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A New Distribution System Power Quality Mitigation Method Using Recursive Least Squares Controlled Dynamic Voltage Restorer

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Abstract: Nonlinear loads are one of the main reasons why power quality problems happen in modern power distribution networks. These loads cause problems, including voltage sag, imbalance, and harmonics, which make the electrical network less reliable and less efficient. This study suggests a new architecture that includes a Dynamic Voltage Restorer (DVR) control method to help fix these problems with power quality. The control technique uses a Recursive Least Squares (RLS) method to get accurate and changing phasor estimates, which let the DVR respond better to changes in power quality in real time. The IEEE-13 node test feeder is used to test how well the planned system works by simulating different failure scenarios and load conditions, including voltage sag, imbalance, and harmonic distortion. Also, the DVR's performance with and without a filter is compared to see how well it can compensate for sagging when the load is not linear. MATLAB/Simulink is used for simulation and modelling, which gives a full picture of how the DVR works at different points in the system. The results show that adding the RLS-based control mechanism greatly enhances the quality of the voltage and keeps the system stable. This shows that the proposed method can improve the resilience and power quality of distribution systems that are exposed to nonlinear and defective operation situations.

Keywords: Power Quality; Dynamic Voltage Restorer; Recursive Least Squares; Voltage Sag; Nonlinear Loads; Distribution System; Voltage Source Converter; Load Conditions.

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1. Introduction

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The research has shown that the presence of nonlinear loads has many deteriorating effects on Power Quality (PQ). Considering the effect of degraded supply quality, it is necessary to minimise its impact. In fulfilling the task, measures have to be taken to mitigate the disturbances in power quality. The impact of a voltage disturbance in the distribution system causes an adverse effect on downstream connected sensitive loads. Especially, in the distribution system, the power quality effects arise and cause very high losses due to voltage sag and swell. The effects, such as short and low voltage sags, are primarily caused by the industries. Any low voltage drop occurring in the range of 10% to 90% of the normal RMS voltage during a period of 0.5 cycle to 1 minute is commonly defined as a Voltage dip [1]. Many of the distribution loads have nonlinear characteristics and produce voltage sag during various load conditions. Disturbances occur in post-fault conditions, and an abrupt heavy change in load results in frequency deviation, DC offset, and harmonics [2]. Hence, the estimation of instantaneous amplitude and phase angle for voltage, current, and frequency is essential to compensate for deviation during disturbances.

There are two common methods of eliminating the PQ issues. The first one is the load conditioning method, in which necessary arrangements are made so that the end equipment is made immune to the disturbances [3]. In certain cases, the end equipment is allowed to ride through the disturbance scenario while ensuring normal operation. The second method of mitigation is by the use of custom power devices. DSTATCOM, Dynamic Voltage Restorer (DVR), and Unified Power Quality Conditioner (UPQC) are applied to inject the required voltage to compensate for the PQ disturbances. Among the custom power devices, DVR has a quick response feature. Therefore, it became the most suitable and effective tool to compensate for the disturbance in the distribution system [4]. By injecting a compensating voltage appropriately, DVR will maintain a constant voltage at the load terminals under balanced and unbalanced load conditions.

Various control algorithms are implemented to provide an accurate phase angle, amplitude, and frequency. Among which, the performance of the least squares algorithm is satisfactory. Still, it has a computational burden. Therefore, to reduce the computational complexity and to achieve a fast convergence, the Recursive Least Squares (RLS) algorithm is implemented. Thus, the RLS algorithm, along with the DVR control scheme, provides fast convergence and elimination of harmonics, DC offset, etc. The RLS algorithm can estimate the difference in phasor quickly and tune the PID controller accurately. This algorithm is supported by the Newton-Raphson iteration method to estimate the parameters in the IEEE 13 bus system.

