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Enhanced Grid Stability with ANN-Tuned Four-Leg Dynamic Voltage Restorer in Grid-Connected Systems

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Abstract: - Unbalanced loads are a typical source of power quality problems in contemporary grid-connected systems, including voltage sags and swells. Electrical system stability and performance can be severely compromised by these disruptions. This study aims to solve this problem by simulating a Dynamic Voltage Restorer (DVR) and an ANN-tuned Four-Leg Voltage Source Converter (VSC). By adding a neutral leg to the four-legged design, the DVR is better equipped to deal with imbalanced situations and direct current in a straight line. The key objective of this research is to enhance grid stability and improve power quality by mitigating voltage disturbances. The ANN-based control strategy dynamically adjusts the DVR's output, ensuring optimal compensation for voltage sags, swells, and harmonic distortion. Using Matlab/Simulink simulations, the proposed system's performance is compared to traditional control methods such as Sliding Mode Controllers (SMC), demonstrating superior results. Simulation results show that the ANN-tuned DVR significantly reduces Total Harmonic Distortion (THD) under various operating conditions, keeping THD well below the IEEE standard of 5%. The ANN-based control system outperforms conventional methods by improving load voltage stabilization and reducing voltage distortions. These findings suggest that the ANN-tuned four-leg DVR is a promising solution for enhancing power quality in grid-connected systems, with potential applications in future smart grids and renewable energy integration.

Keywords: Power Quality, Artificial Neural Network (ANN), Four-Leg Voltage Source Converter (VSC), Voltage Sag, Dynamic Voltage Restorer (DVR), Voltage Swell.

I. INTRODUCTION

Industrial and commercial applications rely on reliable and efficient electrical distribution systems, which are in turn made possible by high-quality power. Damage to sensitive machinery and financial losses can result from voltage fluctuations such as sags, swells, and imbalanced loads. Dynamic Voltage Restorers (DVRs) with three legs and three phases have been around for a long time for these kinds of problems. Nevertheless, these systems frequently have difficulties in handling unequal phase loads, which results in further voltage disruptions. Adding a neutral leg to a Four-Leg VSC-based DVR allows it to better handle unbalanced loads, which is a huge improvement in an industry where more dependable solutions are in high demand. Numerous studies have explored the use of DVRs to mitigate voltage sags and swells, focusing primarily on three-leg configurations. Research has shown that while three-leg DVRs can mitigate basic voltage issues, they lack the capability to address unbalanced loads efficiently, especially in systems with high neutral currents. Other control strategies, such as the SMC, have also been used for DVRs but exhibit limitations when dealing with complex, non-linear disturbances. The introduction of Four-Leg VSC-based DVRs, which provides a dedicated neutral path, has been shown to significantly improve the mitigation of unbalanced conditions. Although Four-Leg VSC-based DVRs present a promising solution, existing research lacks an efficient control strategy that can dynamically adapt to varying power conditions. Traditional control methods fall short in terms of handling complex, non-linear voltage disturbances. Thus, there is a need for a more advanced control mechanism that can offer real-time optimization and improved performance across different operating conditions. Incorporating a control method calibrated by an ANN into the Four-Leg DVR is the main focus of this study with the aim of improving grid stability. Compared to more traditional approaches, this ANN controller can more effectively manage voltage disturbances including sags, swells, and harmonics by dynamically adjusting the DVR's output. Through extensive simulations and comparisons with standard control systems, including the Sliding Mode Controller (SMC), the paper seeks to prove that the ANN-tuned DVR is superior. This research focuses on the performance of an ANN-tuned Four-Leg VSC-based DVR in mitigating power quality disturbances in grid-connected systems. It investigates both balanced and unbalanced voltage conditions, including sags, swells, and harmonic distortion, using Matlab/Simulink simulations. The study does not cover hardware implementations or other control methods beyond the ANN and SMC strategies.

