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Research

PERFORMANCE ENHANCEMENT OF DYNAMIC VOLTAGE RESTORER USING ANFIS -BASED ADAPTIVE CONTROL STRATEGY

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ABSTRACT

Power quality disturbances such as voltage sag, swell, harmonics, and grid faults pose serious challenges to sensitive loads in modern distribution systems. Dynamic Voltage Restorers (DVRs) are widely used custom power devices for mitigating such disturbances by injecting compensating voltages in series with the distribution line. However, the performance of conventional proportional–integral (PI) and fixed-rule fuzzy controllers degrades under nonlinear load variations and severe grid disturbances. To overcome these limitations, this paper proposes an **Adaptive Neuro -Fuzzy Inference System (ANFIS)–controlled DVR** for effective voltage disturbance compensation and power quality enhancement. The proposed controller adaptively tunes control parameters by combining neural network learning capabilities with fuzzy logic reasoning. The DVR performance is evaluated under voltage sag, swell, harmonic distortion, and fault conditions. Simulation results demonstrate superior voltage regulation, fast dynamic response, and significant reduction in total harmonic distortion (THD) compared with conventional controllers, validating the effectiveness of the proposed ANFIS -based DVR.

Index Terms— Dynamic Voltage Restorer (DVR), Adaptive Neuro -Fuzzy Inference System (ANFIS), power quality, voltage sag, voltage swell, harmonic mitigation.

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1. INTRODUCTION

The rapid growth of nonlinear loads, renewable energy integration, and power electronic converters has significantly deteriorated power quality in modern distribution networks. Voltage disturbances such as sag, swell, interruptions, harmonics, and transient faults adversely affect sensitive industrial and commercial loads, leading to equipment malfunction, data loss, and economic losses. Among these disturbances, voltage sag and swell are the most frequent and severe events in distribution systems.

Custom power devices (CPDs) such as Dynamic Voltage Restorers (DVRs), Distribution STATCOMs (DSTATCOMs) , and Unified Power Quality Conditioners (UPQCs) have been extensively deployed to mitigate power quality issues. The DVR is particularly attractive due to its fast response, lower cost, and effective series compensation capability.

Conventional DVR control strategies mainly rely on PI or fixed-gain controllers, which suffer from poor adaptability under parameter variations, nonlinear loads, and grid faults. Fuzzy logic controllers improve robustness but require expert-defined rules and membership functions. To address these challenges, **Adaptive Neuro-Fuzzy Inference System (ANFIS)** control combines the learning ability of neural networks with the linguistic reasoning of fuzzy logic, enabling adaptive and intelligent control.

This paper proposes an **ANFIS-controlled DVR** to enhance voltage regulation and power quality under diverse operating conditions. The controller dynamically adapts to disturbances, ensuring improved compensation performance and reduced harmonic distortion.

2. LITERATURE SURVEY

The increasing penetration of nonlinear loads, renewable energy sources, and power electronic interfaces has significantly stressed power quality (PQ) in distribution networks. Voltage disturbances such as sags, swells, harmonics, and transient faults can interrupt sensitive industrial processes and degrade system reliability. In response, numerous studies have investigated advanced control techniques for custom power devices—particularly **Dynamic Voltage Restorers (DVRs)**—to improve PQ and disturbance mitigation performance.

Early DVR control strategies predominantly relied on classical controllers such as proportional–integral (PI) or hysteresis schemes due to their straightforward implementation and acceptable performance under steady conditions. Wahab and Yusof presented a DVR-based compensation method for voltage sag mitigation using conventional control in distribution networks, demonstrating basic disturbance compensation capabilities [16]. However, fixed-parameter controllers often struggle with parameter variations, nonlinearities, and complex operating scenarios, leading to suboptimal transient responses.

To address these limitations, soft computing and intelligent control techniques have been widely explored. Neural Network (NN) and Fuzzy Logic Controllers (FLC) have shown improved robustness compared with classical PI controllers. Fuzzy logic enables nonlinear mapping and heuristic decision-making without requiring precise mathematical models, which is beneficial for PQ control under nonlinear load conditions. However, fuzzy controllers require expert-designed rule bases and manual tuning of membership functions, which limits adaptability for varying system dynamics.