2. Literature Survey

This article provides an extensive review of power quality improvement techniques, aiming to enhance the quality of the distribution network and improve customer satisfaction. The implementation of filters, such as active, passive, and hybrid filters, leads to improved power quality. Moreover, FACTS devices, such as static VAR compensators, and custom power devices, such as UPQC, can also be used by combining with suitable control techniques. Thereby, the consumer can choose an appropriate technique that suits the particular applications [5]. The new improved DVR with an RLC filter connected between the injection transformer and the voltage source inverter (VSI) is introduced for the improvement of power quality. This DVR topology model is simulated using PSCAD/EMTDC. As a result, a highly efficient tool to eliminate the switching harmonics is achieved [6].

To compensate for the PQ issues related to current factors, a real-time-based three-phase static compensator is developed in Badoni et al. [7]. In this methodology, an adaptive neuro-fuzzy inference system combined with a least mean square-based control scheme is implemented. This method is compared with existing techniques like LMS and VSLMS. The advantages, like fast learning rate, convergence, and fewer errors, are the highlights of this system. An improved method to mitigate voltage sag, swell, interruption, imbalance, and fluctuations in a 3-phase distribution network is developed in Habib et al. [8]. Accordingly, a phase modulator is used to generate PWM switching signals in an IGBT-based Voltage Source Inverter. Thus, the THD is evaluated in different cases to correlate the efficiency of the system.

In addition, a DVR control scheme using a recent Glowworm swarm optimisation tuned PID controller is introduced in Siddarthan and Shunmugalatha [9]. Here, a Versatile Control Synchronous Frame Theory (VCSFT) showed an improved performance compared to PID, PID+GA, and PID+PSO controlled DVR systems. This technique achieved a better result with reduced THD values. Moreover, a coupled topology using a Hybrid Renewable Energy System (HRES) and a PI controller is introduced in Ben Abdelkadar et al. [10]. In which a solar panel, PEM fuel cell, and battery storage are connected to a DC/DC converter, which is interfaced with a DC transmission system. Voltage sag and swell are mitigated within a minimum period and with less THD of 5%. Roa and Priyadharson [11] discussed a PV-based DVR system to mitigate the sag and swell problems in the power network, where a DC/DC converter is utilised to extract the maximum power from the PV system. A hysteresis-based controller is implemented for the switching operation of the VSI in the DVR. Also, the Perturb and Observation method is designed to optimise the MPPT algorithm.

In such a way, the DVR operates to mitigate sag and swell during normal operation and operates as an Uninterrupted Power Supply (UPS) when the grid fails to supply power. This paper aims to reduce the faults that occur due to voltage sag, which triggers the current to attain the peak range in grid-connected loads. It also depicts the mathematical model that describes the behaviour of three-phase grid-connected inverters with RL filter under symmetrical and unsymmetrical voltage sags, and the results are validated using MATLAB simulations [12]. This study presents a comprehensive review of the various DSTATCOM configurations for single-phase (two-wire) and three-phase (three or four-wire) systems and control strategies for the compensation of different PQ problems in distribution systems [14].

In this paper, the proposed RLS algorithm belongs to the Least Mean Square (LMS) family. Several algorithms related to the control of DVR are LMS, Normalised LMS, Kalman Filtering, etc. When compared to those methods, the RLS algorithm is quite superior and promising. In the Least Mean Square method, the sample average is calculated from different realisations of the stochastic process. But, in the RLS algorithm, the mean values of variables are calculated at various time instants. The filter structure remains the same as in the LMS method. Though the RLS algorithm has a computational complexity greater than the LMS algorithm, the convergence speed is much faster than that of the LMS. Also, it provides accuracy and accurate results [13].

3. Proposed System

3.1. DVR Structure

The DVR model consists of a Voltage Source Converter (VSC), which is utilised to convert the DC power to an AC voltage. The Energy Storage unit provides the input to the voltage source converter. Similarly, an injection transformer is connected to inject or absorb the voltage. Moreover, the Isolators and bypass equipment are used to change the modes of operation of the DVR by controlling the isolators and switching equipment. Finally, the filters are employed to absorb the harmonics generated due to the switching operation of VSC (Figure 1).

