ISSN 2277-2685
IJESR/Apr-Jun. 2024/ Vol-14/Issue-2/1737-1755
M. Anjaneyulu et. al., / International Journal of Engineering & Science Research

INTELLIGENT CONTROL OF FOUR-LEG DVR FOR VOLTAGE STABILITY IN GRID NETWORKS WITH ANN

[1]M. Anjaneyulu, M.Tech Student,
Department of Electrical and Electronics Engineering
JNTUH College of Engineering, Jagityal, Telangana, India

[2]Dr.L.Kishore,Associate Professor
Department of Electrical and Electronics Engineering,
Sreekavitha Engineering College, Khammam, Telangana, India.

[3]Dr.R.Durga Rao, Associate Professor
Department of Electrical and Electronics Engineering
JNTUH College of Engineering Manthani, Telangana, India.

Abstract: *This paper explores the simulation of a Dynamic Voltage Restorer (DVR) using a Four-Leg Voltage Source Converter (VSC) with an Artificial Neural Network (ANN)-based control strategy. The Four-Leg VSC includes an additional neutral leg, which enables the converter to manage unbalanced loads more efficiently by providing a path for neutral current. Power quality issues, such as voltage sags and swells, frequently occur in distribution systems due to unbalanced loads. To address these disturbances, a DVR equipped with a Four-Leg VSC and ANN-based control topology is employed. The integration of ANN into the four-leg DVR allows for dynamic adjustment of the DVR output, effectively mitigating voltage disturbances and achieving superior Total Harmonic Distortion (THD) reduction compared to traditional Sliding Mode Controllers (SMC). The ANN controller demonstrates enhanced capability in managing voltage distortions and improving power quality by reducing THD. The performance of the proposed control scheme is validated under various operating conditions using Matlab/Simulink software.*

Index Terms:Four-Leg Voltage Source Converter, Dynamic Voltage Restorer (DVR), Voltage Sag, Voltage Swell, Sliding Mode Controller (SMC), Artificial Neural Network (ANN) Controller.

I. INTRODUCTION

Maintaining power quality in electrical distribution systems is essential for the stable and efficient operation of both industrial and commercial applications. Voltage disturbances, such as sags, swells, and unbalanced loads, pose significant challenges, potentially leading to malfunctioning of sensitive equipment and substantial economic losses. Traditional three-phase, three-leg Dynamic Voltage Restorers (DVRs) have been widely used to mitigate these issues. However, they often struggle with uneven phase loading, which can exacerbate voltage disturbances rather than resolve them. The limitations of conventional three-leg DVRs highlight the need for a more robust solution, particularly in systems where unbalanced conditions are prevalent. The introduction of a Four-Leg Voltage Source Converter (VSC) based DVR offers a significant improvement. By adding a neutral leg, the Four-Leg VSC provides a dedicated path for neutral current, enabling it to handle unbalanced loads more effectively. This configuration ensures that voltage sags and swells are mitigated efficiently, preserving the stability of the power supply andreducing the risk of equipment failure. The Four-Leg VSC-based DVR is particularly advantageous in industrial applications, where three-phase VSCs are commonly used in Uninterruptable Power Supplies (UPS), motor drives, wireless power transfer, and distributed power generation systems. The DVR operates by injecting a compensating voltage of the required magnitude and frequency in series with the distribution feeder, effectively correcting imbalances, harmonics, and voltage fluctuations. This ensures the delivery of a pure sinusoidal voltage within the DVR's bandwidth capabilities, protecting sensitive loads from supply-side disturbances. To further enhance the performance of the Four-Leg DVR, this project incorporates an Artificial Neural Network (ANN) control strategy. The ANN controller is designed to dynamically adjust the DVR's output in real-time, learning from data and adapting to changing conditions to optimize performance. Unlike traditional control methods, the ANN controller excels in handling complex, non-linear tasks, making it an ideal choice for managing voltage disturbances. By maintaining a constant neutral point and ensuring symmetric output voltage, the ANN-tuned Four-Leg DVR offers a superior solution for improving power quality in both balanced and unbalanced conditions. ThisPapervalidates the effectiveness of this approach through comprehensive simulations conducted using Matlab/Simulink.

