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Analysis of novel cubature Kalman filter based DVR control for mitigating power quality issues in electrical distribution systems

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ABSTRACT

Power quality (PQ) is a critical concern in modern distribution networks due to voltage disturbances caused by excessive load tapping at the Point of common coupling (PCC) and nonlinear loads. Voltage sag and swell conditions adversely affect sensitive electrical equipment and system stability. The dynamic voltage restorer (DVR) is an effective power-electronic device for mitigating these disturbances. However, its compensation performance largely depends on the accuracy and response speed of the control algorithm. This paper proposes a cubature Kalman Filter (CKF)-based voltage estimation technique to improve the detection and mitigation of voltage swell disturbances in distribution systems. The proposed CKF algorithm accurately estimates system voltage and generates reference signals for controlling the voltage source converter (VSC) of the DVR. Based on these reference signals, the DVR injects an appropriate compensating voltage into the distribution line, restoring the load voltage to its desired value. The proposed technique improves disturbance detection accuracy, estimation reliability, and dynamic compensation performance. The effectiveness of the CKF-based DVR control strategy is implemented and evaluated using MATLAB/Simulink. Furthermore, its performance is compared with extended Kalman filter (EKF) and linear Kalman filter (LKF) techniques to demonstrate its improved estimation accuracy, faster response, and effectiveness in mitigating voltage swell disturbances in sensitive load-connected distribution systems.

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1. INTRODUCTION

Power quality is essential to ensure uninterrupted and efficient operations of electrical power system with ease. However, with the increasing adoption of modern industrial equipment such as semiconductor devices, programmable logic controllers, and other electronic systems, PQ issues have become more prominent. Voltage sag and swell are primarily characterized by their magnitude and duration. A voltage

swell refers to an increase in root mean square (RMS) voltage or current at the power frequency, lasting from 0.5 cycles to 1 minute, with typical magnitudes ranging from 1.1 to 1.8 per unit (p.u). Power-quality disturbances and harmonic estimation have received considerable attention in modern electrical distribution systems. Various computational and estimation techniques have been investigated for accurate identification and mitigation of power-quality disturbances [1]-[3]. These studies provide the basis for developing advanced estimation and compensation techniques for voltage disturbances in distribution systems. The swell magnitude is defined by the remaining voltage, which always exceeds 1.0 p.u. Common causes of voltage swell include the switching off of large loads and the energization of capacitor banks [4]-[7]. The effects of voltage swell can be detrimental, leading to control delays, equipment tripping, overheating, and in severe cases, permanent damage to electrical systems. To address these challenges, advancements in power electronics and control technologies have facilitated the development of solutions to mitigate PQ problems and protect sensitive loads. Several methods are available to prevent equipment malfunctions caused by voltage swells, but the application of custom power devices is widely regarded as the most effective approach. These devices provide efficient and reliable mitigation of voltage swell disturbances, ensuring stable and uninterrupted operation of industrial equipment [8]-[11].

The DVR is an indispensable tool for mitigating voltage disturbances in modern distribution systems. With its advanced components, such as the energy storage system, voltage source converter, coupling transformer, output filter, and sophisticated control system, the DVR offers a robust solution for ensuring power quality. As industries continue to rely on sensitive electronic equipment, the demand for DVRs is expected to grow, further cementing their role as a cornerstone of power quality improvement technologies [9]-[17]. Its ability to handle voltage swells effectively stems from its sophisticated design and functionality. By rapidly injecting compensating voltages into the distribution line, the DVR prevents adverse effects such as equipment malfunctions, overheating, and system downtime. The DVR can detect and compensate for voltage disturbances in milliseconds, ensuring minimal impact on connected loads. Advanced control algorithms enable accurate voltage compensation, maintaining supply voltage within acceptable limits. The DVR can handle a wide range of disturbances, including voltage sags, swells, and harmonics, making it a versatile solution for various applications. Modern DVR systems are compact and require less installation space compared to other power quality devices, making them suitable for industries with limited space availability.

The DVR is increasingly being adopted in industries such as manufacturing, telecommunications, healthcare, and data centers, where the quality and reliability of power supply are critical. For example, in semiconductor manufacturing, even minor voltage disturbances can lead to significant production losses and equipment damage. Similarly, in data centers, voltage sags or swells can disrupt operations, leading to data loss and service interruptions. The DVR's ability to maintain stable voltage levels ensures uninterrupted operation, reducing downtime and enhancing productivity. In this paper, a cubature Kalman filter (CKF)-based estimation model is proposed to support the DVR's control algorithm. This model is used to estimate the symmetrical components of the supply voltages, which are essential for detecting and compensating for voltage swells [18]-[25].

Recent DVR control strategies have employed conventional reference-generation methods, Kalman-filter-based estimation, and advanced nonlinear estimation techniques to improve voltage-disturbance compensation. Conventional control methods provide relatively simple implementation but may have limited estimation capability during rapidly varying and nonlinear disturbances. The linear Kalman filter (LKF) provides effective state estimation for linear system models; however, its performance can deteriorate when nonlinear system characteristics become significant. The extended Kalman filter (EKF) extends Kalman filtering to nonlinear systems through local linearization, but its performance depends on the accuracy of the linearized model and requires Jacobian calculation. Recent studies have investigated CKF-based estimation for nonlinear power-system and grid-connected converter applications, demonstrating its capability to estimate dynamic states without explicit Jacobian calculation [26]-[29]. These developments indicate that CKF is a promising alternative for voltage-state estimation in DVR applications. However, limited studies have specifically integrated CKF-based symmetrical-component estimation with DVR control for rapid voltage-swell compensation. This gap motivates the development of the proposed CKF-based DVR control strategy.