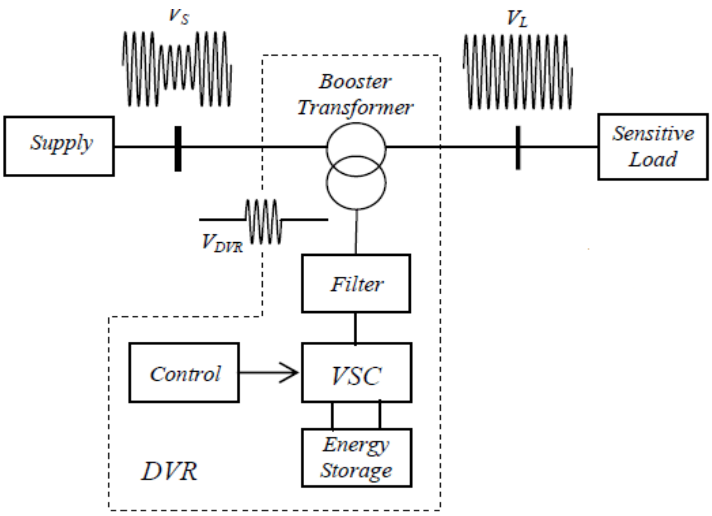

Figure 1: Schematic diagram of the proposed RLS-controlled DVR model

3.2. DVR Compensation Scheme

The compensation strategy should be more effective in recovering the magnitude of the load voltage. In such a case, if any deep sag occurs in the power system, the pre-sag compensation technique is essential. In this technique, the estimation of active power is done, which provides a better performance. The efficiency of pre-sag and in-phase compensation depends on the occurrence of a phase jump and the injection of voltage [15]. The injection of voltage is independent of power factor because the phase angle between the load current and grid voltage is not considered at all.

In such a way, the selection of a particular strategy to reestablish the particular voltage before the sag is quite interesting. If any failure occurs in the grid, the DVR has to deliver a suitable voltage magnitude depending on the phase of the new grid voltage [16]. Hence, in the proposed model, the DVR is designed with a higher voltage rating and less energy consumption from the DC link. Therefore, the Recursive filter is implemented for phasor estimation and to determine the fundamental and harmonic amplitudes. A fast response and more accuracy during normal state and disturbance conditions are achieved using the Recursive filter model. The operation of this DVR with a Recursive filter is explained in the following section.

3.3. DVR Modeling

A DVR is a series compensator that is used to protect the sensitive load during faults and disturbances in the power supply system.DVR is capable of absorbing or generating the real and reactive power at its output terminals. Here, Naidu et al. [17] consider the variables to be amplitude, phase angle, and injection voltage. Figure 2 shows the general model of a DVR connected to a distribution system. Let V_s denotes the supply voltage, I_s denotes the line current, V_t denote the terminal voltage, V_j represent the compensation voltage, and Z_lbe the load impedance.

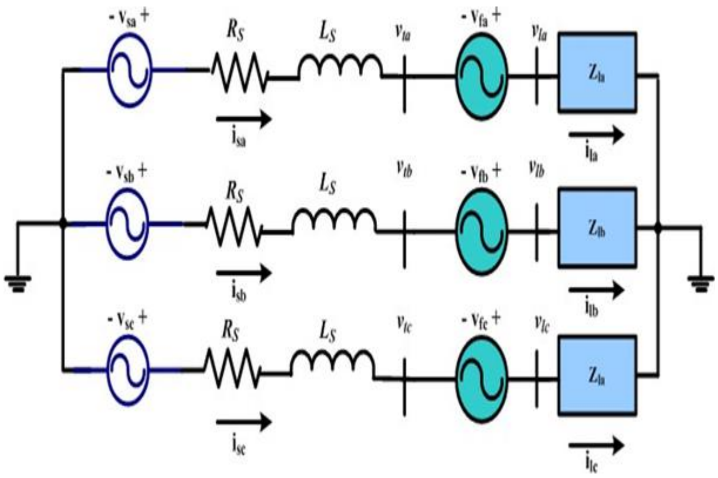

Figure 2: Mathematical modelling of DVR

From the above modelling diagram, the load voltage V_L can be written as the sum of the terminal voltage at V_t and the DVR voltage V_jas.

