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Power Quality Improvement: A Fuzzy Logic Approach to DVR-Based Voltage Sag Mitigation

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ABSTRACT

Voltage sags, characterized by temporary drops in voltage levels, are among the most prevalent and disruptive power quality disturbances in modern electrical systems. These events, caused by factors such as short circuits, sudden load changes, and network faults, pose significant risks to sensitive equipment and industrial processes, leading to operational disruptions and financial losses. Ensuring stable voltage levels is critical for maintaining high power quality standards and uninterrupted operations in today's interconnected and digital environments. Dynamic Voltage Restorers (DVRs) have emerged as effective solutions for mitigating voltage sags by injecting compensatory voltage to stabilize the load-side supply. However, conventional DVR controllers, like proportional-integral (PI) and proportional-integral-derivative (PID) controllers, often face challenges in adapting to dynamic and complex sag conditions. To address these limitations, this study proposes a DVR system enhanced by a fuzzy logic controller (FLC). Fuzzy logic offers a rule-based, adaptive approach, enabling the DVR to respond effectively to varying sag scenarios and improve voltage regulation. Presented FLC is working in different voltage sag ranges in an effective manner. Proposed FLC is adequate, effective and efficient one as it provide required level of voltages by operating in 3 modes (Low compensation, medium compensation and high compensation). This ensure the electric power saving too and hence more efficient than other controller. The research investigates the performance of the FLC-enhanced DVR in mitigating voltage sags under diverse fault conditions.

Keywords: Power quality; Voltage sag; Short circuit fault; Dynamic voltage restorer; Sag mitigation; Fuzzy logic controller.

I. INTRODUCTION

Voltage sags, characterized by a temporary drop in voltage levels, are among the most common and disruptive power quality disturbances in electrical power systems [1-2]. These events can be caused by a variety of factors, including short circuits, sudden load changes, and faults within the network. Voltage sags can lead to significant operational issues, particularly for sensitive electronic equipment, industrial processes, and critical systems that require stable power for reliable performance. As such, addressing voltage sags is crucial for maintaining high power quality standards and ensuring uninterrupted operations. In today's increasingly interconnected and digital world, maintaining high power quality is more essential than ever. Industries and facilities rely on steady voltage levels to prevent equipment malfunctions, downtime, and potential financial losses. Voltage sags not only threaten the stability of power systems but also impose substantial costs due to equipment damage, production loss, and system inefficiencies [10].

To mitigate voltage sags, various solutions have been developed, with Dynamic Voltage Restorers (DVRs) being among the most effective. DVRs inject voltage into the system to counteract sags, thereby maintaining voltage stability at the load side [3-4], [7]. Traditional DVR controllers, such as proportional-integral (PI) and proportional-integral-derivative (PID) controllers, have been widely used due to their simplicity and effectiveness under predictable conditions [7]. However, these conventional control methods often struggle with adaptability, especially in dynamic and complex environments where the characteristics of voltage sags may vary significantly. In this study, we propose a DVR system enhanced by a fuzzy logic controller (FLC) to overcome the limitations of traditional control approaches. Fuzzy logic offers a rule-based, adaptive approach that allows the controller to make flexible, accurate decisions under uncertain and changing conditions [5]. By incorporating fuzzy logic, the DVR can more effectively respond to varying sag scenarios, leading to improved voltage regulation and power quality.

This research aims to explore the effectiveness of a fuzzy logic-controlled DVR in mitigating voltage sags and enhancing overall power quality. Specifically, we investigate the DVR's performance in restoring voltage levels during different fault conditions and examine its ability to maintain system stability across load changes. Presented FLC is working in different voltage sag ranges in an effective manner. Proposed FLC is adequate, effective and efficient one as it provide required level of voltages by operating in 3 modes (Low compensation, medium compensation and high compensation). This ensure the electric power saving too and hence more efficient than other controller. By demonstrating the advantages of using a fuzzy logic approach in DVR systems, this study provides insights into improved methods for power quality enhancement, ultimately contributing to more reliable and resilient power networks.

