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RESEARCH ARTICLE

Fast Passive Anti-Islanding Strategy for AC Microgrids Using Cubature Kalman Filtering Algorithm

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ABSTRACT AC microgrids (ACMGs) represent a promising evolution of traditional distribution systems, driven by environmental advantages and concerns over power quality. However, detecting islanding events within ACMGs poses a significant challenge. In this study, we propose the utilization of the Cubature Kalman Filtering Algorithm (CKFA) to address this challenge by leveraging voltage signals at the point of common coupling (PCC). Initially, CKFA is applied to voltage signatures to compute Voltage Residuals (VR) and Voltage Harmonic Signatures (VHS) through state estimation. These estimated VR and VHS indices are then compared against pre-defined threshold settings to identify islanding states. Subsequently, a tripping decision is made based on the OR operation of both estimated VR and VHS. The proposed method demonstrates efficacy in detecting islanding occurrences under both balanced and unbalanced load/generation conditions and effectively discriminating between islanding and non-islanding conditions. Extensive simulations conducted on MATLAB/Simulink-based IEEE 13-bus test bed and UL-1741 test bed validate the effectiveness of the presented scheme. Results signify a high accuracy rate of 99.9%, tied with low computational complexity and the smallest non-detection zone (NDZ). Additionally, the time of operation for the suggested scheme is less than 1 millisecond, without any false operations, emphasizing its effectiveness in practical application.

INDEX TERMS AC microgrids, anti-islanding, cubature Kalman filter, passive schemes.

I. INTRODUCTION

ACMGs are a modern picture of the existing conventional distribution networks with a lot of benefits as compared to these old grid setups [1], [2]. AC microgrids offer a robust and flexible solution for decentralized power generation and distribution, providing resilience, efficiency, and flexibility in modern power networks [3]. These ACMGs operate independently or in grid-tied mode, have interlinked loads, and have their own distributed energy resources (DERs) [4], [5]. Due to the amalgamation of renewable DERs like wind & solar, the ACMGs are renowned and attractive in the modern world [6], [7]. Due to the practice of local renewable DERs, ACMGs play a vital role in lowering carbon emissions and supporting

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energy independence [8]. However, a big challenge joined with the ACMGs protection is the occurrence of islanding incidents due to fault or any disruption. Islanding is related to a scenario where a part of the microgrid remains working independently when disconnected from the main grid, usually due to a fault or disruption [9]. To prevent the high-cost electrical infrastructure and utility works the rapid detection of the islanding event must be crucial. In addition, rapid detection & addressing islanding are very much important for maintaining grid stability, voltage, and frequency variations that could influence connected loads and DERs [10], [11].

Therefore, to design a robust and dependable anti-islanding scheme with distinctive attributes to protect the ACMGs under various operating conditions [12]. Moreover, these schemes must be capable of sharply distinguishing the typical transients/ switching events & instances of islanding, also considering fluctuations in load demand and renewable DERs [13]. In addition, the schemes must be capable of working in real-time noisy microgrid environments under severe and harsh operation conditions.

ACMG anti-islanding schemes are classified on the basis of their working procedure and utilized tool or algorithm [14]. One primary classification as portrayed in FIGURE 1, is local and remote schemes. Local anti-islanding schemes are further divided into passive, active, and hybrid categories. Passive schemes utilize inherent system traits to identify islanding events, such as monitoring voltage and frequency deviations exceeding predefined threshold levels [15]. These schemes are relatively simple & cost-effective but may have limitations in detecting islanding occurrences under certain states, such as balanced load & generation. On the other hand, active schemes actively inject disturbance into the system/utilize communication protocols to detect islanding states more efficiently [16], [17], [18]. These methods often offer higher accuracy & reliability but may require extra hardware or communication arrangement [19]. Hybrid schemes are a combo of active & passive anti-islanding schemes [20].

Several authors presented passive methods in previous literature. The authors in ref [21] proposed a passive anti-islanding strategy specifically designed for inverter-based DERs within ACMGs. This scheme relies on current & voltage phasors obtained at the PCC and used for computing the anti-islanding indexes; 1st the rate of variation of voltages & 2nd is the ratio of current & voltage magnitude. A novel anti-islanding scheme using the resultant sequential impedance component with zero NDZ was proposed in [22], offering superior stability and efficiency in various scenarios without affecting power quality. A passive anti-islanding method utilizing Variational Mode Decomposition (VMD) using mode energy index was suggested in [23], offering robustness and accuracy in discerning islanding conditions. Another study explored a novel islanding detection scheme [24], utilizing real-time transmission of PCC signal information to DG sites, demonstrating effectiveness and reliability across various test conditions through simulation and experimental validation. Authors in [25] introduced an

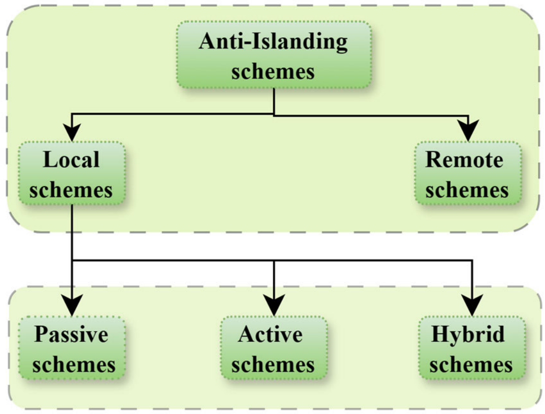

FIGURE 1. The categorization of the islanding detection schemes.

anti-islanding scheme based on equivalent inter-connection line impedance, utilizing synchronized phasors from μPMUs to effectively detect islanding conditions with minimal NDZ and fast detection times, ensuring safety in distribution grids with distributed PV systems. A machine learning based method was also repored in previous literature [26]. An anti-islanding method for grid-tied PV systems was presented in [27], integrating five conventional passive relays in a synergistic approach to enhance islanding detection performance. In ref [28] passive anti-islanding scheme for wind-based DERs utilizing an artificial neural network (ANN) trained on voltage and current signals processed with Fourier transform, demonstrating rapid and efficient detection of islanding operations across various power quality disturbances. Similarly, a machine learning-based and ANN based approach was also proposed in excisting literature [29].