$$V_L = V_t + V_j \qquad (1)$$

The terminal voltage V_t is given as,

$$V_t = V_L - V_j(a_1 + jb_1) \qquad (2)$$

Where, a_1+jb_1is the unit phasor at 900, solving the above equation, we get,

$$V_{j1}^2 = 2a_1 V_L V_{j1} + V_l^2 - V_{t1}^2 = 0 \qquad (3)$$

Therefore, V_j1is obtained from the above equation. Now, the series compensation voltage is obtained by solving equation (4)

$$V_t = V_{t1} - V_t^{com} \qquad (4)$$

$$V_j = V_{j1} - V_t^{com} \qquad (5)$$

Where V_t^com is the unbalanced harmonic voltage, hence, the positive sequence term will cancel all negative and zero sequence components and harmonic components. For a given value of V_t1 and target V_L, it produces two real values of V_j1. The maximum value of V_Lis acquired as:

$$V_L = \frac{V_{t1}}{\sqrt{1 - a_1^2}} \qquad (6)$$

Substituting (5) in (3), the series compensating voltage is simplified as,

$$V_{j1} = a_1 V_L \qquad (7)$$

The modified form of the above equation is expressed as,

$$V_{j1} = \frac{V_{t1}}{cos\varphi_1} \qquad (8)$$

3.4. Extraction of Fundamental Symmetrical Component

Fundamental terminal voltage V_t1 is obtained from the fundamental symmetrical component [12]. By considering a set of three unbalanced voltage phasors in the form:

$$V_a = V_{ma}\sin(\omega t + \varphi_a) \qquad (9)$$

The symmetrical component of three quantities for the three phases can be written as,

$$\begin{bmatrix} V_{a1} \\ V_{b1} \\ V_{c1} \end{bmatrix} = \frac{1}{\sqrt{6}} \begin{bmatrix} V_{ma}e^{j\varphi_a} + V_{mb}e^{j\varphi_b} + V_{mc}e^{j\varphi_c} \\ V_{ma}e^{j\varphi_a} + aV_{mb}e^{j\varphi_b} + a^2V_{mc}e^{j\varphi_c} \\ V_{ma}e^{j\varphi_a} + a^2V_{mb}e^{j\varphi_b} + aV_{mc}e^{j\varphi_c} \end{bmatrix} \qquad (10)$$

The superposition of all harmonic components with the fundamental waveform represents the distortion voltage and current. By applying the Fourier analysis, the harmonic component values are separated from the fundamental component.

Using the expression form of the Fourier series, a periodic signal x(t) can be expressed as,

$$x(t) = \sum_{k=-\infty}^{k=\infty} C_k e^{jk\omega t} \qquad (11)$$

Where the coefficient C_k is given by,

$$C_k = \frac{1}{T}\int x(t)e^{-j\omega t}\, dt \qquad (12)$$

Using (12), the fundamental component is given by,

$$C_{a1} = \frac{1}{t_0\sqrt{3}}[V_{ma}\sin(\omega t + \varphi_a) + aV_{mb}\sin(\omega t + \varphi_b) + a^2V_{mc}\sin(\omega t + \varphi_c)](sin\omega t + jcos\omega t \quad (13)$$

Integrating and simplifying the above equation, we get,

$$C_{a1} = \frac{1}{2\sqrt{3}}[V_{ma}e^{j\varphi_a} + aV_{mb}e^{j\varphi_a} + a^2V_{mc}e^{j\varphi_a}] \qquad (14)$$