As summarized in Table 1, existing DVR strategies provide effective voltage compensation but have limitations in accurately estimating nonlinear voltage states during disturbances. CKF offers an attractive estimation framework because it avoids explicit Jacobian calculation while retaining nonlinear state-estimation capability. Therefore, this study investigates the integration of CKF-based symmetrical-component estimation with DVR control for voltage-swell mitigation and evaluates its performance against conventional, LKF, and EKF-based approaches.

The proposed work integrates a CKF with the DVR control system to estimate the symmetrical components of the supply voltage and accurately detect voltage-swell disturbances. The estimated positive-

sequence voltage is used to generate the required DVR compensating-voltage reference. The proposed method is compared with conventional, KF-based, and EKF-based DVR controllers to evaluate its voltage compensation and harmonic performance.

Table 1. Critical comparison of DVR estimation and control approaches

Approach	Main advantage	Major limitation
Conventional DVR control	Simple implementation	Limited state-estimation capability
LKF-based DVR	Effective for linear estimation	Limited for nonlinear system behavior
EKF-based DVR	Handles nonlinear models	Requires linearization and Jacobian calculation
CKF-based estimation	Nonlinear estimation without explicit Jacobian	Higher computational requirement than basic KF

2. DYNAMIC VOLTAGE RESTORER WITH PROPOSED SYSTEM

The main objective of the DVR is to protect sensitive loads from voltage sags and swells originating in the distribution network. Beyond compensating for voltage sags and swells, the DVR can also be used to address line voltage harmonics, reduce voltage transients, and restrict fault currents. In this study, a CKF-based estimation technique is proposed to improve the DVR's effectiveness in mitigating voltage swell issues in electrical distribution systems. The proposed CKF-based DVR is designed to address both voltage sags and swells. The control algorithm leverages the symmetrical components of the supply voltages to detect and mitigate voltage distortions. By employing this control strategy, the DVR can preemptively address voltage sag and swell disturbances, ensuring that the voltage delivered to the load is free from distortion. This ensures that sensitive loads connected to the DVR are effectively protected. Furthermore, the DVR's control and protection unit is optimized to enhance system performance while minimizing operational losses based on the prevailing conditions [26]-[33].

The integration of the CKF-based estimation method enables precise and rapid compensation, making the DVR a highly effective solution for maintaining power quality and ensuring the reliable operation of sensitive equipment in the distribution network. Figure 1 illustrates the block diagram of the proposed control scheme, where the CKF model is employed to estimate the symmetrical components of the supply voltage. These estimated symmetrical components are then compared with the reference symmetrical components to determine the appropriate injecting voltage required by the DVR to compensate for the detected voltage swell. The reference symmetrical components represent the desired symmetrical components that correspond to the voltage swell conditions, which are calculated using the proposed control algorithm. This control scheme ensures accurate detection and compensation of voltage swells by generating the necessary injection voltage [26], [27], [31]-[33]. The detailed methodology for obtaining these reference symmetrical components and their role in the compensation process is elaborated upon in this section.

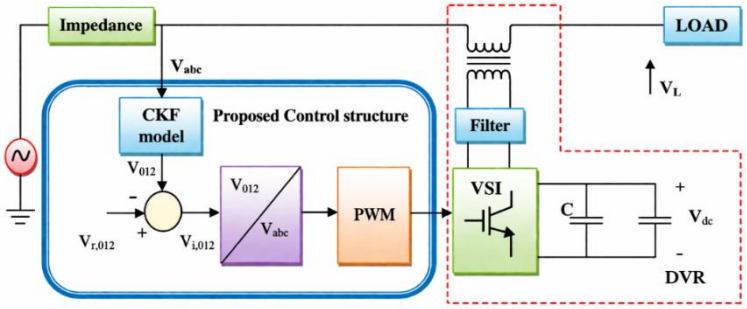

Figure 1. System control structure with DVR

3. METHODOLOGY OF THE PROPOSED CONTROLLER

The CKF-based control methodology begins with the measurement of the three-phase supply voltages. These measured voltages are represented mathematically and used as the measurement input to the estimation model. The (1)-(5) describe the voltage measurement and state representation used for the CKF estimator. The state vector contains the voltage-related variables required to estimate the instantaneous system condition, while the measurement vector represents the measured supply-voltage quantities.

