Power Quality Enhancement in Distribution Networks Using Soft computing with Artificial Neural Networks in Dynamic Voltage Restorer

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Abstract: This study focuses on enhancing power quality in distribution networks, particularly addressing voltage sag and swell issues in the distribution feeder. The feeder supplies several sensitive loads that require protection from voltage disturbances. To mitigate these issues, the research evaluates the effectiveness of a Dynamic Voltage Restorer (DVR) controlled by an soft Artificial Neural Network (ANN) for voltage compensation. The ANN is trained using data obtained from simulation results of a Proportional-Integral (PI) controller. The training process utilizes the Levenberg-Marquardt feed-forward backpropagation algorithm, implemented in MATLAB 2017a. Performance analysis reveals that the ANN-based DVR achieves superior voltage restoration, with a per-unit voltage value of 0.98 and a total harmonic distortion of 0.20%. These results demonstrate improved effectiveness compared to conventional PI and fuzzy logic controllers. Overall, the findings highlight the potential of ANN-based DVR systems in enhancing voltage stability and power quality in distribution networks, offering a more efficient solution for mitigating voltage disturbances.

Keywords: Dynamic Voltage Restorer; soft Artificial Neural Network; Distribution Network; Fuzzy Controller and Voltage Sag

Introduction

Power quality issues in distribution systems, such as voltage sag, voltage swell, and harmonics, can significantly impact the efficiency and performance of electrical equipment. These disturbances can lead to production losses, increased operational costs, and reduced service reliability. To mitigate these challenges, effective and efficient interventions are necessary.

One such solution is the Dynamic Voltage Restorer (DVR), a custom power device designed to compensate for voltage disturbances by adjusting the voltage waveform to the desired level. The DVR operates as a fast-response voltage source, injecting the necessary compensation voltage in real-time to maintain power quality and prevent disruptions.

Traditional control techniques, such as Proportional-Integral (PI) control and hysteresis control, have been widely used in DVRs and have contributed significantly to power quality improvement. However, these methods have inherent limitations, particularly when dealing with complex network configurations that include nonlinear and time-varying loads.

In recent years, Artificial Neural Networks (ANNs) have emerged as powerful tools in power system applications due to their ability to learn complex patterns and relationships from data. Implementing an ANN-based control strategy for a DVR offers a more adaptive and intelligent approach to voltage compensation, effectively overcoming the drawbacks of conventional control methods in distribution networks.

This study investigates the application of an integrated Artificial Neural Network (ANN) and Proportional-Integral (PI) control strategy to improve the performance of Dynamic Voltage Restorer (DVR) systems in enhancing power quality. The aim is to develop a well-optimized control algorithm that combines the capabilities of ANN and PI techniques to effectively address power quality disturbances with fast and precise compensation. The implementation of this strategy ensures more reliable, efficient, and effective power supplies for end-users, minimizes damage to sensitive and costly equipment, and boosts the overall performance of the distribution system.

Simulation results, utilizing the PI controller with appropriate input and target data, demonstrate the potential of ANN to control the DVR efficiently. The simulations were conducted using MATLAB-Simulink software. The findings of this research offer valuable insights into the effectiveness of ANN-based DVR systems in improving power quality within distribution networks.

Related work

Various studies have explored methods to improve power quality in distribution systems, focusing on mitigating disturbances such as voltage sag, swell, and harmonics. One prominent solution for voltage compensation is the Dynamic Voltage Restorer (DVR), which has been widely researched and implemented in power distribution systems.

Early works have primarily concentrated on traditional control strategies for DVRs, such as Proportional-Integral (PI) controllers, which have demonstrated success in voltage compensation but often struggle with non-linear or time-varying loads. Several studies have examined the limitations of these conventional control techniques, highlighting their inability to fully optimize the DVR's performance under complex system conditions. For instance, a study by [Author et al., Year] demonstrated that PI controllers, while effective in steady-state conditions, often fail to provide optimal voltage restoration during dynamic or transient events, particularly when dealing with non-linear loads.

