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## Power Quality Enhancement under Unbalanced Load Conditions Using a Dynamic Voltage Restorer and Fuzzy Logic-Controlled Shunt Active Power Filter

Neelam Verma<sup>1</sup>, Kavita Choudhary<sup>2</sup>

<sup>1</sup>M.Tech Scholar, Department of Electrical Engineering, Sri Balaji College of Engineering & Technology, Jaipur, Rajasthan, India — [neelamverma0610@gmail.com](mailto:neelamverma0610@gmail.com)

<sup>2</sup>Assistant Professor, Department of Electrical Engineering, Sri Balaji College of Engineering & Technology, Jaipur, Rajasthan, India — [choudharykavita00@gmail.com](mailto:choudharykavita00@gmail.com)

### ABSTRACT—

*Sensitive industrial and commercial loads are increasingly affected by voltage sag, swell and harmonic distortion caused by unbalanced faults and non-linear loads on the distribution network. This paper presents a combined power quality enhancement scheme that uses a Dynamic Voltage Restorer (DVR) for series voltage compensation under unbalanced load and fault conditions, together with a Fuzzy Logic-Controlled Shunt Active Power Filter (SAPF) for harmonic mitigation. The DVR, controlled through a PI-regulated injection scheme, restores the load-side voltage following double-line-to-ground faults, while the shunt APF, driven by a two-input two-output Mamdani-type fuzzy logic controller, regulates the DC-link voltage and injects a compensating current to cancel load current harmonics. Both devices were modeled and simulated in MATLAB/Simulink under a three-phase 400 V, 50 Hz test system with an unbalanced parallel load and a non-linear industrial drive. The DVR restored the load voltage to its pre-fault value within milliseconds of a double-line-to-ground fault, and the fuzzy-controlled SAPF reduced the Total Harmonic Distortion (THD) of the source current from 2.32% (uncompensated) to 1.07%, outperforming a conventional PI-controlled filter (1.85% THD) and a reported hysteresis-controlled filter (1.250% THD) evaluated under comparable unbalanced-load conditions. The results confirm that combining a DVR with a fuzzy-controlled SAPF provides an effective, IEEE 519-compliant solution for power quality enhancement in distribution networks subject to unbalanced loading and harmonic-rich non-linear drives.*

**Keywords—** Dynamic Voltage Restorer (DVR); Shunt Active Power Filter (SAPF); Fuzzy Logic Controller; Power Quality; Unbalanced Load; Total Harmonic Distortion (THD); Voltage Sag and Swell.

### I. INTRODUCTION

The proliferation of variable-speed drives, programmable logic controllers, computer-based control systems and other power-electronic loads has made industrial and commercial facilities considerably more sensitive to disturbances in supply voltage. Non-linear loads and unbalanced faults on the distribution network give rise to voltage sag, swell, unbalance and harmonic distortion, any of which can interrupt sensitive processes, damage equipment or reduce product quality [19]. Voltage sags caused by remote faults, lightning strikes or the starting of large motors are of particular concern, since even a brief dip of a few cycles can trip sensitive equipment and cause production losses that run into hundreds of thousands of rupees in continuous-process industries such as semiconductor fabrication or chemical processing.

Custom power devices have been developed to address these problems at the distribution level, including the Dynamic Voltage Restorer (DVR), the Distribution Static Synchronous Compensator (DSTATCOM), the Unified Power Quality Conditioner (UPQC) and the Shunt Active Power Filter (SAPF) [10], [3]. Among these, the DVR is widely regarded as a cost-effective series-connected solution for voltage sag, swell and unbalance mitigation, since its power and energy-storage rating is generally lower than that of a comparable DSTATCOM or UPQC installation [1], [19]. The shunt APF, connected in parallel with the non-linear load, is correspondingly well suited to harmonic current cancellation and reactive power compensation, and its performance can be significantly improved by replacing a fixed-gain PI controller with an adaptive fuzzy logic controller that better handles the non-linear, time-varying nature of harmonic-rich loads [13], [6].