The (1) represents the measured supply-voltage signal, while the (2) expresses the corresponding measurement relationship. The (3)-(5) establish the relationship between the measured quantities and the state variables used by the estimator. The measurement matrix defines how the state variables are related to the available voltage measurements.

$$\begin{bmatrix} V_a(t) \\ V_b(t) \\ V_c(t) \end{bmatrix} = \begin{bmatrix} V_m^a \sin(\omega t + \varphi_a) \\ V_m^b \sin(\omega t + \varphi_b) \\ V_m^c \sin(\omega t + \varphi_c) \end{bmatrix} \quad (1)$$

$$V_a(t) = \begin{bmatrix} V_m^0 \sin(\omega t + \varphi_0) \\ V_m^1 \sin(\omega t + \varphi_p) \\ V_m^2 \sin(\omega t + \varphi_n) \end{bmatrix} \quad (2)$$

$$V_b(t) = \begin{bmatrix} V_m^0 \sin(\omega t + \varphi_0) \\ V_m^1 \sin(\omega t + \varphi_p - 120) \\ V_m^2 \sin(\omega t + \varphi_n + 120) \end{bmatrix} \quad (3)$$

$$V_c(t) = \begin{bmatrix} V_m^0 \sin(\omega t + \varphi_0) \\ V_m^1 \sin(\omega t + \varphi_p + 120) \\ V_m^2 \sin(\omega t + \varphi_n - 120) \end{bmatrix} \quad (4)$$

$$\begin{bmatrix} V_a(t) \\ V_b(t) \\ V_c(t) \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} & h_{13} & h_{14} & h_{15} & h_{16} \\ h_{21} & h_{22} & h_{23} & h_{24} & h_{25} & h_{26} \\ h_{31} & h_{32} & h_{33} & h_{34} & h_{35} & h_{36} \end{bmatrix} \begin{bmatrix} V_m^0 \cos(\varphi_0) \\ V_m^0 \sin(\varphi_0) \\ V_m^1 \cos(\varphi_1) \\ V_m^1 \sin(\varphi_1) \\ V_m^2 \cos(\varphi_2) \\ V_m^2 \sin(\varphi_2) \end{bmatrix} \quad (5)$$

Where h_{ij} is i^{th}, j^{th} element of the measurement matrix.

The state-space representation used for CKF estimation is introduced in (6)-(8). The (6) defines the state vector used by the estimator, whereas (7) represents the measured voltage information at the corresponding sampling instant. The (8) relates the state variables to the measured quantities. These equations provide the mathematical basis for applying the CKF to the measured three-phase supply voltage.

$$X(t) = \begin{bmatrix} x_1(t) \\ x_2(t) \\ x_3(t) \\ x_4(t) \\ x_5(t) \\ x_6(t) \end{bmatrix} = \begin{bmatrix} V_m^0 \cos(\varphi_0) \\ V_m^0 \sin(\varphi_0) \\ V_m^1 \cos(\varphi_1) \\ V_m^1 \sin(\varphi_1) \\ V_m^2 \cos(\varphi_2) \\ V_m^2 \sin(\varphi_2) \end{bmatrix} \quad (6)$$

This representation allows for a systematic characterization of the state variables, facilitating the analysis and implementation of the proposed control algorithm. By employing symmetrical components, the state variables effectively capture the key attributes of the system dynamics under various operating conditions, including voltage sags and swells. The detailed formulation of the state vector is provided below to establish a clear framework for its utilization in the proposed model.

$$Z(t) = H(t).X(t) \quad (7)$$

Where: $Z(t)$ is the measured voltage matrix at time instant t; and $H(t)$ is the measurement matrix. We have:

$$\begin{bmatrix} x_1(k) \\ x_2(k) \\ x_3(k) \\ x_4(k) \\ x_5(k) \\ x_6(k) \end{bmatrix} = \begin{bmatrix} V_m^0 \cos(\varphi_0) \\ V_m^0 \sin(\varphi_0) \\ V_m^1 \cos(\varphi_1) \\ V_m^1 \sin(\varphi_1) \\ V_m^2 \cos(\varphi_2) \\ V_m^2 \sin(\varphi_2) \end{bmatrix} \quad (8)$$

Where, $x_i(k)$ is the kth sample of ith state variable.

The (9)-(11) simplify the state and measurement relationships and provide the mathematical form required for the subsequent CKF prediction and update operations. The estimated state variables obtained

from this process are subsequently used to determine the symmetrical components of the supply voltage. Thus, (1)-(11) establish the mathematical relationship between the measured supply voltage and the state variables required for the proposed CKF-based DVR control. From the simplification of (8), we get:

$$\begin{bmatrix} x_1(k+1) \\ . \\ . \\ . \\ x. \\ x_6(k+1) \end{bmatrix} \approx \begin{bmatrix} x_1(k) \\ . \\ . \\ . \\ . \\ x_6(k) \end{bmatrix} \tag{9}$$

$$X(k+1) = X(k) \tag{10}$$

$$\left.\begin{aligned} X(k+1) &= f[X(k),k] + w(k) \\ Z(k) &= h[X(k),k] + v(k) \end{aligned}\right\} \tag{11}$$

In (9)-(11), (X(k)) denotes the state vector at the (k^{th}) sampling instant, (Z(k)) denotes the measured voltage vector, and (H) represents the measurement matrix. The state vector contains the voltage-related variables estimated by the CKF, while the measurement vector contains the corresponding measured supply-voltage quantities. The measurement matrix establishes the relationship between the state variables and measured voltages. The process and measurement uncertainties are represented by their corresponding covariance matrices. These definitions provide the required information for implementing the CKF prediction and measurement-update stages described in the following subsections.

