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Research

A HIGH PERFORMANCE FUZZY INFERENCE CONTROLLED ADAPTIVE DVR FOR HARMONIC AND VOLTAGE VARIATIONS MITIGATION

Dr. S. Gopal Reddy
Associate Professor
Department of EEE
Jyothishmathi Institute of Technology & Science, Karimnagar.
sanepalle.gopal1980@gmail.com

Ushana Swathi
Electrical & Electronics Engg.
Jyothishmathi Institute of Technology & Science, Karimnagar.
ajayushana@gmail.com

Todenga Vinay
Electrical & Electronics Engg.
Jyothishmathi Institute of Technology & Science, Karimnagar.
thodengavinay@gmail.com

Maheshuni Nikhil
Electrical & Electronics Engg.
Jyothishmathi Institute of Technology & Science, Karimnagar.
nikhilmaheshuni@gmail.com

Pogula Rakesh
Electrical & Electronics Engg.
Jyothishmathi Institute of Technology & Science, Karimnagar.
pogularakesh1437@gmail.com

Abstract

Power quality disturbances such as voltage sags, swells, and harmonics significantly affect the reliable operation of sensitive electrical loads in modern distribution systems. Dynamic Voltage Restorers (DVRs) are widely employed as effective custom power devices to mitigate these disturbances. However, the performance of DVRs largely depends on the employed control strategy. Conventional PI controllers suffer from poor adaptability under nonlinear and varying system conditions. This paper proposes a **fuzzy controller–based Dynamic Voltage Restorer** to enhance power quality in distribution networks. The fuzzy controller dynamically regulates the DVR injection voltage to compensate voltage disturbances effectively. The proposed system is modeled and simulated in MATLAB/Simulink, and its performance is evaluated under various power quality disturbances. Simulation results demonstrate that the fuzzy-controlled DVR provides faster dynamic response, reduced voltage distortion, and improved compensation capability compared with conventional PI-controlled DVR systems.

Keywords— Dynamic Voltage Restorer (DVR), Fuzzy Logic Controller, Power Quality, Voltage Sag, Voltage Swell, Harmonic Mitigation.

1. INTRODUCTION

The increasing use of sensitive electronic equipment and nonlinear loads in modern power distribution systems has intensified power quality issues such as voltage sags, swells, harmonics, and flicker. These disturbances can lead to malfunction, reduced lifespan, or complete shutdown of critical loads, resulting in significant economic losses.

Custom power devices based on power electronic converters have emerged as effective solutions for mitigating power quality problems. Among them, the Dynamic Voltage Restorer (DVR) is one of the most efficient devices for series compensation of voltage disturbances. A DVR injects a controlled voltage in series with the supply to maintain the load voltage at its nominal value during disturbances.

Conventional DVR control strategies primarily employ PI controllers, which require accurate system modeling and constant parameter tuning. Due to system nonlinearities and operating condition variations, PI controllers often fail to deliver optimal performance. To overcome these limitations, intelligent control techniques such as fuzzy logic controllers (FLCs) have gained considerable attention.

This paper presents a **fuzzy controller–based DVR** for improving power quality by effectively mitigating voltage sags, swells, and harmonic distortions.

2. DYNAMIC VOLTAGE RESTORER CONFIGURATION

The DVR is connected in series between the distribution supply and sensitive load. The main components of the DVR include:

- Voltage Source Inverter (VSI)
- Injection transformer
- Energy storage unit
- Passive LC filter

During voltage disturbances, the DVR injects an appropriate compensating voltage to restore the load voltage to its rated value.

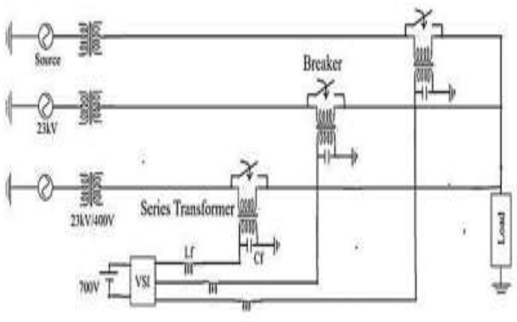

Fig 1. Dvr model

3. MATHEMATICAL MODELLING OF DVR

The DVR operation is based on the injection of a compensating voltage V_{inj} such that:

$$V_{load} = V_{source} + V_{inj}$$

The control algorithm calculates the reference injection voltage using a synchronous reference frame (d–q) transformation. This approach enables effective decoupling of active and reactive components, facilitating precise voltage compensation.

