ROBUST POWER QUALITY ENHANCEMENT USING A FUZZY SLIDING MODE CONTROLLED FOUR-LEG DYNAMIC VOLTAGE RESTORER

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Abstract: Modern electrical power systems are more dependent on power quality than ever before due to the proliferation of sensitive electronic equipment, dispersed energy supplies, and nonlinear loads. Damage to sensitive loads can occur from a variety of power quality issues, including voltage dips and spikes, interruptions, imbalanced voltage, and harmonic distortion. To lessen the impact of voltage-related disruptions, the Dynamic Voltage Restorer (DVR) operates as an efficient power electronic compensator. When dealing with nonlinear system dynamics, parameter fluctuations, and quickly changing grid conditions, a traditional DVR controller's performance might degrade. of order to enhance the power quality of three-phase four-wire distribution systems, this research suggests a four-leg Dynamic Voltage Restorer using a robust fuzzy sliding mode control (FSMC) approach. The neutral current and three-phase compensating voltages may be independently controlled by the four-leg inverter, allowing for effective compensation of voltage imbalance and disruptions to the neutral. Sliding mode control's robustness and fuzzy logic's adaptive decision-making capabilities are brought together in the proposed fuzzy sliding mode controller. In order to decrease steady-state error and chattering, the fuzzy mechanism dynamically modifies the switching gain. Voltage sag, swell, harmonics, imbalance, and neutral voltage disturbances can be mitigated by the suggested controller, which is aimed at regulating the DVR output voltage. Under varying disturbance conditions, the system is modelled and studied in MATLAB/Simulink. In comparison to traditional control methods, the anticipated outcomes show better voltage restoration, lower total harmonic distortion, quicker dynamic response, and increased robustness.

Index Terms— The following terms are used to describe a three-phase four-wire system: dynamic voltage restorer, fuzzy sliding mode control, four-legged inverter, power quality, voltage sag, voltage swelling, and voltage harmonics.
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I. INTRODUCTION

Nonlinear loads, power electronic converters, dispersed generating systems, and sensitive industrial equipment are becoming more prevalent in today's electrical distribution systems, making power quality a big obstacle. Voltage fluctuations can cause serious problems for modern loads including automated industrial systems, computers, medical equipment, and programmable logic controllers (PLCs). Some sensitive equipment can be rendered inoperable or even shut down by even a brief voltage dip.

Distribution network power quality issues most often manifest as voltage sag, swell, interruption, harmonics, imbalance, and distortion of the neutral current. Some potential sources of these disruptions are short-circuit failures, the energization of transformers, the beginning of big motors, nonlinear loads, and abrupt changes in the operating parameters of the system.

One of the best power electronic devices for reducing power quality issues caused by voltage is the Dynamic Voltage Restorer. In order to keep the load voltage at the intended reference value, a DVR injects a compensating voltage and is often linked in series with the distribution feeder. The DVR's control approach is crucial to its success.

For DVR control, traditional PI controllers are commonly employed. The choice of controller gains, however, has a major impact on how well they work. The effectiveness of PI controllers can diminish when subjected to nonlinear operating circumstances and changes in parameters. The resilience of SMC is enhanced when model uncertainties and external disruptions are considered. But the high-frequency switching motion causes chattering in traditional SMC. Sliding mode controllers can have their switching gains adaptively modified using fuzzy logic control. Hence, a Fuzzy Sliding Mode Controller may merge the stability of SMC with the flexibility of fuzzy logic for adaptive control.

A four-leg DVR is suggested in this research as a control approach for a robust fuzzy sliding mode. Adapted to three-phase, four-wire distribution networks, the suggested system can mitigate neutral, balanced, and unbalanced voltage disturbances.

The main things this study accomplished are:

1. Enhancement of three-phase four-wire power quality through the development of a four-leg digital video recorder.
2. A reliable fuzzy sliding mode controller for regulating the voltage of DVRs has been designed.
3. Sliding mode switching gain adaptively adjusted with fuzzy logic.
4. Voltage sag, swell, harmonic, imbalance, and neutral disturbance compensation.
5. Stabilization error and chattering are reduced and dynamic responsiveness is improved.