Similarly, some active methods were presented in previous literature. An active islanding detection scheme for ACMGs with parallel inverters was proposed in [19], leveraging small periodic step changes in active power injection and d-axis component ratios at the PCC to achieve zero non-detection zones. An analytical evaluation of the NDZ in an active anti-islanding scheme for DG units was proposed in [30], mitigating the NDZ by injecting negative-sequence currents and evaluating performance under UL-1741 test conditions through laboratory and simulation-based verification. An active anti-islanding method for inverter-based distribution generation systems was presented in [31], leveraging the virtual capacitor behavior induced by frequency deviations to detect islanding events promptly during utility power interruptions. A Negative Sequence Current Injection-based active anti-islanding scheme for ACMGs was proposed in [32], offering superior High Impedance Fault detection capability without requiring communication, validated through comprehensive simulation studies encompassing various fault scenarios and system configurations. An analytical-based algorithm for constant voltage-controlled inverters in distributed generation systems was proposed in [33], incorporating a frequency-dependent ZIP-Exponential load model

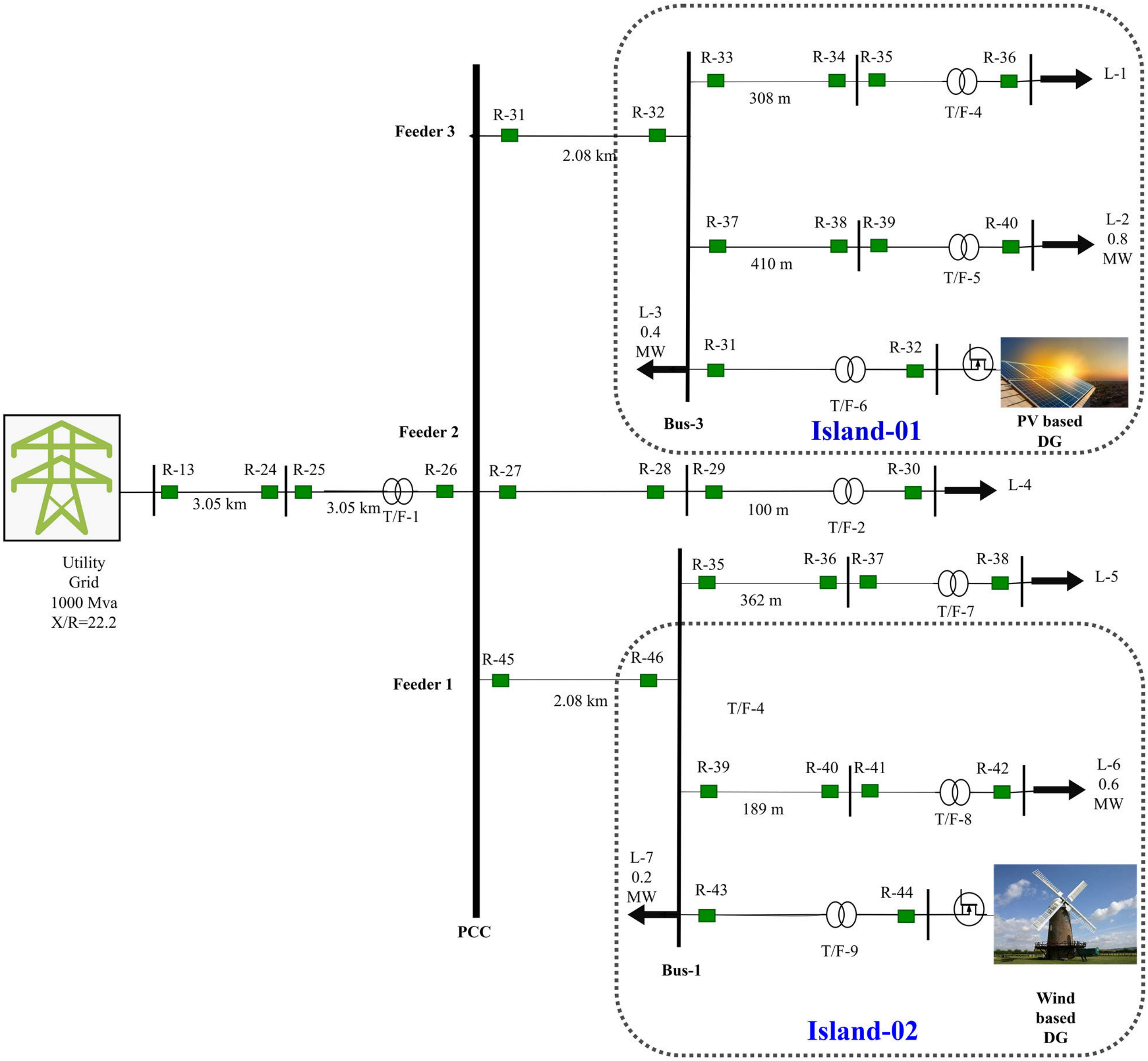

FIGURE 2. The IEEE 13-bus test bed is utilized in the proposed anti-islanding scheme.

to enhance islanding detection independent of DG operation point.

Some hybrid methods were also presented in previous literature. A hybrid anti-islanding method was suggested in [6] for inverter-based distributed generation units, combining passive voltage unbalance & total harmonic distortion detection with an active bilateral reactive power variation method. A hybrid anti-islanding method for grid-connected ACMGs was suggested in [34], utilizing linear reactive power disturbance synchronization and adaptive disturbance slope adjustment, along with passive criteria and frequency-related correlations. Another hybrid anti-islanding technique for distributed generation systems was proposed in [35], utilizing Lissajous pattern analysis and active control via battery energy storage to enhance reliability, sensitivity, and certainty under diverse real-time scenarios and nonlinear loading conditions. Ref [36] introduced a hybrid islanding detection approach for ACMGs connected to smart grids, combining passive, active, and communication-based methods using the probability of islanding calculated at smart grid sides processed by wavelet transform and ANN. Existing schemes in literature tried to solve microgrid issues in many aspects however, they have the following limitations.

1. Some existing methods may be sensitive to grid parameter fluctuations, leading to false alarms or missed detections.
2. Some methods struggle with balanced load generation island events.
3. Accuracy relies on grid synchronization, susceptible to communication delays or failures.
4. Methods using external signals are prone to interference or malicious attacks.

5. A few advanced phasor measurement units (PMU)-based methods can be complex and costly to implement, posing barriers to adoption.
6. Some methods have very high computational complexity.

In our investigation, we propose employing the CKFA to tackle the anti-islanding issue by utilizing voltage signals at the PCC. Initially, the CKFA is deployed on voltage signatures to compute VR and VHS via state estimation. These estimated VR and VHS indices are subsequently compared against predefined threshold settings to discern islanding states. Following this comparison, a tripping decision is determined through the OR operation of both estimated VR and VHS. The efficacy of our approach is demonstrated in detecting islanding occurrences under various load/generation conditions, including both balanced and unbalanced scenarios, and effectively distinguishing between islanding and non-islanding conditions. Extensive simulations conducted on MATLAB/Simulink-based IEEE 13-bus test bed and UL-1741 test bed corroborate the usefulness of the suggested method. The proposed scheme has the following value additions.

1. The presented method deployed the CKFA in both time/frequency domains in a passive islanding scheme for the first time.
2. The proposed scheme offers improved accuracy of 99.9% and reliability in identifying islanding events compared to traditional methods.
3. By employing CKFA for state estimation, the proposed method computes VR and VHS from voltage signatures. This comprehensive approach provides a more nuanced understanding of system dynamics, enabling better discrimination between islanding & non-islanding situations.
4. The proposed scheme is very exorbitant, has less computational complexity, and is easy to implement.
5. The proposed method is capable of handling noisy measurements.

Following the introduction, the manuscript proceeds with a detailed exposition of the basic principles of the presented anti-islanding scheme utilizing the CKFA. Section II enlightened the utilized IEEE-13 bus test bed for validation of the suggested scheme. Section III explains the principles of the presented CKFA-based scheme. Section IV outlines implementation steps, whereas Section V depicts scheme usefulness through simulation & results. Section VI presents comparative & NDZ analysis on the UL-1741 test bed. Finally, Section VII concludes with key findings & future suggestions.

