J. Electrical Systems 20-9s (2024): 2837-2847

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Comparative Evaluation of Conventional Fuzzy and Type-2 fuzzy Controllers to Offset Sag and Swell in Voltage for Power Quality Improvement

Abstract: - Voltage sag and swell impact sensitive equipment in commercial and industrial environments, posing a serious risk to power systems performance and stability. A compensator is the ideal use for a dynamic voltage restorer (DVR) in order to lessen the effects of voltage sag and swell. In this work, the load terminal voltage is managed using proportional and integral (PI) controllers while the source voltage experiences a 20% voltage sag and swell. The reference load voltage for voltage source converter switching is produced using the synchronous reference frame algorithm. Conventional FLC and Type-2 FLC are used to obtain optimal settings for the gains of PI controllers. The usage of fuzzy logic controllers (FLC) and Type-2 fuzzy logic controllers (T2FLC) in Dynamic Voltage Restorers (DVR) to reduce the impact of voltage sag and swell is examined in this study. The goal of the research is to find improvements in voltage stability and power quality by contrasting the performance of these two control systems. With the aid of MATLAB software, the DVR's control approach is simulated for both controllers, and their performance is examined.

Keywords: Dynamic Voltage Restorer (DVR), Power Quality, Fuzzy Logic Controller (FLC), Type -2 FLC, Voltage Sag and Swell, and Synchronous Reference Frame (SRF) Algorithm.

I. INTRODUCTION

A specialized power electronic device called the DVR is used to add compensating voltage in order to overcome power quality issues. Connected in series with the supply and load, the DVR works by correcting voltage discrepancies between the rated voltage and actual variations. It offers enhanced control, effectively addressing both voltage swell and sag. Primarily, the DVR's role is to detect and mitigate voltage fluctuations in the power supply, safeguarding critical loads on the distribution side from power quality disturbances. Critical and sensitive loads in the distribution system are negatively impacted by voltage swell and sag. When a Dynamic Voltage Restorer (DVR) is linked in series with the system, it reduces voltage sags and swells through well-organized regulation. It has been noted that there are several conventional control systems for DVR control [1].

The regulated load terminal voltage has experienced undershoot and overshoot during sag dynamics, despite the DVR's effective performance in mitigating voltage sags and swell. Numerous control systems, including voltage space–vector control, sliding mode control, proportional and integral (PI) control, and others, have been considered for the capacitor supported DVR [2]. The literature discusses control algorithms for various control systems based on power quality reactive instantaneous power theory, instantaneous symmetrical components, synchronous reference frame theory (SRFT), adaline-based fundamental extraction, energy-optimized control, and the DVR [3].Numerous intelligent algorithms, such as fuzzy logic, neural networks, genetic algorithms, and particle swarm optimization, have been reported for the optimization of controller settings (gains) [4,5,6,7].

This research examines a DVR-connected system that is supported by capacitors and has a 20% voltage sag in the source voltage. Here, a sensitive linear load in the form of a resistive-inductive load is used. DVR is intended to use PI controllers in the AC-link (load) and DC-link control loops to reduce voltage sag and control the load's terminal voltage [8]. The regulation of voltage is impacted by controller gains. Therefore, to maximize the gains, Kp and Ki, of the PI controllers, an artificial intelligence controllers are proposed. This research studies the DVR performance using conventional FLC and Type-2 FLC regulated gain parameters of PI controllers. By creating and running the model for both FLC and Type-2 FLC DVR-connected system in MATLAB with Simulink and Power System blocksets, the DVR performance is verified.

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II. METHODOLOGY

Voltage sags and swells are significant concerns impacting loads on the distribution side in power quality issues. To address these challenges and safeguard the various components of power systems, custom power devices were developed. The most notable and cost-effective of them is the Dynamic Voltage Restorer device. In order to stabilize the voltage throughout the load, the DVR increases efficiency and reliability by adding extra voltage to the transmission system. At the point of common connection, the DVR acts as a series compensating device and is usually situated at the distribution side between the distribution feeder and the load. It restores the desired load side voltage by using voltage boost technology through solid-state switches in a three-phase voltage source converter [9].

In addition to correcting voltage sags and swells, limiting fault currents and suppressing phase voltage harmonics, the DVR also lowers voltage spikes. As seen in Figure 1, the essential parts of the DVR consist of boosting or injection transformers, a voltage source converter (VSC), a control track, a filtering circuit, and a DC energy storage system consisting of capacitors and batteries for power injection.