II. PROPOSED SYSTEM CONFIGURATION

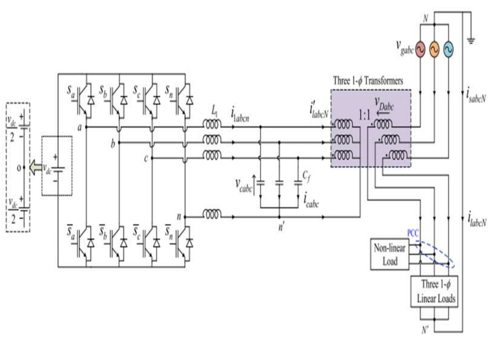

Fig. 1. Visual representation of the four-legged VSC-based DVR.

Here are the primary parts of the DVR system that has been proposed:

- utility source with three phases and four wires
- Transformerless series interface or series injection transformer
- a voltage source inverter with four legs
- DC-coupled capacitor
- The circuit for the filter
- Delicate burden
- A unit for measuring voltage and current
- Sliding mode controller with fuzzy logic

There are four inverter legs in the four-leg inverter. The third leg establishes a neutral current route that is separate from the first three, while the first three legs provide the three-phase compensating voltages. The fundamental tenet of compensation is stated as

$$□_□ = □_□ + □_{□□□}$$

when it comes to:

- $□_□$ the voltage that is ideal for the load,
- $□_□$stands for the voltage at the source, and
- $□_{□□□}$ is the DVR-injected compensation voltage.

Hence, the necessary voltage for the DVR is

$$□^*_{□□□} = □^*_□ - □_□$$

Where the reference load voltage is denoted by V_L^*.
For the four-leg inverter, the controller determines the voltage error and produces the necessary switching signals.

FOUR-LEG DVR TOPOLOGY

An extra degree of flexibility for neutral current compensation is provided by the four-leg inverter, which is why it is chosen.
It is not always possible to manipulate the neutral point separately in a traditional three-leg inverter. Because of this, compensating for imbalanced loads and zero-sequence components is not as easy. A distinct switching route for compensating for neutral current is provided by the fourth leg.
An inverter with four legs can make up for it:

- Disruptions to the positive-sequence voltage
- Voltage disturbances with a negative sequence
- components of voltage with zero sequence
- Voltage imbalance in the load
- Flow without direction
- A harmonic series with no zeros

Because of this, three-phase four-wire distribution systems are well-suited to the suggested topology.

MATHEMATICAL MODEL OF THE DVR

In order to inject the inverter's output voltage into the distribution system, it is filtered first. Here is an expression for the simplified filter equation:

$$□_□ \frac{□□_□}{□□} = □_{□□□} - □_{□□□} - □_□□_□$$

when it comes to:

- $□_□$ the inductance of the filter
- $□_□$ denotes the filter's resistance,
- $□_□$ that flows through the filter,
- $□_{□□□}$stands for the voltage output by the inverter, and
- $□_{□□□}$ is the voltage that counteracts it.

One definition of voltage error is

$$□_□ = □^*_□ - □_□$$

in which V_L is the real load voltage and V_L^* is the reference load voltage. Reducing the voltage error to zero is the controller's primary goal:

$$\lim_{□\to\infty} □_□(□) = 0$$

FUZZY SLIDING MODE CONTROL STRATEGY

A. Sliding Mode Control

One nonlinear control approach that offers resilience against system uncertainties and external disturbances is sliding mode control.
We define the sliding surface as

$$□ = \dot{□} + □□$$

when it comes to:

- □is the inaccuracy in voltage tracking,
- $\dot{□}$ is the product of the mistake's derivative and
- □ is the coefficient of a sliding surface that is positive.

An alternative representation of the control law is

$$□ = □_{□□} + □_{□□}$$

□□□is the switching control component and □□□is the comparable control component. Traditional notation for the switching component reads as

$$□_{□□} = □\mathrm{sgn}(□)$$

The switching gain is located at Ki.
Chattering may occur due to the discontinuous switching action, despite the robustness provided by this control law.