II. LITERATURE REVIEW

A thorough review of various research articles was conducted to understand recent advancements in the field of dynamic voltage restoration, focusing on the mitigation of voltage sags and swells using innovative control strategies. Key contributions from prominent studies are highlighted below.In [1], the authors discuss a modified voltage space vector Pulse Width Modulation (PWM) algorithm designed for a four-wire Dynamic Voltage Restorer (DVR). This switching strategy, which is applied in three-dimensional control of three-phase four-wire inverter systems like split-capacitor PWM and four-leg PWM inverters, is analyzed for its effectiveness in reducing Total Harmonic Distortion (THD), weighted THD, neutral line ripple, and switching losses across various modulation indices during both balanced and unbalanced voltage sags. The study in [2] explores a transformer-less, self-charging DVR series compensation device, which is utilized to mitigate voltage sags. The research provides a detailed analysis of the DVR’s performance under voltage restoration and self-charging conditions, with a focus on control mechanisms for voltage sag mitigation and dc-link voltage regulation. In [4], a novel dual-function fault-current limiter-dynamic voltage restorer (FCL-DVR) topology is introduced. This topology not only performs typical fault-current limiting tasks but also improves the voltage quality at the point of common coupling. The FCL-DVR design is notable for its reduced number of semiconductor switches and simplified gate drive and control circuits, resulting in lower power loss compared to other FCL-DVR structures. The authors in [5] delve into fault current-limiting dynamic voltage restorers (FCL-DVRs), also known as dual-functional DVRs, which integrate both fault current limiting and voltage compensation (VC) functions. The paper addresses challenges such as the need for a high-capacity storage system in the dc-link and the oversizing of the power converter. To overcome these issues, an improved FCL-DVR featuring an energy-optimized control strategy and an LC filter coupled with a series coupling capacitor (LCC) is proposed. In [6], the application of a DVR in conjunction with a wind-turbine-driven Doubly Fed Induction Generator (DFIG) is examined. The setup is designed to allow wind turbines to maintain uninterrupted operation during voltage dips, meeting grid code requirements. The DVR is shown to be more effective in comparison to traditional low-voltage ride-through methods, particularly in scenarios involving asymmetrical grid faults.. The study in [7] proposes the use of a DVR to enhance power quality and improve the low voltage ride-through (LVRT) capability in a three-phase medium-voltage network connected to a hybrid distribution generation system. This system, which includes both photovoltaic (PV) and wind turbine generator (WTG) components, benefits from the DVR's ability to manage various fault conditions, ensuring compliance with LVRT grid codes Research in [8] revisits the modifiedvoltage space vector PWM algorithm for four-wire DVRs, focusing on a three-dimensional αβO voltage space. This advanced control strategy outperforms conventional methods by instantaneously controlling positive, negative, and zero-sequence components of terminal voltages, significantly improving THD and voltage stability during phase angle jumps in both balanced and unbalanced sags. Finally, [9] addresses the use of four-leg dc-ac power converters in power grids to manage voltage unbalance caused by single-phase or three-phase unbalanced loads. The study emphasizes the challenges of controlling these converters, particularly when they are placed in isolated microgrids without interconnecting links. The proposed approach improves common current sharing and selective voltagequality enhancement, ensuring that converters connected to sensitive load buses are selectively activated when voltage unbalances exceed predefined thresholds. These studies contribute significantly to the understanding and development of power quality improvement techniques. However, the application of an Artificial Neural Network (ANN)-tuned Four-Leg DVR stands out as a powerful solution for compensating voltage sags and swells under both balanced and unbalanced conditions. The ANN controller's ability to dynamically adjust based on converter neutral point voltage (NPV) and its superior performance in reducing THD compared to traditional Sliding Mode Controllers (SMC) highlight its potential for improving overall system performance.

III. METHODOLOGY

System Design and Modeling

System Overview: The proposed system comprises a Four-Leg Voltage Source Converter (VSC) integrated with a Dynamic Voltage Restorer (DVR) and controlled by an Artificial Neural Network (ANN). The Four-Leg VSC includes an additional neutral leg, allowing it to manage unbalanced loads effectively by providing a path for neutral current.The above figure 3.1 shows the block diagram of the Four-Leg VSC based DVR using ANN Controller. The block diagram explains the function of proposed system. Uneven phase loading and voltage disturbances near load side from AC grid create need for four-leg VSC based DVR in distribution system.

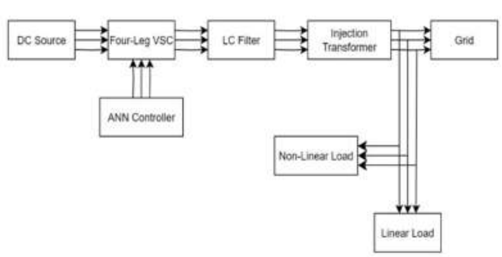


Fig. 3.1. Block diagram of the four-leg VSC-based DVR using ANN Controller

The balanced and unbalanced voltage sags, swells and zero sequence components are mitigated using four-leg DVR. The inclusion of a four-leg converter, filters, transformers play a crucial role in maintaining power quality when the disturbances occur in Non-linear loads from the AC grid. Whenever the voltage disturbances or malfunction of equipments occur at the load side the voltage disturbances are sensed by ANN tuned Four-Leg VSC based DVR. The four-leg VSC based DVR receives DC voltage and converts it into AC voltage required to mitigate voltage unbalances to protect the loads. The four-leg DVR is composed with eight IGBTs and ANN controlling topology which senses the input signals from sensors when disturbances occur, then process those signals and generates an output signal to mitigate disturbances.

Four-Leg Voltage Source Converter (VSC): The VSC is designed with four legs to handle unbalanced loads, mitigate harmonic distortions, and ensure better fault tolerance. It uses Insulated Gate Bipolar Transistors (IGBTs) to switch and control the power flow. The VSC is crucial in maintaining stable voltage levels, reducing harmonics, and improving power quality.

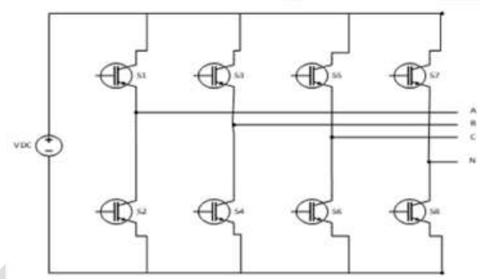


Fig. 3.2 Four-leg Voltage Source Converter

The four-leg DVR is composed with eight IGBTs which senses the input signals from sensors when disturbances occur, then process those signals and generates an output signal to mitigate disturbances. When IGBT switches are involved, referring to the middle point of the DC link, the voltages in each leg are defined separately for the positive and negative cycles of Alternating Current (AC) which is based on consideration of the IGBT states. The relationship can be described as,

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

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

Where, *Van, Vbn, Vcn and Vnn*are the voltage potentials between points a, b, c and n respectively.