Comparing (10) and (14), we get,

$$V_{a1} = \sqrt{2}C_{a1}V_{a1} = \frac{\sqrt{2}}{T_0}\int V_{a1}e^{-j(\omega t - \frac{\varphi}{2})}dt \qquad (15)$$

Similarly, $V_{a0} = \sqrt{2}C_{a0}V_{a2} = \sqrt{2}C_{a2}$ (16)

Equation (10) can be rewritten as,

$$C_{a1} = \frac{1}{\sqrt{6}}[V_{ma}e^{j\varphi_a} + aV_{mb}e^{j\varphi_a} + a^2V_{mc}e^{j\varphi_a}] \qquad (17)$$

Where, V_a1=V_t1, ie, the fundamental terminal voltage or actual value determined in terms of magnitude and phase angle. The desired output response is obtained by comparing the reference with actual values.

3.5. Phasor Estimation using Recursive Filter

As described in the previous section, Martins et al. [18], DVR is a series compensating device for the low or medium distribution system to mitigate the power quality disturbances. Admittedly, Phasor estimation is essential to achieve the desired performance of DVR, which is highlighted in this section. The power system signal with noise is represented in the following manner:

$$y(t) = A_1 \sin(\omega_0 t + \varphi_1) + \epsilon(t) \qquad (18)$$

$$y(t) = A_1 sin\omega_0 kt \times cos\varphi_1 + A_1 cos\omega_0 kt \times sin\varphi_1 + \epsilon(k) \qquad (19)$$

$$y(t) = [sin\omega_0 kt \times cos\omega_0 kt] \times [\alpha\beta]^T + \epsilon(k) \qquad (20)$$

Further simplification can be done, and expressing it in a Recursive form gives:

$$y(k) = h(k)\theta + \epsilon(k) \qquad (21)$$

The estimation of parameters is done using the RLS estimation technique, using the following computational steps.

$$\hat{\theta} = \theta(k-1) + k(k)\epsilon(k) \qquad (22)$$

The measurement error is given by:

$$\epsilon(k) = y(k) - h(k)^T\theta(k-1) \qquad (23)$$

Later, the gain 'k' is updated using the equation.

$$k(k) = p(k-1)h(k)[\eta I + h(k)^T p(k-1)h(k)]^{-1} \qquad (24)$$

Where, $\alpha_1 = \theta_{11} = A_1 cos\theta_1, \beta_1 = \theta_{21} = A_1 sin\theta_1$and ϵ(k) is the error signal, θ(k) is the currently estimated values, θ(k-1) is the past estimated value, k(k)is the kalman gain, p(k) is the error covariance matrix and ($0<\eta<1$) is the forgetting factor.

The Covariance matrix can be updated using the following updating law as given by:

$$P(k)=\frac{[1-k(k)h(k)^T](p(k-1))}{\eta} \qquad (25)$$

Eqs (23) to (25) are initialised at t=0. The initial covariance matrix is usually chosen to be very large, p=δI, where δ is a large number and I is a square identity matrix. After getting the final estimation of θ=[αβ]^T, the fundamental amplitude A_1 and φ_1 phase can be estimated as given below.

$$A_1 = \sqrt{(A_1 cos\varphi_1)^2 + (A_1 sin\varphi_1)^2} \qquad (26)$$

where, $A_1 = \sqrt{\alpha^2 + \beta^2}$ and $\varphi = tan^{-1}(\frac{\beta}{\alpha})$

3.6. Algorithm of Recursive Least Squares

Step 1: Initialise the magnitude of power system parameters, f, and ϕ.
Step 2: Evaluate the discredited signal from the known value of the unknown parameters.
Step 3: Calculate the difference between the actual error and the estimated error.
Step 4: Form a covariance matrix with the past and present events.
Step 5: Compute the gain value.
Step 6: Calculate the power and phase angle of the power signal.
Step 7: Update the corresponding gain value.
Step 8: Repeat the procedure from step 4 until the final iteration is reached.
Step 9: Evaluate the amplitude and phase angle of the harmonic component.