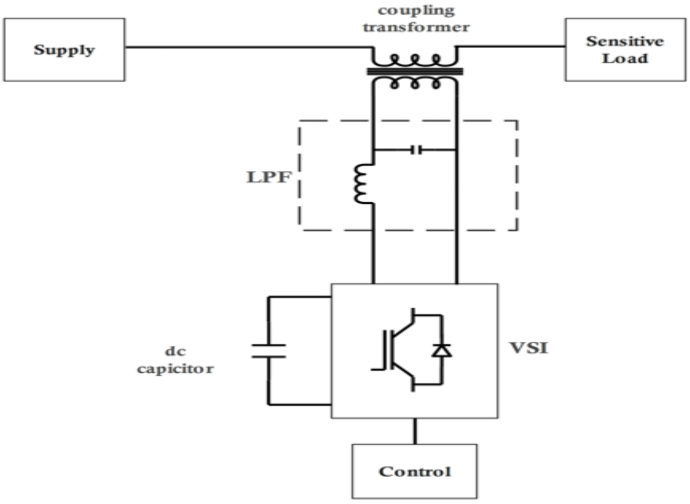


Figure 1 Basic Components of DVR

When it comes to handling power quality problems like voltage sag and swell at the distribution side, the Dynamic Voltage Restorer (DVR) is by far the most practical and satisfactory option. It is essential in fault conditions because it shapes the load voltage profile at the point of common connection, allowing reactive and active power to be exchanged. Upon detecting a sag in the load voltage profile, the DVR transitions from standby mode to active mode, initiating the restoration process by adjusting each phase voltage utilizing the inverter switches in the voltage source converter to return it to its predefined pre-sag value. Source-side voltage and load-side voltage are represented by V_S and V_L, respectively[10], in Figure 2, which shows the DVR providing both reactive and active power. The required voltage is injected by inserting the DVR in series. Circuits for power and control make up its main configuration.

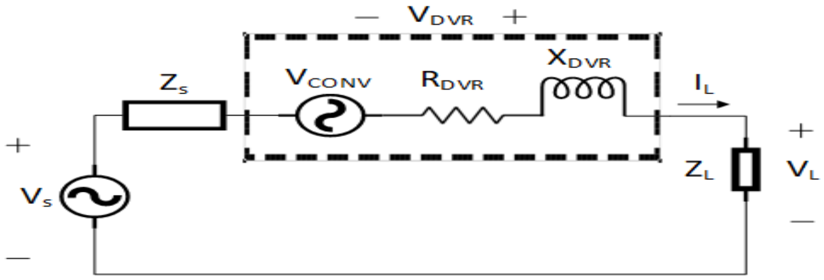


Figure 2 Schematic Diagram of DVR

$$V_{DVR} = V_{TH} + I_L Z_{TH} + V_L \qquad (1)$$

In Equation 1, the load voltage (V_L) , the load impedance (Z_{TH}), and the load current (I_L) are all indicated.

In Equation 2, P_L and Q_L stands for loads side's active and reactive power..

$$I_L = \frac{P_L + jQ_L}{V_L} \qquad (2)$$

In Equation 3, α indicates the angle of the DVR voltage, and β represents the angle of V_{TH}. In Equation 4, the power angle of the load is denoted by θ.

$$V_{DVR} < \alpha = V_L < 0 + Z_{TH} I_L < (\beta - \theta) + V_{TH} < \delta \qquad (3)$$

$$\theta = \tan^{-1} \frac{Q_L}{P_L} \qquad (4)$$

As indicated in Equation 5, the DVR injects complex power, denoted as S_{DVR}.

$$S_{DVR} = V_{DVR} I_L^* \qquad (5)$$

A capacitor-supported DVR that uses the synchronous reference frame (SRF) theory is depicted in Figure 3. The voltages at the point of common coupling (PCC) in this configuration are converted into the rotating reference frame via an abc to dq0 transformation[11,12]. During the voltage suppression process, low pass filters (LPFs) are used to filter out harmonics and oscillations. The abc-dq0 conversion, which is used by the SRF approach to apply Park's transformation and convert the load voltages from the abc frame into the rotating reference frame (dq0) is clearly described.