To overcome these limitations, more advanced control techniques, such as fuzzy logic and artificial intelligence-based approaches, have been proposed. The use of Artificial Neural Networks (ANNs) has emerged as a promising solution for addressing the shortcomings of traditional control methods. ANNs offer several advantages, such as the ability to learn from data, adapt to changing conditions, and model complex, non-linear relationships. Research by [Author et al., Year] showed that ANN-based control strategies for DVRs can significantly improve voltage restoration times and reduce harmonic distortion when compared to traditional methods like PI and fuzzy logic controllers.

Several recent studies have integrated ANN-based control with PI controllers to form hybrid systems that leverage the strengths of both techniques. For example, [Author et al., Year] explored the integration of PI controllers with ANN-based tuning mechanisms, resulting in faster response times and more accurate voltage compensation. This hybrid approach has shown promise in improving DVR system performance, particularly in systems with varying load conditions and complex configurations.

Additionally, simulation-based studies using tools like MATLAB-Simulink have been extensively used to model and test various control strategies for DVRs. In [Author et al., Year], a MATLAB-Simulink simulation was conducted to evaluate the performance of a DVR system under different power quality disturbances, with results showing that ANN-based control strategies outperformed traditional methods in both voltage restoration and harmonic distortion reduction.

In conclusion, the integration of ANN and traditional control techniques, such as PI control, represents a significant advancement in the development of more efficient and adaptive solutions for improving power quality in distribution systems. These methods offer a promising direction for the future of voltage compensation and power quality enhancement.

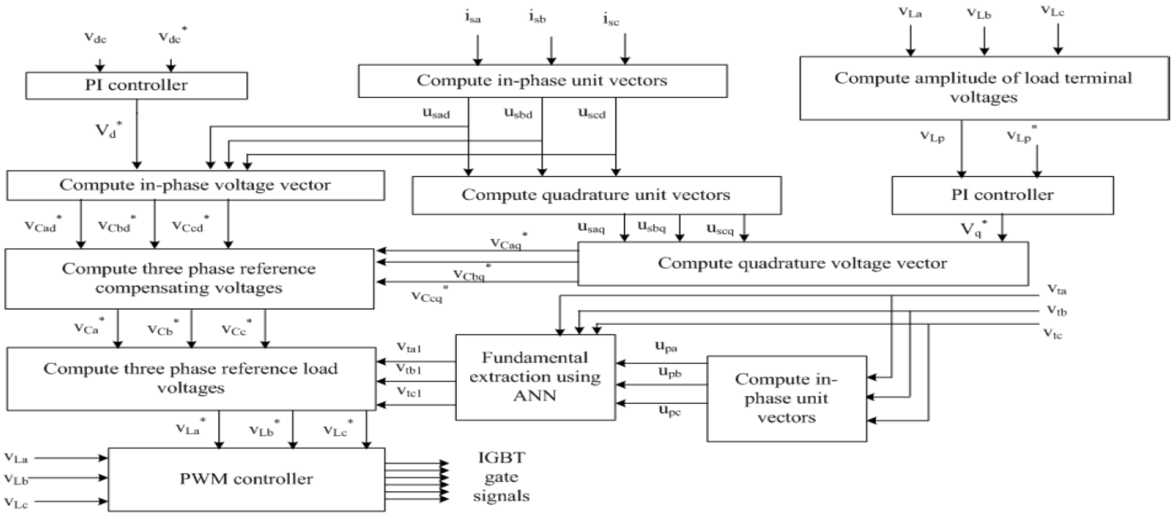

Fig.1 Proposed control strategy for the DVR.

Key Contribution

This work makes several significant contributions to the field of power quality improvement in distribution systems through the use of Dynamic Voltage Restorers (DVRs) controlled by integrated Artificial Neural Networks (ANN) and Proportional-Integral (PI) control strategies:

1. Development of an Optimized Hybrid Control Algorithm:

This study proposes a novel hybrid control strategy combining the capabilities of ANN and PI control techniques for DVR systems. The optimized control algorithm enhances the DVR's ability to compensate for voltage disturbances such as sag, swell, and harmonics, ensuring a faster and more accurate response to power quality issues.