4. Results and Discussion

Figure 3 above shows the IEEE-13 bus system, which is considered for the implementation of the proposed work. The modelling is done using MATLAB, and the Newton-Raphson method is used to get the power system parameters. In which the source voltage 11.5 KV is connected through the main transformer between the nodes 1 and 2.

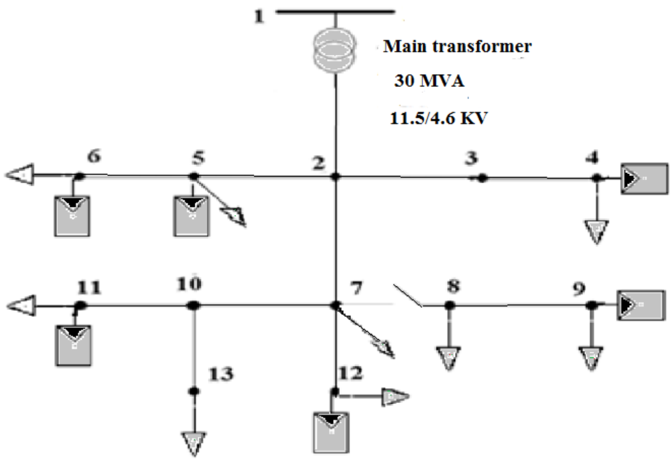

Figure 3: IEEE 13- bus radial distribution system

Likewise, the line voltages and currents are measured across the nodes 1,2, 3, and 4. A phase fault is created at node three, and a voltage sag is experienced at node 3. The simulations are tested under linear and nonlinear load conditions. Compensation for sag is carried out with the base load. Moreover, Yildirim et al. [19] mitigate the harmonics and unbalances that occur under fault conditions. Thus, the performance of the DVR is compared with the output that includes the recursive filter.

4.1. Case 1: Compensation of Unbalances with Linear Load

Normally, the distribution system gets distorted and unbalanced under three-phase and single-phase load conditions due to various types of consumers. In such a case, the current amplitude shows an unbalanced waveform. When the DVR, along with the designed controller, is connected to the system, the current gets compensated after the injection of a series voltage. Figure 4(a) shows the compensation of Unbalances with a linear load voltage waveform. Figures 4(b) and 4(c) show the current waveform before and after the compensation. Moreover, the series injected voltage is depicted in Figure 4(d). Likewise, the regulated DC capacitor voltage is presented in Figure 4(e).