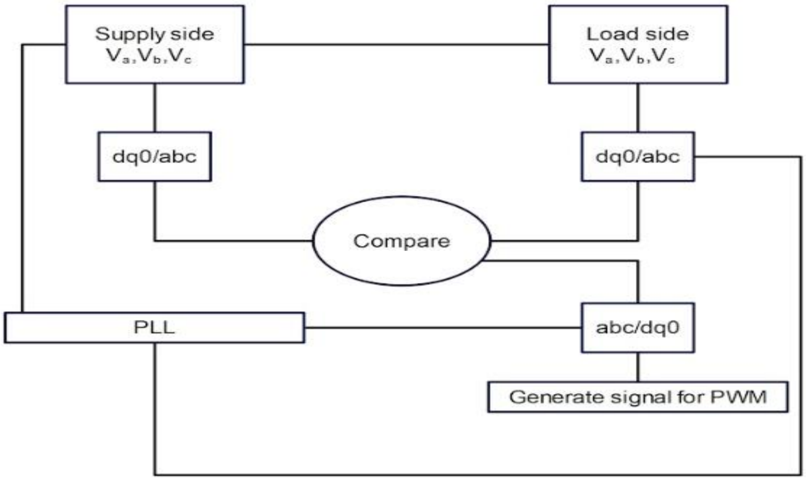


Figure 3 Schematic Diagram of DVR

The application of reverse Park's transformation, which employs the dq0-abc conversion method to translate the load voltages from the rotating reference frame $v_{ld}, v_{lq}, v_{lo})$ back to the abc frame load voltages.To enhance power quality, mitigation strategies are devised to establish the compensatory approach for voltage correction. These strategies maintain the load terminal voltage at the rated level and prevent any distortion [13,14]. Within the DC link control loop, a PI controller is employed to maintain the DC-link voltage at its reference value, v_{dc} =200V. In the Pulse Width Modulation (PWM) process, the difference between the sensed load voltage and the reference load voltages is utilized to generate gate pulses for the Voltage Source Converter (VSC) of the DVR.

A. Fuzzy Logic Controller (FLC)

In the past, the DVR's energy storage system parameters would fluctuate because of voltage sag and swell occurrences, making it difficult for the PI controller to regulate the injected voltage[15]. Capacitors connected directly through a rectifier are part of the DVR's energy storage system. The DC-link capacitors' stored energy affects the inverter's output. A fuzzy logic controller (FLC) has been added to the system to overcome these drawbacks and improve performance under both steady-state and transient circumstances[16,17]. This approach eliminates the need for complex mathematical computations. Fuzzy logic control operates through three stages:

fuzzification, decision-making, and defuzzification as shown in figure 4[18,19]. The input and output variable fuzzy membership functions are shown in figure 5.