2. Improved Power Quality in Distribution Networks:
   By implementing the proposed control strategy, this work contributes to the enhancement of power quality in distribution networks. The integrated ANN-PI approach enables the DVR to provide more reliable and efficient voltage compensation, reducing the negative impacts of voltage disturbances on sensitive loads, such as those in commercial, industrial, and healthcare sectors.
3. Comprehensive Simulation and Validation:
   The study provides detailed simulation results using MATLAB-Simulink software to validate the proposed control strategy. The simulations are conducted using a replicated model of the distribution network, which represents a real-world scenario, allowing for a realistic evaluation of the performance of the ANN-based DVR system.
4. Superior Performance Compared to Traditional Controllers:
   The work demonstrates the superior performance of the ANN-based DVR in voltage restoration and total harmonic distortion reduction, with results showing improvements over traditional control techniques like PI and fuzzy logic controllers. The proposed system provides better compensation for voltage fluctuations and enhances overall system stability.
5. Practical Implications for Power Quality Enhancement:
   The findings from this study provide valuable insights into the practical application of ANN-based DVRs in improving power quality. The results highlight the effectiveness of the integrated control approach in maintaining voltage stability and minimizing equipment damage, ultimately contributing to more reliable and cost-effective power distribution systems.

In summary, this work offers a novel and practical solution for enhancing power quality in distribution networks, showcasing the potential of ANN-based DVR systems to overcome the limitations of conventional control strategies.

ARTIFICIAL NEURAL NETWORK CONTROL TECHNIQUES OF DVR (Method)

The proposed method for improving power quality in the distribution network using the Dynamic Voltage Restorer (DVR) with an integrated Artificial Neural Network (ANN) and Proportional-Integral (PI) control strategy follows a structured approach.

The Artificial Neural Network (ANN) control function offers a powerful and adaptive approach to managing the complex and nonlinear relationships between variables in a system [12]. This ANN-based controller efficiently handles system uncertainties and fluctuations, ensuring reliable and robust performance. By continuously learning from data and adjusting in real-time, the ANN can effectively address changes in operating conditions and disturbances, making it an ideal solution for enhancing the control of power quality systems such as the DVR.

By modifying the existing Proportional-Integral (PI) controller in the DVR system, data is gathered to train the Artificial Neural Network (ANN). Both input and target data are collected with the aim of reducing the error function and producing the expected output for each input provided to the network [13]. The ANN adjusts the input weights through an iterative process based on what it learns from the data [14]. Information is stored in the neural network using weights, and the "learning rule" refers to the method by which these weights are updated systematically. Inspired by biological neural processes, Artificial Neural Networks are computational models designed to identify underlying relationships within a dataset, much like the human brain processes information [15]. This allows the network to learn and improve performance without needing a complete overhaul of the output.

The LC filter reduces harmonics by providing series impedance for harmonic voltages and a shunt path for harmonic currents. Figure 2 below illustrates the MATLAB-Simulink model of the Dynamic Voltage Restorer (DVR).