B. Fuzzy Gain Adaptation

In order to enhance dynamic performance and decrease chattering, a fuzzy logic controller dynamically modified the switching gain Kis.
Possible inputs to the fuzzy controller are:

- Smooth floor □
- Alteration to the running surfaceΔ□

What comes out of the fuzzy controller is:

- Optimized switching efficiency□

In this case, the general control legislation is

$$□ = □_{□□} + □(□, Δ□)\ \mathrm{sat}\left(\frac{□}{□}\right)$$

when it comes to:

- □(□, Δ□) stand as the gains from adaptive fuzzy switching,
- □is the thickness of the boundary layer, and
- sat(·) fulfills the criteria for saturation.

Minimizing chattering and discontinuity near the sliding surface is achieved by the saturation function.

FUZZY LOGIC CONTROLLER DESIGN

To find the right switching gain, the fuzzy controller looks at linguistic variables.
You may specify the input membership functions as:

- Low Value
- Devoid of Medium
- Decreasing Mini
- Nothing
- Pleasant, Minimal
- Moderately Positive (PM)
- Good, sizable,

The switching gain is generated by the fuzzy controller based on the sliding surface's magnitude and direction.

Sample Fuzzy Rule

The switching gain is large if si is positive and Δsis is positive and large.
IF both si and Δs are zero, then the switching advantage is insignificant.
The adaptive gain is highest when there are major disruptions and lowest when the system is running at steady state.

III. CONTROL STRUCTURE OF THE FOUR-LEG DVR

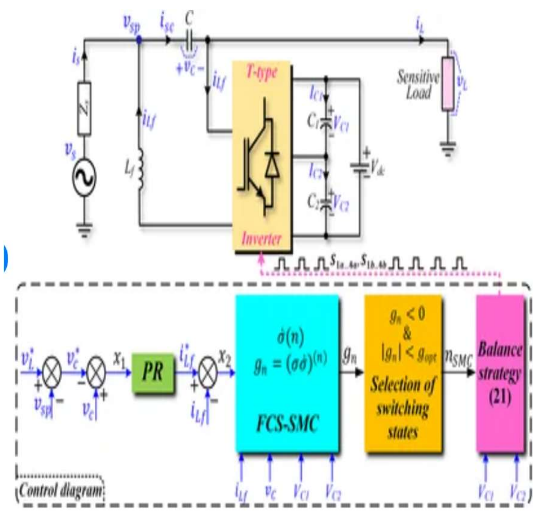

Fig. 2. Visual representation of the suggested SMC control mechanism
Here are the control phases that make up the proposed scheme:

Step 1: Voltage Measurement

Continuous measurements are taken of the source and load voltages.

Step 2: Reference Voltage Generation

From the nominal grid voltage, we may get the load voltage reference that you require.

Step 3: Voltage Error Calculation

One way to determine the voltage error is by

$$□_{□} = □^{*}_{□} - □_{□}$$

Step 4: Sliding Surface Generation

To create the sliding surface, the voltage error and its derivative are employed.

Step 5: Fuzzy Gain Adjustment

In response to changes in the sliding surface, the fuzzy controller determines the optimal switching gain.

Step 6: Control Signal Generation

The voltage reference for the inverter is generated by the fuzzy sliding mode controller.

Step 7: PWM Generation

The four-leg inverter's switching pulses are generated by comparing the reference voltage with a carrier signal.

Step 8: Voltage Injection

The DVR is responsible for injecting the distribution feeder with the necessary compensating voltage.

IV. POWER QUALITY COMPENSATION OPERATION

A. Voltage Sag Compensation

When the voltage from the source drops below its nominal value, it is called a voltage sag.
When the load voltage drops, the DVR steps in with a compensating voltage that is phase-locked with the source voltage.

$$\square_{\square\square\square} = \square_{\square}^{*} - \square_{\square}$$

In response to a drop in voltage, the suggested FSMC quickly produces the necessary compensatory voltage.

B. Voltage Swell Compensation

A voltage swell occurs when the voltage at the source goes up over its nominal value.
In order to lower the voltage applied to the load, the DVR produces a compensating voltage that is both large and phase-correct.

C. Voltage Harmonic Compensation

A nearly sinusoidal load voltage is maintained by the controller by detecting harmonic components in the source voltage and generating compensating voltage components.

D. Voltage Unbalance Compensation

The four-leg inverter allows for separate regulation of the phase voltages. Thus, the controller is able to keep the load voltage balanced and adjust for imbalances in the source voltage.