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II. LITERATURE REVIEW

Previous research on three-leg DVRs has identified challenges in managing uneven phase loading and neutral current imbalances. Zhan et al. [1] and Sng et al. [2] discuss these limitations, particularly in systems with unbalanced loads. However, a robust solution for mitigating high neutral currents remains unresolved. Sliding-mode control techniques, such as those presented by Komurcugil and Biricik [3], offer promise in dynamic control but struggle with varying switching frequencies and complex non-linear disturbances. Adaptive control strategies are needed to improve real-time performance and stability in DVR operations. Ghavidel et al. [4] and Guo et al. [5] propose designs that reduce the number of components in DVRs, such as transformerless designs. However, issues persist in controlling DC-link voltage and optimizing capacity. The challenge remains to create efficient designs that minimize components without sacrificing performance. Studies by Wessels et al. [6] and Benali et al. [7] explore the integration of DVRs with renewable energy systems and their fault ride-through capabilities. Despite advancements, further research is needed to optimize DVR performance during symmetrical and asymmetrical grid faults, particularly in hybrid wind-PV systems. Zhan et al. [8] and Zhou et al. [9] introduced Four-Leg VSCs to address unbalanced loads, but refinement is necessary in current-sharing and voltage-quality enhancement. Current methods do not fully harness the potential of Four-Leg converters in large-scale applications like microgrids. The integration of BESS with DVRs, as explored by Jayaprakash et al. [12], shows promise for enhancing power quality. However, optimizing energy utilization and minimizing storage costs in real-time applications remain key challenges. Research by Krishna et al. [16] and Naidu et al. [17] focuses on optimized PI controllers and gradient adaptive variable step control algorithms. These methods show potential but require further refinement to enhance dynamic responses and reduce computational complexity under varying grid conditions. Chen et al. [18] and Karthikeyan et al. [19] explore hybrid DVR systems integrated with energy storage and renewable energy sources. Persistent issues include harmonics management and transient response, especially in medium-voltage applications. For large power converters and energy-optimized control methods, see [6]. This setup uses an LC filter in conjunction with a series capacitor. In DFIG systems powered by wind turbines, this method enhances the DVR's efficiency, particularly in the event of asymmetrical grid disturbances. Benali et al. [7] propose DVR usage in hybrid distribution generation systems to enhance power quality and LVRT capabilities, particularly in three-phase medium-voltage networks. The DVR ensures compliance with grid codes during faults in systems integrating PV and WTG components. When designing four-wire DVRs, Zhan et al. [8] turned to a voltage space vector pulse width modulation method that goes back to square one: the three-dimensional space of voltages. This approach greatly enhances voltage stability and total harmonic distortion (THD), especially in cases of balanced and unbalanced voltage sags characterized by phase angle jumps. Zhou et al. [9] investigate four-leg DC-AC power converters as a means of controlling power grid voltage imbalance, particularly in standalone microgrids. Although this method enhances common current sharing and selective voltage-quality enhancement, it is still difficult to manage these converters, which is particularly problematic in microgrids that have sensitive loads. Evidence from studies shows that a Four-Leg DVR customized using artificial neural networks (ANNs) may mitigate voltage drops and spikes in balanced and unbalanced environments. By making adjustments in real-time according to the converter's neutral point voltage (NPV), ANN controllers improve system performance, decrease transient harmonic distortion (THD), and outperform conventional Sliding Mode Controllers (SMC). Despite the significant advancements in DVR technologies, several gaps remain that require further exploration. Traditional three-leg DVRs struggle to handle unbalanced loads and neutral current imbalances effectively, and while Four-Leg VSCs offer some improvements, their control mechanisms particularly in large-scale applications such as microgrids are still underdeveloped. Additionally, current control strategies like sliding-mode and PI controllers show limitations in managing dynamic, time-varying disturbances and maintaining computational efficiency in real-time applications. Moreover, while hybrid systems integrating DVRs with renewable energy and storage solutions have been proposed, there is a lack of comprehensive solutions that effectively manage harmonics, transient responses, and optimal energy utilization, especially in medium- and large-scale distributed generation systems. The application of Battery Energy Storage Systems (BESS) in conjunction with DVRs offers promise, but optimizing energy storage costs and utilization remains a challenge. A critical gap exists in leveraging advanced machine learning techniques, such as Artificial Neural Networks (ANN), to improve DVR performance. While ANN-tuned DVRs have shown potential for superior control of voltage sags, swells, and THD reduction, their application in large-scale, real-time environments is not fully explored, particularly in complex systems like renewable energy-integrated microgrids. Thus, there is a need for advanced, adaptive control algorithms that optimize performance in diverse and unbalanced grid conditions, along with more efficient designs that minimize components while maintaining high power quality.

III. METHODOLOGY

3.1 The Design and Modeling of Systems

General Overview of the System: The suggested setup uses an ANN to regulate a Four-Leg VSC and a DVR. By including an extra neutral leg, the Four-Leg VSC is able to successfully control uneven loads by creating a path for neutral current. Using an ANN controller, the four-legged VSC-based DVR is depicted in figure 3.1 above. The suggested system's operation is depicted in the block diagram. A distribution system that uses a four-leg VSC based DVR is necessary due to voltage disturbances on the load side and uneven phase loading from the AC grid.

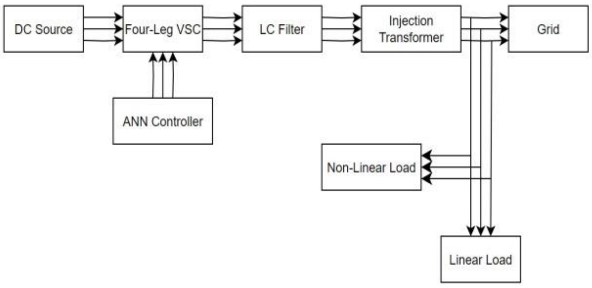


Fig. 3.1. Structure of the ANN Controller-based four-legged VSC-based DVR

The use of four-leg DVR helps mitigate the impacts of zero sequence components, swells, balanced and unbalanced voltage sags, and swells. Incorporating filters, transformers, and a four-leg converter is essential for preserving power quality in the face of AC grid disturbances experienced by non-linear loads. An ANN tuned four-legged VSC based DVR can detect voltage fluctuations or equipment malfunctions on the load side. The four-legged DVR detects disturbances by receiving input signals from sensors, processing those signals, and then producing an output signal to reduce the impact of those disturbances. It is built of eight IGBTs and uses an ANN controlling topology.

Four-Leg Voltage Source Converter (VSC): In order to manage imbalanced loads, reduce harmonic distortions, and improve fault tolerance, the VSC is built with four legs. The power flow is controlled and switched by means of Insulated Gate Bipolar Transistors (IGBTs). When it comes to lowering harmonics, enhancing power quality, and keeping voltage levels steady, the VSC is indispensable.