II. BACKGROUN AND RELATED WORKS

Voltage sags, defined as short-duration drops in voltage levels, are significant power quality issues that can severely disrupt industrial and commercial operations [6]. These events, often caused by system faults, motor startups, or sudden load changes, can lead to equipment malfunctions, process interruptions, and increased maintenance costs [9]. As a result, voltage sag mitigation has become a priority for maintaining power quality and ensuring the uninterrupted operation of sensitive equipment.

A. Dynamic Voltage Restorer (DVR) Technology

Dynamic Voltage Restorers (DVRs) are widely recognized as effective solutions for addressing voltage sags in power systems. DVRs are customarily connected in series with the power distribution system and function by injecting a compensating voltage to restore the voltage level at the load side [3-4]. A typical DVR consists of components such as a voltage source inverter (VSI), an energy storage device, and a coupling transformer [8]. When a sag is detected, the DVR rapidly injects voltage in-phase with the existing supply, thereby counteracting the sag and stabilizing voltage at the load end. Due to their fast response times and efficient operation, DVRs have become a preferred choice for enhancing power quality.

B. Control Techniques for DVR Systems

Effective control of DVR systems is essential to ensure timely and accurate voltage compensation. Traditional control methods, including proportional-integral (PI) and proportional-integral-derivative (PID) controllers, have been extensively used in DVR applications. While these conventional controllers are straightforward to implement and perform well under steady-state conditions, they often struggle in dynamic or unpredictable environments where voltage sags vary in duration, magnitude, and phase. These limitations have led to an exploration of more adaptive and robust control techniques, with a focus on enhancing DVR performance in real-world scenarios.

C. Introduction to Fuzzy Logic Control

Fuzzy logic control (FLC) is an advanced control approach that mimics human reasoning by making decisions based on a set of rules rather than relying solely on mathematical models. Unlike traditional control methods, FLC can handle imprecise inputs, allowing for more flexible and adaptive control in complex systems. Fuzzy logic is particularly suited for applications where the system dynamics are challenging to model accurately, as it enables controllers to adapt to changing conditions by using a rule-based structure. This adaptability makes FLC an attractive solution for DVR control, especially in power systems where voltage sag characteristics may fluctuate widely.

D. Related Research in Fuzzy Logic-Controlled DVR Systems

Recent research has highlighted the potential of fuzzy logic-controlled DVR systems in power quality applications. Studies have demonstrated that FLC-equipped DVRs can respond more effectively to varying sag scenarios, achieving quicker voltage restoration and reducing the overshoot commonly associated with conventional controllers. In comparison to PI or PID controllers, FLC offers a more robust response to both small and large sags and has shown to improve transient stability during voltage disturbances [5]. Additionally, fuzzy logic's ability to manage non-linearities and uncertainties makes it a reliable choice for ensuring stable power quality in dynamic and unpredictable power system environments.

Several works have investigated hybrid approaches, combining fuzzy logic with other control methods to further optimize DVR performance. For example, adaptive fuzzy controllers and neural network-based fuzzy controllers have been explored to enhance DVR response times and efficiency. These studies underscore the versatility and effectiveness of fuzzy logic control in managing voltage sags and stabilizing power quality, particularly in cases where traditional methods fall short.

D. *Scope of the Present Study*

Building upon this foundation, the current study focuses on the design and implementation of a fuzzy logic-controlled DVR system specifically tailored for voltage sag mitigation. By leveraging fuzzy logic, we aim to overcome the adaptability limitations of traditional DVR control methods and demonstrate how this approach can improve voltage sag mitigation under varied and challenging conditions. This work contributes to the growing body of research on advanced control techniques in power quality management, offering a practical solution to enhance voltage stability and ensure reliable power system performance.

III. SYSTEM MODEL AND DESIGN OF FUZZY LOGIC CONTROLLERWORKS

A. *Power System Model*

The power system model in this study represents a typical distribution network that includes a source, transmission lines, and various load types sensitive to voltage disturbances. Voltage sags are simulated under different fault conditions, such as single-phase and three-phase faults, and sudden load variations. The primary objective of the system model is to create scenarios where voltage sags occur, allowing for a realistic assessment of the Dynamic Voltage Restorer (DVR) and its control mechanism.