II. IEEE 13-BUS TEST BED

The IEEE 13-bus test bed is a standardized model of ACMGs renowned for its significant role in assessing and benchmarking the performance of anti-islanding schemes. It denotes a typical feeder configuration found in many suburban areas, containing 13 buses, with lines that simulate the electrical paths between them. This testbed includes numerous components such as distribution lines, capacitors, transformers, and loads, providing a comprehensive structure for testing. For islanding detection studies, the IEEE 13-bus bed offers realistic & challenging conditions due to its mixed load types, complex topology, and presence of PV & wind-based DERs. The IEEE 13-bus bed is modeled in MATLAB/Simulink 2022b, and its single-line design is depicted in FIGURE 2.

We simply open the circuit breaker R-32 to generate or simulate the islanding scenarios within the IEEE test bed in the PV-based DG, connected to bus B-3, which is named island-01. Likewise, We simply open the circuit breaker R-46 to generate or simulate the islanding scenarios within the IEEE test bed in the wind-based DG, connected to bus B-1, which is named island-02. System parameters utilized in this test beds are attained from [37] and [38]. For extensive simulations to assess the valuableness of the suggested scheme, a diverse range of islanding & non-islanding scenarios are simulated on the IEEE 13-bus test bed.

III. PRINCIPALS OF PROPOSED METHOD

A. PCC VOLATAGE SIGNATURE ATTRIBUTES

The PCC is an important point inside ACMGs where distributed generation systems join the utility grid. Different features of the voltage signals of DERs at the PCC are revealing of the dynamic behaviour of the ACMGs. Plentiful variables, like as load variations, the kind and capacity of DG units, and grid conditions, affect these PCC voltage signatures. The inconsistent nature of DERs like solar & wind power is one prominent feature of the voltage signatures of DG terminals and PCCs. Additionally, the PCC's voltage signatures provide principal details about the health and operational state of DG units. These voltage signatures are also essential for islanding detection, which is a vital component of ACMG operation. Fluctuations in voltage characteristics, such as frequency deviations or harmonics, can act as indicators of islanding happenings, where a portion of the microgrid becomes disconnected from the main utility grid. By monitoring these voltage features & implementing suitable anti-islanding algorithms, operators can mitigate the risks linked with islanding and uphold grid stability [17], [39]. The measured PCC voltage signature is shown as follows.

$$v_t = \acute{v}_t \, sin(\acute{\omega}) + \aleph \tag{1}$$

The v_t is the measured 3-phase, dynamic, & non-linear, voltage signal PCC with some random & measurement noise $\aleph$. Secondly, the $\acute{v}_t$ shows the magnitude of the measured voltage. However, the $sin(\acute{\omega})$ is modeled vesion of voltage signal which is not other than sine wave.

B. STATE SPACE MODEL

For utilizing the CKFA for anti-islanding or state estimation of electrical magnitudes in ACMGs, the state space model plays a fundamental role. This model is fundamental in defining how the system's state evolves and how measurements are related to the state variables. For a simplified scenario focusing on the measured voltage, the state space model can be represented as follows:

The $\boldsymbol{X}$ is the state equation, $\boldsymbol{Y}$ is the measurement equation, $\widehat{x_t}$ represents the predicted state at time t, and $\widehat{y_t}$ denote the measured values at time t, while tn is the time instance t at n$^{\text{th}}$ sample.

$$X_{tn+1} = B(x_{(tn)}) + A\omega_{tn} \quad (2)$$

The measurement eq is.

$$Y_{tn} = C(x_{(tn)}) + u_{tn} \quad (3)$$

where, the $x_{tn} = \begin{bmatrix} v_{tn} & v_{tn-1} \end{bmatrix}^{-1}$; x_{tn} = system states; and the $A = \begin{bmatrix} 1 & 0 \end{bmatrix}^T$; while the $C = \begin{bmatrix} 1 & 0 \end{bmatrix}^T$; and $B = \begin{bmatrix} 2\cos\omega_{tn} & -1 \\ 1 & 0 \end{bmatrix}$. These are the state space model equations for the CKFA. The trigonometric derivative of eq (1) outcomes in the discrete and iterative conversion as mentioned below.

$$\widehat{v}_{t+1} + \widehat{v}_{t-1} = 2\sin\left(\acute{\omega}\right) V_t + e \quad (4)$$

The CKFA pseudo code depicted in eq (6) to (17) is when implemented on eq (4) by following the state space model equations for the CKFA, it estimates the voltage signature follows.

$$\widehat{v_t} = \acute{v}_t + e \quad (5)$$

The $\widehat{v_t}$ represents the estimated voltage with a random error e. FIGURE 3 illustrate the measured & the CKFA estimated voltage signature.

C. CKFA DETAILED EXPLANATION

In the context of ACMG, the Cubature Kalman Filtering Algorithm is a state estimation technique that provides a useful way to monitor and analyze voltage data. By directly propagating the probability distribution across a set of cubature points, CKFA offers improved accuracy and resilience over typical Kalman filters, which rely on linearization techniques that could cause mistakes in nonlinear systems.

As we know the ACMG has dynamic and non-linear behavior and the CKFA is capable of handling the nonlinear dynamics that are a feature of microgrid operations, which makes it a suitable tool for designing anti-islanding schemes. Because CKFA can exactly estimate the states of ACMGs and identify deviations in voltage signatures at the PCC/distributed generation (DG) terminals, it is the suggested choice for passive anti-islanding. Through the use of voltage measurements from DERs and loads devoted to the ACMGs, CKFA can exactly evaluate variations in voltage and detect possible islanding incidents. Moreover, CKFA has the benefit of adaptability to changing load/generation circumstances, which qualifies it for real-time monitoring and

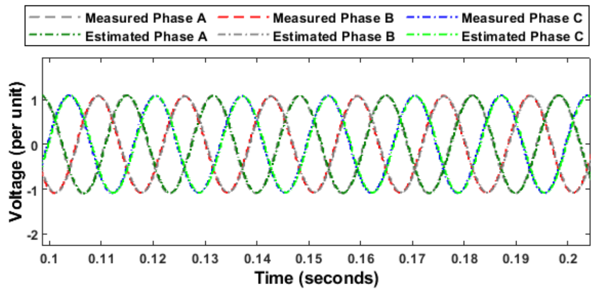

FIGURE 3. The measured & the CKFA estimated voltage signature.