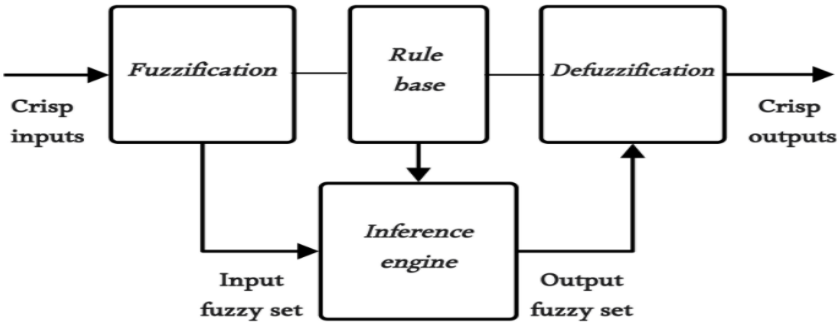


Figure 4 Basic Elements of Fuzzy Logic Controller

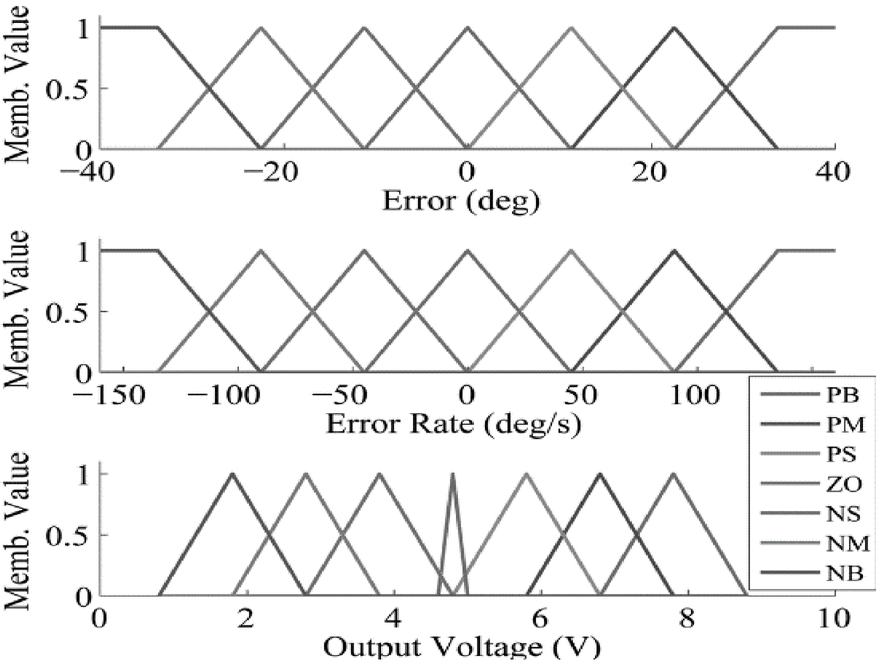


Figure 5 Input and Output Variable Fuzzy Membership Functions

B. Advanced Fuzzy Logic Controller (Type-2 FLC)

Conventional fuzzy controller, widely integrated into numerous applications, face challenges in handling substantial uncertainties inherent in real-world scenario [20]. These uncertainties, which conventional FLCs manage using fuzzy sets of crisp inputs, are not adequately addressed by conventional fuzzy controllers. However, by employing Type-2 fuzzy sets, sophisticated Type-2 fuzzy controllers are able to efficiently handle uncertainty. The membership grade represents these sets ranging between 0 and 1. This capability allows Type-2 FLCs to potentially outperform conventional FLCs in applications requiring robust uncertainty management, thus advancing fuzzy control technology. A method has been developed for enhancing power quality by adjusting PI controller gains through Type-2 fuzzy logic controller [21]. Despite the practical effectiveness of conventional Type-1 FLCs, in diverse applications they face challenges associated with significant levels of uncertainty.Type-2 fuzzy sets provide greater flexibility by representing membership values as fuzzy sets in a three-dimensional space rather than two-dimensional. Figure 6 illustrates how Type-2 FLC can effectively control uncertainties, leading to reduced harmonic distortion and improved power quality [22].

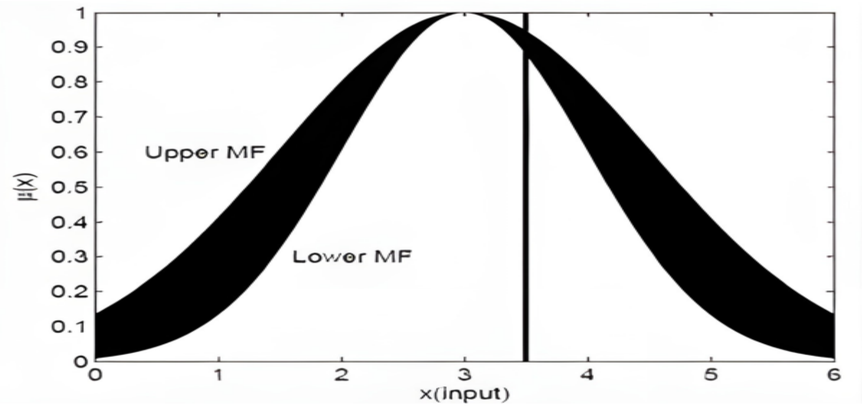


Figure 6 A Gaussian Type-2 Fuzzy Membership Function (FOU)

III. RESULTS

In this scenario, the voltage $v_{in\,(t\,)abc}$ is used to simulate sag/swell events. The constant output voltage $v_{out(t)abc}$ is maintained due to the $v_{inj(t)\,abc}$ generated by various controllers. The load-side voltage's total harmonic distortion (THD) analysis, depicted in Figure 7 is conducted before implementing DVR for adjustment of power quality issues like sag and swell.The test parameters listed below have been taken into considerations.