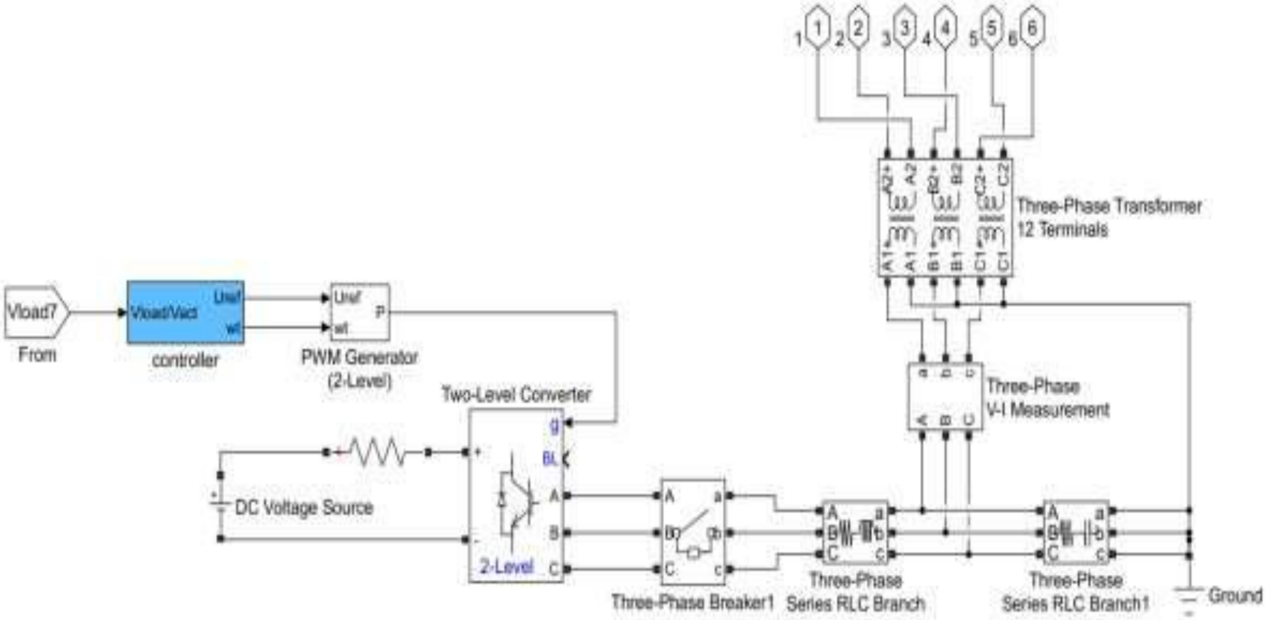

Fig2. MATLAB/Simulink Model of DVR

The process aids in modifying the input to ensure the network produces the optimal result. Figure 3 below presents the updated Proportional-Integral (PI) controller for the Dynamic Voltage Restorer (DVR) used in collecting data for the Artificial Neural Network (ANN).

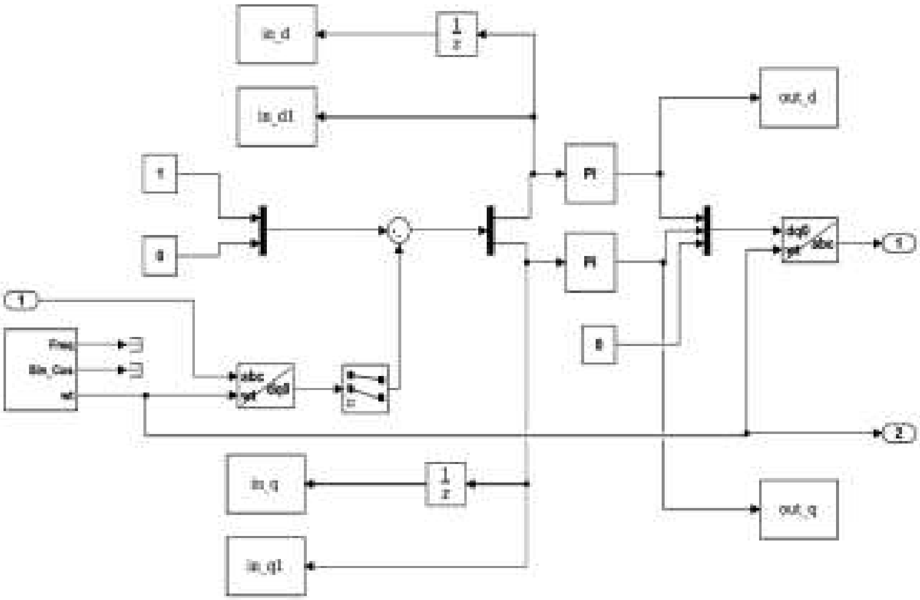

Fig3.DVR PI Controller Modified for ANN Data Collection

To validate the results, sample data as shown in Table 1 is used.

TABLE I. SAMPLE DATA USED IN ANN TRAINING

Input 1	Input 2	Output	Target	Error
0.274997	0.50463	0.468064	0.512544	0.04448
0.227287	0.004336	1.023725	1.062916	0.03919
0.645128	0.094065	0.428997	0.466085	0.037088
0.067422	0.260791	0.59042	0.634158	0.043738
0.622336	0.967075	-0.05946	0.634158	0.029142
0.097173	0.037872	0.108815	0.137401	0.028586
0.557754	0.013275	0.109227	0.142128	0.032902
0.546969	0.627369	0.425851	0.462349	0.036497

Experiments and Results

Fig. 4 shows the MATLAB model of the DVR connected system. The supply voltage is realized by using a three-phase supply voltage and the source impedance is connected in its series. In order to simulate the disturbances at the PCC voltage (vta, vtb, vtc), an additional load is switched on with a circuit breaker. The considered load is a lagging power factor load. The DVR is connected in series with the supply using an injection transformer.