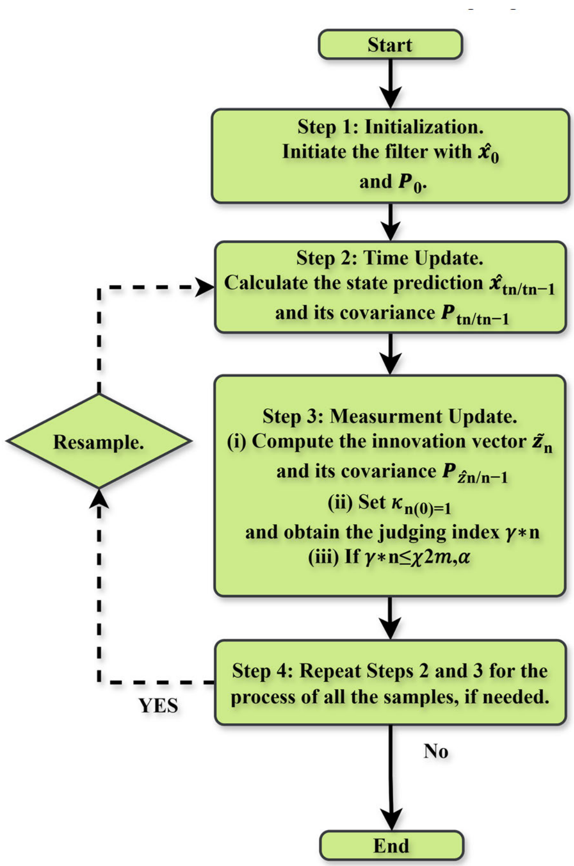

FIGURE 4. The flow chart of the CKF algorithm.

islanding scenario detection without requiring extra disturbances or communication load [40].

The CKFA's main idea is to use a spherical-radial cubature rule to mathematically calculate the multivariate moment integrals that are a part of nonlinear Bayesian filtering. We specifically start a third-degree spherical-radial cubature rule, which aids in the creation of cubature points with a linear scaling resembling the dimension of the state vector. As such, the CKFA provides an organized approach to high-dimensional nonlinear filtering problems. The flow chart of CKFA is portrayed in FIGURE 4, while the pseudo-code of CKFA is demonstrated as follows.

1) TIME UPDATE

Let's suppose at time t, the prior estimate is.

$$p_{n-1:n-1} = s_{n-1:n-1} * s^{T}_{n-1:n-1} \tag{6}$$

"s" is the posterior tensity at nth sample. Then compute the cubature points as (k = 1, 2, 3, ...c).

$$x_{k,n-1:n-1} = s_{n-1:n-1\boldsymbol{\varepsilon k}} * \widehat{\boldsymbol{x}}_{n-1:n-1} \tag{7}$$

where the εk is true/estimated position at kth Monte-Calo run, and k = $2n_x$

Then compute the propagated cubature points as (k = 1, 2, 3, ...c).

$$x^{*}_{k,n:n-1} = F(x_{kn-1:n-1}, \widehat{u}_{n-1}) \tag{8}$$

Then, the predicted state is estimated as follows.

$$\widehat{\boldsymbol{x}}_{n:n-1} = \frac{1}{c}\sum_{k=1}^{c} x^{*}_{k,n:n-1} \tag{9}$$

The $\widehat{\boldsymbol{x}}$ depicts the estimated state. While the error covariance of the predicted state is estimated as follows.

$$p_{n-1:n-1} = \sum\nolimits_{k=1}^{c} x^{*}_{k,n:n-1}x^{*T}_{k,n:n-1} - \widehat{\boldsymbol{x}}_{n:n-1}\widehat{x}^{*T}_{n:n-1} + Q_{n-1} \tag{10}$$

2) MEASUREMENT UPDATE

Factorize.

$$p_{n:n-1} = s_{n:n-1} * s^{T}_{n:n-1} \tag{11}$$

Then compute the cubature points as (k = 1, 2, 3, ...c).

$$x_{k,n:n-1} = s_{n:n-1\boldsymbol{\varepsilon k}} * \widehat{\boldsymbol{x}}_{n:n-1} \tag{12}$$

where k = $2n_x$

Then compute the propagated cubature points as (k = 1, 2, 3, ...c).

$$z^{*}_{k,n:n-1} = H(x_{kn:n-1}, \widehat{u}_{n}) \tag{13}$$

Then, the predicted state is estimated as follows.

$$\widehat{\boldsymbol{Z}}_{n:n-1} = \frac{1}{c}\sum_{k=1}^{c} z^{*}_{k,n:n-1} \tag{14}$$

While the error covariance of the predicted state is estimated as follows.

$$p_{x,z,n-1:n-1} = \sum\nolimits_{k=1}^{c} z^{*}_{k,n:n-1}z^{*T}_{k,n:n-1} - \widehat{\boldsymbol{Z}}_{n:n-1}\widehat{\boldsymbol{x}}^{*T}_{n:n-1} + R_{n} \tag{15}$$

Then compute the Kalman gain.

$$K^{g}_{n} = p_{x,z,n-1:n-1} * p^{-1}_{x,z,n-1:n-1} \tag{16}$$

Then update the estimated state.

$$\widehat{\boldsymbol{x}}_{n:n} = \widehat{\boldsymbol{x}}_{n:n-1} + K^{g}_{n}(\widehat{\boldsymbol{Z}}_{n} - \widehat{\boldsymbol{Z}}_{n:n-1}) \tag{17}$$

This estimation is utilized for the calculation of the anti-islanding index.

D. ANTI-ISLANDING INDEX GENERATION

The generation of an anti-islanding index holds principal significance in the design & implementation of any method aimed at anti-islanding in ACMGs. This index works as a crucial metric for estimating the risk of islanding occurrences and plays a central role in ensuring the reliability & safety of the grid. Moreover, the anti-islanding index works as a key factor in triggering protective actions, such as tripping circuit breakers or initiating islanding protection instruments, when the computed index exceeds pre-specified thresholds. Likewise, the continuous monitoring & computation of the anti-islanding index enable real-time calculation of the grid's stability, allowing for swift detection & mitigation of islanding events to prevent potential destruction to equipment, guarantee grid stability, and defend the integrity of the power supply. Besides, precise computation and application of the anti-islanding index are vital factors in crafting resilient and efficient islanding detection methods, significantly enhancing the overall reliability and resilience of contemporary ACMGs.

In the suggested scheme two anti-islanding indexes are proposed to avoid nuisance tripping & blinding of the challenging islanding occurrences. Both the indexes are as follows.

1. Voltage residuals
2. Voltage harmonic signature.

Initially, the voltage residuals are computed by computing the mathematical differentiation of the CKFA-estimated voltage signature from the measured voltage signature. The mathematical model of the VR index is as follows.

$$VR = \widehat{v_t} - v_t \tag{18}$$

Secondly, In the realm of AC microgrids, the computation of the voltage harmonic signature using CKFA state estimation and harmonic content analysis is challenging. By accurately estimating the system's state, and precisely voltage magnitudes, CKFA facilitates the identification and characterization of harmonic distortions present in the measured PCC voltage. Through harmonic content analysis, the VHS is computed, quantifying the level of distortion in the grid's voltage waveform caused by harmonics. The VHS index was chosen based on its ability to capture distinct changes in harmonic patterns that occur during islanding events. This index serves as a key indicator of islanding detection in the proposed scheme. The mathematical model of the VHS index is as follows.

$$VHS_t = \frac{\sqrt{\sum_{n=2,3}^{\infty} \widehat{v}^{2}_{n\_rms}}}{\widehat{v_1}} \tag{19}$$

Ultimately, OR-logical operations are performed on both the VA and VHS indices to facilitate efficient decision-making regarding islanding events. This OR operation aims to ensure swift detection and mitigation of islanding occurrences in contemporary AC microgrids.