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

Based on the typical Operation of four-leg Voltage Source Converter, the switches are often controlled to create the desired Output Voltages on Phases A, B, C and the Neural(N). Here is a basic outline of how you can define the switching pulses generation matrix:

Switching states:

- **S1, S3, S5, S7** are the Upper switches
- **S2, S4, S6, S8** are the Lower switches

Each leg (A, B, C, N) has two switches(an upper and lower switch). For three-phase modulation scheme, the generation of switching pulses can be represented as follows:

- **Leg A:** Upper switch S1 and Lower switch S2
- **Leg B:** Upper switch S3 and Lower switch S4
- **Leg C:** Upper switch S5 and Lower switch S6
- **Leg N:** Upper switch S7 and Lower switch S8

Here the matrix table shows the state of the switches based on the modulation signals mA, mB, mC, mN:

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

Here, **1** represents switch is **ON, 0** represents switch is **OFF**

This matrix must be updated based on the specific PWM signals generated for each phase and the neutral point.
Dynamic Voltage Restorer (DVR): The DVR is integrated with the VSC to correct voltage disturbances like sags and swells. The DVR continuously monitors the voltage waveform at the point of common coupling (PCC) and injects a compensating voltage waveform when disturbances are detected.

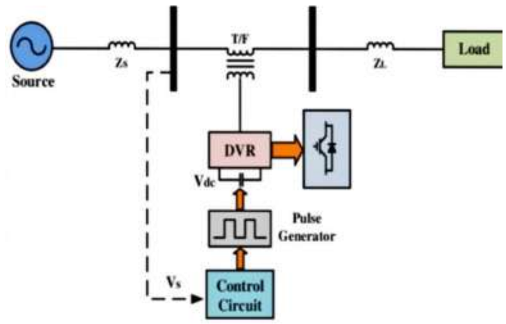


Fig. 3.3 Dynamic Voltage Restorer

Overall, the operation of a DVR involves continuous monitoring of the voltage waveform, rapid detection of voltage disturbances, and precise generation of compensating voltage waveforms to restore the voltage waveform to its nominal value. This allows the DVR to protect sensitive equipment from voltage sags and swells, ensuring uninterrupted operation and minimizing the risk of equipment damage.

Control Strategy Implementation

ANN-based Control Strategy: The ANN is employed to tune the DVR's operation dynamically. It is trained to optimize the DVR's response to different voltage disturbances, enhancing its ability to mitigate voltage sags and swells more effectively than traditional methods like Sliding Mode Control (SMC).

Mathematical modeling of ANN controller:

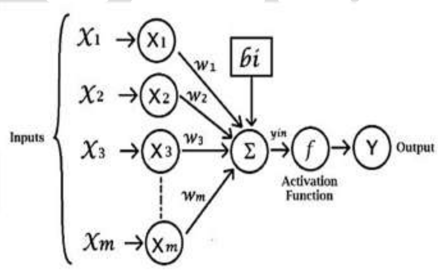


Fig 3.4 Mathematical model of ANN

The basic operation is presented in figure. For example, a set of neurons say X1, X2,…..,Xm transmitting signals towards other neuron Y. Here X1, X2,…..,Xm are considered as input neurons and Y is the output neuron which receives the signals. The input neurons X1, X2,….,Xm are connected to the output neuron Y over a weighted interconnection links W1, W2…..Wm. The net input for figure can be mathematically presented as follows:

Here 'bi' denotes bias and it has its impact in calculating the net input, the bias can be a positive and negative value and 'i' denotes i^{th} processing components of the neural network.

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

Where x1, x2….xm are the activations of the input neurons X1, X2….Xm and W1, W2…..Wm are the weights denoting the strength of the synapse between input and output neuron. The output can be obtained by applying activation function to the net input 'Yin' and written as,Y = f (yin),

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

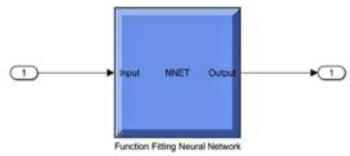


Fig. 3.5 ANN Controller

Pulse Width Modulation (PWM):PWM is used to control the VSC's output voltage by adjusting the switching of IGBTs. This method ensures precise control of the average power delivered to the load, which is crucial for maintaining power quality..

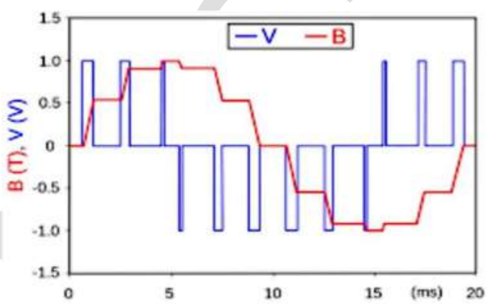


Fig.3.6 Pulse width modulation

Pulse-width modulation (PWM) is a Method of controlling the average power delivered by an electrical signal. The Average value of voltage (and current) fed to the load is controlled by switching the supply between 0 and 100% at a rate faster than it takes the load to change Significantly. The longer the switch is on, the higher the total power supplied to the load.PWM is particularly suited for running inertial loads such as motors, which are not as easily affected by this discrete switching. The goal of PWM is to control a load. However, the PWM switching frequency must be selected carefully in order to smoothly do so.

Simulation Setup

Software and Environment: The entire system, including the distribution network, DVR, Four-Leg VSC, and ANN controller, is modeled and simulated using MATLAB/Simulink. The simulation environment is configured to replicate various operating conditions, including balanced and unbalanced voltage sags and swells.