E. Neutral Voltage Compensation

A separate neutral route is provided by the fourth leg of the inverter. This allows for the correction of neutral current disturbances and zero-sequence voltage components.

REFERENCE FRAME CONSIDERATIONS

It is possible to apply the suggested controller in the natural absolute frame. The three-phase voltage variables are processed directly in the natural reference frame without the need for coordinate manipulations.
Using a natural reference frame has several benefits, such as:

- Processing phase quantities directly.
- Easy implementation for systems that are not harmonious.
- Effective compensation of zero-sequence components.
- Inverters with four legs work well.
- Complexity of computing decreased.

When controlling unbalanced or zero-sequence components separately is necessary in three-phase four-wire systems, the natural-frame control technique shines.

V. MATLAB/SIMULINK IMPLEMENTATION

Here is the MATLAB/Simulink representation of the suggested system: The system is tested under various voltage disturbance situations.

SIMULATION CASE STUDIES

Case 1: Voltage Sag

The source voltage is subjected to a voltage drop for a predetermined amount of time. Injecting the necessary compensating voltage, the proposed DVR identifies the disturbance.

Case 2: Voltage Swell

The source is subjected to a voltage surge.

Case 3: Harmonic Distortion

The source voltage becomes contaminated with harmonic components.

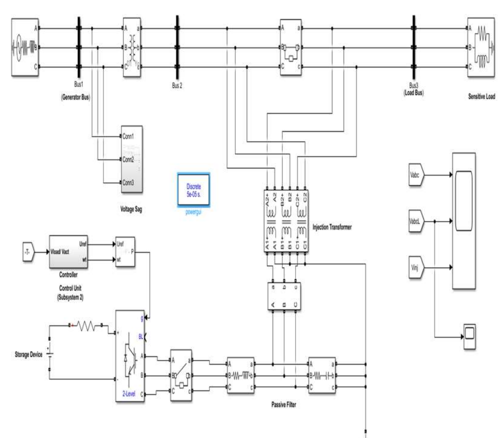

Fig 3: Model of the simulation circuit

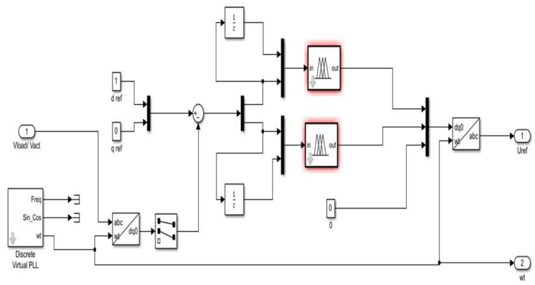

Fig 4. The control structure of a dvr that is based on Fast SMC.

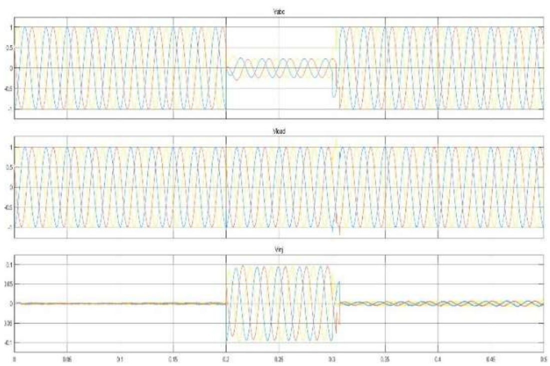

Fig 5. The voltages under sag conditions: grid voltage, load voltage, and dvr injected voltage.

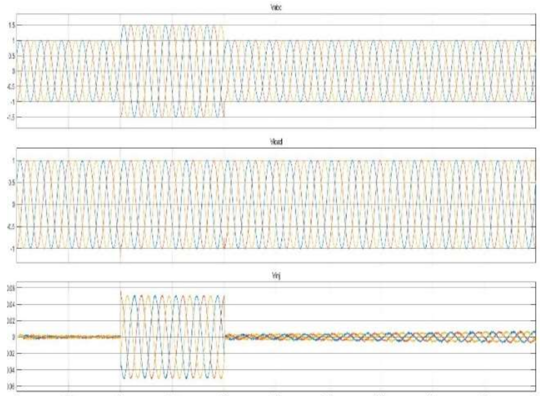

Fig 6. The voltages under swell conditions: grid voltage, load voltage, and dvr injected voltage.