To overcome the drawbacks of individual techniques, hybrid intelligent controllers such as **Adaptive Neuro-Fuzzy Inference Systems (ANFIS)** have been proposed. The ANFIS, first introduced by Jang, fuses the linguistic reasoning of fuzzy logic with the learning capability of neural networks, enabling adaptive and self-tuning control [1]. This makes ANFIS particularly suited for dynamic and uncertain environments like DVR control under diverse disturbances.

Several studies have applied ANFIS in PQ device control. Vardhan et al. investigated an ANFIS-based Unified Power Quality Conditioner (UPQC) to compensate for voltage sag, swell, and reactive power under distorted conditions, highlighting significant improvements over fixed fuzzy logic control [7]. Research by Ramya et al. explored a multi-level inverter-based DVR controlled by a neuro-fuzzy controller, demonstrating enhanced voltage compensation performance compared with conventional controllers under sag and swell conditions [4].

Recent works have focused on optimized ANFIS structures and integration with advanced signal processing. Saritha and

Sidram developed a PLL-based ANFIS optimized PI controller for DVR systems, demonstrating enhanced dynamic response and improved PQ metrics under voltage disturbances [3]. Bhavani et al. proposed an ultra-capacitor integrated DVR with ANFIS control to enhance ride-through capability during grid faults, achieving fast transient response and effective mitigation of voltage deviations [5]. These studies confirm that ANFIS-based control strategies improve DVR performance in terms of voltage regulation, harmonic mitigation, and adaptability to varying load conditions.

In addition, research integrating ANFIS with renewable energy sources has gained traction. Sobha Rani et al. utilized an ANFIS-controlled DVR in a grid-connected photovoltaic system to compensate voltage distortions and enhance PQ, illustrating robust performance under variable generation and nonlinear loads [9]. Furthermore, hybrid approaches combining ANFIS with optimization algorithms have been investigated to automate membership function tuning and rule extraction, which further elevate controller adaptability and reduce design complexity.

Despite these advances, many existing works focus primarily on specific disturbances such as sag or swell, or are limited to simulation studies without real-time implementation. Moreover, comparative analyses of ANFIS against other intelligent controllers under multiple fault types and nonlinear load scenarios remain limited. Therefore, further research is needed to validate ANFIS-based control strategies in real-world hardware setups and to benchmark their performance comprehensively against alternative adaptive control schemes.

In summary, literature indicates that ANFIS controllers offer superior adaptability, disturbance rejection, and PQ enhancement capability for DVR applications compared with conventional and standalone fuzzy or neural network approaches. The integration of ANFIS with DVR systems presents a promising solution for dynamic voltage disturbance compensation across a range of PQ issues.

3. DYNAMIC VOLTAGE RESTORER CONFIGURATION

A typical DVR consists of:

- Series injection transformer
- Voltage source inverter (VSI)
- DC-link energy storage system
- Passive filter
- Control and synchronization unit

The DVR injects a controlled voltage in series with the supply to maintain the load voltage at the desired reference level. The injected voltage is given by:

$$V_{DVR} = V_L^* - V_S$$

where $V_L^*$is the reference load voltage and $V_S$is the supply voltage.

During sag, swell, or fault conditions, the DVR compensates by injecting an appropriate voltage magnitude and phase to restore the load voltage.

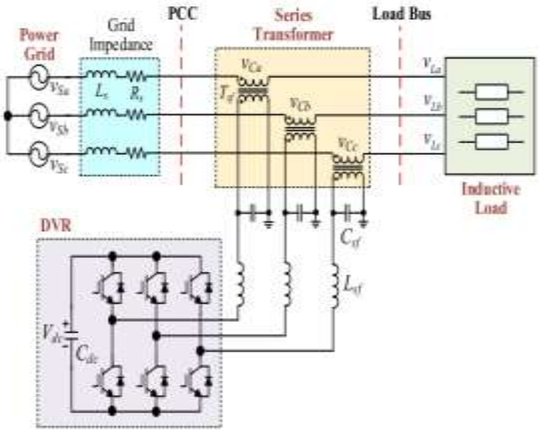

Fig 1. Dvr model connected to power grid

4. ANFIS-BASED DVR CONTROL STRATEGY

A. ANFIS Structure

The ANFIS controller integrates a Sugeno-type fuzzy inference system with a neural network learning algorithm. It consists of five layers:

1. **Fuzzification layer**
2. **Rule layer**
3. **Normalization layer**
4. **Defuzzification layer**
5. **Output layer**

The inputs to the ANFIS controller are:

- Voltage error $e(k) = V_{ref} - V_L$
- Change in voltage error $\Delta e(k)$

The output is the reference compensating voltage signal for the DVR inverter.