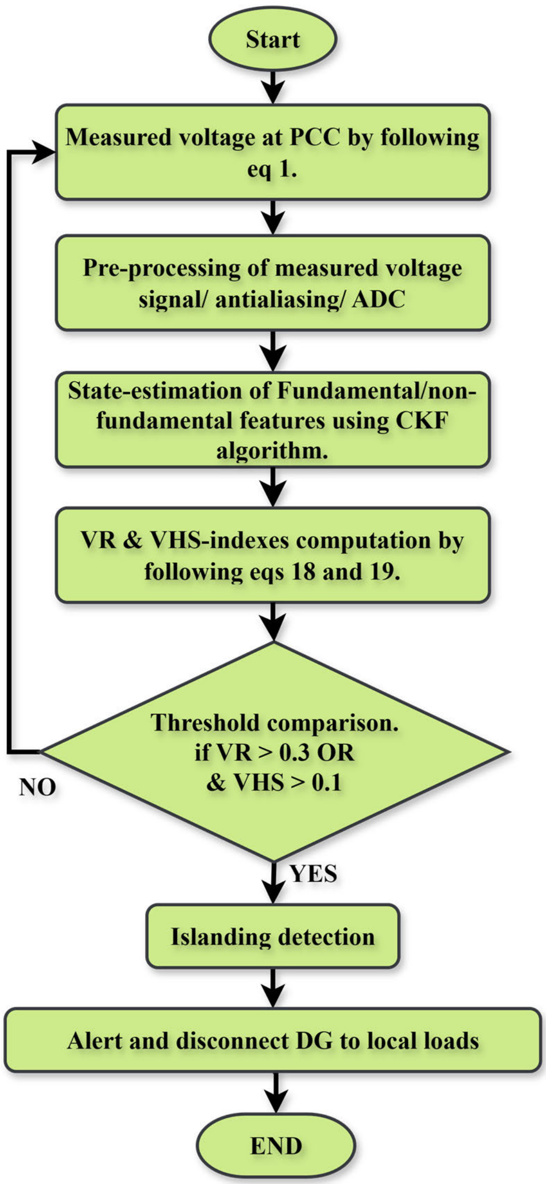

FIGURE 5. The workflow of the presented CKF-based anti-islanding scheme.

E. THRESHOLD SETTING

The significance of threshold setting lies in its ability to ensure effective islanding detection while minimizing false alarms, maintaining grid stability, ensuring safety, preventing unintended islanded operation, and optimizing system performance. Properly calibrated thresholds are essential for the successful implementation of any anti-islanding scheme in modern ACMGs. In the proposed scheme after plenty of extensive simulations in different islanding and non-islanding conditions on MATLAB/Simulink 2022b.The threshold level chosen for VR is 0.3 while 0.1 for VHS. However, both indexes are zero in normal conditions. If any of the VR and VHS is greater than the pre-specified threshold setting the islanding event is detected.

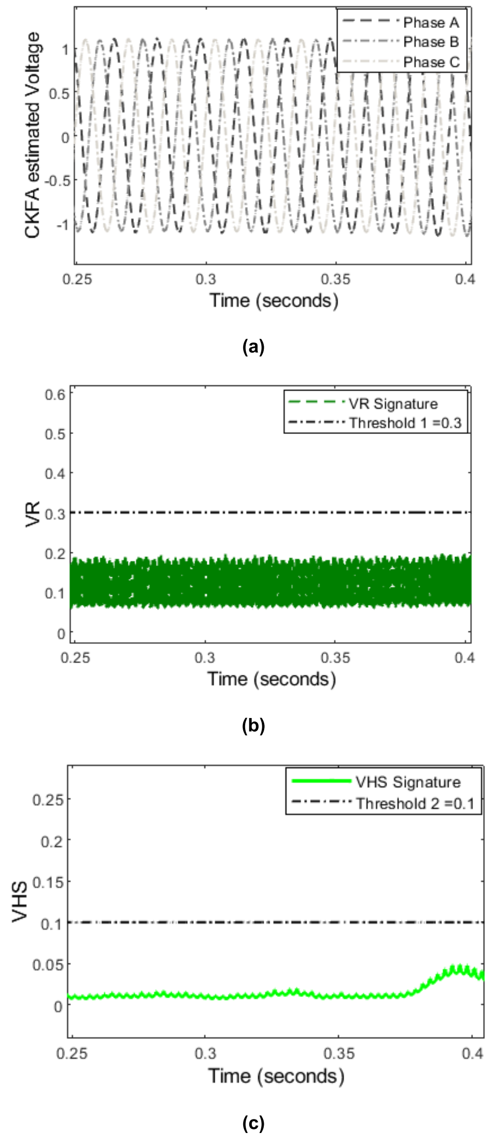

FIGURE 6. Normal operation without any islanding/non-islanding and transient conditions.

IV. IMPLEMENTATION STEPS OF PROPOSED SCHEME

The islanding detection method presented for ACMGs operates through a systematic approach consisting of five distinct steps, each autonomously tasked with identifying and mitigating islanding events while distinguishing them from non-islanding incidents. The detailed flowchart illustrating this scheme is illustrated in FIGURE 5.

Initially, the process begins with the pre-processing of voltage signals, encompassing two critical tasks. Firstly, anti-aliasing is employed, a crucial step aimed at enhancing signal quality and minimizing noise interference, achieved through Chebyshev filtering techniques with a sampling frequency of 1600 Hz to ensure optimal conditioning of voltage signals for subsequent analysis. Secondly, analog-to-digital conversion is executed using a 12-bit ADC operating at a 3.4 kHz switching frequency.

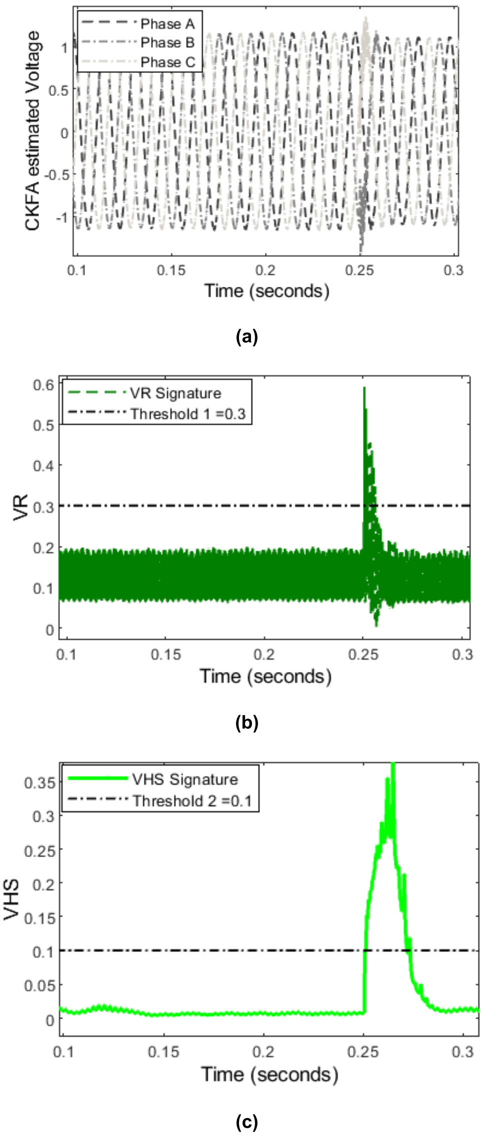

FIGURE 7. **Islanding condition of PV-based DG unit at 0.25 seconds as mentioned in island 01 during unbalanced load/generation.**