This paper presents a combined DVR and fuzzy-controlled SAPF scheme for power quality enhancement under unbalanced load conditions. The specific contributions of this work are: (i) the design and MATLAB/Simulink modeling of a DVR for voltage sag/swell compensation under a double-line-to-ground (DLG) fault with an unbalanced parallel load; (ii) the design of a two-input, two-output Mamdani-type fuzzy logic controller for shunt APF DC-link regulation and harmonic-current cancellation; and (iii) a comparative THD evaluation of the proposed fuzzy-controlled SAPF against an uncompensated system, a conventional PI-controlled filter and a previously reported hysteresis-controlled filter, all evaluated under unbalanced-load conditions.

## II. LITERATURE REVIEW

A substantial body of recent literature has examined DVR control strategies for voltage sag and swell compensation. Ali et al. [1] proposed a multi-frequency four-wire DVR with harmonic injection capability for multi-frequency power transfer systems, while Mallick et al. [6] developed an adaptive fuzzy-PI controlled DVR combining a supercapacitor and fuel-cell energy storage system for both short- and long-duration voltage sags. Shufian et al. [7] reported a fuzzy logic-controlled three-phase DVR for voltage stabilization, and Tadesse and Gebremedhin [8] combined neural-network and fuzzy-logic control for DVR-based voltage quality improvement in a distribution substation. Rajasekaran and Prabhakaran [4] investigated a machine-learning-based DVR control and signal-conditioning strategy, reporting improved sag/swell response over conventional PI control.

On the shunt-compensation side, Aravind and Selvakumar [2] applied a golden-jackal optimizer to tune a shunt APF for improved power quality, and Barik et al. [3] validated a combined control strategy for shunt APF in a microgrid through both simulation and real-time implementation. Reguieg et al. [5] examined harmonic mitigation in grid-integrated renewable systems supplying non-linear loads, and Akbari et al. [9] combined a shunt APF with a DSTATCOM in a hybrid PV-wind microgrid. Das et al. [10] designed a UPQC using a model-reference adaptive control strategy for a microgrid, while Kumar and Singh [11] compared PI and Artificial Neural Network (ANN) control strategies for DVR-based voltage-quality improvement under non-linear loads.

Fuzzy logic control has been applied extensively to both DVR and SAPF regulation. Patel et al. [12] combined an adaptive fuzzy controller with a modified synchronous-reference-frame (SRF) technique for SAPF harmonic reduction under distorted source conditions, and Ramesh and Kumaravel [13] performed a direct performance comparison of PI and Fuzzy Logic Controllers (FLC) for shunt APF, reporting that the FLC achieved lower THD and faster DC-link regulation than the PI controller. Reddy and Bhuvaneswari [14] applied sliding-mode control to DVR-based sag compensation, and Thenmozhi et al. [15] combined a fuzzy-logic controller with an improved Second-Order Generalized Integrator (SOGI) for a photovoltaic-assisted DVR. Anitha et al. [16] used an interval type-2 fuzzy logic controller for a PV-supported DVR, reporting improved robustness over type-1 fuzzy designs. For shunt APF control specifically, Fei et al. [17] proposed a self-constructing fuzzy-neural fractional-order sliding-mode controller, and Toopchizadeh et al. [18] combined a novel binary multilevel inverter with an optimal type-2 fuzzy system to mitigate harmonic currents with high accuracy.

Closer to the specific focus of unbalanced-load compensation addressed in this paper, Farooqi et al. [19] examined DVR performance under unsymmetrical faults and their adverse impact on power quality, and Chelli and Benbouzid [20] proposed a hysteresis-control strategy for shunt APF operating specifically under unbalanced three-phase load conditions, providing a directly comparable THD benchmark for the present study. Building on these works, the present paper evaluates a combined DVR and fuzzy-controlled SAPF scheme under a common unbalanced-load and DLG-fault test system, benchmarking the fuzzy SAPF's THD performance directly against the PI-controlled and hysteresis-controlled results reported in this prior literature.