CKF is an advanced nonlinear filtering technique developed for the accurate estimation of states in high-dimensional systems. Its methodology is grounded in the spherical-radial cubature rule, which facilitates precise numerical computation of the multivariate moment integrals required in nonlinear Bayesian filtering. One of the primary strengths of the CKF lies in its adoption of a third-degree cubature rule, which generates a set of cubature points that scale linearly with the dimensionality of the state vector. This linear scaling not only enhances computational efficiency but also ensures that the filter remains effective and practical for systems with a large number of state variables. CKF effectively approximates the multi-dimensional integrals. This approach allows the CKF to essentially perform nonlinear filtering through the application of linear estimation theory, hence its name. The CKF demonstrates high numerical accuracy and exhibits excellent scalability for high-dimensional problems, making it a valuable tool for a wide range of applications.

The CKF estimates the voltage states using the measured three-phase supply voltages. The state vector is initialized, and cubature points are generated and propagated through the system and measurement models. The predicted state is corrected using the measured voltage, process-noise covariance (Q), and measurement-noise covariance (R). The estimated states are then used to obtain the symmetrical components required for voltage-swell detection and DVR compensation. Based on the state-space formulation in (1)-(11), the CKF is applied in three principal stages: initialization, prediction, and measurement update. The corresponding estimation procedure is described in the following subsections.

i) Initialisation

$$\hat{x}_0 = E[x_0] \tag{12}$$

$$P_0 = E[(x_0 - \hat{x}_0)(x_0 - \hat{x}_0)^t] \tag{13}$$

The unit sigma points are calculated as (14).

$$\xi^{(i)} = \begin{cases} \sqrt{n}e_i, \text{ i} = 1,\ldots,2\text{n} \\ -\sqrt{n}e_{i-n}, \text{i} = n+1,\ldots,2\text{n}. \end{cases} \tag{14}$$

where e_i denotes a unit vector. Approximating the integral as (15).

$$\int g(x)N(x|m,P)dx \approx \frac{1}{n}\sum_{i=1}^{2n} g(m + \sqrt{P}\xi^{(i)} \tag{15}$$

where $\sqrt{P}$ is a matrix square root defined by $P = \sqrt{P}\sqrt{P}^T$.

ii) Prediction

The sigma points are calculated as (16):

$$X_{k-1}^{(i)} = m_{k-1} + \sqrt{P_{k-1}}\xi^{(i)} \text{ i=1,…….2n} \quad (16)$$

where the unit sigma points are defined as (17).

$$\xi^{(i)} = \begin{cases} \sqrt{n}e_i, \text{ i} = 1,\ldots,2\text{n} \\ -\sqrt{n}e_{i-n}, \text{i} = n+1,\ldots,2\text{n}. \end{cases} \quad (17)$$

The sigma points are propagated through the dynamic model and calculated as (18).

$$\hat{X}_k^{(i)} = f(X_{k-1}^{(i)}),\ \text{i} = 1,\ldots,2\text{n} \quad (18)$$

The predicted mean and the predicted covariance are calculated as (19).

$$\begin{aligned} m_k^- &= \tfrac{1}{2\text{n}}\textstyle\sum_{i=1}^{2\text{n}} \hat{X}_k^{(i)}, \\ P_k^- &= \tfrac{1}{2\text{n}}\textstyle\sum_{i=1}^{2\text{n}} (\hat{X}_k^{(i)} - m_k^-)(\hat{X}_k^{(i)} - m_k^-)^T + Q_{k-1}. \end{aligned} \quad (19)$$

iii) Update

$$X_k^{-(i)} = m_k^{(i)} + \sqrt{P_k^-}\xi^{(i)}, \text{ i} = 1,\ldots..,2\text{n}, \quad (20)$$

Sigma points are propagated through the measurement model as (21).

$$\hat{y}_k^{(i)} = h(X_k^{-(i)}),\ \text{i} = 1\ldots2\text{n} \quad (21)$$

Finally, we have:

$$\begin{aligned} \mu_k &= \tfrac{1}{2n}\textstyle\sum_{i=1}^{2n} \hat{y}_k^{(i)}, \\ S_k &= \frac{1}{2n}\sum_{i=1}^{2n} (\hat{y}_k^{(i)} - \mu_k)(\hat{y}_k^{(i)} - \mu_k)^T + R_k, \\ C_k &= \tfrac{1}{2n}\textstyle\sum_{i=1}^{2n} (X_k^{-(i)} - m_k^-)(\hat{y}_k^{(i)} - \mu_k)^T. \end{aligned} \quad (22)$$

The filter gain K_k and the filtered state mean m_k and covariance P_k are calculated as (23).

$$\begin{aligned} K_k &= C_k S_k^{-1}, \\ m_k &= m_k^- + K_k[y_k - \mu_k], \\ P_k &= P_k^- - K_k S_k K_k^T. \end{aligned} \quad (23)$$

The estimation of state variables is conducted using the CKF model. Based on these estimated state variables, the corresponding symmetrical components are derived. This process is mathematically represented as (24).

$$\left.\begin{aligned} V_{0m} &= \sqrt{x_1^2 + x_2^2}; \phi_0 = tan^{-1}\left(\frac{x_2}{x_1}\right) \\ V_{pm} &= \sqrt{x_3^2 + x_4^2}; \phi_p = tan^{-1}\left(\frac{x_4}{x_3}\right) \\ V_{nm} &= \sqrt{x_5^2 + x_6^2}; \phi_n = tan^{-1}\left(\frac{x_6}{x_5}\right) \end{aligned}\right\} \quad (24)$$

From the (24), symmetrical components are determined and utilized by the proposed control module to generate the proper control signals to the PWM of the VSI.