3.1. DVR Mathematical Modeling

The Dynamic Voltage Restorer (DVR) is a series-connected compensator that injects a voltage to maintain the load voltage at its nominal value.

3.1.1 Voltage Injection Principle

The DVR injected voltage is given by:

$$\mathbf{V}_{\text{inj}} = \mathbf{V}_{\text{load}}^{*} - \mathbf{V}_{\text{source}}$$

where

- $\mathbf{V}_{\text{inj}}$= DVR injected voltage
- $\mathbf{V}_{\text{load}}^{*}$= reference load voltage
- $\mathbf{V}_{\text{source}}$= supply voltage

Thus, the load voltage is maintained as:

$$\mathbf{V}_{\text{load}} = \mathbf{V}_{\text{source}} + \mathbf{V}_{\text{inj}}$$

3.2. Synchronous Reference Frame (SRF) Control

To decouple control variables, the three-phase voltages are transformed into the rotating $dq0$frame.

3.2.1 Clarke Transformation

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}$$

3.2.2 Park Transformation

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix}$$

where $\theta$is obtained from the Phase-Locked Loop (PLL).

3.3. Voltage Error Computation

The DVR control is based on voltage error signals:

$$e_d = v_d^* - v_d$$
$$e_q = v_q^* - v_q$$

3.4. Reference Voltage Generation

The reference DVR injection voltage in dqframe:

$$v_{d,\text{inj}}^* = u_d$$
$$v_{q,\text{inj}}^* = u_q$$

Inverse Park transformation is applied to generate three-phase reference voltages:

$$\begin{bmatrix} v_a^* \\ v_b^* \\ v_c^* \end{bmatrix} = T_{dq}^{-1} \begin{bmatrix} v_{d,\mathrm{inj}}^* \\ v_{q,\mathrm{inj}}^* \end{bmatrix}$$

These signals are fed to the PWM generator for VSI switching.

4.FUZZY LOGIC CONTROLLER DESIGN

4.1 Structure of the Fuzzy Controller

The fuzzy logic controller consists of:

- Two inputs: voltage error and change in voltage error
- One output: modulation index or reference control signal

Triangular membership functions are used for simplicity, and a Mamdani-type inference system is employed.

4.2 Rule Base and Inference Mechanism

A set of linguistic rules is formulated based on expert knowledge to generate the control action. The defuzzification process uses the centroid method to produce a crisp output signal for inverter control.

4.3 Advantages of Fuzzy Control

- No requirement for precise mathematical modeling
- Robust performance under nonlinear and uncertain conditions
- Faster dynamic response compared with PI control

4.4 Fuzzy Logic Controller (FLC) Formulation

4.4.1 Inputs and Output

- **Inputs**:
  - Voltage error e
  - Change in voltage error Δe
- **Output**:
  - Control signal u(modulation index or reference voltage)

4.4.2 Fuzzy Rule Base

Typical rule structure:

IF $e$is *Negative Large* AND $\Delta e$is *Negative Small*

THEN output is *Positive Medium*

The defuzzified output is obtained using the centroid method:

$$u = \frac{\sum_{i=1}^{N} \mu_i z_i}{\sum_{i=1}^{N} \mu_i}$$

where

- μ_i= firing strength of rule i
- z_i= rule output

The fuzzy controller uses:

- Error e
- Change in error Δe

$$\Delta e(k) = e(k) - e(k-1)$$

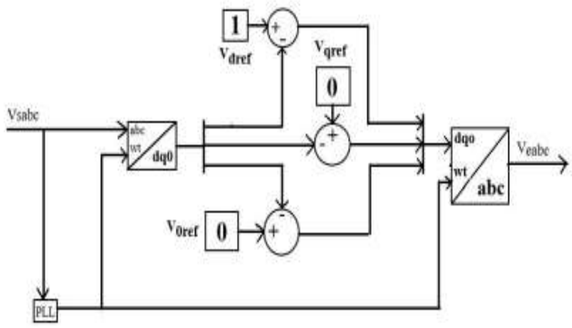

Fig 2. Control methodology

5. SIMULATION RESULTS AND DISCUSSION

The proposed fuzzy-controlled DVR is simulated in MATLAB/Simulink under various operating conditions.