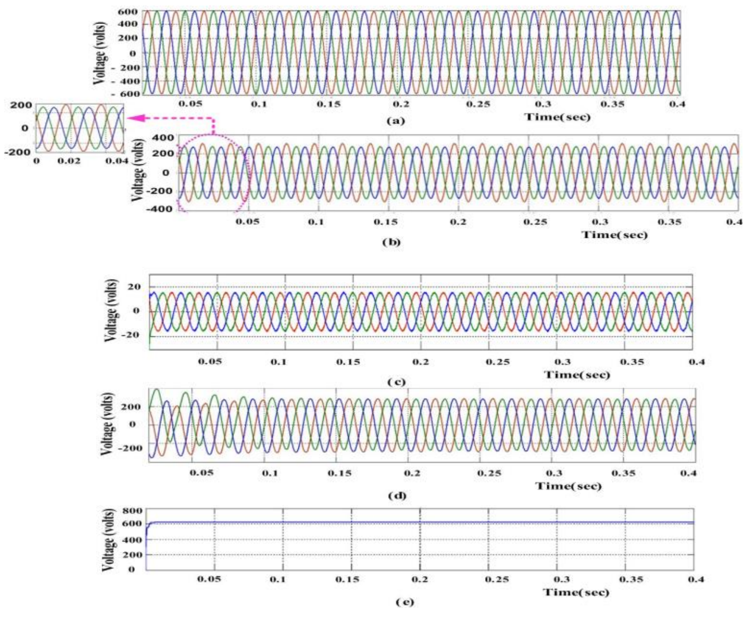

Figure 4: Compensation of imbalances with linear load

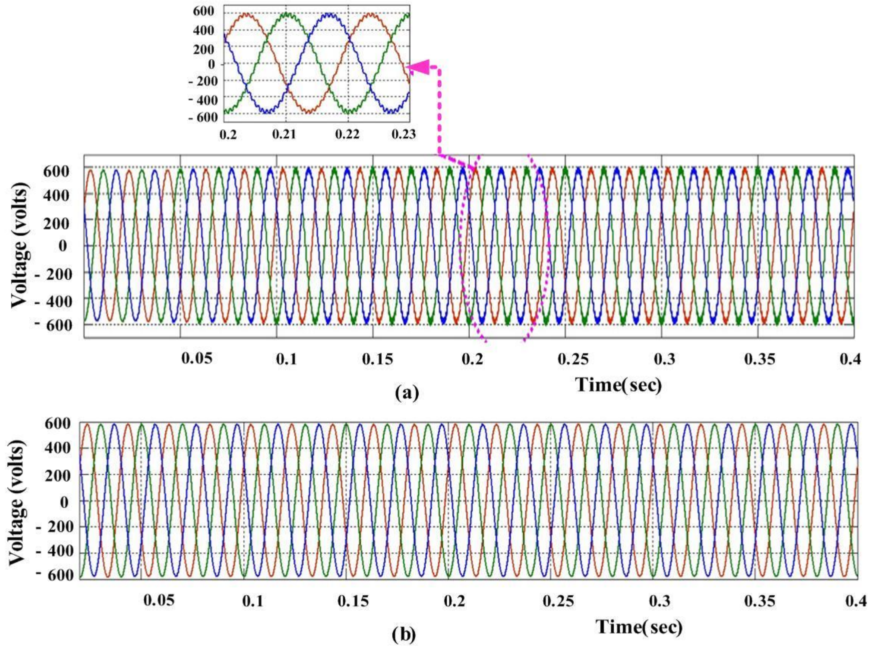

Figure 5: Compensation of harmonics with nonlinear load

Similarly, the distribution system gets disturbed by harmonics under three-phase and single-phase nonlinear load conditions due to various types of consumers. In such a case, the voltage amplitude shows a waveform of harmonic nature (Figure 6 (a), (b) & (c)). When the DVR, along with the designed controller, is connected to the system, the voltage gets compensated after the injection of a series voltage (Figure 7 (a), (b) & (c)). Figure 5 (a) shows the voltage waveform before compensation, and Figure 5(b) shows the voltage waveform after the compensation.