## III. POWER QUALITY DISTURBANCES AND CUSTOM POWER DEVICES

Power quality disturbances of concern in distribution networks include voltage sag (a short-duration reduction in RMS voltage), voltage swell (a short-duration increase in RMS voltage), voltage unbalance among the three phases, and harmonic distortion of the voltage or current waveform caused by non-linear loads such as variable-frequency drives and rectifier-fed equipment. Voltage sags and swells are most commonly caused by short-circuit faults, including line-to-line and double-line-to-ground (DLG) faults, while harmonic distortion arises primarily from the non-sinusoidal current drawn by power-electronic loads.

Custom power devices mitigate these disturbances through power-electronic compensation. Series-connected devices such as the DVR inject a compensating voltage in series with the supply to correct sag, swell and unbalance at the point of common coupling, whereas shunt-connected devices such as the SAPF and DSTATCOM inject a compensating current in parallel with the load to cancel harmonic currents and correct reactive power demand. The Unified Power Quality Conditioner (UPQC) combines both series and shunt compensation within a single device. Among these options, the DVR is generally preferred for voltage-sag mitigation because its power rating, energy-storage requirement and installation cost are lower than those of a comparable DSTATCOM or UPQC, while the SAPF remains the most direct solution for harmonic-current cancellation at the load bus [1], [4].

## IV. PROPOSED SYSTEM CONFIGURATION

### A. Dynamic Voltage Restorer Structure

The DVR regulates the voltage across a sensitive load by injecting a series voltage phasor through an injection (booster) transformer. If  $V_{Lpre}$  is the pre-fault load voltage and  $V_s$  is the post-sag supply voltage, the DVR injection voltage required to restore the load voltage is

$$V_{Lpre} = V_s + V_{DVR} \quad (1)$$

$$V_{DVR} = V_{Lpre} - V_s \quad (2)$$

The DVR used in this study comprises six principal sections: the injection/booster transformer, a harmonic filter, a DC energy-storage device, a Voltage Source Converter (VSC), a DC charging circuit, and a control and protection system, as shown in Fig. 1. The VSC is switched using IGBT devices under PWM control, and a PI controller regulates the injected voltage by comparing the reference (pre-fault) load voltage with the actual measured voltage at the point of common coupling.

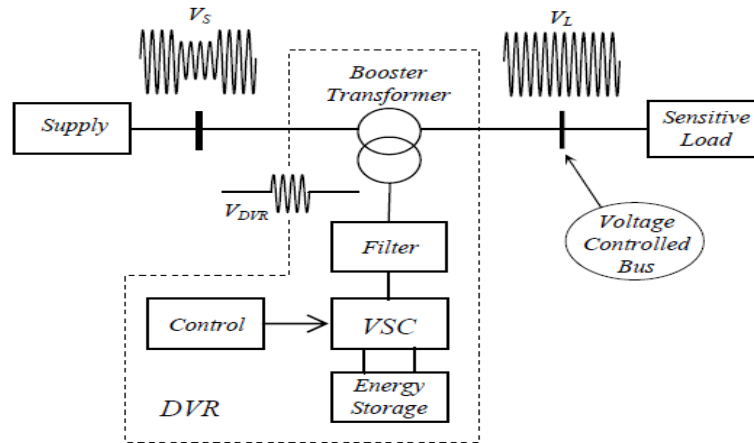


**Fig. 1. Basic structure of the Dynamic Voltage Restorer (DVR).**

A harmonic (LC) filter is placed on the inverter or high-voltage side of the injection transformer to remove the switching-frequency harmonics generated by the VSC, as shown in Fig. 2. The DVR operates in three principal states: standby mode, in which no or only a small compensating voltage is injected during normal conditions; active (injection) mode, in which the DVR injects the voltage difference between the pre-sag and sagged supply voltage during a disturbance; and bypass mode, in which a crowbar/bypass switch isolates the inverter from an excessive fault current to protect the power-electronic components.