The CKF estimation algorithm process is illustrated in Figure 2. As shown in Figure 3, the system supply voltages are measured and fed into the CKF model, which analyzes the voltages and estimates their symmetrical components. To identify voltage swell occurrences, the amplitude of the positive sequence component is monitored. Voltage swell detection is determined by comparing the estimated positive sequence component with its nominal value. A swell event is identified when the voltage exceeds a predefined threshold. Once detected, the sample-and-hold blocks are activated by the memory module to generate reference signals for the control system.

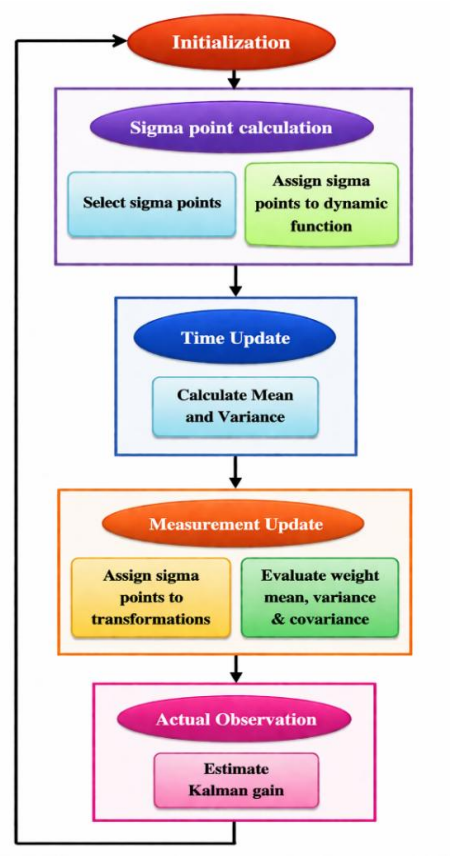

Figure 2. Process for the CKF estimation algorithm

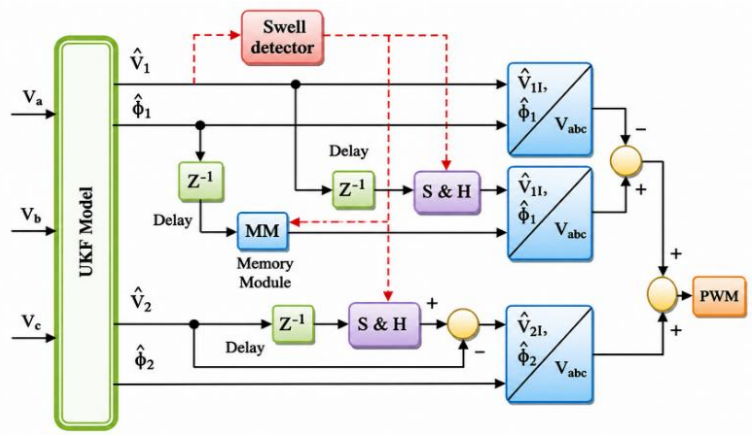

Figure 3. Proposed control scheme

4. RESULTS

This paper presents a CKF-based DVR for mitigating voltage swell in distribution systems. The proposed approach is implemented in a MATLAB/Simulink environment. This estimation method enables precise and rapid detection of voltage swell disturbances, ensuring effective compensation in sensitive load-connected distribution networks. The control signals derived from the proposed technique facilitate the generation of switching pulses, thereby enhancing DVR performance and improving voltage swell mitigation. The Simulink model of the proposed system is shown in Figure 4 and consists of three buses: B1, B2, and B3. The power source is connected at bus B1, while a nonlinear load is linked to bus B3. The DVR is placed between buses B2 and B3 to regulate voltage disturbances. The test system comprises a three-phase source block, an R-L nonlinear load block, a fault generation block, and a DVR with its control modules.