B. Control Algorithm

1. Measure three-phase supply and load voltages
2. Transform voltages into the synchronous reference frame (dq)
3. Compute voltage error and change in error
4. Process error signals through the ANFIS controller
5. Generate reference injection voltage
6. Produce gating signals using PWM technique

The adaptive learning capability enables the controller to update parameters online, improving dynamic response under varying disturbances.

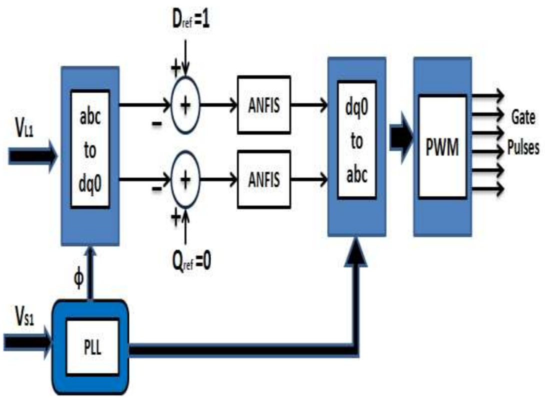

Fig 2. Anfis controller model for dvr application

5. VOLTAGE DISTURBANCE COMPENSATION MECHANISM

A. Voltage Sag Compensation

During sag conditions, the DVR injects an in-phase voltage to restore the load voltage magnitude. The ANFIS controller ensures fast detection and accurate compensation with minimal overshoot.

B. Voltage Swell Compensation

For voltage swell events, the DVR injects a voltage in opposite phase to the supply voltage. The adaptive nature of ANFIS improves response time and stability.

C. Fault Condition Mitigation

During symmetrical and unsymmetrical faults, the DVR maintains load voltage continuity by dynamically adjusting injection voltage magnitude and phase, enhancing fault ride-through capability.

6. POWER QUALITY ENHANCEMENT

In addition to voltage regulation, the proposed ANFIS-controlled DVR effectively mitigates harmonic distortion caused by nonlinear loads. The passive filter and intelligent control reduce switching harmonics, resulting in improved voltage waveform quality.

The Total Harmonic Distortion (THD) is calculated as:

$$THD = \frac{\sqrt{\sum_{n=2}^{\infty} V_n^2}}{V_1} \times 100\%$$

Simulation results show that the load voltage THD is significantly reduced and maintained within IEEE-519 standards.

7. SIMULATION RESULTS AND DISCUSSION

The proposed system is modeled and simulated in MATLAB/Simulink under the following scenarios:

- 30% voltage sag
- 25% voltage swell
- Single-line-to-ground and three-phase faults
- Nonlinear load conditions

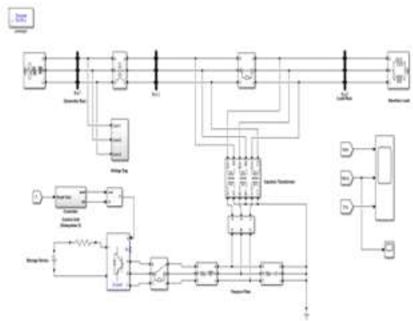

Fig 3. Simulation diagram of the sytem.