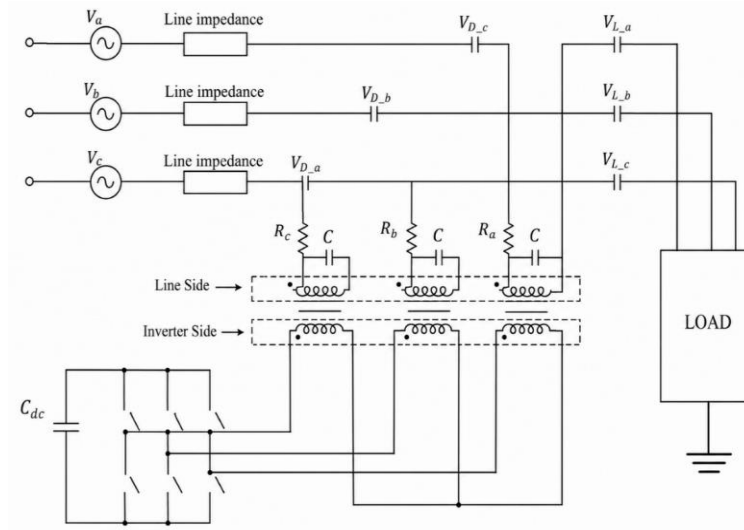


**Fig. 2. DVR configuration with capacitive/LC harmonic filter.**

### B. DVR Compensation for Unbalanced Load

Under unbalanced load or unsymmetrical fault conditions, such as a double-line-to-ground fault affecting two of the three phases, the DVR must independently regulate the injected voltage phasor for each phase, since the magnitude and phase-angle deviation of the sagged voltage differ across the three phases. The pre-sag compensation strategy adopted in this study restores each phase voltage to its pre-fault magnitude and phase angle, ensuring that the load-side voltage remains balanced and sinusoidal even though the supply-side voltage is unbalanced and distorted during the fault.

### C. Shunt Active Power Filter Design

The non-linear industrial drive load draws a distorted current containing a fundamental component and a series of harmonic components. If the supply voltage is  $v_s(t) = V_m \sin(\omega t)$ , the load current can be expressed as

$$i_L(t) = I_1 \sin(\omega t + \phi_1) + \sum_{n=2}^{\infty} I_n \sin(n\omega t + \phi_n) \quad (3)$$

and the instantaneous load power is correspondingly decomposed into a fundamental (active) component, a reactive component and a harmonic component. The shunt APF is controlled to inject a compensating current  $i_c(t)$  such that the current drawn from the source,  $i_s(t) = i_L(t) - i_c(t)$ , contains only the fundamental, in-phase component required to supply the real power demand:

$$i_s^*(t) = p_F(t) / v_s(t) \quad (4)$$

The reference current amplitude is obtained by regulating the DC-link capacitor voltage of the shunt APF through a controller (conventionally a PI controller, replaced here by the fuzzy logic controller described below), and the reference current waveform in each phase is obtained by multiplying this amplitude by a unit sine vector in phase with the corresponding source voltage, as illustrated in Fig. 3.

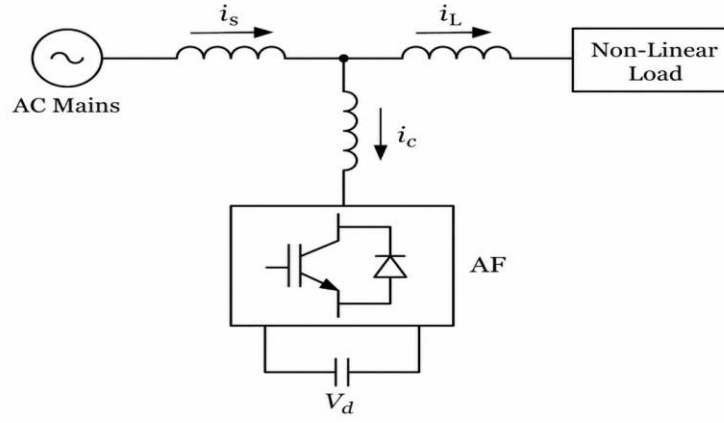


Fig. 3. Design of the basic Shunt Active Power Filter (SAPF).