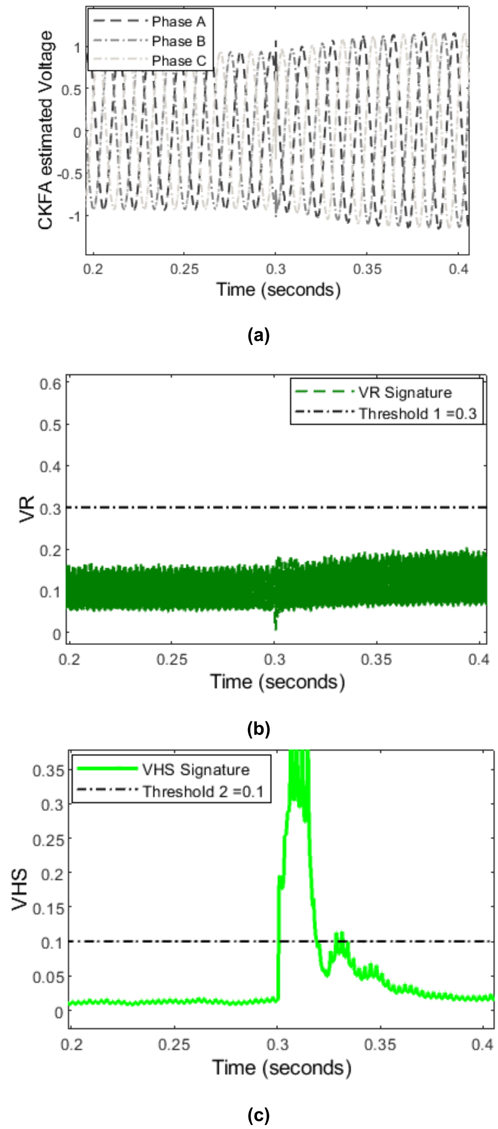

FIGURE 8. **Islanding condition of wind-based DG unit at 0.3 seconds as mentioned in island 02 during balanced load/generation.**

After the pre-processing stage, the method leverages the state-of-the-art Cubature Kalman Filtering Algorithm (CKFA) to conduct precise state estimation of the voltage signals within the AC microgrids. Applied on eq (1), which represents voltage measured at PCC/DG's terminal, this decisive step aids dynamic tracking of the PCC voltage with remarkable precision, authenticating a robust foundation for islanding detection aptitudes. Therefore, fundamental & non-fundamental features of voltages are extracted utilizing CKFA in this stage.

Subsequently, the computation of the islanding detection index is embarked on in this step. The VR and VHS are precisely computed based on the state estimation of voltage components from the prior step. These computed indices serve as key indicators for assessing the system's behavior & detecting and classifying the potential islanding events.

Finally, the decision-making step executes an OR operation between the computed VR & VHS values. This logical operation acts as a keystone for identifying and categorizing islanding incidents from normal operations.

By incorporating info from both VR & VHS indices, the proposed anti-islanding scheme improves its sensitivity to variations in ACMGs, thereby sustaining the accuracy of the islanding detection scheme. This across-the-board approach ensures swift detection of islanding events.

V. RESULTS AND DISCUSSION

To confirm the efficacy of the presented anti-islanding scheme, a range of islanding & non-islanding scenarios were scrutinized utilizing the IEEE 13-bus test system and UL-1741 test bed. Here, we present the results obtained from implementing the proposed anti-islanding approach across a spectrum of islanding and non-islanding occurrences. The

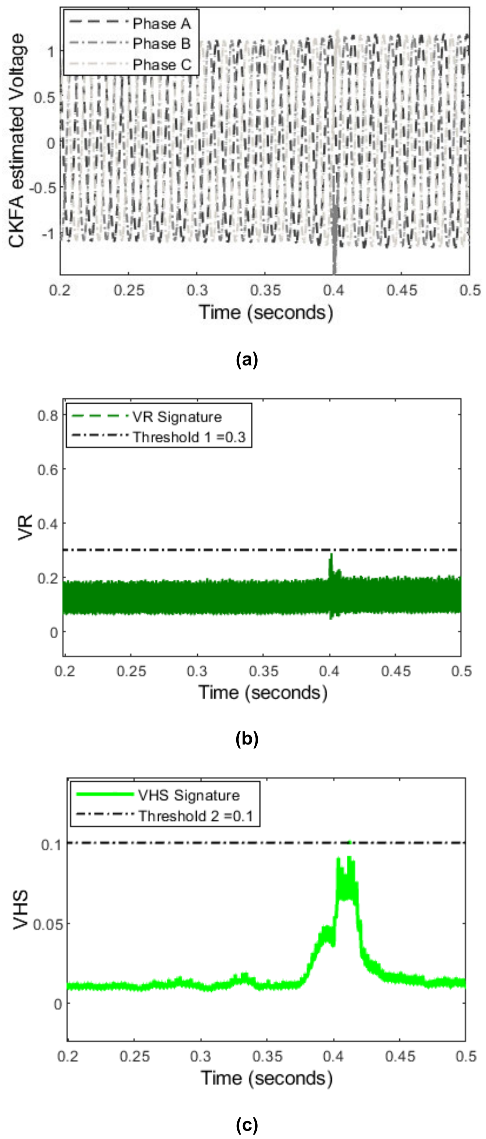

FIGURE 9. A non-islanding condition of a capacitor switching at 0.4 seconds.

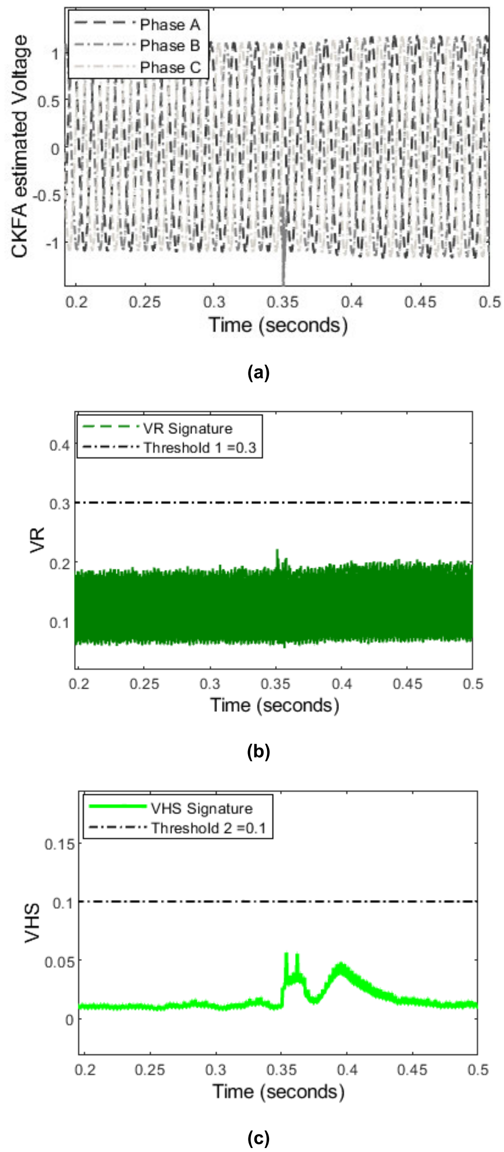

FIGURE 10. A non-islanding condition of a heavy load switching at 0.35 seconds.

normal operational case of the presented scheme is illustrated in FIGURE 6.