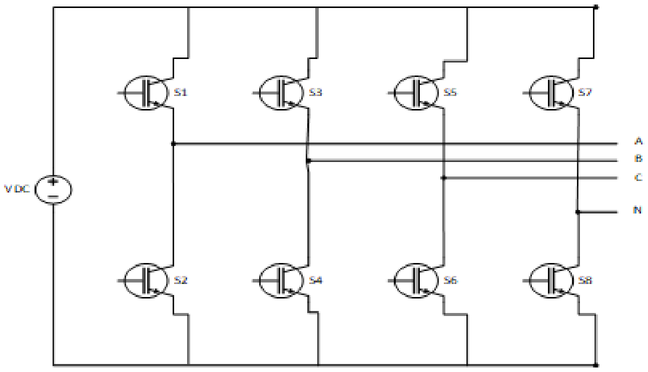


Fig. 3.2. A Converter for Four-Legged Voltage Source

In the event of a disturbance, the four-leg DVR's eight IGBTs take in signals from the sensors, process them, and then provide an output signal to lessen the impact of the disturbance. The positive and negative AC cycle voltages in each leg of an integrated gate bipolar transistor (IGBT) switch are defined independently with respect to the DC link's midway. This is done by taking the IGBT states into account. It is possible to characterize the connection as,

$$\begin{bmatrix} Van \\ Vbn \\ Vcn \\ Vnn \end{bmatrix} = \begin{bmatrix} 2Sa-1 \\ 2Sb-1 \\ 2Sc-1 \\ 2Sn-1 \end{bmatrix} * \frac{Vdc}{2} \text{ (T1, T3, T5, T7 is on)}$$

$$\begin{bmatrix} Van \\ Vbn \\ Vcn \\ Vnn \end{bmatrix} = \begin{bmatrix} 1-2Sa \\ 1-2Sb \\ 1-2Sc \\ 1-2Sn \end{bmatrix} * \frac{Vdc}{2} \text{ (T1, T3, T5, T7 is off)}$$

Points a, b, c, and n are represented by the voltage potentials Vbn, Vcn, and Vnn, respectively.

$$Si = \begin{cases} 1, & whenSiison \\ 0, & whenSiisoff \end{cases} \quad \text{(i=a, b, c, n)}$$

It is common practice to regulate the switches on Phases A, B, C, and the Neural(N) to generate the desired output voltages, as is done in a standard four-leg voltage source converter. A simple framework for defining the switching pulses generating matrix is provided here:

3.2 Switching states:

- Switches S1, S3, S5, and S7 make up the upper rows.
- S2, S4, S6, and S8 are the lower-level switches.

An upper and lower switch are present for each of the four legs (A, B, C, and N). This is the representation of the generation of switching pulses for a three-phase modulation scheme:

- **S7 on the upper leg and S8 on the lower leg make up Leg N.**
- **S1 on the upper leg and S2 on the lower leg make up Leg A.**
- **S3 on the upper leg and S4 on the lower leg make up Leg B.**
- **Lower switch S6 and Upper switch S5 are located on Leg C.**

A matrix table displaying switch states according to mA, mB, mC, and mN modulation signals is presented here:

$$\begin{bmatrix} S \\ S1 \\ S2 \\ S3 \\ S4 \\ S5 \\ S6 \\ S7 \\ S8 \end{bmatrix} = \begin{bmatrix} \boldsymbol{a} & b & c & n \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

Switches are either turned on (represented by 1) or off (represented by 0).

The unique pulse width modulation (PWM) signals produced by each phase and the zero point must be used to update this matrix.

Dynamic Voltage Restorer (DVR): In order to fix voltage irregularities such as sags and swells, the DVR is connected to the VSC. The DVR keeps a close eye on the voltage waveform at the PCC and injects a compensatory voltage waveform whenever it detects irregularities.

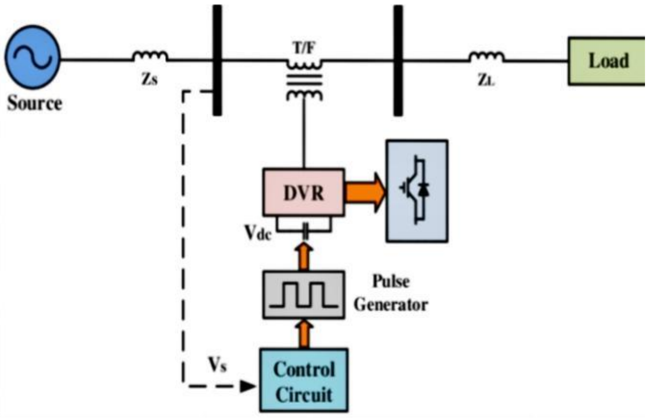


Fig. 3.3. Restoration of Dynamic Voltage

The main functions of a voltage reference rectifier (DVR) are to continuously monitor the voltage waveform, quickly detect voltage abnormalities, and precisely synthesize compensatory voltage waveforms to return the voltage waveform to its normal value. By doing so, the DVR can safeguard delicate electronics from power surges and dips, preventing disruptions in service and reducing the likelihood of damage.

3.3 Alignment of Control Strategies

ANN-based Control Strategy: In order to fine-tune the DVR's operation on the fly, an ANN is utilized. The DVR's response to various voltage disturbances is optimized through training, making it more successful at mitigating voltage sags and swells than more conventional approaches such as Sliding Mode Control (SMC).