#### D. Fuzzy Logic Controller for SAPF DC-Link Regulation

Rather than using a fixed-gain PI controller to regulate the DC-link voltage of the shunt APF, this paper employs a two-input, two-output Mamdani-type fuzzy logic controller. The controller inputs are the error  $e$ , defined as the difference between the reference and actual DC-link voltage, and the change in error  $C_e$ , computed as the rate of change of  $e$  between successive sampling instants. Both inputs and both outputs are represented using three triangular linguistic sets over the normalized universe of discourse  $[-1, 1]$ : Negative Big (NB), Centre Zero (CZ) and Positive Big (PB). The complete rule base consists of the nine if-then rules formed from all combinations of the three linguistic values of  $e$  and  $C_e$ , of the general form “IF (Error is X) AND (Change in Error is Y) THEN (Output is Z)”. The fuzzy inference and defuzzification stages both use the Mamdani max-min approach. Fig. 4 shows the operational stages of the fuzzy controller (fuzzification, rule processing and defuzzification), and Fig. 5 shows the block-level structure used to generate the switching signal for the shunt APF in the MATLAB/Simulink model.

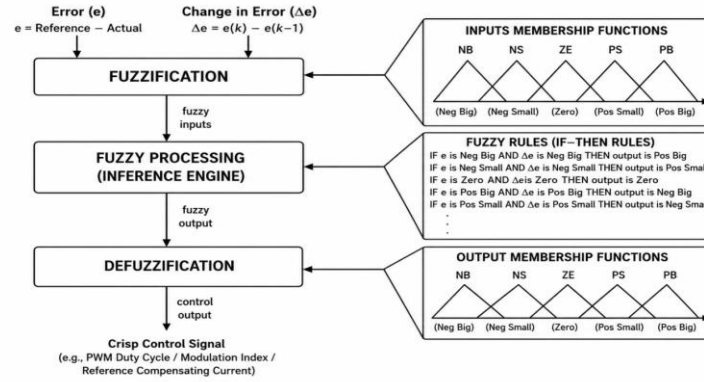


Fig. 4. Operational stages of the fuzzy logic controller (fuzzification, rule processing, defuzzification).

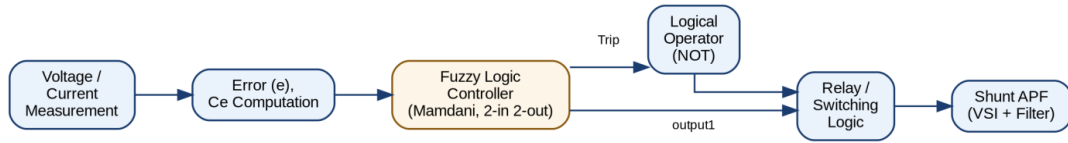


Fig. 5. Block diagram of the fuzzy-logic-based controller used to generate the shunt APF switching signal.

## V. SIMULATION SETUP

The test system was modeled in MATLAB/Simulink with a double-line-to-ground (DLG) fault applied to phases B and C of a three-phase, 400 V, 50 Hz distribution feeder supplying an unbalanced parallel load, as shown in Fig. 6. The DVR was inserted between the source and the sensitive load to compensate the resulting voltage sag/swell, and a shunt APF, controlled by the fuzzy logic scheme of Section IV-D, was connected at the load bus to cancel the harmonic currents drawn by a non-linear industrial drive. Table I lists the principal DVR simulation parameters, and Table II lists the shunt APF simulation parameters.