The DVR is placed in series with the load and connected through a coupling transformer, which facilitates the injection of compensating voltage. An energy storage unit (e.g., a capacitor bank or battery) supplies power to the DVR's inverter, allowing for the rapid response needed to correct voltage sags. The power system model at where research is done is shown in Fig. 1.

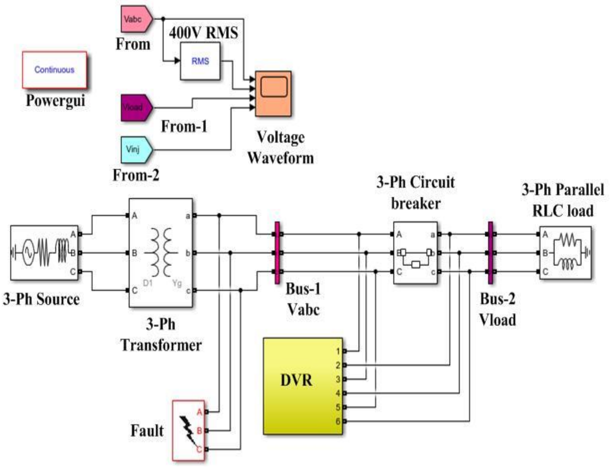

Fig. 1. Power system model

B. *Dynamic Voltage Restorer (DVR) Configuration*

The DVR system used in this study consists of:

- Voltage Source Inverter (VSI): Converts DC power from the energy storage unit into AC power, allowing the DVR to inject the required compensating voltage.
- Energy Storage: Provides the necessary power during sag events, enabling the DVR to maintain stable voltage at the load. Common storage options include super capacitors or batteries.
- Coupling Transformer: Connects the DVR to the distribution system in series and scales the injected voltage to match the system requirements.

The DVR detects voltage sags by monitoring the incoming supply voltage. When a sag occurs, the control system activates the VSI to inject a compensating voltage equal to the difference between the desired and actual load-side voltage, ensuring minimal disturbance to the sensitive loads. The simulink model of DVR is shown Fig. 2.

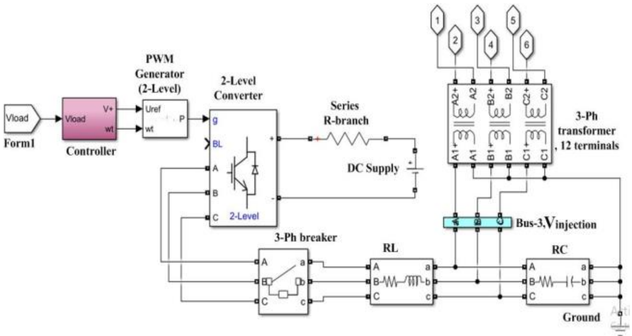

Fig. 2. Simulink model of DVR

C. *Design of Fuzzy Logic Controller (FLC)*

The Fuzzy Logic Controller (FLC) is the core of the proposed DVR control strategy. Unlike traditional PI or PID controllers, which rely on fixed mathematical models, the FLC uses a rule-based approach to adaptively handle varying sag conditions. This adaptability allows the FLC to respond more efficiently to fluctuations in voltage levels, providing a robust solution for voltage sag mitigation. The proposed fuzzy controller is shown Fig. 3.

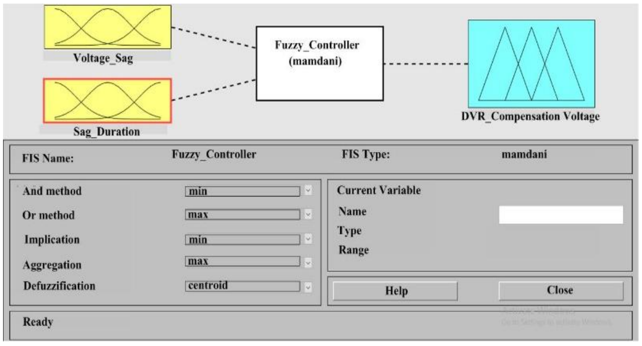

Fig. 3. Proposed fuzzy controller

The proposed fuzzy controller takes two input and produces one output. One input is "voltage sag", another is "sag duration" and the output is "DVR compensation voltage".

