it emerges from the tree [35].

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$$X_i^{P1}: x_{i,j}^{P1} = x_{i,j} + r.\left(K_j - I.x_{i,j}\right), \text{for } i = 1,2,\ldots,\lfloor N\ 2 \rfloor \text{ and } j = 1,2,\ldots,m \quad \textbf{(4.4)}$$

The iguana (K) is placed at random within the search area after being lowered to the ground. Based on this random position, Coatis on the ground move in the search space, which is approximated using Eqs. (4.5) and (4.6).

$$K^G: K_j^G = lb_j + r\left(ub_j - lb_j\right), \quad ,j = 1,2,\ldots,m \quad (4.5)$$

$$X_i^{P1}: x_{i,j}^{P1} = \begin{cases} x_{i,j} + r.\ \left(K_j^G - I.x_{i,j}\right), & F_{K^G} < F_i \\ x_{i,j} + r.\ \left(x_{i,j} - K_j^G\right), & else, \end{cases} \quad \textbf{(4.6)}$$

$$for\ i = \left[\frac{N}{2}\right] + 1, \left[\frac{N}{2}\right] + 2, \ldots\ldots, N\ and\ j = 1,2,\ldots,m$$

If the updated position for each coati increases the objective function's value, it is permissible for the update process; otherwise, the coati remains in its previous position. Using Eq. (4.6), this update condition is replicated for. $i = 1,2,\ldots,N$

$$X_i = \begin{cases} X_i^{P1}, & F_i^{P1} < F_i, \\ X_i, & else \end{cases} \quad (4.7)$$

In the given context, X_i^{P1} denotes the updated position of the ith coati, while, $x_{i,j}^{P1}$, is its jth dimension, F_i^{P1} is its objective function value, r is a random real number in the interval [0, 1], K represents the iguana's position in the search space, which actually refers to the position of the best member, K_j is its j_{th} dimension, I is an integer, which is randomly selected from the set {1, 2}, K^G is the position of the iguana on the ground, which is randomly generated, K_j^G is its jth dimension, F_{K^G} is its value of the objective function, The floor function, denoted by $\lfloor\cdot\rfloor$, is used to obtain the greatest integer that is less than or equal to the given value.

The second stage of the process of updating the position of coatis in the search space is mathematically represented based on their typical behavior when confronting and evading predators. A coati escapes when it is attacked by a predator. The fact that Coati is currently in a secure location close to its current location demonstrates the COA's capacity for local search exploitation. To imitate this behavior, a random position close to where each coati is positioned is generated based on Equations (4.8) and (4.9).

$$lb_j^{local} = \frac{lb_j}{t}, ub_j^{local} = \frac{ub_j}{t}, \text{ where } t = 1,2,\ldots,T \quad \textbf{(4.8)}$$

$$X_i^{P2}: x_{i,j}^{P2} = x_{i,j} + (1-2r).\left(lb_j^{local} + r.\left(ub_j^{local} - lb_j^{local}\right)\right), \quad \textbf{(4.9)}$$

$i = 1,2,\ldots,N, j = 1,2,\ldots,m,$

The newly calculated position is acceptable if it improves the value of the objective function, that this condition simulates using Eq. (4.10)

$$X_i = \begin{cases} X_i^{P2}, & F_i^{P2} < F_i, \\ X_i, & else \end{cases} \quad (4.10)$$

The equation X_i^{P2} represents the updated position of the ith coati, which is determined through the second phase of COA. The variable $x_{i,j}^{P2}$ denotes the jth dimension of the coati's position, while F_i^{P2} represents its objective function value. The variables r, t, lb_j^{local}, $ub_j^{local}, lb_j, and\ ub_j$ are defined as a random number between 0 and 1, the iteration counter, the local lower bound and upper bound of the jth decision variable, and the lower and upper bound of the jth decision variable, respectively.