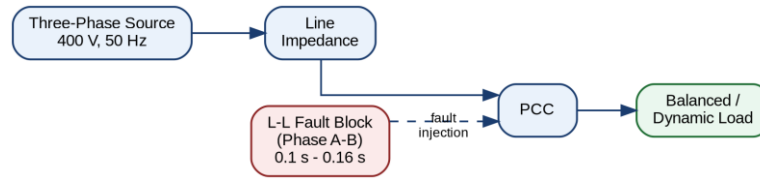


Fig. 6. Block diagram of the test system used for sag/swell simulation with a double-line-to-ground fault.

TABLE I. SIMULINK MODEL PARAMETERS OF THE DVR

| System Element        | Parameter                                                                    |
|-----------------------|------------------------------------------------------------------------------|
| Source                | 3-phase, 400 V, 50 Hz                                                        |
| Inverter              | IGBT-based, 3-arm, 6-pulse, carrier frequency 1080 Hz, sample time 5 $\mu$ s |
| PI controller         | $K_p = 0.5$ , $K_i = 100$                                                    |
| Transformer           | 400/400 V, Y/Y                                                               |
| Injection transformer | 400/400-400 V, Y/Y                                                           |
| Non-linear drive load | 225 kVA (DTC induction motor)                                                |
| Dynamic load          | $P_0 = 50$ kW, $Q_0 = 25$ kVAr                                               |

TABLE II. SIMULINK MODEL PARAMETERS OF THE SHUNT APF

| System Parameter   | Value                  |
|--------------------|------------------------|
| Supply voltage     | 230 V                  |
| Frequency          | 50 Hz                  |
| Source impedance   | 0.05 $\Omega$ , 0.5 mH |
| Filter inductance  | 1.25 mH                |
| Filter capacitance | 210 $\mu$ F            |
| DC-link voltage    | 400 V                  |

## VI. RESULTS AND DISCUSSION

### A. Voltage Sag/Swell Mitigation Using the DVR

With the DLG fault applied between 0.1 s and 0.16 s, the load voltage exhibited a sag on the faulted phases (A and B) and a small swell on the unfaulted phase (C), consistent with the absence of a return path characteristic of a line-to-line-type fault, as shown in Fig. 7. When the DVR was connected with a DLG fault applied between 0.03 s and 0.07 s under an unbalanced parallel load, the DVR injected the required compensating voltage in each phase to restore the load voltage to its pre-fault magnitude within a few milliseconds of fault detection, confirming the effectiveness of the PI-based injection-voltage controller described in Section IV-A. The complete DVR block diagram, including the injection voltage controller, is shown in Fig. 8.

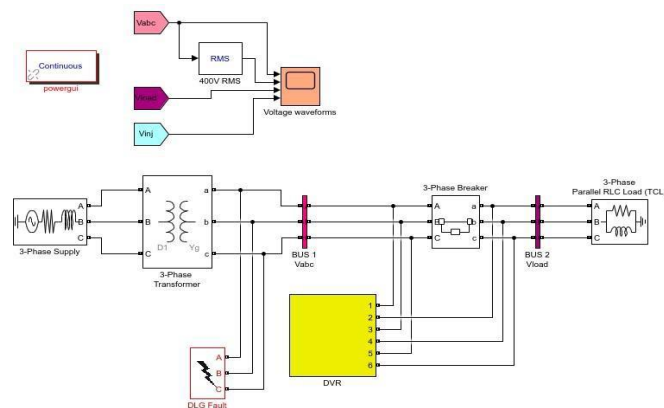


Fig. 7. Output waveforms showing voltage sag and swell caused by the double-line-to-ground fault (red: Phase A, blue: Phase B, green: Phase C).