Mathematical modeling of ANN controller:

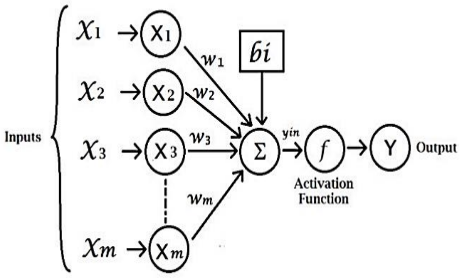


Fig 3.4. ANN computational model

The basic procedure is illustrated in the figure. Imagine a network of neurons X1, X2,..., Xm communicating with a single neuron Y. Y is the neuron that receives signals as an output from the neurons X1, X2,..., Xm that send signals into the network. The weighted interconnection links W1, W2,..., Wm connect the input neurons X1, X2,..., Xm to the output neuron Y. Here is a mathematical representation of the net input for figure:

The 'i' stands for the i^th processing component of the neural network, and 'bi' represents bias, which affects the calculation of the net input and can take on positive or negative values.

$$yin = (x_1 w_1 + x_2 w_2 + \cdots x_m w_m) + bi = \sum_{i=1}^{m} xiwi + bi$$

[W1, W2]–..In this context, x1, x2... and Wm are weights that represent the strength of the synaptic connection between the input and output neurons.An input neuron's activations are denoted by xm. The output of applying an activation function to the net input 'Yin' is given by the formula Y = f (yin),

Y = $f \sum_{i=1}^{m} xiwi + bi$

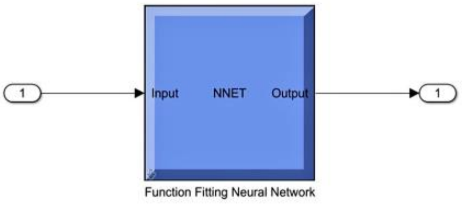


Fig. 3.5. ANN Controller

Pulse Width Modulation (PWM): Adjusting the switching of IGBTs allows the VSC's output voltage to be controlled using pulse width modulation (PWM). Important for preserving power quality, this approach guarantees tight regulation of the average power supplied to the load.

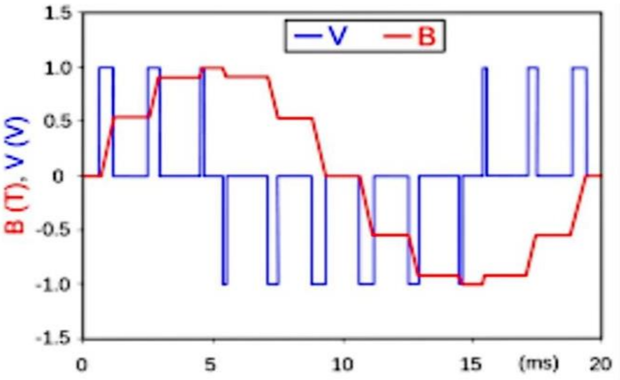


Fig.3.6. Pulse width modulation

The average power generated by an electrical signal can be controlled using pulse-width modulation (PWM). Controlling the average voltage (and current) supplied to the load is as simple as varying the supply from zero to one hundred percent at a rate greater than the rate at which the load changes significantly. Since PWM's discrete switching has less of an impact on inertial loads like motors, it is well suited for their operation. To regulate a load is the primary objective of pulse width modulation (PWM). Nevertheless, for a seamless operation, it is crucial to carefully determine the PWM switching frequency.

3.4 Simulation Setup

Software and Environment: We use MATLAB/Simulink to model and simulate the whole system. Several operational scenarios, including as balanced and unbalanced voltage sags and swells, can be reproduced in the modeling environment.

Setup Settings for the System

S.No	System Parameters	Values
1	1-Ø Transformer	1.4 KVA, 230/230V, Lt=4mH
2	Filter Parameters	L1=10mH, Cf=75μF, Rf=3.5Ω
3	Linear Load	Ra=48.5 Ω, Rb=32 Ω, Rc=54 Ω
4	Rated Supply Phase Voltage	50V, 50Hz
5	DC Link Voltage	Vdc=200V
6	Non-Linear Load	3-Ø diode bridge rectifier with R=92 Ω, L=85.7mH

Simulation Diagram

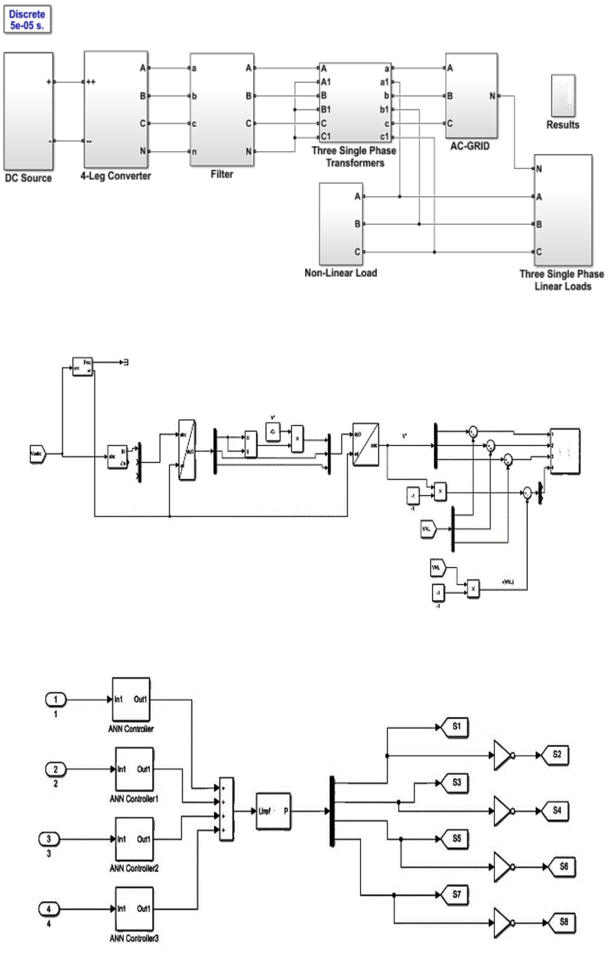


Fig. 3.7. Visualization of the Suggested Approach

The suggested system's setup is shown in the simulation diagram, which also shows how the Four-Leg VSC, DVR, and ANN controller are interconnected.