Further fuzzy logic plays a pivotal role in the proposed method, allowing for the effective management of uncertainties and the optimization of performance in the optimization process. In the proposed method, fuzzy logic is utilized to handle the complexities and uncertainties involved in the optimization process. The ability of fuzzy logic to operate on multiple values and handle imprecise reasoning is leveraged to achieve the desired outcomes. Linguistic variables are employed in the proposed method to represent and control different aspects of the optimization problem. These variables are characterized by fuzzy sets with membership functions that define the degrees of truth or relevance associated with different values. Membership functions are used to determine how the truth values of linguistic variables vary across the range of possible values. By appropriately designing and adjusting these membership functions, the uncertainties and imprecisions present in the optimization process can be effectively represented and reasoned over. Fuzzy logic controllers, such as PI and fuzzy logic algorithms, are employed in the proposed method to guide the optimization process. These controllers utilize the linguistic variables and membership functions to make decisions and adjust parameters based on the current system conditions. The dynamic nature of fuzzy logic allows for the continuous updating of membership functions as the initial conditions change. This adaptive behavior ensures that steady state errors are minimized by optimizing the performance of the fuzzy logic algorithms. By incorporating fuzzy logic in the proposed method, the uncertainties, complexities, and changing conditions in the optimization process are effectively managed. The utilization of fuzzy logic enables the representation and reasoning over incomplete knowledge, handling of linguistic variables, and dynamic adaptation of membership functions.

5. Results:

The findings have been classified into two distinct categories. As previously discussed in the preceding chapters, sags and swells are two primary issues that require mitigation. The proposed method addresses only sags problem. The primary Simulink model, incorporates the implementation of two breakers in conjunction with three phase faults. To initiate sag in the model, it is necessary to close breaker 2 and open breaker 1. It is possible to exert control over the introduction of faults with respect to timing. The duration of the experiment ranged from 0.1 to 0.3 seconds. The selection of a fuzzy controller is the initial choice for controlling a DVR. The outcome is depicted in **Figure 5.1.**

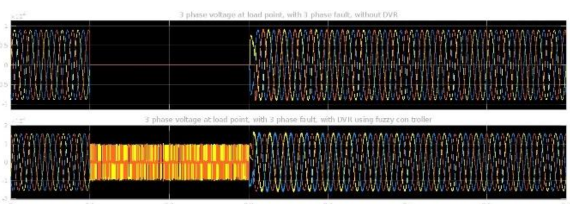

Figure 5.1: Uncompensated and Compensated output

Upon visual inspection of the aforementioned figure, it is apparent that the implementation of a fuzzy controller with DVR results in optimal sag compensation. However, upon closer examination of Figure 5.1, minor distortions in the output are discernible. The presented figure has been magnified within the Simulink interface and directly extracted from the software. The measurement of total harmonic distortions is conducted through FFT analysis due to the presence of such distortions. The present study employs FFT analysis from the 'powergui' block, which is situated within the model to establish the appropriate environment for the simpower toolbox in simulink. The total harmonic distortion (THD) ascertained by the aforementioned computation is visually represented in figure 5.2. The Total Harmonic Distortion (THD) value in this instance is 378.58%. Figure 5.3 depicts the total harmonic distortions, in case of fuzzy controlled DVR as observed in the aforementioned scenario. The resulting value is 60.04% which is lower than the distortions observed in without DVR controlled systems.