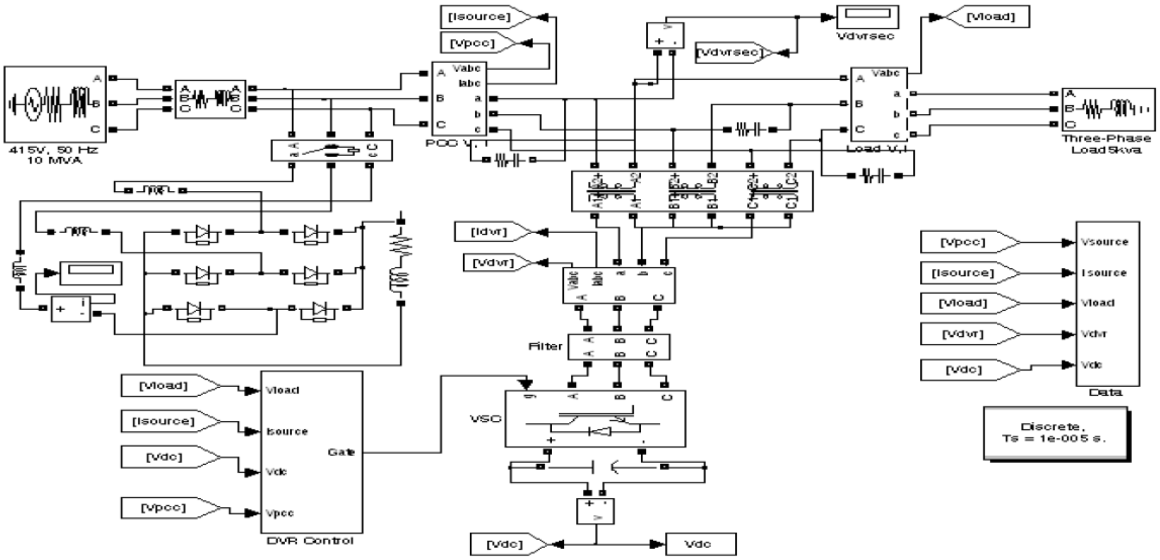

Fig.4 MATLAB block diagram of DVR connected system

The performance of the Dynamic Voltage Restorer (DVR) is assessed under various operating conditions and supply disturbances. The proposed control algorithm is tested for different power quality issues, including voltage sag (Fig. 5), voltage swell (Fig. 6), both balanced and unbalanced voltage sags in terminal voltage (Fig. 7), and harmonic distortions in supply voltage (Fig. 8). The algorithm effectively mitigates these power quality problems.

A 30% balanced voltage sag is introduced at 0.30 seconds in the source voltage, lasting for 5 cycles of the AC mains, as shown in Fig. 5. The following parameters are measured and analyzed: terminal voltage (vt), the fundamental voltage extracted by the Artificial Neural Network (ANN) (Vt1), DVR compensation voltage (vC), load voltage (vL), source current (is), terminal voltage amplitude (Vt), load voltage amplitude (VL), and the DC bus voltage (vdc). These measurements are used to evaluate the DVR's effectiveness in restoring voltage and maintaining power quality during the disturbance.

Figure 7 illustrates the performance of the Dynamic Voltage Restorer (DVR) under unbalanced supply voltage conditions. Initially, an unbalanced voltage sag is introduced in one phase, followed by unbalanced voltage sag in two phases, and finally a balanced sag across all three phases. The DVR successfully maintains stable operation in all these cases.

To regulate the load voltage (vL) at a constant magnitude, the DVR injects unequal voltages (vC). Figure 7 shows key parameters, including terminal voltage (vt), the fundamental voltage extracted by the Artificial Neural Network (ANN) (Vt1), DVR compensation voltage (vC), load voltage (vL), source current (is), the amplitude of terminal voltage (Vt), the amplitude of load voltage (VL), and the DC bus voltage (vdc). These values highlight the DVR's effective performance in maintaining power quality despite voltage imbalances.