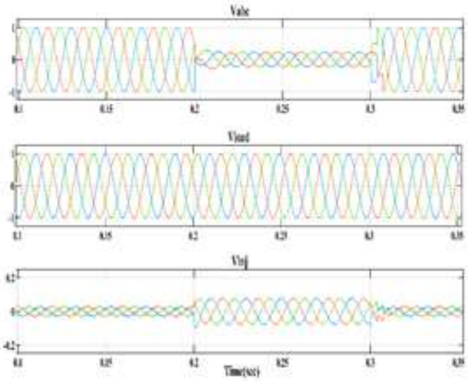

Fig 4. grid voltage, load voltage and dvr injected voltage in sag condition

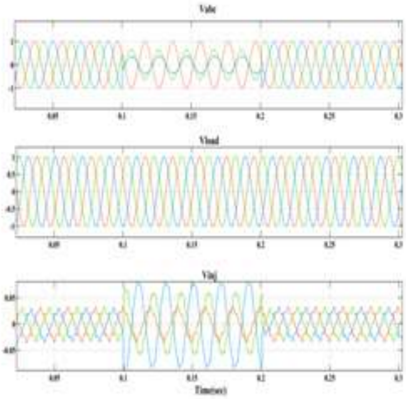

Fig 5. grid voltage load voltage and dvr injected voltage in swell condition

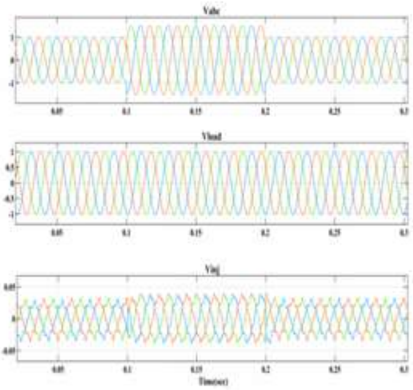

Fig 6. grid voltage load voltage and dvr injected voltage in fault condition

Key performance metrics include:

- Voltage recovery time
- Peak overshoot
- Steady-state error
- THD level

THD Results :

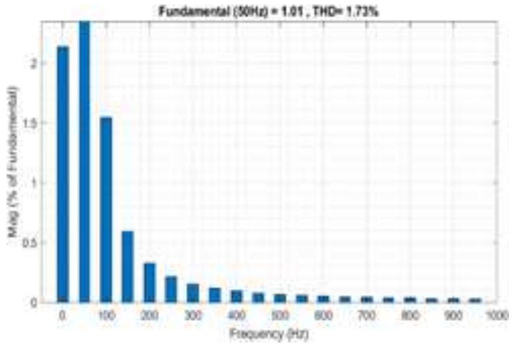

Fig 7. %THD value during sag using ANFIS controller.

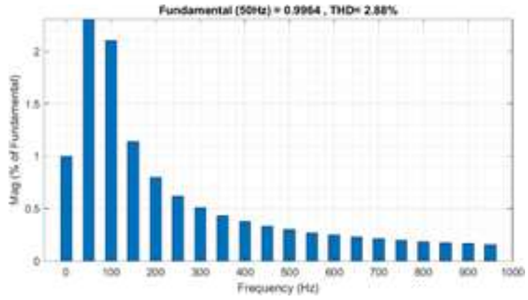

Fig 8. %THD value during swell using ANFIS controller.

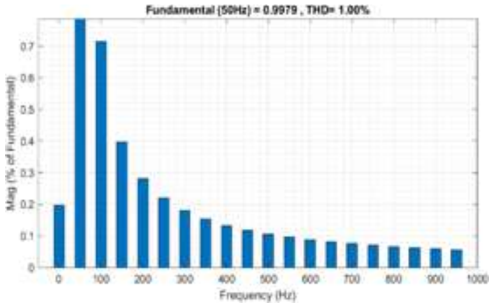

Fig 9. %THD value during fault using ANFIS controller.

The ANFIS-controlled DVR demonstrates faster response, improved voltage regulation, and lower THD compared with conventional PI, fuzzy and ANN controllers.

Comparision Table :

Controller Type	THD% During sag	THD% During swell	THD% During fault
ANN Controller	1.83	1.29	3.26
ANFIS Controller	1.74	1.00	2.88

8. CONCLUSION

This paper presented an **ANFIS -controlled Dynamic Voltage Restorer** for voltage disturbance compensation and power quality enhancement in distribution systems. The proposed intelligent controller effectively mitigates voltage sag, swell, harmonics, and fault-induced disturbances. Simulation results confirm superior performance in terms of dynamic response, robustness, and harmonic reduction. The ANFIS-based DVR is a promising solution for modern power distribution networks with high penetration of nonlinear and sensitive loads.

Future Scope

- Hardware implementation using DSP/FPGA
- Integration with renewable energy-based DC-link sources
- Real-time adaptive learning under microgrid environments

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