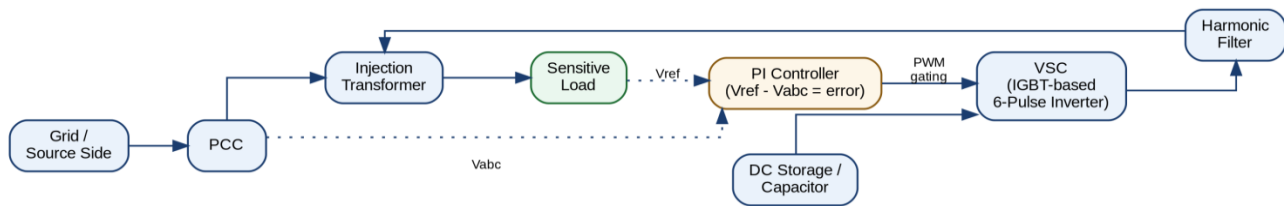


Fig. 8. Block diagram of the Dynamic Voltage Restorer as modeled in MATLAB/Simulink, showing the PI-based injection-voltage controller.

### B. Harmonic Mitigation Using the Fuzzy-Controlled SAPF

With the non-linear industrial drive connected to the test system, the shunt APF was activated with its DC-link regulated by the fuzzy logic controller of Section IV-D. During start-up, the DC-link capacitor first charges through the anti-parallel diodes of the IGBT bridge (equivalent to an uncontrolled three-phase rectifier), after which the fuzzy controller gradually regulates the DC-link voltage to its rated value without overshoot. Fig. 9 shows the resulting voltage waveform and Fig. 10 the resulting current waveform at the point of common coupling with the fuzzy-controlled SAPF in operation; in both cases the waveforms are close to sinusoidal and balanced across the three phases, confirming effective harmonic-current cancellation and voltage regulation under the unbalanced non-linear load.

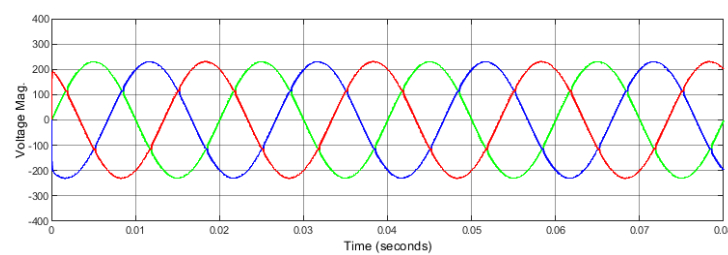


Fig. 9. Voltage waveform at the point of common coupling with the fuzzy logic-controlled shunt APF in operation.

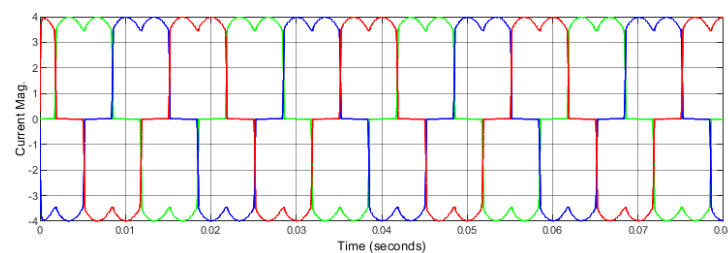


Fig. 10. Source current waveform with the fuzzy logic-controlled shunt APF in operation.

### C. Total Harmonic Distortion (THD) Analysis

Table III compares the percentage THD of the source current for the uncompensated system, a conventional PI-controlled shunt APF, the hysteresis-controlled shunt APF reported by Chelli and Benbouzid for unbalanced three-phase loads [20], and the proposed fuzzy logic-controlled shunt APF, all evaluated under comparable unbalanced non-linear load conditions and measured in accordance with IEEE Std. 519 at the point of common coupling.