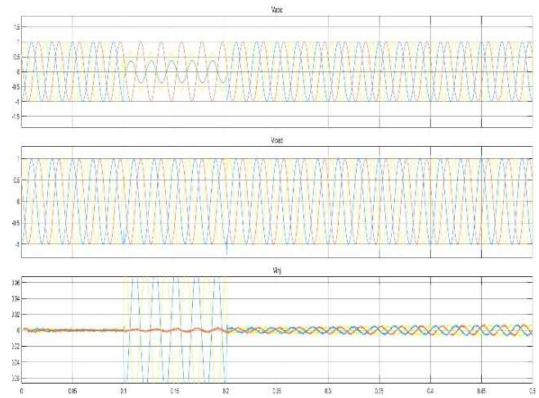

Fig 7. The voltages that are injected into the grid, load, and dvr in the event of a failure or harmonic injection.

PERFORMANCE EVALUATION

The following parameters can be used to assess the proposed controller's performance:

Voltage Error

$$\square_{\square} = \square^{*}_{\square} - \square_{\square}$$

Voltage regulation is improved when the voltage error is less.

Total Harmonic Distortion

$$\square\square\square = \frac{\sqrt{\square_2^2 + \square_3^2 + \cdots + \square_{\square}^2}}{\square_1} \times 100$$

with V_1 being the basic voltage component.

Voltage Sag Compensation Time

One way to measure the dynamic response is by looking at how long it takes for the DVR to get the load voltage back up and running after a disturbance.

.**Voltage Unbalance Factor**

Using the negative-sequence and positive-sequence components, one may evaluate the voltage imbalance factor:

$$\square\square\square = \frac{\square_2}{\square_1} \times 100$$

where V_1 is the voltage in the positive sequence and V_2 is the voltage in the negative sequence. With its suggested fuzzy sliding mode control, the four-leg DVR is able to accomplish

In the presence of strong disturbances, the controller can raise the switching gain using the fuzzy adaptation mechanism; in the vicinity of steady-state operation, the gain can be decreased. The trade-off between chattering reduction and resilience is improved by this.

ADVANTAGES OF THE PROPOSED SYSTEM

Among the many benefits of the suggested system are:

1. Secure functioning in the face of unknown system parameters.
2. Immediate correction for voltage instability.
3. Lessened tracking error at steady state.
4. Minimized chattering in sliding mode.
5. Swell and voltage sag compensation achieved.
6. Voltage harmonic compensation has been enhanced.
7. Compensation of unbalanced three-phase voltages.
8. Adjustment of the neutral current via the fourth leg of the inverter.
9. Enhanced responsiveness.
10. Work well with nonlinear and imbalanced loads.

VI. CONCLUSION

A four-leg Dynamic Voltage Restorer was developed to enhance power quality in three-phase four-wire distribution systems. In this study, a robust fuzzy sliding mode control approach for this device was provided. A four-leg voltage source inverter is employed by the suggested DVR to offer neutral component and three-phase voltage disturbance independent correction. Fuzzy sliding mode controllers combine traditional sliding mode controls' ruggedness with fuzzy logic's adaptive decision-making capabilities.

It is possible to compensate for voltage sag, swell, harmonics, imbalance, and neutral disturbances with the suggested control method. By adapting the sliding mode switching gain dynamically to the system's operating situation, the fuzzy logic method improves transient performance and reduces chattering. Additional options for zero-sequence and neutral current compensation are provided by the four-leg topology.

In comparison to traditional control methods, the suggested system should improve voltage regulation, restore voltage more quickly, decrease harmonic distortion, and make the system more resilient. Fuzzy sliding mode controlled four-leg DVRs are ideal for microgrids, advanced power quality applications, distribution systems that integrate renewable energy, and sensitive industrial loads.

Integration of the DVR with renewable power sources, energy storage systems based on batteries, adaptive neural-fuzzy controllers, model predictive control, and optimization-based parameter tuning techniques may be the subject of future research.

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