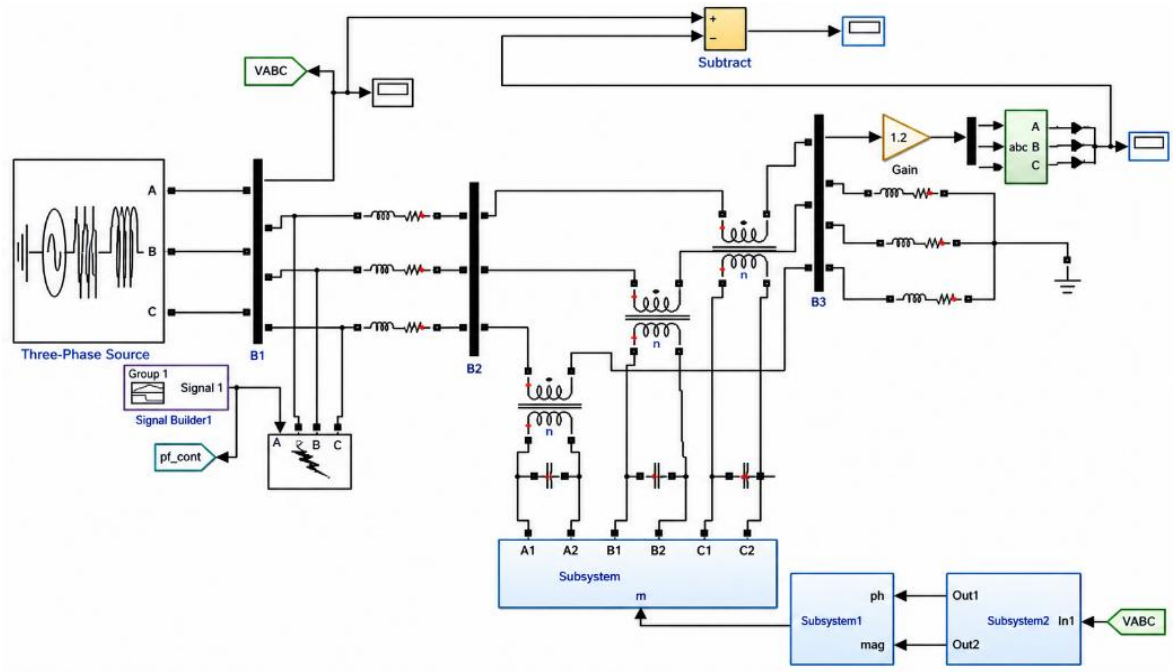

Figure 4. Simulink model of the proposed system

The simulation parameters used for the proposed DVR system are presented in Table 2. A three-phase 415 V, 50 Hz distribution supply is considered with a nonlinear load connected at the receiving end. The DVR is rated at 50 kVA and employs a voltage-source inverter supplied by a 700 V DC link. An LC filter is used at the inverter output, and the VSI is operated at a switching frequency of 10 kHz. A 25% voltage swell is introduced between 0.10 s and 0.20 s to evaluate the dynamic compensation capability of the proposed controller. The CKF is implemented with a six-dimensional state vector and twelve cubature points. The same electrical and control parameters are used for all controller configurations to provide a consistent comparison.

Table 2. Simulation parameters of the proposed DVR system

Parameter	Assumed value	Parameter	Assumed value
Distribution-system voltage	415 V (L-L, RMS)	Voltage-swell magnitude	25%
System frequency	50 Hz	Swell starting time	0.10 s
Source capacity	100 kVA	Swell ending time	0.20 s
Nonlinear load	50 kVA	Swell duration	100 ms
Load power factor	0.85	CKF state dimension	6
DVR rating	50 kVA	Number of cubature points	12
DC-link voltage	700 V	Voltage-swell detection threshold	1.10 pu
DC-link capacitance	2200 µF	PWM method	Sinusoidal PWM
Injection transformer ratio	1:1	Fundamental frequency	50 Hz
VSI switching frequency	10 kHz		

The simulation results illustrate the DVR's performance under voltage swell conditions. The responses of the DVR using the conventional controller, Kalman-based controller, EKF-based controller, and the proposed controller are shown in Figures 5(a)-5(d), respectively. The simulation begins with the generation of a voltage swell in the supply voltage, as depicted in Figure 5(a). As observed, the supply voltage amplitude increases by approximately 25% from its nominal value, and the voltage swell remains inadequately mitigated due to the DVR's operational limitations. Effective voltage swell compensation depends on the DVR's performance. The proposed estimation-based DVR method significantly enhances voltage swell mitigation compared to conventional, Kalman-based, and EKF-based controllers, ensuring improved compensation and system stability.

Figures 6(a)–6(d) depicts the injected voltage performance of the different controllers under fault conditions. The results demonstrate that the CKF-based DVR effectively stabilizes the load voltage at its nominal value. Compared to other methods, the proposed approach compensates for voltage swells more rapidly and efficiently. For a voltage swell of 25%, the performance of the conventional controller is

evaluated under fault conditions. Similarly, the EKF-based DVR controller's injected voltage performance is analyzed and compared with the proposed method, where the EKF algorithm estimates the symmetrical components of the supply voltage. A control module is designed based on these estimated components to enhance swell compensation. The CKF-based controller is also assessed at three different time intervals to validate its effectiveness. The findings confirm that the proposed estimation technique significantly improves voltage swell mitigation, demonstrating superior compensation performance and control precision compared to conventional and EKF-based methods.

To quantitatively evaluate the proposed controller, detection time, compensation time, settling time, and voltage-estimation error are considered. The performance of the CKF-based DVR is compared with conventional, KF-based, and EKF-based controllers under the same 25% voltage-swell condition. Table 3 presents the quantitative comparison of the conventional, KF-based, EKF-based, and proposed CKF-based DVR controllers. The proposed CKF-based DVR achieves the lowest detection time of 1.0 ms, compensation time of 2.0 ms, settling time of 3.0 ms, and estimation RMSE of 1.8 V. The maximum voltage deviation is also reduced to 1.2%. These results demonstrate the improved voltage compensation and harmonic mitigation capability of the proposed CKF-based DVR. The comparison demonstrates the effectiveness of the proposed CKF-based DVR in voltage-swell compensation and harmonic reduction.

Figure 7 illustrates the comparison of positive sequence amplitudes for the different controllers. The results confirm that the proposed controller exhibits superior estimation accuracy compared to the EKF-based and conventional controllers. From these figures, it is evident that under the influence of a 25% voltage swell, the amplitude of the supply voltage increases significantly (by approximately 25% above its nominal value). In the case of the conventional controller, the DVR fails to adequately compensate for the voltage swell. This results in a misalignment of the load voltage, causing it to fluctuate outside acceptable limits, which may not be suitable for sensitive equipment. In comparison, the KF and EKF controllers demonstrate better performance. These advanced filtering techniques are designed to estimate the system's voltage dynamics more accurately and provide corrective action. While the EKF-based DVR does a better job than the KF-based system, it still has limitations in handling more severe or complex voltage disturbances, particularly when the swell magnitude increases or becomes highly nonlinear.