System Parameters

S.No	System Parameters	Values
1.	Rated Supply Phase Voltage	50V, 50Hz

2.	Filter Parameters	L1=10mH, Cf=75µF, Rf=3.5Ω
3.	DC Link Voltage	Vdc=200V
4.	1-Ø Transformer	1.4 KVA, 230/230V, Lt=4mH
5.	Linear Load	Ra=48.5 Ω, Rb=32 Ω, Rc=54 Ω
6.	Non-Linear Load	3-Ø diode bridge rectifier with R=92 Ω, L=85.7mH

Simulation Diagram

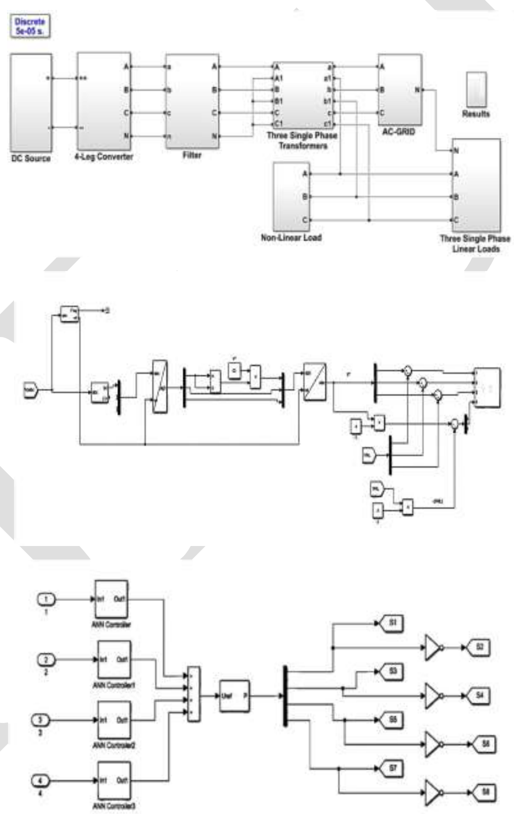


Fig. 3.7: Simulation Diagram of Proposed Method

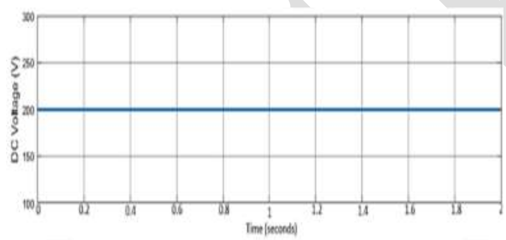
The simulation diagram represents the configuration of the proposed system, showcasing the interconnection between the Four-Leg VSC, DVR, and the ANN controller.

IV. RESULTS AND DISCUSSION

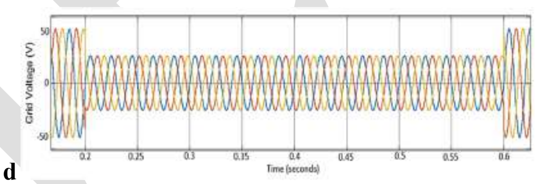
This section presents the results obtained from the simulation of the Dynamic Voltage Restorer (DVR) integrated with an Artificial Neural Network (ANN)-tuned Four-Leg Voltage Source Converter (VSC). The discussion is structured around key performance metrics, including load voltage stabilization, DVR injected voltage, and Total Harmonic Distortion (THD). Comparative analysis with traditional control strategies, such as the Sliding Mode Controller (SMC), is also presented.

CASE 1: Simulation Results During balanced sag

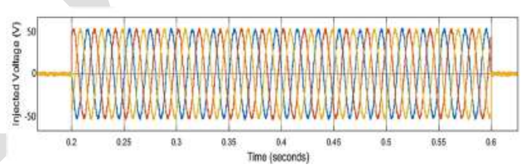
Voltage sag is the short duration decrease in the magnitude and can be defined as a drop in RMS voltage between 0.1p.u and 0.9p.u at the power frequency for durations ranging from 0.5 cycle to 1 minute. The voltage sag of 0.5 p.u is initiated during the time of 0.2 to 0.6 seconds. Here the results depicts that the four-leg DVR with ANN controller has compensated the Load voltage by injecting the voltage.



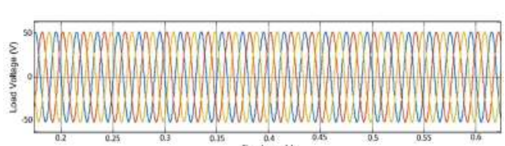
(a) **DC voltage**



(b) Grid Voltage d uring voltage sag



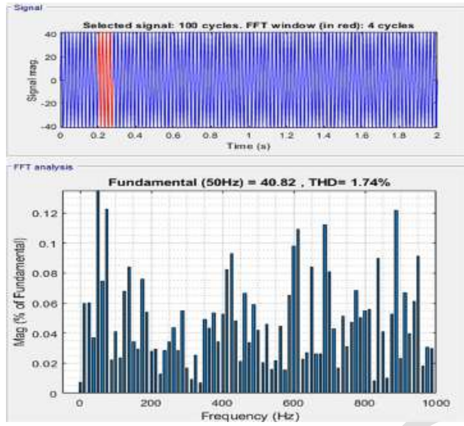
(c) DVR injected voltage



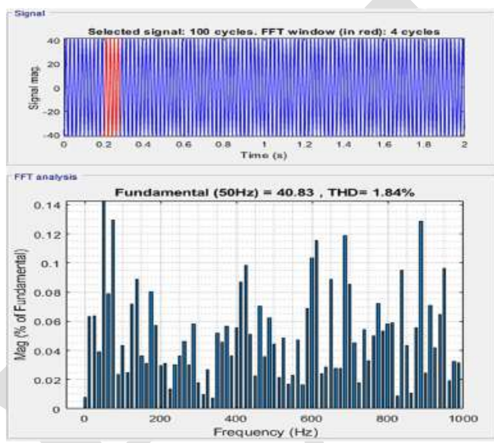
(d) Load Voltage

During balanced sag condition the THDs of load voltages in phase a, b, c are recorded as 1.74%, 1.84%, 1.82%.