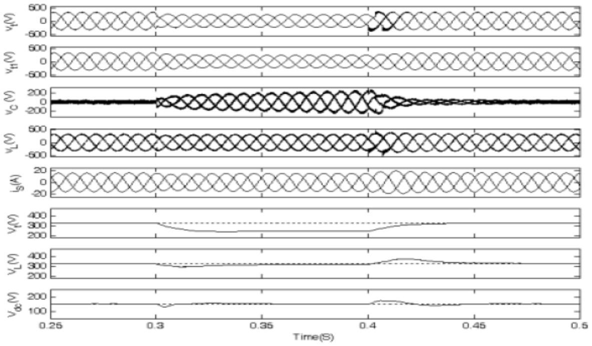

Fig.5 Voltage sag compensation using ANN controlled DVR.

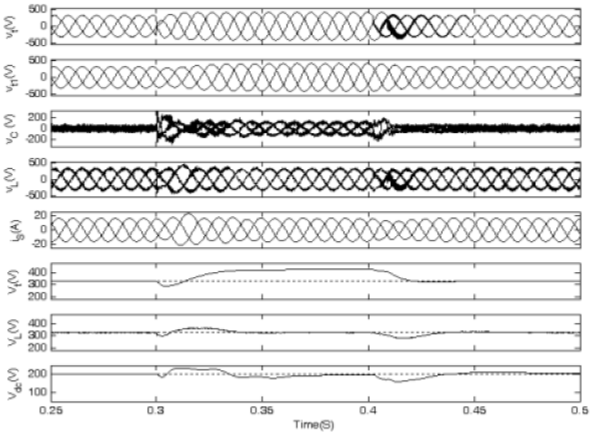

Fig.6 Voltage swell compensation using ANN controlled DVR

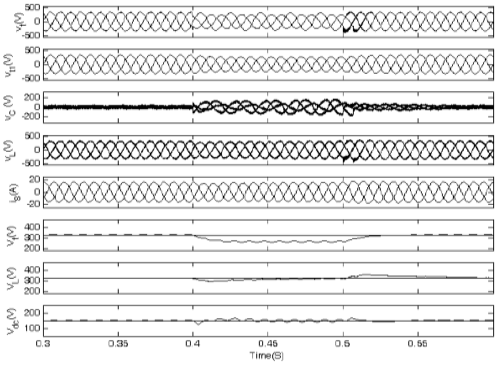

Fig.7 Unbalanced Voltage sag compensation using ANN controlled DVR.

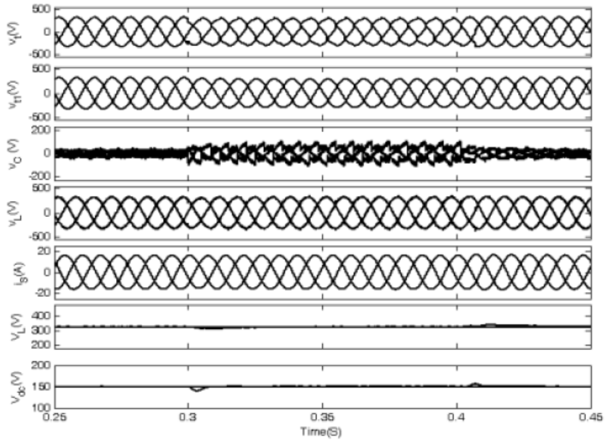

Fig.8. Voltage harmonic compensation using ANN controlled DVR.

Figure 8 demonstrates the successful compensation of harmonics in the load voltage. It shows various parameters, including the terminal voltage (vt), the fundamental voltage extracted by the Artificial Neural Network (ANN) (Vt1), DVR compensation voltage (vC), load voltage (vL), source current (is), terminal voltage amplitude (Vt), load voltage amplitude (VL), and DC bus voltage (vdc). The terminal voltage (vt) is distorted due to the switching of the non-linear load, whereas the load voltage (vL) remains sinusoidal and stable in magnitude due to the harmonic voltage (vC) injected by the DVR.

At the time of disturbance, the load voltage (vLa) exhibits a total harmonic distortion (THD) of 1.67% (Fig. 9(a)), while the voltage at the point of common coupling (PCC), vta, has a THD of 7.27% (Fig. 9(b)). The source current remains sinusoidal with a THD of 0.20% (Fig. 9(c)), showing that the DVR effectively mitigates harmonic distortions.