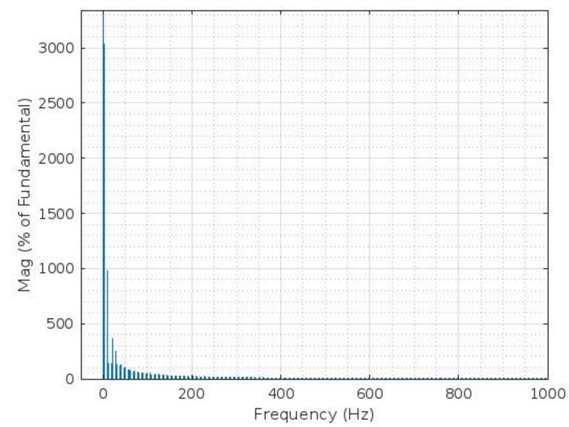

Figure 5.2: THD of uncompensated output

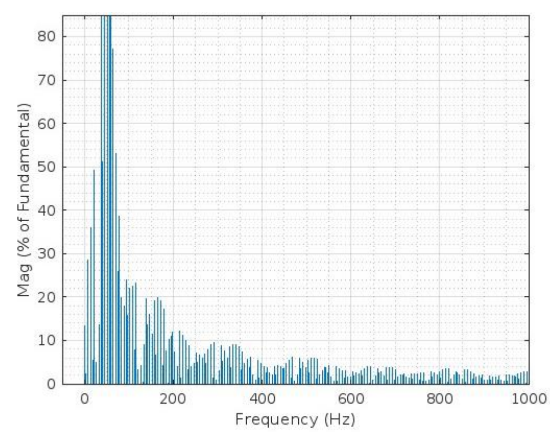

Figure 5.3: Compensated output

The second controller being utilized is the COA-optimized fuzzy logic controller. Chapter 3 has provided a discussion on the optimization technique known as COA. Table 5.2 presents the parameters utilized for COA optimization.

Table 5.2: Parameters used for COA

Dimension of search space	12
The number of Coatis	30
Number of iteration	100

Chapter 3 provides a discussion on the optimization of the membership function of fuzzy logic. Following optimization by COA, new membership functions are depicted in Figure 5.4.

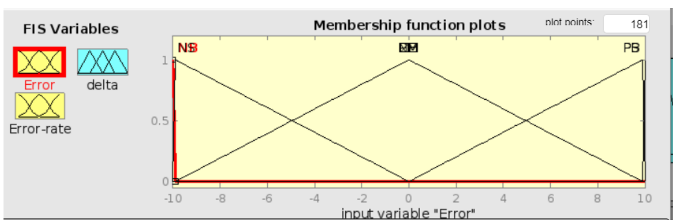

Figure 5.4(a): membership function for error

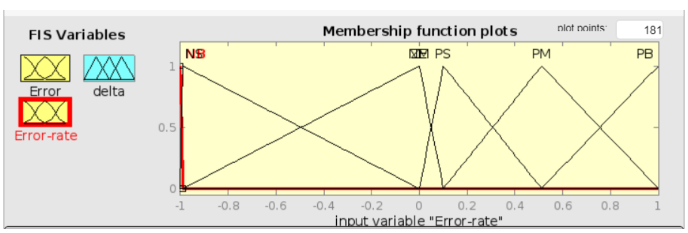

Figure 5.4(b): membership function for error rate

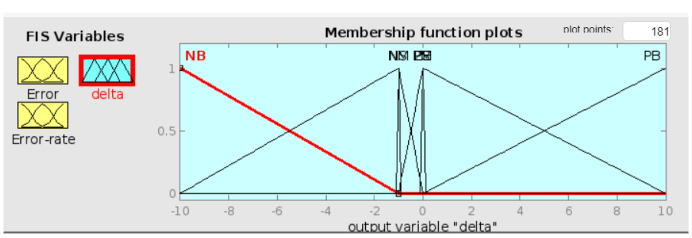

Figure 5.4 (c): membership function for output

It is noteworthy that there has been a modification in the scope of the membership functions across all variables. The membership function for optimised fuzzy logic is depicted in Figure 5.5, despite the fact that the ruleset remains unaltered.