C.1 Inputs and Outputs of the Fuzzy Logic Controller

The FLC takes two main inputs that are voltage sag and voltage sag duration. The voltage sag is categorized into 8 sub-categories. These are voltage sag low-1, low-2, medium-1, medium-2, high-1, high-2, very high-1 and very high-2. The voltage sag duration is categorized into 3 sub-categories. These are low, medium and long sag duration. These categories are shown in Table I and Table II.

C.2 Fuzzification

In the fuzzification stage, the input variables (voltage error and rate of change of voltage error) are transformed into linguistic variables, such as Low, Medium, and High. Each linguistic variable is represented by a membership function, typically in triangular or trapezoidal shapes, to define its degree of membership in the fuzzy set. In this study triangular membership function is taken. This step allows the FLC to interpret and process imprecise inputs, making the controller adaptable to a wide range of voltage sag conditions.

C.3. Rule Base and Inference Mechanism

The FLC relies on a rule base, which consists of a set of IF-THEN rules that define the control action based on the fuzzy input variables. The rules are listed as shown below and also shown in Table I. Categories of sag and its voltage range is shown in Table II.

- Rule 1: If sag magnitude category is low-1 and its duration is low then high compensation (HC) is needed.
- Rule 6: If sag magnitude category is low-2 and its duration is long then HC is needed..
- Rule 24: If sag magnitude category is very high-2 and its duration is long then low compensation (LC) is needed.

TABLE I

FUZZY RULE OF PROPOSED DVR

		Sag duration (Sec)		
		Low	Medium	Long
Sag magnitude (p.u.)	Low-1	HC	HC	HC
	Low-2	HC	HC	HC
	Medium-1	MC	HC	HC
	Medium-2	MC	HC	HC
	High-1	LC	MC	HC
	High-2	LC	MC	HC
	Very High-1	None	None	LC
	Very High-2	None	None	LC

TABLE II
CATEGORY OF SAG AND ITS MAGNITUDE RANGE

Category of Sag magnitude	Sag magnitude
Low-1	0.1-0.2 p.u.
Low-2	0.2-0.3 p.u.
Medium-1	0.3-0.4 p.u.
Medium-2	0.4-0.5 p.u.
High-1	0.5-0.6 p.u.
High-2	0.6-0.7 p.u.
Very High-1	0.7-0.8 p.u.
Very High-2	0.8-0.9 p.u.

The rule base is designed to provide appropriate responses for different combinations of input conditions, ensuring a quick and stable recovery from voltage sags. The inference mechanism interprets these rules, determining the strength of each applicable rule based on the membership values of the input variables.

C.4 Defuzzification

Once the inference mechanism processes the rules, the resulting fuzzy outputs are converted back into a crisp value through a defuzzification process. In this study, centroid defuzzification methods is used. The resulting crisp output value dictates the control signal applied to the VSI, specifying the exact amount of voltage compensation required to mitigate the sag.

C.5 Comparison with Traditional Control Methods

Traditional DVR controllers, such as PI and PID controllers, have fixed gain parameters, making them less responsive to rapid or unexpected changes in sag characteristics. In contrast, the FLC adapts in real-time by interpreting linguistic variables and applying corresponding control rules, making it more versatile and capable of handling non-linearities. This adaptability leads to faster voltage restoration, reduced overshoot, and improved stability during transient conditions.

IV. RESULTS and DISCUSSIONS

The simulation result is shown in Fig. 4, Fig. 5. Fig. 6 and Fig. 7. The voltage waveform associated to symmetrical fault is shown Fig.4. Similarly, voltage waveform associated to single line to ground fault (SLGF), double line to ground fault (DLGF) and line to line fault (LLF) are shown in Fig. 5. Fig. 6 and Fig. 7 respectively.

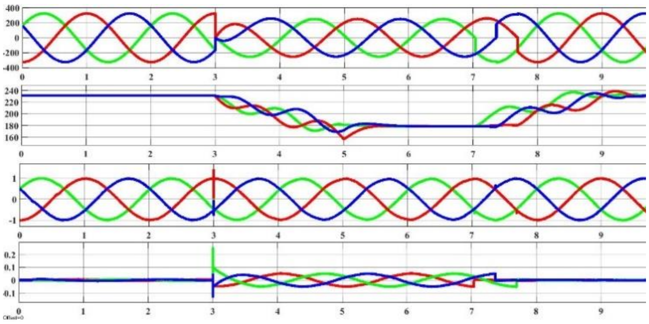

Fig. 4. Voltage waveform associated to symmetrical fault.