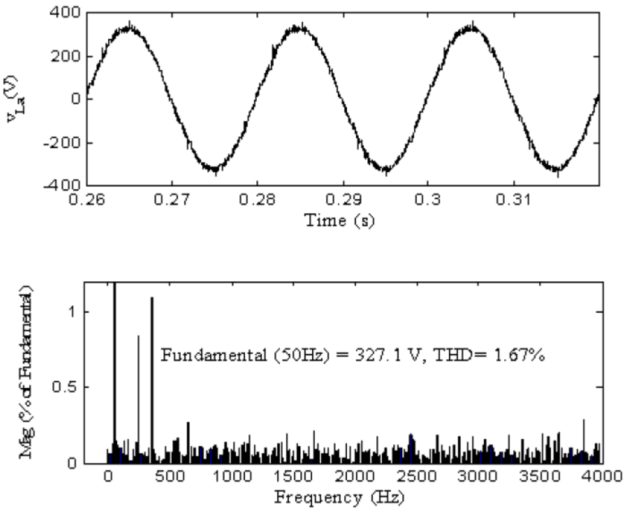

Fig.9 (a) Load voltage and harmonic spectrum

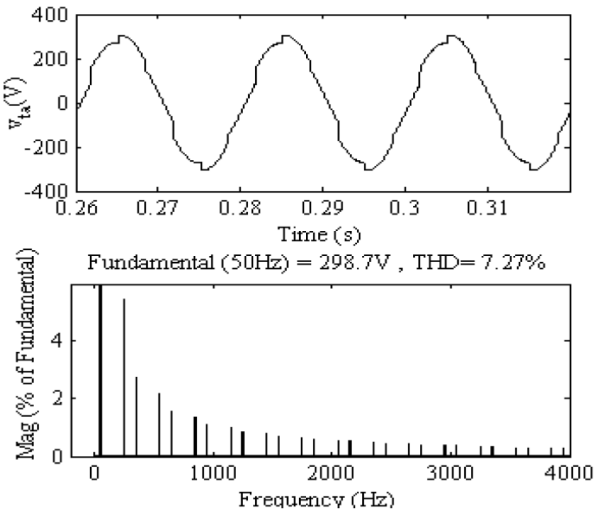

Fig9.(b) Terminal voltage and harmonic spectrum.

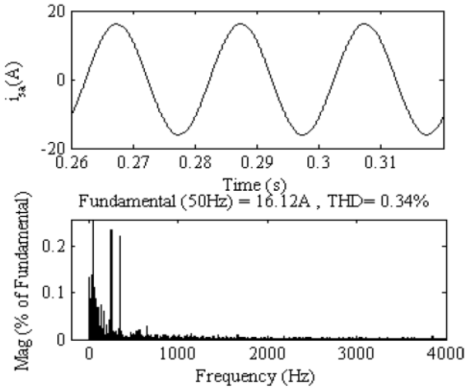

Fig.9 (c)Supply current and harmonic spectrum

Discussions

These results demonstrate the DVR's effectiveness in compensating for harmonics in supply voltages, as well as its ability to mitigate voltage sags, swells, and imbalances, leading to enhanced power quality.

Conclusions

The research findings clearly demonstrate that the integration of a Dynamic Voltage Restorer (DVR) with Artificial Neural Network (ANN) optimization techniques has significantly improved the power quality of the distribution network system. Data analysis indicates that the ANN-based DVR system outperforms alternative methods, such as fuzzy logic and PI controllers, particularly in terms of voltage sag and swell compensation. The ANN-based DVR successfully restores voltage sag and swell with a peak Unit Power (PU) value exceeding 0.98, offering better performance than both fuzzy logic and PI controllers. This high PU value signifies the system's ability to regulate voltage within acceptable limits, ensuring a stable and reliable power supply to connected loads. Additionally, the total harmonic distortion (THD) of 0.20% achieved by the ANN-based DVR system reflects a significant reduction in harmonic distortion within the distribution network. These results further validate the effectiveness of the ANN-based DVR system in improving power quality in the distribution network.

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