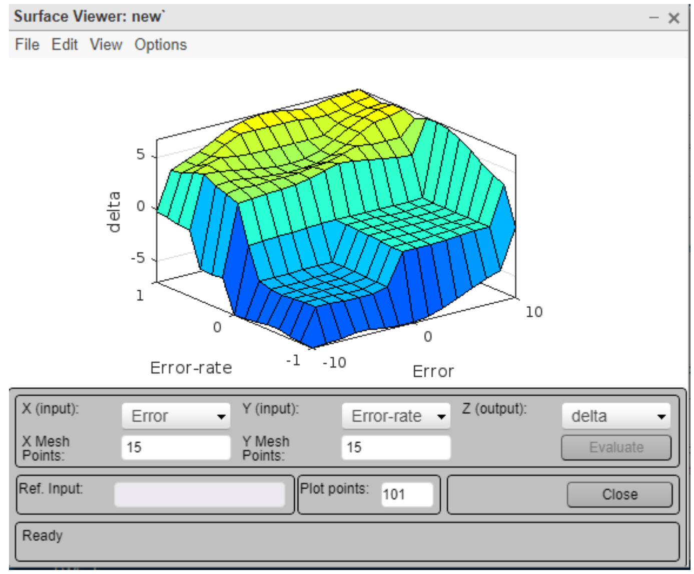

Figure 5.5: Surface view of optimized fuzzy logic's membership function.

Figure 5.6 depicts the output for COA-fuzzy control, which is analogous to the fuzzy logic outputs presented earlier. Similarly, the total harmonic distortion (THD) is illustrated in Figure 5.7 and is determined to be 60.12%, indicating a significant improvement compared to the fuzzy logic approach. Empirical evidence supports the superiority of COA-optimized fuzzy logic over both fuzzy logic control. Table 5.3 presents a comprehensive comparison of various controlling methodologies.

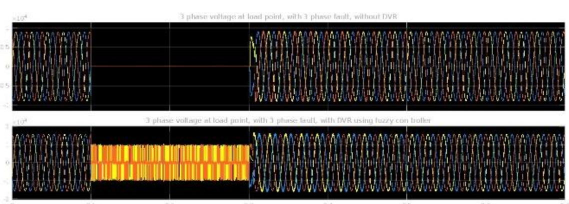

Figure 5.6: Output of COA fuzzy logic controller

Table 5.3: Comparison of THD's of all method

Controllers	THD (%)
Without Control	378.58
Fuzzy Logic	162.57
COA- Fuzzy Logic	60.12

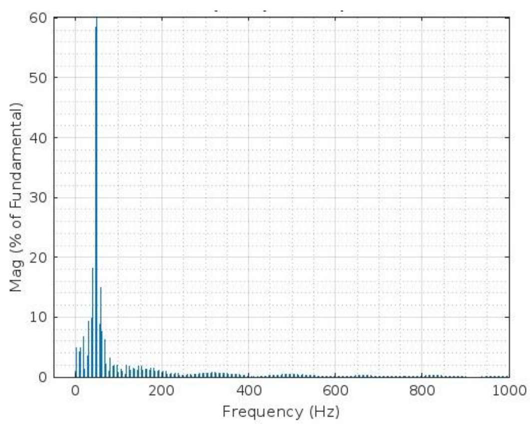

Figure 5.7: Compensated output

6. Conclusion:

Harmonic currents are generated by nonlinear loads and fault-related disturbances; they can travel throughout the electrical system before returning to their source. As a consequence, harmonic voltages are generated across power networks due to the propagation of harmonic currents. A custom power device DVR has designed and implemented mitigating measures to maintain harmonic voltages and currents within permitted limits. A DVR with PI Controller and Fuzzy Logic Controller has been devised to mitigate the effects of power quality problems during a three-phase fault state. However, the membership function of fuzzy logic is optimized using Coati optimization (COA) because there is always space for development in reducing distortions, and it has been demonstrated that overall harmonic distortions are significantly lower than with the other two procedures. MATLAB/Simulink has effectively demonstrated the investigation of DVR installation on a power distribution system, with a primary focus on harmonic reduction and voltage regulation performance. In the operation of the DVR as a customized power device, COA-Fuzzy Logic Control is found to be more efficient than fuzzy control technique.

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