A. PV-BASED DGs ISLANDING SCENARIOS

In the presented anti-islanding scheme, special consideration is given to the unique characteristics and operational dynamics of PV-based DG systems to ensure robust and reliable detection performance. By leveraging the inherent features of photovoltaic generation, such as rapid response to irradiance changes and distinctive voltage signatures, the detection scheme is tailored to effectively discern islanding events specific to PV-based DGs during balanced and unbalanced load/generation conditions.

FIGURE 7 illustrates an island 01 condition when PV-based DG is out of the system due to an islanding event at 0.25 seconds during unbalanced load/generation conditions. The VR and VHS indixes in this case are greater than pre-specified threshold values indicating the successful detection and classification of the islanding event.

B. WIND-BASED DGs ISLANDING SCENARIOS

Wind turbines, as a prevalent form of renewable energy generation, introduce distinct operational dynamics and grid interactions compared to PV systems. The intermittent and variable nature of wind resources, coupled with the complex aerodynamic and mechanical behavior of wind turbines, present additional complexities in islanding detection for wind-based DGs. In the proposed islanding detection scheme, specific adaptations are made to accommodate these challenges, such as incorporating algorithms that account for the transient response of wind turbines to sudden changes in wind speed and direction.

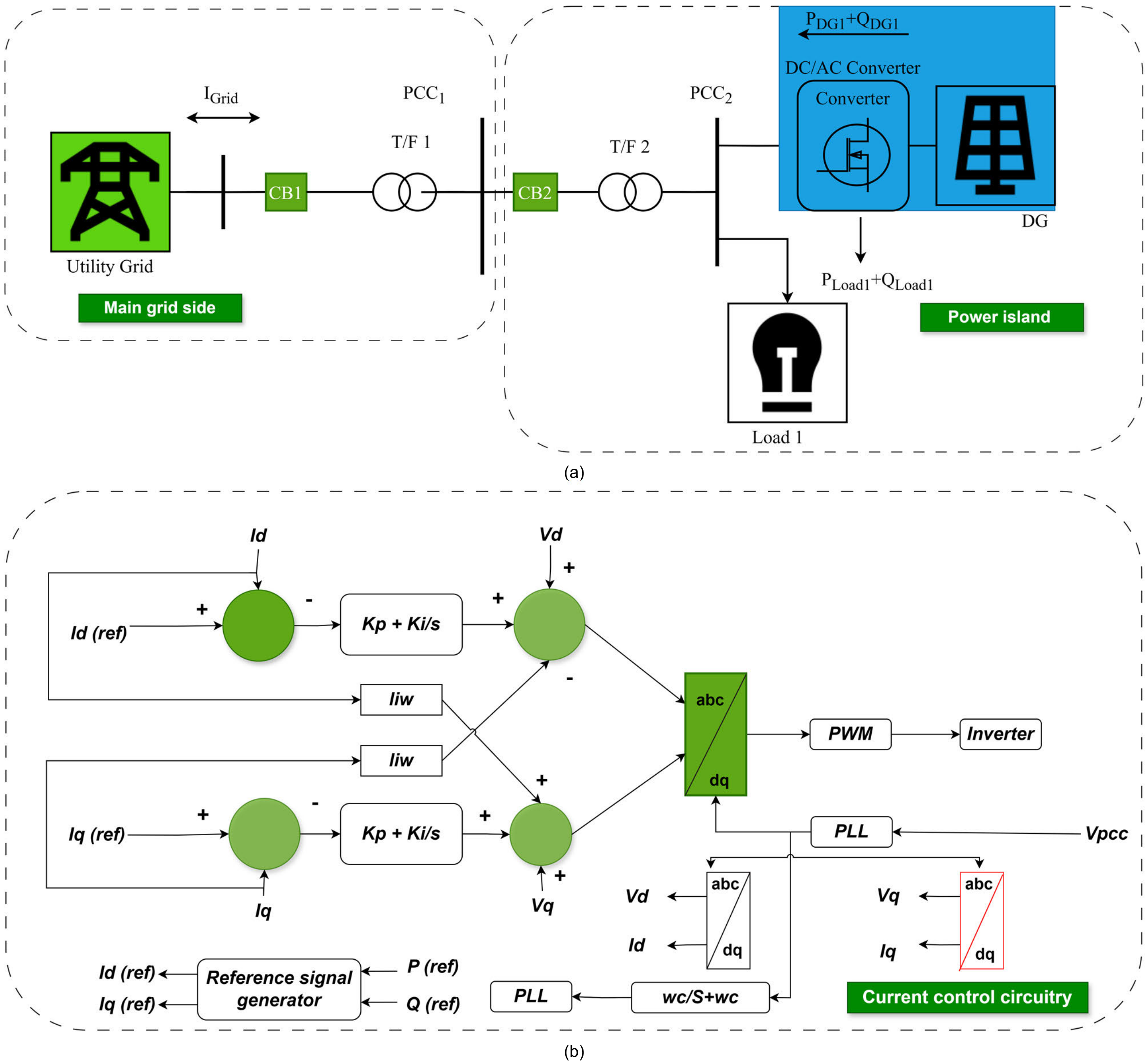

FIGURE 11. a) The UL-1741 test system for NDZ analysis of the proposed CKFA-based scheme, (b) and the current controlled circuitry of the UL-1741 test bed.

FIGURE 8 illustrates an island 02 condition when wind-based DG is out of the system due to an islanding event at 0.3 seconds during balanced load/generation conditions. Due to challenging balanced conditions, the VR is less than threshold limits and fails to detect while the VHS index in this case is more than pre-defined threshold values indicating the successful detection & classification of the islanding event.

C. NON-ISLANDING SCENARIOS

Considering non-islanding conditions such as capacitor switching and heavy load switching is essential in the design and evaluation of islanding detection schemes for ACMGs. While the primary focus of these schemes is to promptly and accurately detect islanding events to ensure grid stability and safety, it is equally important to minimize false detections and ensure reliable operation under various grid conditions. Therefore, the presented scheme is also tested across various non-islanding conditions like capacitor switching and heavy load switching.