IV. RESULTS

Here we detail the outcomes of a scenario involving the Dynamic Voltage Restorer (DVR) and a Four-Leg Voltage Source Converter (VSC) that was modified using artificial neural networks (ANNs). Main performance measures that will lead the discussion are load voltage stabilization, Total Harmonic Distortion (THD), and DVR injected voltage. Additionally, we offer a comparison with more conventional control systems like the Sliding Mode Controller (SMC).

CASE 1: Findings from the Simulation Under Balanced Sagging

A voltage sag occurs when the root-mean-square (RMS) voltage falls abruptly from 0.1p.u to 0.9p.u at the power frequency over periods of half a cycle to one minute. About half a second to a minute after the stimulus starts, the 0.5 p.u. voltage decrease starts. Using an ANN controller, the four-leg DVR was able to compensate by injecting voltage into the load, as shown in these data.

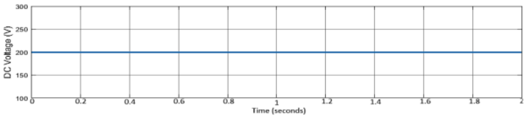


Fig. 4.1 (a) Voltage under DC Condition

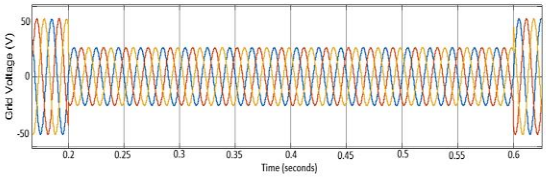


Fig. 4.1 (b) Power outage voltage on the grid

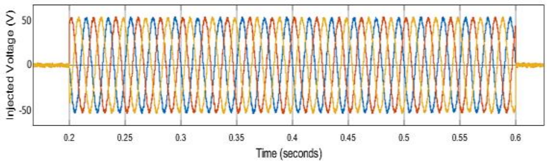


Fig. 4.1 (c) The voltage injected by the DVR

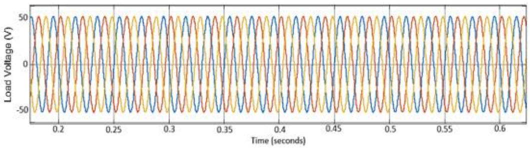
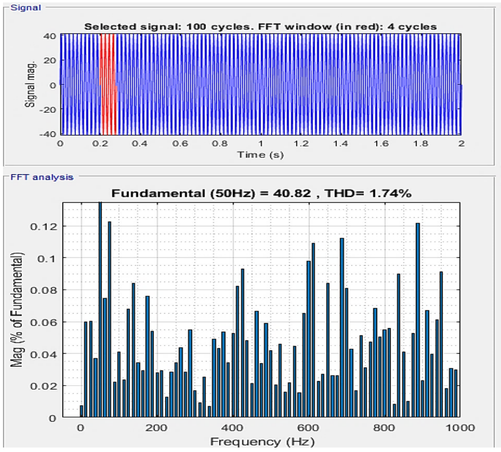
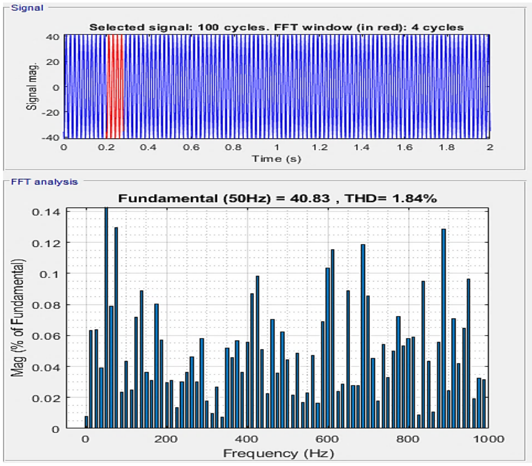


Fig. 4.1 (d) Voltage Required to Hold Load

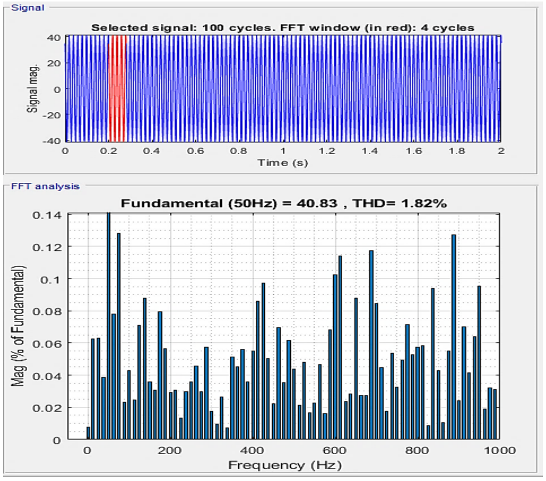
In the balanced sag state, the total harmonic distortion (THD) of the load voltages in phases a, b, and c are 1.74%, 1.84%, and 1.82%, respectively.



THD of the Voltage at the Load in Phase-A



THD of the Voltage at the Load in Phase-B



THD of the Voltage at the Load in Phase-C

CASE 2: Findings from the Balanced Swell Simulation

An RMS voltage rise of 1.1p.u to 1.8p.u at the power frequency over durations of half a cycle to one minute is an example of a voltage swell, a brief but noticeable increase in magnitude. Between half a second and a half a second later, the 1.5 p.u. voltage swell begins. This set of results shows that the four-leg DVR with an ANN controller was able to inject voltage into the load to compensate for it.