5.1 Voltage Sag Compensation

During voltage sag events, the DVR rapidly injects the required compensating voltage, maintaining the load voltage close to its nominal value.

5.2 Voltage Swell Compensation

The fuzzy controller effectively suppresses voltage swells by injecting a voltage with appropriate magnitude and phase opposition.

5.3 Harmonic Mitigation

The DVR significantly reduces harmonic distortion in the load voltage, maintaining Total Harmonic Distortion (THD) within IEEE-519 limits.

5.4 Comparative Performance

Compared to the PI-controlled DVR, the fuzzy-controlled DVR exhibits:

- Faster settling time
- Reduced overshoot

- Improved voltage regulation

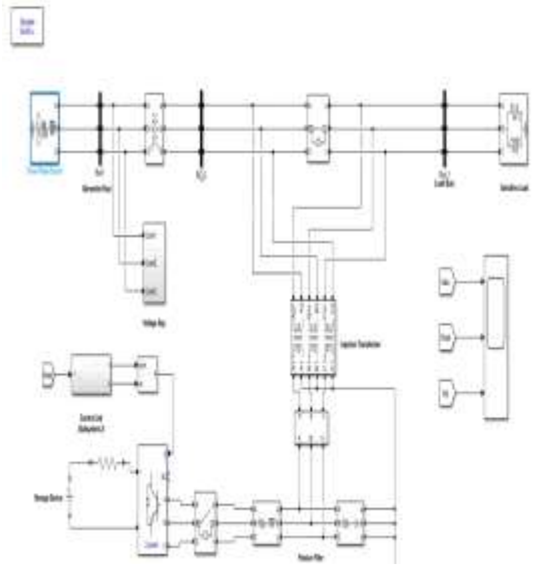

Fig 3. simulation circuit of DVR

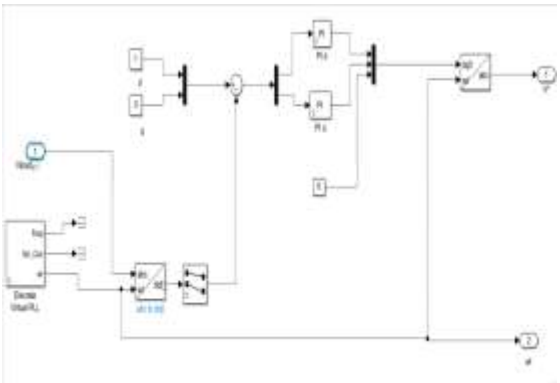

Fig 4. Pi based dvr controller circuit

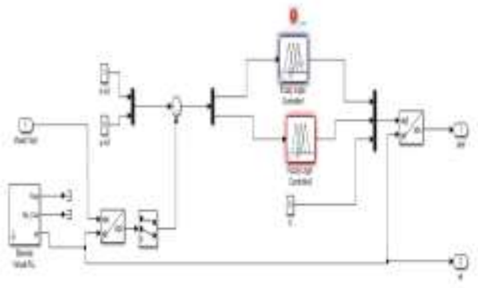

Fig 5. Fuzzy based dvr controller circuit

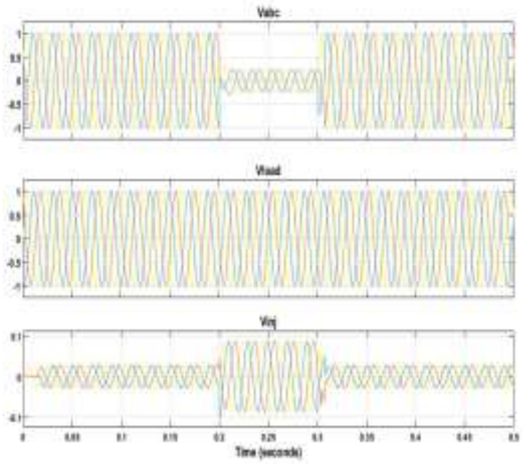

Fig 6. grid voltage load voltage and dvr injected voltage in sag condition

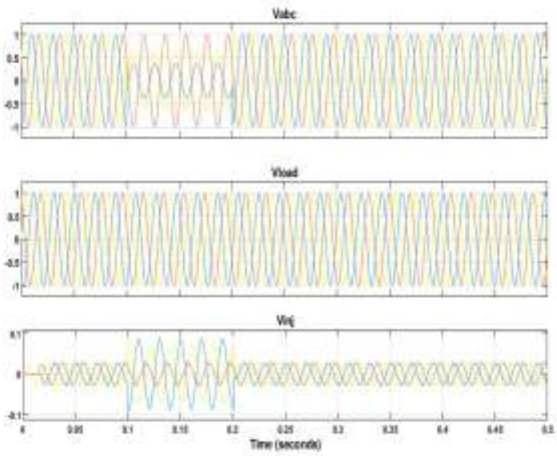

Fig 7. grid voltage load voltage and dvr injected voltage in fault condition

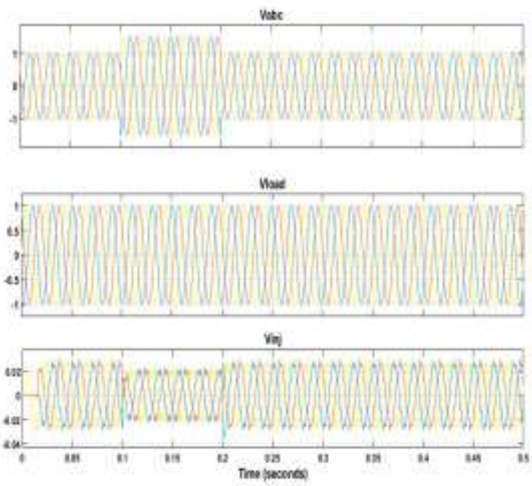