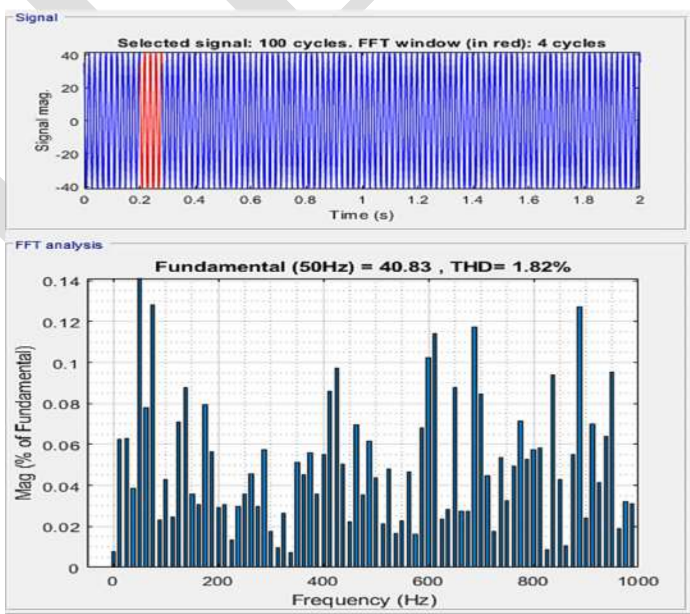
ISSN 2277-2685
IJESR/Apr-Jun. 2024/ Vol-14/Issue-2/1737-1755
M. Anjaneyulu et. al., / International Journal of Engineering & Science Research



THD of Load Voltage in Phase-A



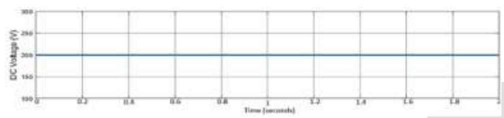
THD of Load Voltage in Phase-B



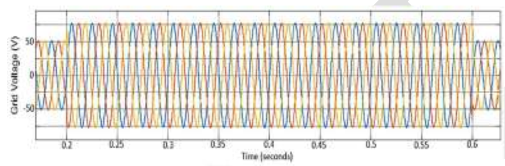
THD of Load Voltage in Phase-C

CASE 2: Simulation Results during Balanced Swell

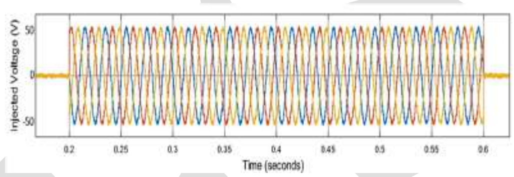
Voltage swell is the short duration increase in the magnitude and can be defined as a rise in RMS voltage between 1.1p.u and 1.8p.u at the power frequency for durations ranging from 0.5 cycle to 1 minute. The voltage swell of 1.5 p.u is initiated during the time of 0.2 to 0.6 seconds. Here the results depicts that the four-leg DVR with ANN controller has compensated the Load voltage by injecting the voltage.



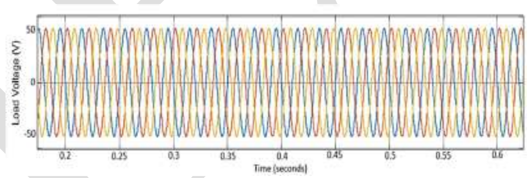
(a)DC Voltage



(b)Grid voltage during swell

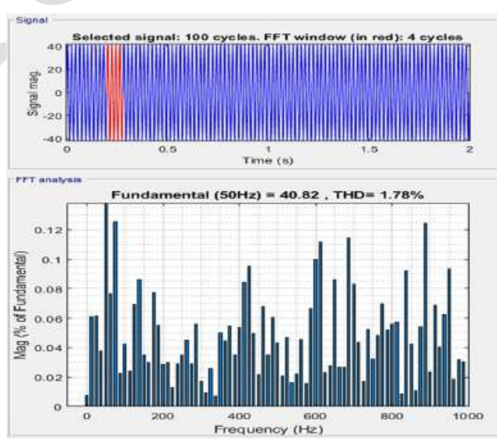


(c)DVR injected voltage



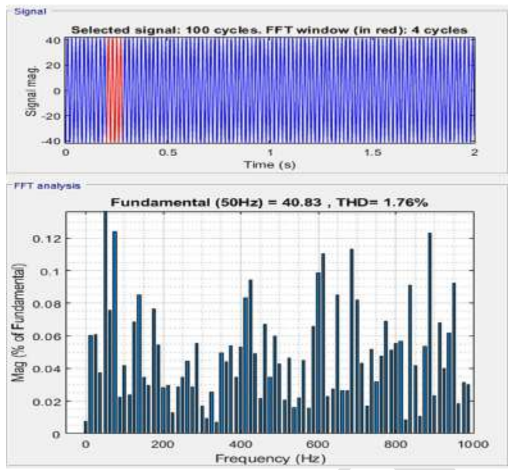
(d)Load Voltage

During balanced sag condition the THDs of load voltages in phase a, b, c are recorded as 1.78%, 1.76%, 1.79%.