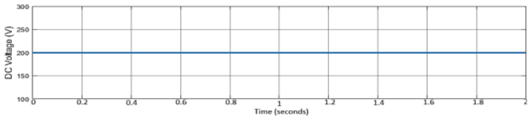


Fig. 4.2 (a) Voltage under DC Condition

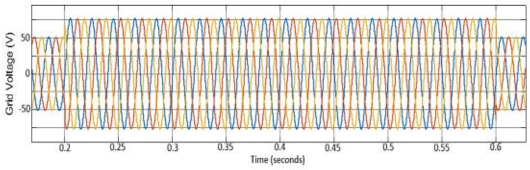


Fig. 4.2 (b) Power outage voltage on the grid

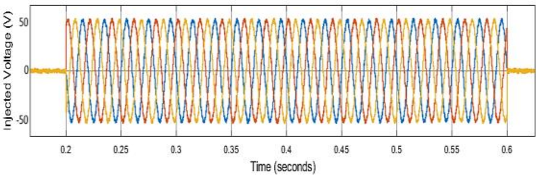


Fig. 4.2 (c) The voltage injected by the DVR

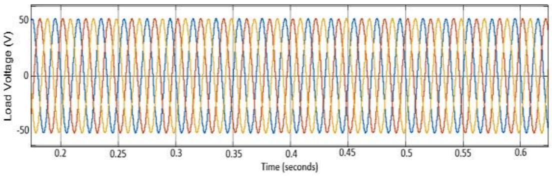
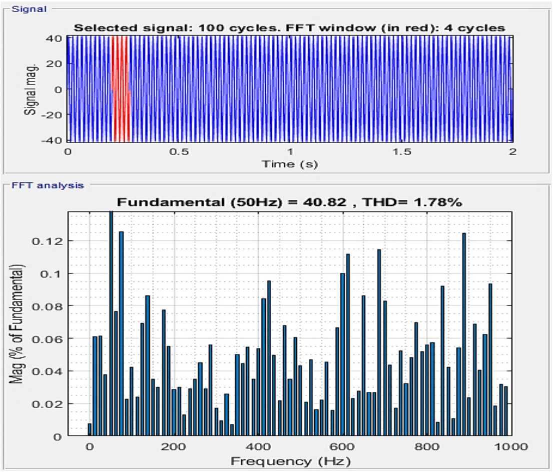
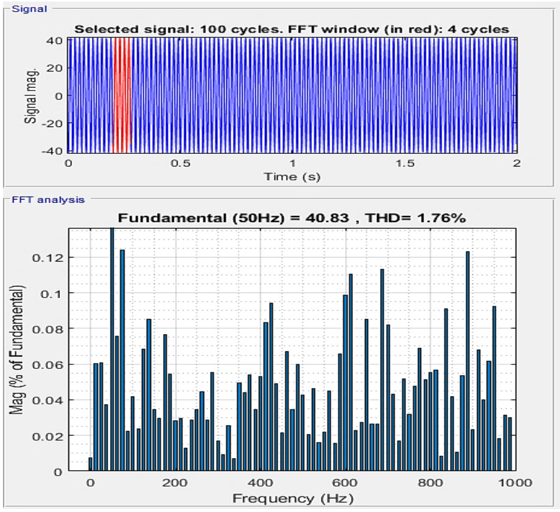


Fig. 4.2 (d) Load Voltage

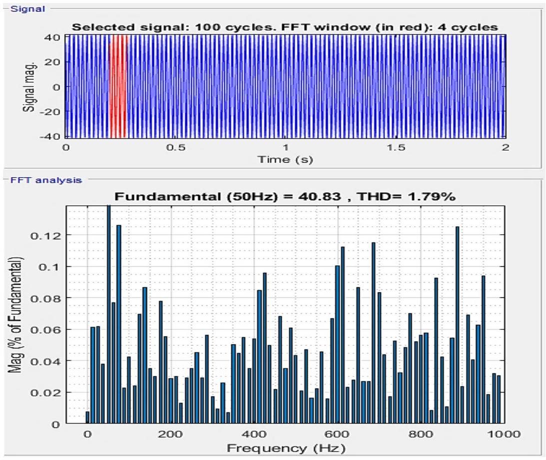
Phase a, phase b, and phase c total harmonic distortion (THD) values are 1.78%, 1.76%, and 1.79%, respectively, under balanced sag conditions.



THD of the Voltage at the Load in Phase-A



THD of the Voltage at the Load in Phase-B



THD of the Voltage at the Load in Phase-C

CASE 3: Preliminary Findings from a Single-Phase Unbalanced Sag Simulation

In the event of a phase-a voltage sag (Vga=0.5pu), the following voltages are displayed in the figure: DC voltage, grid voltage, voltage injected by the DVR, and load voltage.