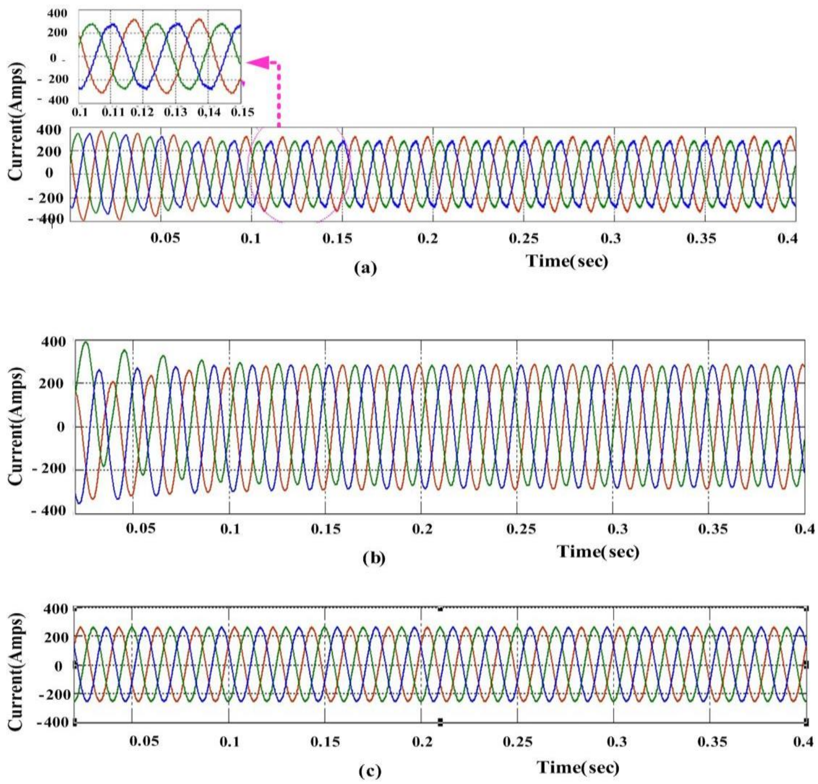

Figure 6: Compensation of harmonics and unbalance with nonlinear load

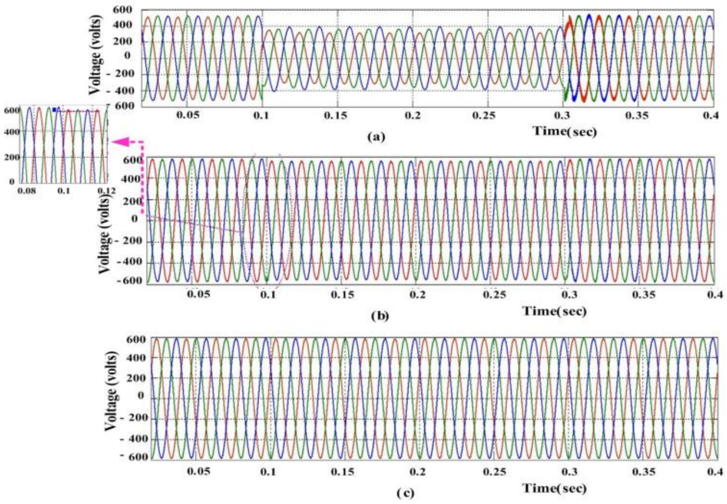

Figure 7: Compensation of sag

5. Conclusion

A real IEEE-13 node distribution system with mostly nonlinear loads is used to test how well the proposed method works. These nonlinearities cause problems with power quality (PQ), such as voltage drops, harmonic distortions, and imbalances. To solve these problems, we evaluated and implemented the suggested Dynamic Voltage Restorer (DVR) with a Recursive Least Squares (RLS) phasor estimation algorithm. The simulation findings show that the DVR works well even when there are faults, such as balanced and unbalanced three-phase failures. The DVR works well to fix voltage sags and improve voltage quality at the point of common coupling (PCC), no matter what kind of fault or load imbalance there is. The RLS method makes voltage estimation more accurate and faster, which lets the DVR respond quickly and effectively to system problems. This ability to adapt ensures that the power distribution system remains stable and strong, even when things go wrong or aren't working right. The DVR with the recursive filter always does better than standard PQ compensation methods in all of the case studies, even when there is sag, voltage imbalance, or harmonic distortion. The results show that the system can offer important loads with a steady, high-quality voltage supply, which means less downtime and better reliability. In general, the suggested DVR with RLS not only improves PQ in a better way, but it is also a cost-effective and computationally efficient solution. Its efficacy and dependability make it a key part of specialised power devices for smart grids and delicate load settings.

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Ethics and Consent Statement: This manuscript is the authors' original work, not previously published or under consideration elsewhere, and truthfully reflects their research and analysis. The author has been informed of all risks and benefits, with questions answered satisfactorily. Participation in the study is voluntary, with continued access to the research team for any future concerns.

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