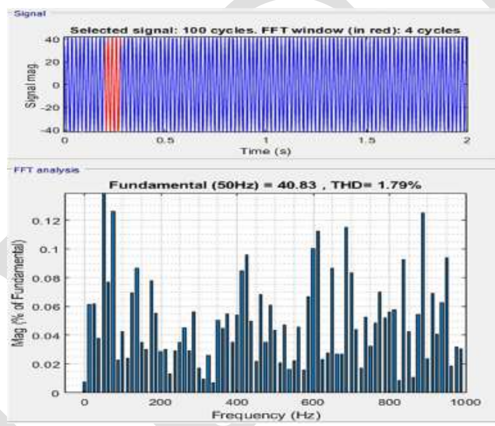


THD of Load Voltage in Phase-A

ISSN 2277-2685
IJESR/Apr-Jun. 2024/ Vol-14/Issue-2/1737-1755



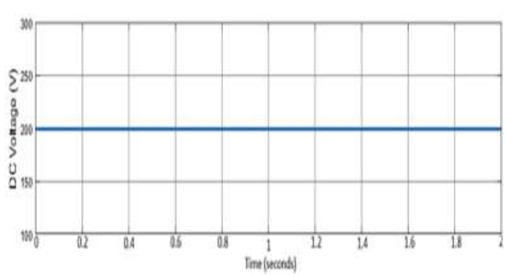
THD of Load Voltage in Phase-B



THD of Load Voltage in Phase-C

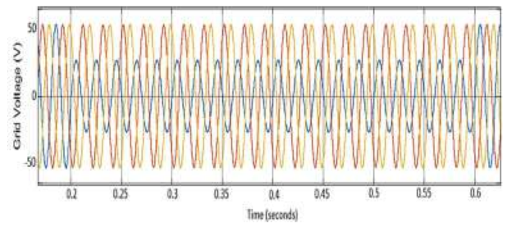
CASE 3: Simulation Results during Single Phase Unbalanced Sag

The figure shows the DC Voltage, Grid voltage, DVR injected voltage and Load Voltage during an unbalanced voltage sag on the phase-a grid voltage (Vga=0.5pu).

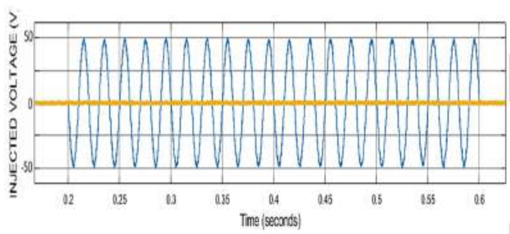


(a) DC Voltage

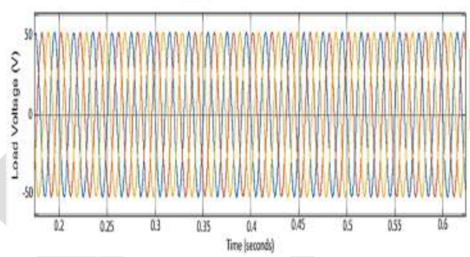
ISSN 2277-2685
IJESR/Apr-Jun. 2024/ Vol-14/Issue-2/1737-1755
M. Anjaneyulu et. al., / International Journal of Engineering & Science Research



(b) Grid Voltage during single-phase sag

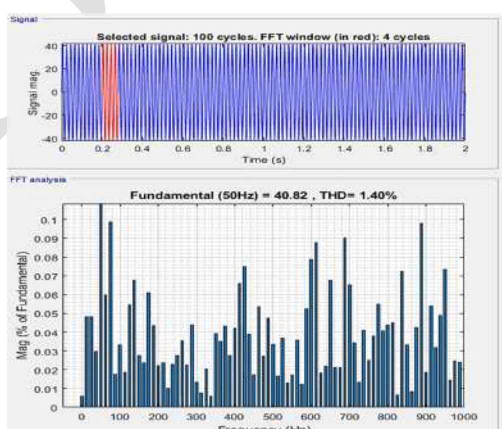


(c) **DVR injected voltage**



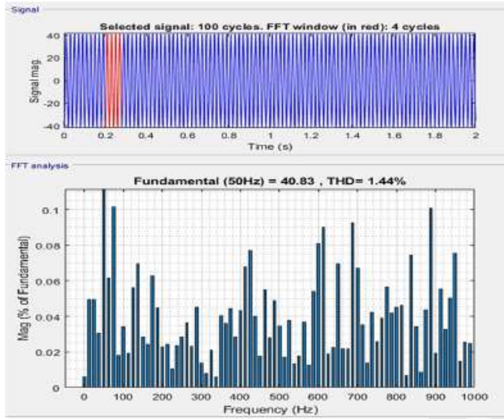
(d) Load Voltage

During unbalanced sag in phase-a grid voltage, the THDs of load voltages in phases a, b, and c are recorded as 1.40%, 1.44%, 1.48%.

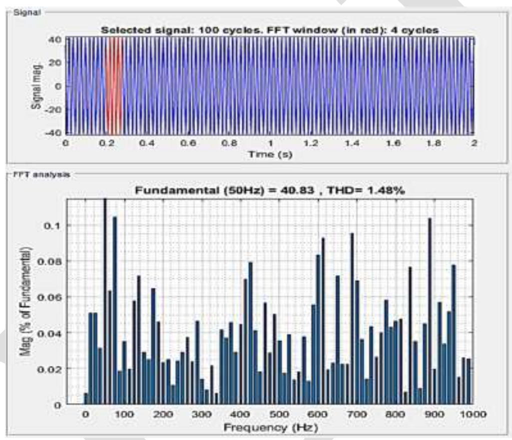


THD of Load Voltage in Phase-A

ISSN 2277-2685
IJESR/Apr-Jun. 2024/ Vol-14/Issue-2/1737-1755
M. Anjaneyulu et. al., / International Journal of Engineering & Science Research



THD of Load Voltage in Phase-B

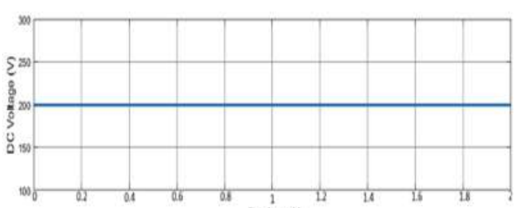


THD of Load Voltage in Phase-C

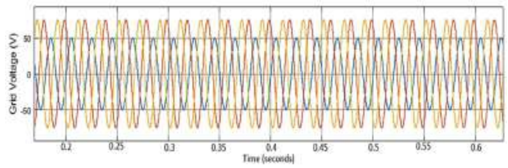
CASE 4: Simulation Results during Two-Phase Unbalanced Swell

The figure shows the DC Voltage, Grid voltage, DVR injected voltage and Load Voltage during an unbalanced voltage swell on the phase-a and phase-c grid voltage (Vga=Vgc=1.5pu).