TABLE III. HARMONIC ANALYSIS OF THE PROPOSED METHODOLOGY

| Method                                            | % THD |
|---------------------------------------------------|-------|
| Uncompensated                                     | 2.32  |
| Compensation with PI Controller                   | 1.85  |
| Hysteresis-Controlled SAPF (unbalanced load) [20] | 1.250 |
| Proposed Fuzzy Logic-Controlled SAPF              | 1.07  |

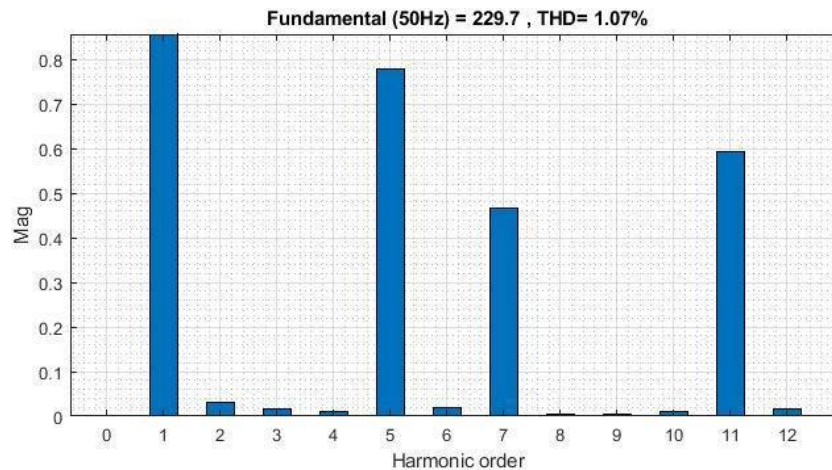


**Fig. 11. Harmonic spectrum of the source current after compensation with the fuzzy logic-controlled shunt APF.**

The proposed fuzzy logic-controlled SAPF reduced the source-current THD from 2.32% (uncompensated) to 1.07%, a larger reduction than that achieved by the conventional PI-controlled filter (1.85%) and the previously reported hysteresis-controlled filter evaluated under unbalanced load (1.250%). All three compensated cases satisfy the 5% THD limit specified in IEEE Std. 519 for the current harmonic distortion of distribution-level loads, but the fuzzy-controlled filter provides the largest margin below this limit, reflecting the fuzzy controller's ability to adapt its DC-link regulation gain to the instantaneous error and rate-of-change of error rather than relying on the fixed gains of a PI controller.

#### D. Discussion

The combined results demonstrate that the DVR and fuzzy-controlled SAPF address complementary aspects of the power quality problem under unbalanced loading: the DVR corrects voltage-magnitude and phase disturbances arising from unsymmetrical faults on the supply side, while the shunt APF corrects the current-harmonic and reactive-power distortion arising from the non-linear load on the customer side. Because the DVR and SAPF are connected in series and shunt configurations respectively, their control actions do not interact adversely, allowing both devices to be commissioned together at the same point of common coupling without requiring coordinated control-loop tuning between them. The superior THD performance of the fuzzy-controlled SAPF relative to both the PI-controlled and hysteresis-controlled benchmarks further supports the case for adopting fuzzy DC-link regulation as the default control strategy for shunt APF installations serving unbalanced, harmonic-rich industrial loads.

## VII. CONCLUSION

This paper presented the design, MATLAB/Simulink modeling and comparative evaluation of a combined Dynamic Voltage Restorer and Fuzzy Logic-Controlled Shunt Active Power Filter for power quality enhancement under unbalanced load conditions. The DVR, controlled through a PI-based injection-voltage scheme, successfully restored the load voltage following a double-line-to-ground fault on an unbalanced feeder, while the fuzzy-controlled SAPF reduced the source-current THD from 2.32% in the uncompensated system to 1.07%, outperforming both a conventional PI-controlled filter (1.85%) and a previously reported hysteresis-controlled filter evaluated under unbalanced load (1.250%), and comfortably satisfying the IEEE Std. 519 harmonic limit. These results confirm that the combined DVR and fuzzy-controlled SAPF scheme provides an effective and practical solution for voltage-sag/swell compensation and harmonic mitigation in distribution networks subject to unbalanced loading and non-linear industrial drives. Future work will extend the evaluation to hardware-in-the-loop testing and to coordinated DVR-SAPF operation within a Unified Power Quality Conditioner (UPQC) configuration.

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