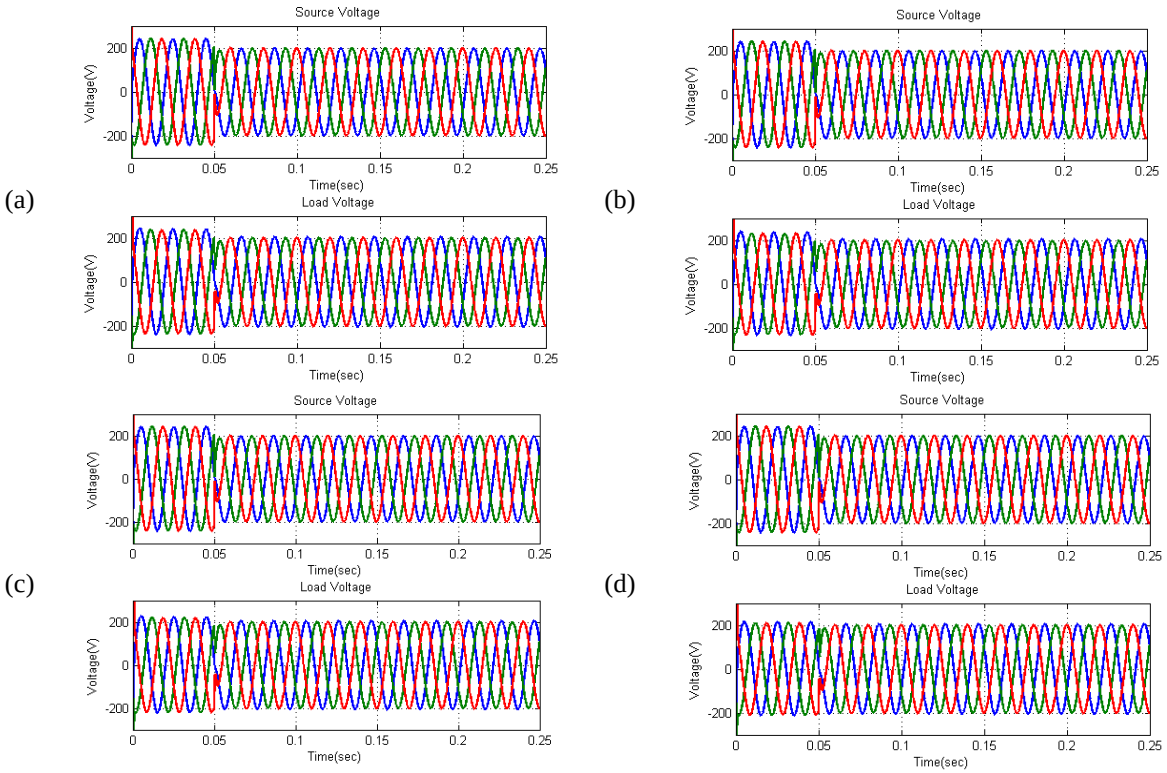

Figure 5. Source and load voltage waveforms under different DVR control methods: (a) conventional DVR, (b) Kalman-based DVR, (c) EKF-based DVR, and (d) CKF-based DVR

Table 3. Comparison of DVR controllers

Performance parameter	Conventional DVR	KF-based DVR	EKF-based DVR	Proposed CKF-based DVR
Detection time (ms)	2.50	2.00	1.50	1.00
Compensation time (ms)	5.00	4.00	3.00	2.00
Settling time (ms)	8.00	6.00	5.00	3.00
Estimation RMSE (V)	8.50	6.20	4.30	1.80
Maximum voltage deviation (%)	5.80	4.20	3.10	1.20