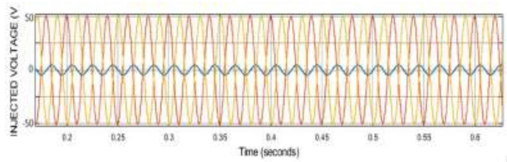
During unbalanced swell in phase-a& c grid voltage, the THDs of load voltages in phases a, b, and c are recorded as 1.36%, 1.36%, 1.36%.



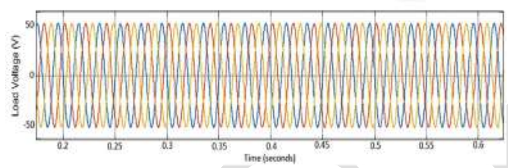
(a): DC Voltage



(b): Grid Voltage during two-phase swell

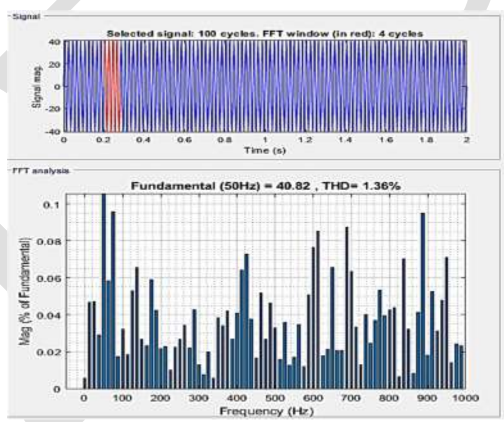


(c): DVR injected voltage

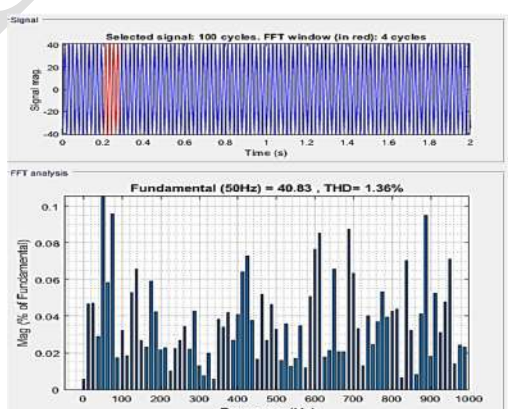


(d): Load Voltage

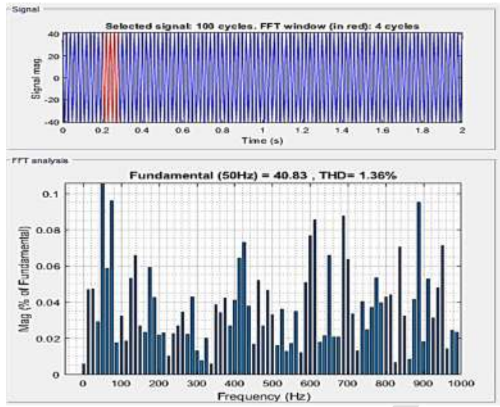
During unbalanced swell in phase-a&c grid voltage, the THDs of load voltages in phases a, b, and c are recorded as 1.36%, 1.36%, 1.36%.



THD of Load Voltage in Phase-A



THD of Load Voltage in Phase-B



THD of Load Voltage in Phase-C

Tables I and II present the Total Harmonic Distortion (THD) values for balanced and unbalanced voltage sags and swells. The simulations demonstrate that voltage sag occurs at a magnitude of 0.5 pu, and voltage swell at 1.5 pu. The ANN-tuned four-leg Dynamic Voltage Restorer (DVR) effectively mitigates these disturbances, showing a significant reduction in THD compared to traditional control methods. The ANN controller consistently maintained the THD of load voltages below 5%, adhering to IEEE standards, thereby confirming its superior performance in enhancing power quality.

TABLE-1: THD Values without 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: THD Values with ANN Controller

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%

5. CONCLUSION

The project, "ANN Tuned Four-Leg DVR in Grid Connected Systems" effectively demonstrates the advantages of using an Artificial Neural Network (ANN) controller for a four-leg Dynamic Voltage Restorer (DVR) in grid-connected systems. The meticulously designed ANN controller enhances the DVR's capability to address voltage disturbances and ensure high power quality. Through extensive Matlab/Simulink simulations, the ANN-based control scheme was validated under various operating conditions, showing a marked improvement in Total Harmonic Distortion (THD) reduction compared to traditional Sliding Mode Control (SMC) methods. The adaptive learning features of the ANN controller allowed it to efficiently manage voltage sags, swells, and other transient disturbances, leading to a more stable and reliable power supply. The four-leg configuration of the DVR effectively handled unbalanced loads and maintained neutral point voltage, contributing to overall system stability. In conclusion, the four-leg DVR with ANN control demonstrated superior THD reduction across different scenarios, including 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). The study confirms that the ANN-tuned DVR system is a robust and efficient solution for maintaining power quality in modern distribution networks, particularly in environments prone to voltage fluctuations.