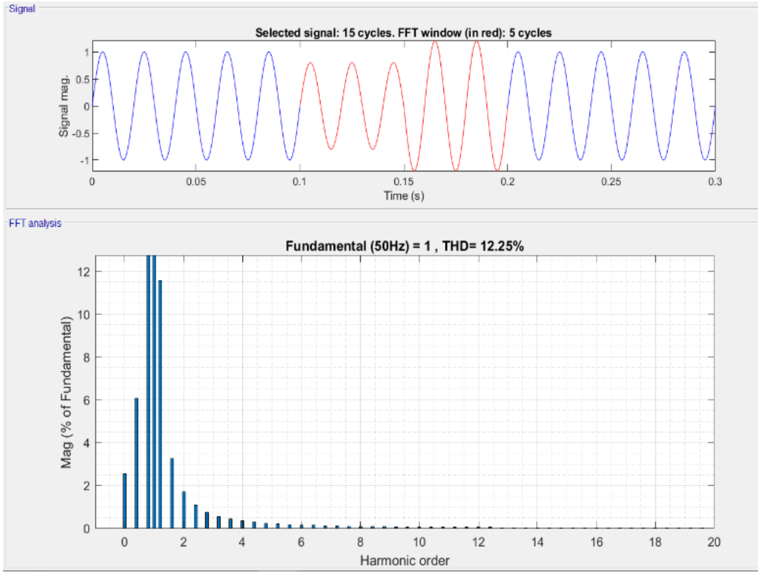


Figure 7 Load-side Voltage's Total Harmonic Distortion (THD) Without DVR

Between time intervals of 0.1 and 0.2 seconds, there is a voltage sag or rise in the source-side voltage that affects the load-side voltage's power quality. To reduce the impact of these harmonics, multiple controllers are used.As a result, the system fails to maintain the required output voltage at the load side in the absence of DVR intervention. The DVR is deployed to introduce voltage and mitigate the effects of voltage sag. Figure 8 depicts the Simulink model of the DVR connected. Figure 9 illustrates the basic configuration of the DVR, showing all essential components.

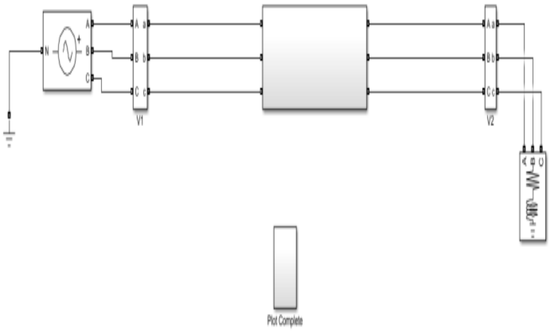


Figure 8 A Simulink Model of DVR

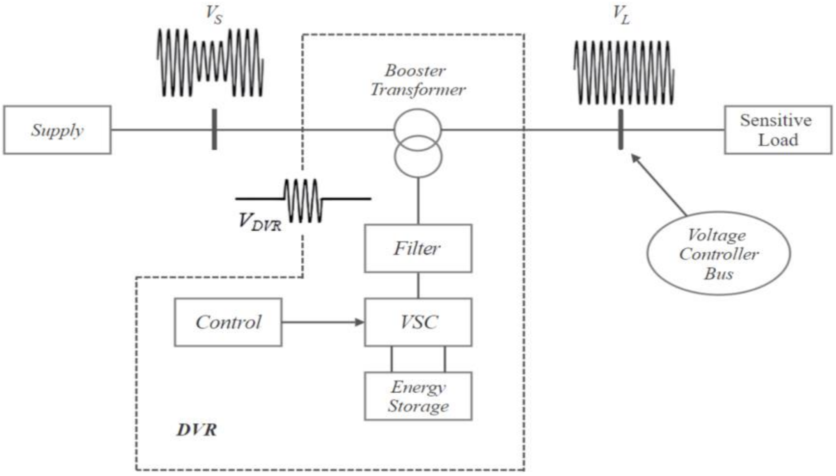


Figure 9 Basic configuration system of DVR

Figure 10 displays the basic configuration of the DVR, showing a Simulink diagram of its core components such as the control system, injection transformer, filter circuit, and energy storage device. Figure 11 illustrates the Simulink model of the DVR's control circuit using the synchronous reference frame algorithm.