Fig 8. grid voltage load voltage and dvr injected voltage in swell condition

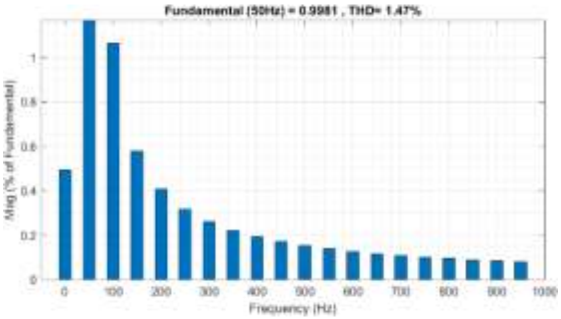

Fig 9. %THD value during swell using fuzzy controller.

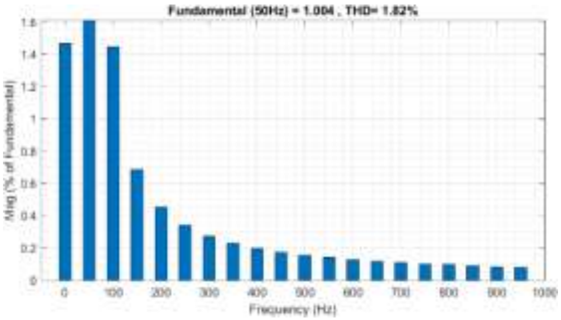

Fig 10. %THD value during sag using fuzzy controller.

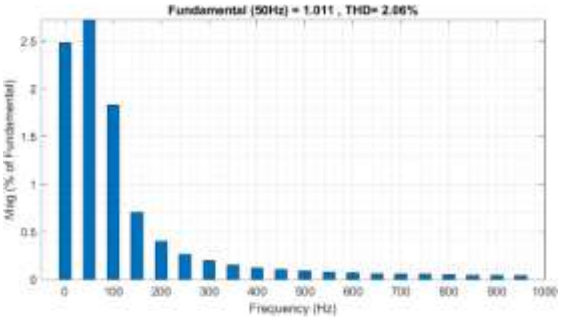

Fig 11. %THD value during fault using fuzzy controller.

COMPARISION TABLE

CONDITION	PI THD%	FUZZY THD%
SAG	4.18%	1.82%
SWELL	2.32%	1.47%
FAULT	4.37%	2.06%

6. CONCLUSION

A fuzzy controller–based Dynamic Voltage Restorer for power quality improvement has been presented in this paper. The proposed approach effectively mitigates voltage sags, swells, and harmonics under diverse operating conditions. Simulation results validate the superiority of the fuzzy-controlled DVR over conventional PI-based methods in terms of dynamic response and robustness. The proposed system offers a reliable and intelligent solution for power quality enhancement in modern distribution networks.

Future Scope

- Extension to ANFIS or adaptive fuzzy control
- Hardware implementation using DSP or FPGA
- Integration with renewable energy–based microgrids

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