REFERENCES

[1] Changjiang Zhan; A. Arulampalam; N. Jenkins, “Four-wire dynamic voltage restorer based on a three-dimensional voltage space vector PWM algorithm,” IEEE Transactions on Power Electronics, vol. 18, pp. 2003.

[2] E. Sng, S. Choi, and D. Vilathgamuwa, “Analysis of series compensation and DC-link voltage controls of a transformerless self-charging dynamic voltage restorer,” IEEE Trans. Power Del., vol. 19, no. 3, pp. 1511–1518, Jul. 2004.

[3] H. Komurcugil and S. Biricik, "Time-varying and constant switching frequency-based sliding-mode control methods for transformerless DVR employing half-bridge VSI," IEEE Trans. Ind. Electron., vol. 64, no. 4, pp. 2570–2579, Apr. 2017.

[4] P. Ghavidel, M. Farhadi, M. Dabbaghjamanesh, A. Jolfaei, and M. Sabahi, "Fault current limiter dynamic voltage restorer (FCL-DVR) with reduced number of components," IEEE Trans. Emerg. Sel. Topics Ind. Electron., vol. 2, no. 4, pp. 526–534, Oct. 2021.

[5] Q. Guo, C. Tu, F. Jiang, R. Zhu, and J. Gao, "Improved dual-functional DVR with integrated auxiliary capacitor for capacity optimization," IEEE Trans. Ind. Electron., vol. 68, no. 10, pp. 9755–9766, Oct. 2021.

[6] C. Wessels, F. Gebhardt, and F. W. Fuchs, "Fault ride-through of a DFIG wind turbine using a dynamic voltage restorer during symmetrical and asymmetrical grid faults," IEEE Trans. Power Electron., vol. 26, no. 3, pp. 807–815, Mar. 2011.

[7] Benali, M. Khiat, T. Allaoui, and M. Denaï, "Power quality improvement and low voltage ride through capability in hybrid wind-PV farms grid-connected using dynamic voltage restorer," IEEE Access, vol. 6, pp. 68634–68648, 2018.

[8] Zhan, A. Arulampalam, and N. Jenkins, "Four-wire dynamic voltage restorer based on a three-dimensional voltage space vector PWM algorithm," IEEE Trans. Power Electron., vol. 18, no. 4, pp. 1093–1102, Jul. 2003.

[9] X. Zhou, F. Tang, P. C. Loh, X. Jin, and W. Cao, "Four-leg converters with improved common current sharing and selective voltage-quality enhancement for islanded microgrids," IEEE Trans. Power Del., vol. 31, no. 2, pp. 522–531, Apr. 2016.

[10] V. Narayanan, S. Kewat, and B. Singh, "Control and implementation of a multifunctional solar PV-BES-DEGS based microgrid," IEEE Trans. Ind. Electron., vol. 68, no. 9, pp. 8241–8252, Sep. 2021.

[11] M. Pichan and H. Rastegar, "Sliding-mode control of four-leg inverter with fixed switching frequency for uninterruptible power supply applications," IEEE Trans. Ind. Electron., vol. 64, no. 8, pp. 6805–6814, Aug. 2017.

[12] P. Jayaprakash, B. Singh, D. P. Kothari, A. Chandra, and K. Al-Haddad, "Control of reduced-rating dynamic voltage restorer with a battery energy storage system," IEEE Trans. Ind. Appl., vol. 50, no. 2, pp. 1295–1303, May/Jun. 2014.

[13] D. Vilathgamuwa, A. Perera, and S. Choi, "Voltage sag compensation with energy optimized dynamic voltage restorer," IEEE Trans. Power Del., vol. 18, no. 3, pp. 928–936, Jul. 2003.

[14] J. Nielsen and F. Blaabjerg, "A detailed comparison of system topologies for dynamic voltage restorers," IEEE Trans. Ind. Appl., vol. 41, no. 5, pp. 1272–1280, Sep./Oct. 2005.

[15] M. Pradhan and Mahesh K. Mishra, "Dual P-Q theory based energy optimized dynamic voltage restorer for power quality improvement in a distribution system," IEEE Trans. Ind. Electron., vol. 66, no. 4, pp. 2946–2955, Apr. 2019.

[16] D. G. A. Krishna, K. Anbalagan, K. K. Prabhakaran, and S. Kumar, "An efficient pseudo-derivative-feedback-based voltage controller for DVR under distorted grid conditions," IEEE Trans. Emerg. Sel. Topics Ind. Electron., vol. 2, no. 1, pp. 71–81, Jan. 2021.

[17] T. Appala Naidu, S. R. Arya, R. Maurya, and S. Padmanaban, "Performance of DVR using optimized PI controller based gradient adaptive variable step LMS control algorithm," IEEE Trans. Emerg. Sel. Topics Ind. Electron., vol. 2, no. 2, pp. 155–163, Apr. 2021.

[18] X. Chen, L. Yan, X. Zhou, and H. Sun, "A novel DVR-ESS-embedded wind-energy conversion system," IEEE Trans. Sustain. Energy, vol. 9, no. 3, pp. 1265–1274, Jul. 2018.

[19] Karthikeyan, D. G. A. Krishna, S. Kumar, B. V. Perumal, and S. Mishra, "Dual role CDSC-based dual vector control for effective operation of DVR with harmonic mitigation," IEEE Trans. Ind. Electron., vol. 66, no. 1, pp. 4–13, Jan. 2019.

[20] Y. W. Li, P. C. Loh, F. Blaabjerg, and D. M. Vilathgamuwa, "Investigation and improvement of transient response of DVR at medium voltage level," IEEE Trans. Ind. Appl., vol. 43, no. 5, pp. 1309–1319, Sep./Oct. 2007.