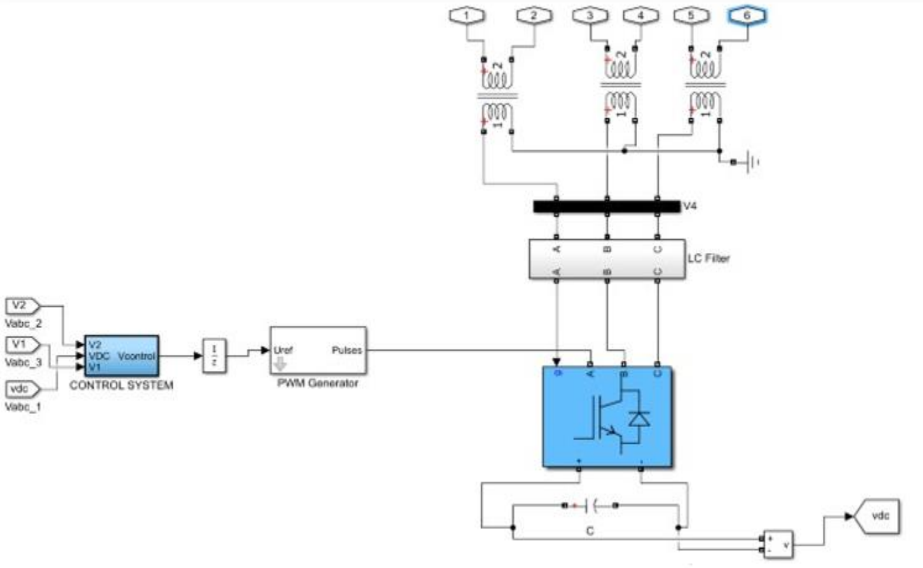


Figure 10 Simulink Model of Basic Components of DVR

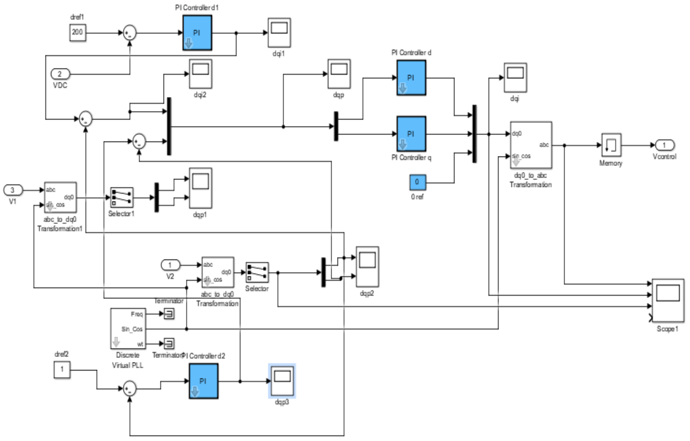


Figure 11 Simulink Model of the Control Circuit of DVR using SRF Algorithm

A. *Fuzzy Logic Controller (FLC) built DVR*

Figure 12 shows the matlab model of a typical FLC, favored over conventional SRF-based PI controllers for its ability to handle system parameter fluctuations and ease of use. Figure 13 illustrates a significant improvement in total harmonic distortion (THD) to 3.50% on the load side voltage when using voltage sag and swell correction with a conventional fuzzy logic controller-based DVR. This performance exceeds that of an SRF-based PI controller. This type aims to clarify the contrast between the PI controller and FLC employing Synchronous Reference Frame (SRF) algorithm.

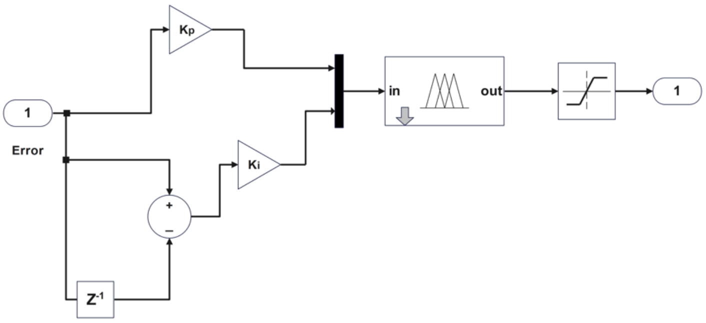
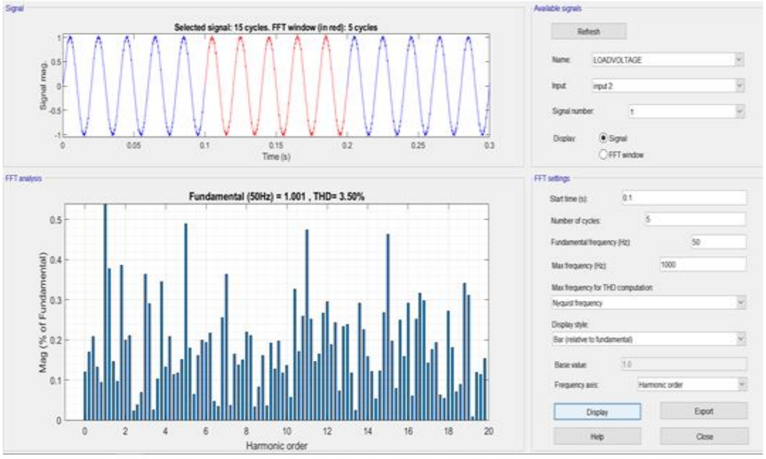