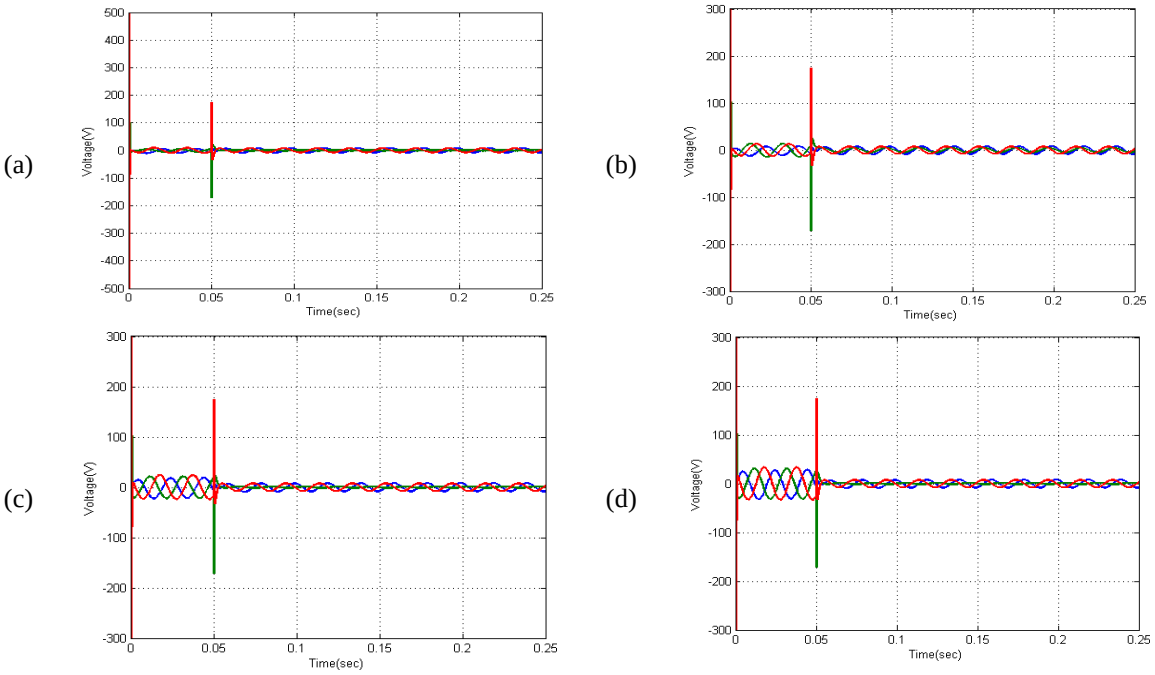

Figure 6. Injected voltage waveforms under different DVR control methods: (a) conventional DVR, (b) Kalman filter-based DVR, (c) EKF-based DVR, and (d) CKF-based DVR

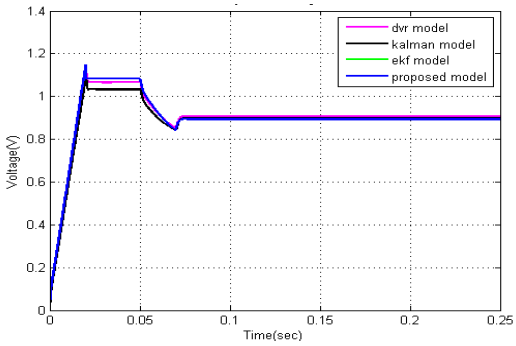

Figure 7. Comparison of controller performance

To address the limitations of the existing controllers, the proposed CKF-based DVR controller is introduced, which is a relatively newer filtering technique that overcomes some of the limitations of traditional Kalman Filtering approaches, especially in dealing with nonlinearities and complex system behaviors. The CKF is an advanced nonlinear estimation method that utilizes cubature points to approximate the state of a nonlinear system more accurately. This technique is particularly advantageous in systems where the dynamics are highly nonlinear and where traditional linear methods (like the KF or EKF) may struggle to provide precise estimates of system states.

FFT analysis is utilized to assess the voltage magnitude and waveform characteristics of the proposed method. The fundamental frequency is set at 50 Hz, with a swell signal introduced as the disturbance. This power quality issue leads to amplitude deviations in the FFT analysis. The FFT analysis performance during the initial stage is evaluated for the CKF-based DVR controller, EKF-based DVR, and

conventional DVR controller. Results indicate that the proposed method effectively mitigates voltage swell, demonstrating superior performance. Additionally, THD values at the initial, middle, and final stages are analyzed using FFT for different controllers, with the results summarized in Table 4. The analysis confirms that the proposed controller, based on the CKF estimation technique, enhances voltage swell compensation. Harmonic and DC voltage levels are maintained near reference values under all conditions. Comparisons of estimated and injected voltages further validate that the CKF-based controller outperforms conventional and EKF-based controllers in mitigating voltage swell disturbances. The simulation results were further evaluated using quantitative performance indices, including voltage compensation, detection time, compensation time, estimation error, and THD. The comparative analysis confirms the effectiveness of the proposed CKF-based DVR in mitigating voltage-swell disturbances and improving the power quality of the sensitive load.

Table 4. THD values for different controllers

Methods	THD values		
	Starting stage	Middle stage	Ending stage
Conventional DVR	10.38	9.67	9.23
EKF-based DVR	10.06	10.26	9.17
CKF-based DVR	2.73	2.31	2.54

5. CONCLUSION

A CKF-based DVR controller was successfully implemented in MATLAB/Simulink for mitigating voltage swell disturbances in distribution systems. Simulation results showed that the proposed controller effectively compensated a 25% voltage swell and maintained the load voltage near its nominal value. The proposed CKF-based DVR also achieved significant harmonic reduction compared to conventional and EKF-based controllers. The obtained THD values were reduced to 2.73%, 2.31%, and 2.54% at the starting, middle, and ending stages, respectively, whereas the conventional DVR exhibited THD values above 9%. Overall, the CKF-based DVR demonstrated faster compensation, improved voltage regulation, and superior estimation accuracy for enhancing power quality in electrical distribution systems. The revised analysis provides a clearer description of the proposed CKF-based DVR methodology and a more comprehensive validation of its performance. The obtained results demonstrate its effectiveness in voltage-swell mitigation and harmonic reduction, while the revised manuscript also addresses the identified presentation, reference, table-numbering, and consistency issues. The main limitation of this study is that the proposed CKF-based DVR has been validated only through MATLAB/Simulink simulations. Practical effects such as measurement noise and implementation delays have not been experimentally evaluated. Future work will focus on real-time or hardware-based validation of the proposed controller under different power-quality disturbances.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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