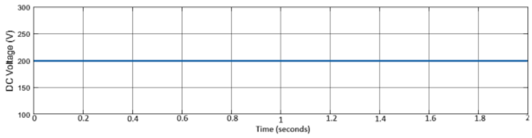


Fig. 4.3 (a) Voltage under DC Condition

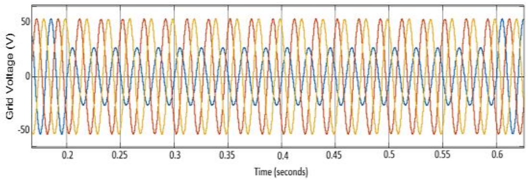


Fig. 4.3 (b) Power outage voltage on the grid

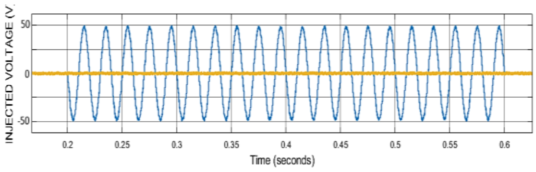


Fig. 4.3 (c) The voltage injected by the DVR

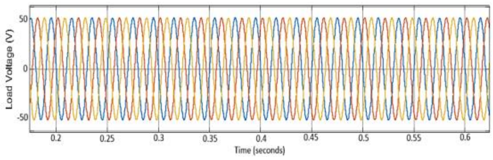
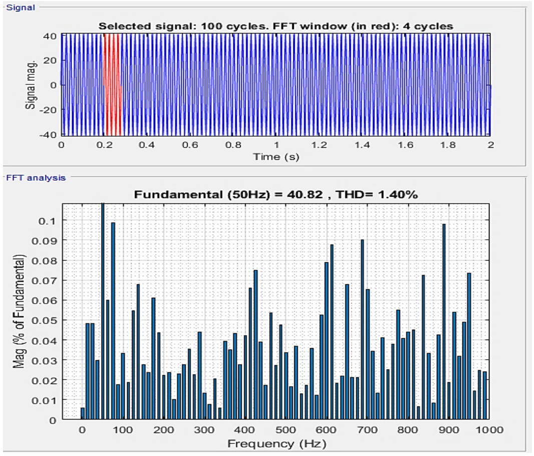
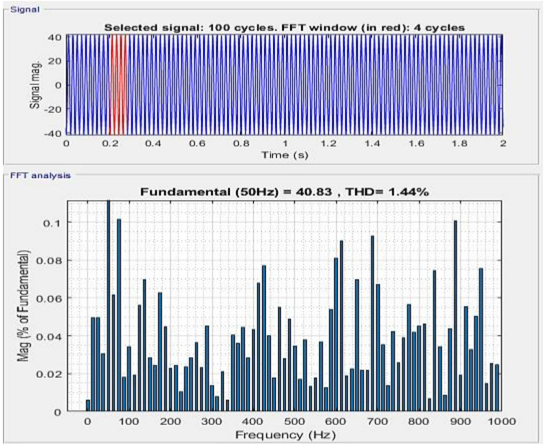


Fig. 4.3 (d) Load Voltage

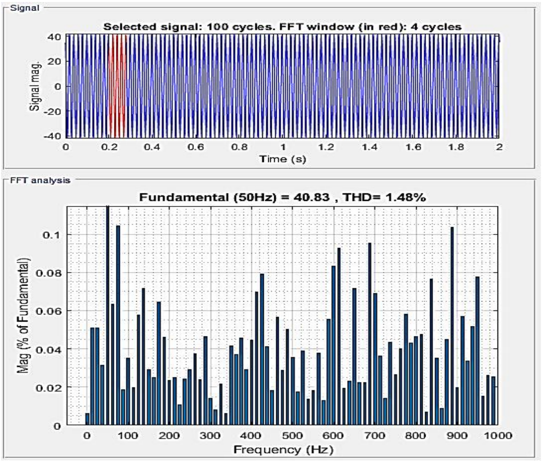
The total harmonic distortion (THD) of the load voltages in phases a, b, and c are 1.40%, 1.44%, and 1.48%, respectively, during the imbalanced sag in phase-a grid voltage.



THD of the Voltage at the Load in Phase-A



THD of the Voltage at the Load in Phase-B



THD of the Voltage at the Load in Phase-C

CASE 4: Findings from the Two-Phase Unbalanced Swell Simulation

As shown in the figure, the voltages on phases a and c of the grid (Vga=Vgc=1.5pu) are DC, grid, DVR injected, load, and unbalanced.

Phase a, phase b, and phase c load voltage total harmonic distortions are measured as 1.36%, 1.36%, and 1.36%, respectively, during an imbalanced swell in the phase a and c grid voltage.