Figure 12 Simulink Model of Conventional FLC built DVR



Name: LOADVOLTAGE
Input: input 2
Signal number: 1
Display: ● Signal ○ FFT window
Start time (s): 0.1
Number of cycles: 5
Fundamental frequency (Hz): 50
Max frequency (Hz): 1000
Max frequency for THD computation: Nyquist frequency
Display style: Bar (relative to fundamental)
Base value: 1.0
Frequency axis: Harmonic order

Figure 13 Load-side Voltage's Total Harmonic Distortion (THD) with conventional FLC

B. Type -2 Fuzzy Controller based DVR

As seen in figure 14, a reliable unique technique employing an advanced Type-2 Fuzzy controller to inject compensating voltage at the load side as optimally as possible. Based on the preceding chart, it can be inferred that DVR has effectively kept v_{dc} at its rated value, demonstrating its dynamic responsiveness and validation. The DVR system's designed controller's performance can control the balanced sag state.

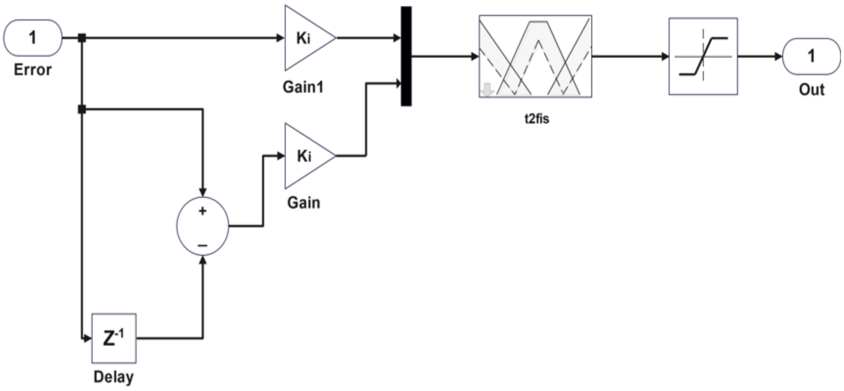


Figure 14 Simulink Model of Advanced Type-2 Fuzzy

The advanced Type-2 fuzzy is noted for its significant degree of freedom and utilization of 3D rather than 2D space, allowing effective control of uncertainties. Following compensation for voltage sag/swell, it effectively reduces overall harmonic distortion, thereby enhancing power quality.