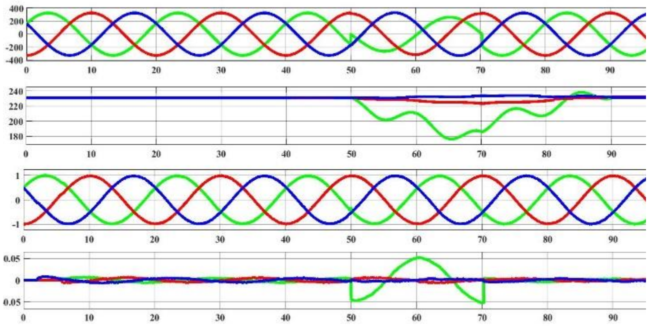

Fig. 5. Voltage waveform associated to single line to ground fault.

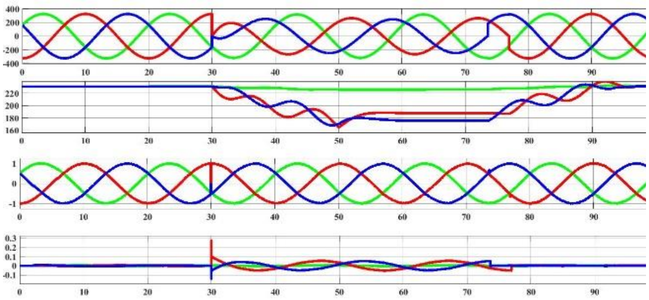

Fig. 6. Voltage waveform associated to double line to ground fault.

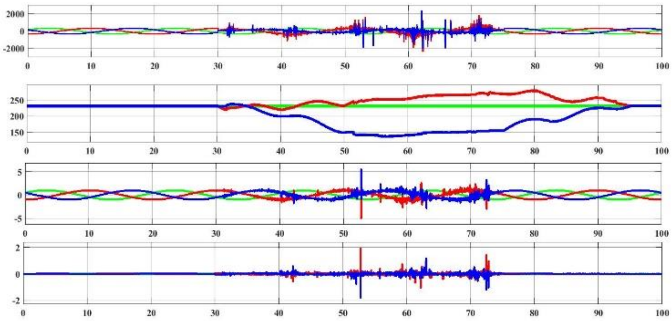

Fig. 7. Voltage waveform associated to single line to line fault.

In each figure, 4 sub figures are there. First sub-figure indicate 3-phase load voltage waveform along with existence of fault, RMS voltage waveforms of associated fault, third is post fault load voltage waveform and the four is injection voltage contributed by DVR.

IV. CONCLUSION

Voltage sags are one of the most disruptive power quality issues, impacting the stability and reliability of modern electrical systems. Dynamic Voltage Restorers (DVRs) have proven to be effective solutions for mitigating voltage sags; however, the performance of conventional controllers like PI and PID can be limited under dynamic and unpredictable conditions. This study demonstrates the potential of a fuzzy logic controller (FLC) as a robust alternative for enhancing the performance of DVR systems.

The fuzzy logic approach introduces adaptability and precision in sag mitigation by leveraging rule-based decision-making under varying conditions. Through comprehensive analysis and simulations, the FLC-enhanced DVR exhibited superior performance in restoring voltage levels, maintaining system stability during load changes, and ensuring transient stability under diverse fault scenarios. These results highlight the effectiveness of fuzzy logic in addressing the limitations of traditional control methods, providing a significant improvement in power quality. By integrating fuzzy logic control into DVR systems, this research contributes to advancing power quality enhancement strategies and supports the development of more resilient and efficient electrical networks. Future work could explore further optimization of fuzzy logic systems and their integration with other advanced control techniques for broader applications in power systems.

Ethical Statements: This paper is not submitted to any other conferences or journal/Proceedings for publications.

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