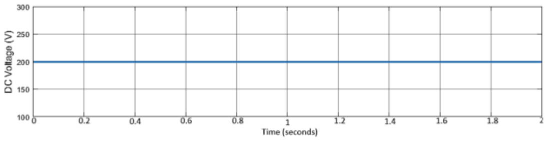


Fig. 4.4 (a) Voltage under DC Condition

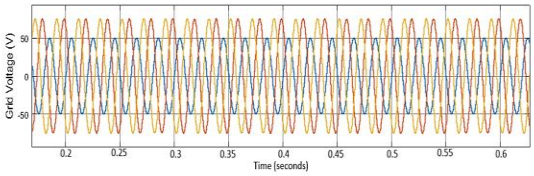


Fig. 4.4 (b) Voltage on the Grid during Two-Phase Swell

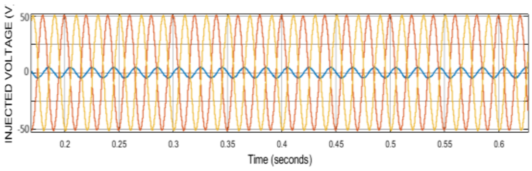


Fig. 4.4 (c) voltage injected via DVR

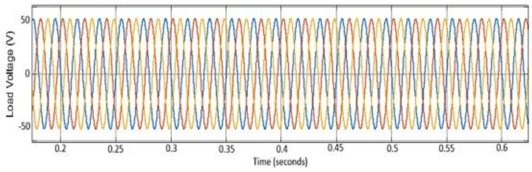
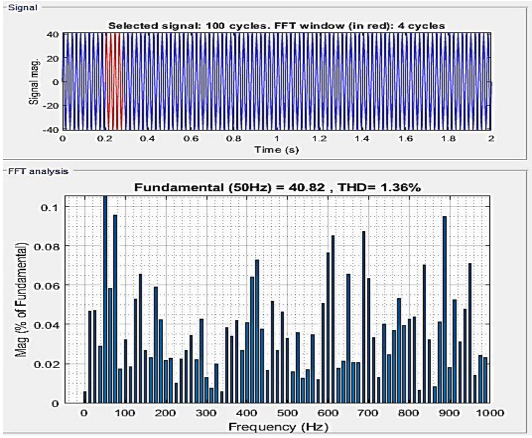
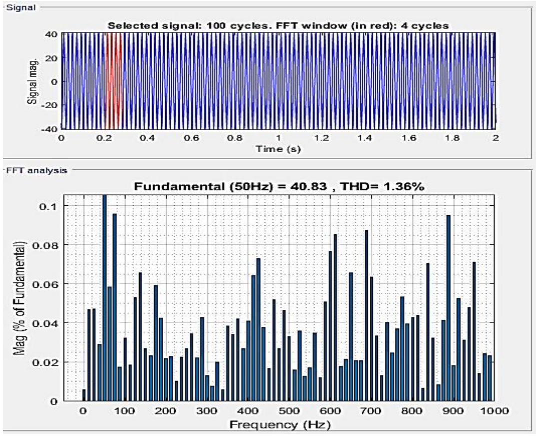


Fig. 4.4 (d) Load Voltage

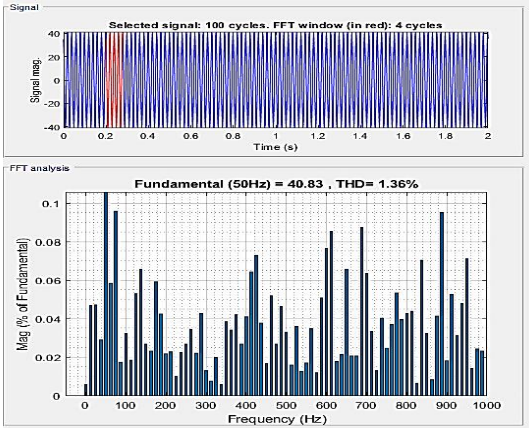
Phase a, b, and c load voltage THDs are 1.36%, 1.36%, and 1.36%, respectively, during an imbalanced swell in the phase-a&c grid voltage.



THD of the Voltage at the Load in Phase-A



THD of the Voltage at the Load in Phase-B



THD of the Voltage at the Load in Phase-C

Table I shows the Total Harmonic Distortion (THD) values for balanced voltage sags and swells, whereas Table II shows the values for unbalanced voltage distortions. Both voltage sag and voltage swell are observed in the simulations at magnitudes of 0.5 pu and 1.5 pu, respectively. When compared to conventional control methods, the Dynamic Voltage Restorer (DVR) with four legs tuned by artificial neural networks (ANNs) significantly reduces total harmonic distortion (THD). By meeting or exceeding IEEE requirements, the ANN controller proved time and time again that it was the best option for improving power quality by keeping the total harmonic distortion (THD) of load voltages below 5%.

Table 1: THDV Readings Devoid of an ANN Controller

Case	Condition	THD in Phase-A	THD in Phase-B	THD in Phase-C
1	Sag=0.5 p.u	4.09%	5.45%	4.14%
2	Swell=1.5 p.u	2.89%	3.34%	2.22%
3	Sag on Phase-A=0.5 p.u	2.25%	3.62%	2.48%
4	Swell on Phase A&C=1.5 p.u	2.62%	2.59%	1.81%

Table 2: ANN Controller and Total Harmonic Distortion Values

Case	Condition	THD in Phase-A	THD in Phase-B	THD in Phase-C
1	Sag=0.5 p.u	1.74%	1.84%	1.82%
2	Swell=1.5 p.u	1.78%	1.76%	1.79%
3	Sag on Phase-A=0.5 p.u	1.40%	1.44%	1.48%
4	Swell on Phase A&C=1.5 p.u	1.36%	1.36%	1.36%

V. CONCLUSION

An ANN-tuned four-leg DVR in a grid-connected system is advantageous, as this project "ANN Tuned Four-Leg DVR in Grid Connected Systems" shows. The DVR is better able to handle voltage disturbances and maintain good power quality thanks to the carefully crafted ANN controller. Through extensive simulations in Matlab/Simulink, the ANN-based control method was validated under a range of operating circumstances. Findings showed a considerable improvement over traditional SMC methods in lowering Total Harmonic Distortion (THD). An improved and more consistent power supply was the result of the ANN controller's adaptive learning capabilities, which empowered it to effectively handle voltage dips, surges, and other transient disturbances. The DVR's four-legged design improved system stability by regulating neutral point voltage and efficiently handling unbalanced loads. In conclusion, the four-leg DVR with ANN control reduced total harmonic distortion (THD) better in several situations, such as balanced sag (0.5 pu), balanced swell (1.5 pu), single-phase unbalanced sag (0.5 pu), and two-phase unbalanced swell (1.5 pu). In areas where voltage swings are common, this study's findings lend credence to the idea that an ANN-tuned DVR system can help current distribution networks keep power quality high.

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