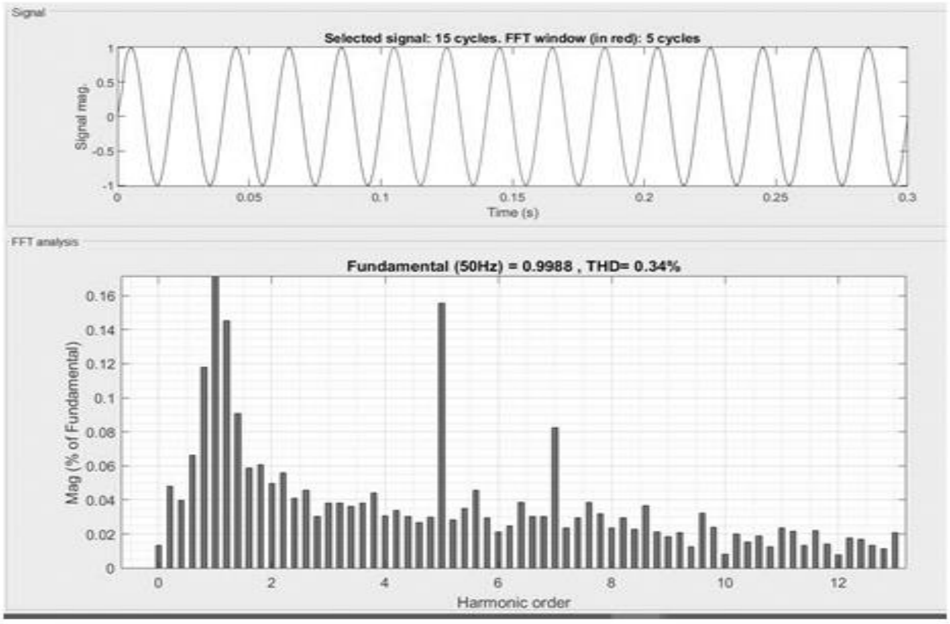


Figure 15 Load-side Voltage's Total Harmonic Distortion (THD) with Type-2 FLC

IV. DISCUSSION

Figure 15 demonstrates that the Type-2 fuzzy regulated controller for DVR, achieves superior performance compared to FLC controlled DVR, achieving a total harmonic distortion of 0.34% at the load side. This unique approach ensures this distortion value less than 5%, with a concentrated value of only 0.34%, even under severe 20% voltage sag conditions at the source side. Table 1 provides a comparative evaluation of performance of both controllers, highlighting the Type-2 controller's superiority.

Using this advanced fuzzy controller i.e. Type-2 fuzzy, the controller remains stable and effectively operates under significant sag and swell conditions. Extensive evaluation of various soft computing-based controllers has been conducted to improve power quality indicators, focusing on voltage sag, swell and THD metrics. The study underscores that robust DVR control performance can be achieved without additional equipment or complex modifications, leveraging optimal PI controller coefficients through software adjustments.

Stability analysis has been integral to this study, determining the controllers' effectiveness under dynamic faults in distribution systems and their impact on raising power quality indices. The results obtained from testing is that the Type-2 fuzzy controller emerges as a preferred choice for enhancing overall power quality. The study also discusses how developed algorithms mitigate oscillations, undershoots, and overshoots. The paragraph discusses the evaluation of different types of controllers—conventional fuzzy logic controllers, Type-2 fuzzy controllers and their effectiveness in enhancing power quality.

1. Controller Comparison: The study compares conventional fuzzy logic controllers, Type-2 fuzzy controllers. These controllers are evaluated based on their performance in handling AC loads, particularly in the context of a Dynamic Voltage Restorer (DVR).
2. Introduction: It was observed that Type-2 fuzzy computing-based DVRs exhibit superior performance compared to conventional fuzzy logic controllers in mitigating voltage sag and swell, thus improving overall power quality metrics. This superiority is attributed to Type-2 fuzzy systems' capability to manage uncertainties and fluctuating parameters more effectively.
3. **St**ability Under Severe Sag Conditions: Type-2 fuzzy controllers are noted for their ability to maintain stability and ensure satisfactory performance even under severe voltage sag conditions. This robust performance is crucial in ensuring uninterrupted operation and reliability of power supply systems during adverse voltage events.
4. Comprehensive Assessment: The study encompasses a thorough assessment to evaluate the effectiveness of various soft computing-based controllers in improving metrics. Key metrics, such as T.H.D levels during voltage sag and swell events, are analyzed for each type of controller.

Table 1 Comparative Evaluation of Performance of both Controllers

Factors	With Fuzzy logic	With advanced Type-2 fuzzy
Sag 20% t(sec)= 0.1-0.15	Compensated	Compensated
Swell 20% t(sec)= 0.1-0.15	Compensated	Compensated
Multi-mode Oscillations	Not observed	Not observed
Source side THD	12.25%	12.25%
Load side THD	3.50%	0.34%

V. CONCLUSION

The effectiveness of conventional Fuzzy Logic Controller (FLC), Type-2 fuzzy controller based DVR was thoroughly examined. According to this study, Type-2 fuzzy controlled DVRs perform better at reducing the impact of voltage sags and swells than conventional FLC controlled DVR. Power quality and voltage stabilization are improved by the Type-2 FLC with better management of uncertainties and nonlinearities. Key power quality indicators evaluated for each controller include THD levels for both voltage sag and voltage swell. The Type-2 fuzzy controlled DVR, achieves superior performance compared to the conventional FLC controlled DVR with a total harmonic distortion (THD) of 0.34% at the load side. This unique approach ensures this distortion value is less than 3.50% achieved by using FLC controlled DVR. Future studies will concentrate on Type-2 fuzzy controller application in the real world and additional optimization for different power quality issues.

ACKNOWLEDGMENT

There is no specific funding to support this research.

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