FIGURE 9 illustrates a non-islanding condition when a capacitive switching is occurred at 0.4. The VR and VHS indices are too sensitive to differentiate between islanding and non-islanding events therefore, in this case, both are less than pre-defined threshold values indicating the successful operation of the presented scheme.

FIGURE 10 illustrates a non-islanding condition when a heavy load switching has occurred at 0.35. The VR and VHS indices are too sensitive to differentiate between islanding and non-islanding events therefore, in this case, both are less

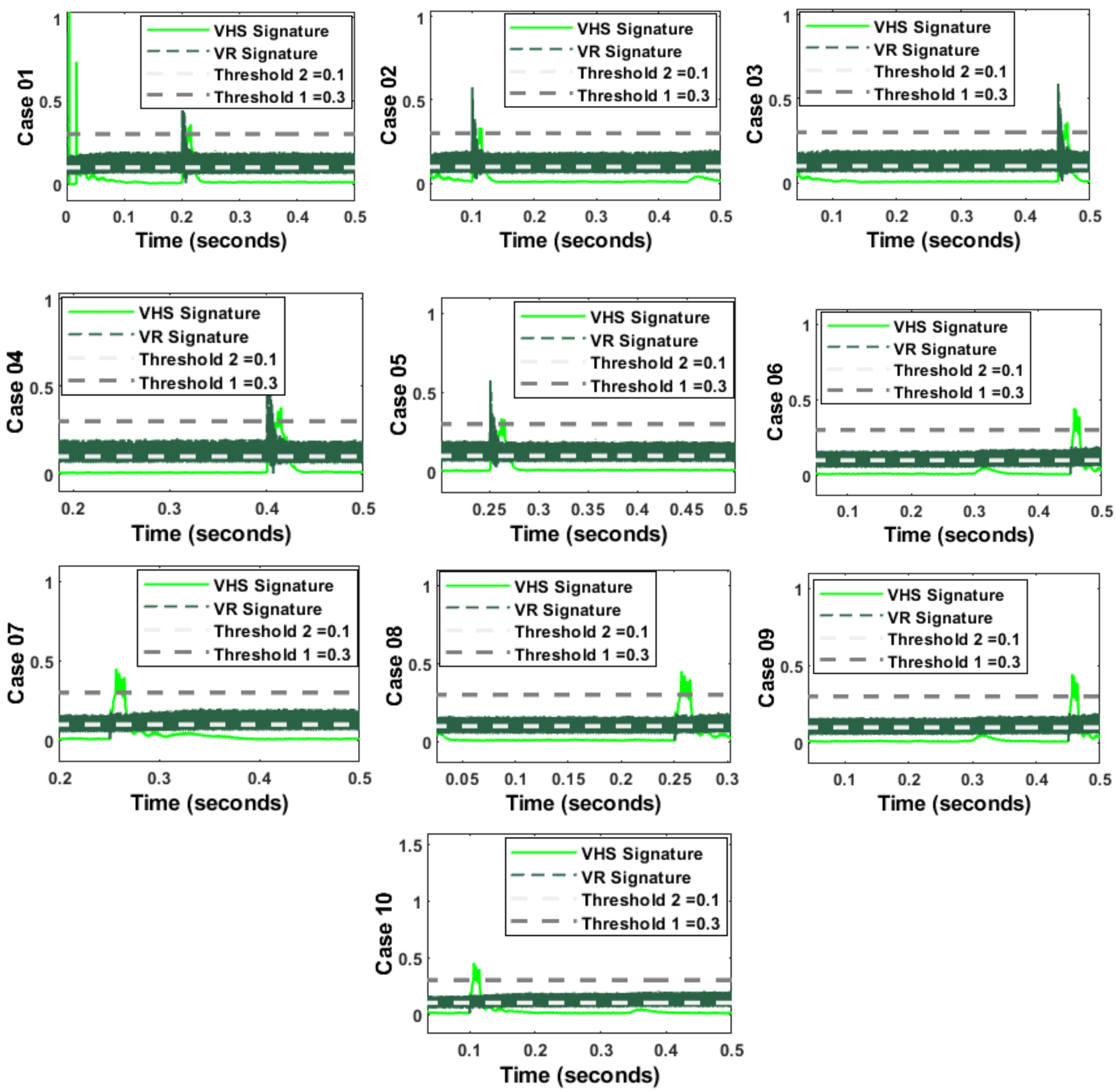

FIGURE 12. The test cases on the UL-1741 for NDZ analysis of the proposed CKF-based scheme.

TABLE 1. Testing cases of proposed CKFA-based scheme on Ul-174.

Utilized Parameters	Case results for the NDZ analysis of the suggested CKFA-based scheme.									
	Utilized UL-1741 testing parameters.					**Proposed CKFA-based scheme testing in load variations.**				
	01	02	03	04	05	06	07	08	09	10
Resistance (ohm)	1.815	3.51	1.815	1.815	1.815	2.057	3.62	1.45	1.815	1.815
Capacitance (mF)	3.174	3.174	3.174	3.174	3.174	3.174	3.174	3.174	3.174	3.174
Inductance (mH)	3.193	3.193	3.193	3.193	3.193	3.193	3.193	3.193	3.193	3.193
Reactive power %	101	101	101	98	102	102	102	102	98	102
Active power %	101	51	135	102	102	102	51	135	102	102

TABLE 2. Benchmark schemes compared with the proposed scheme.

Considered parameters for comparison	Benchmark schemes compared with the proposed scheme					CKFA-based Proposed scheme
	[28]	[35]	[42]	[41]	[38]	
Time of operation	16.7 milli sec	40 milli sec	8.3 milli sec	8.3 milli sec	5 milli sec	1 milli sec
Noise consideration	×	✓	✓	×	✓	✓
Computational burden	High	High	Very low	High	Very low	Very low
Accuracy	90.25%	100%	91.1%	97.89%	86.88%	99.9%

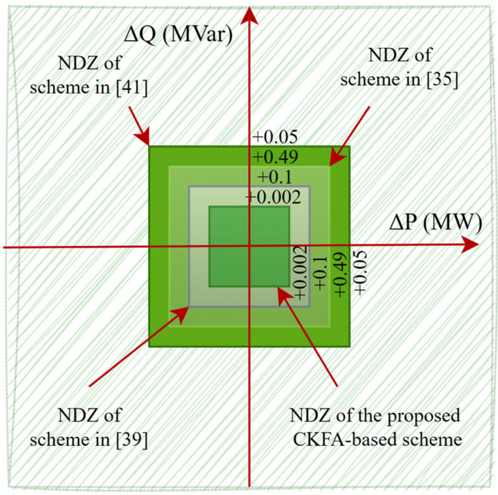

FIGURE 13. The NDZ comparison of the suggested CKFA-based.

than pre-defined threshold values indicating the successful operation of the proposed scheme.

VI. PERFORMANCE COMPARISON AND NDZ ANALYSIS

Detailed performance and comparative analysis of the presented CKFA-based scheme have been performed. The presented scheme is tested on the UL-1741 test bed. The single-line diagram of the UL-1741 test bed and its current controlled circuitry is shown in FIGURE 11. The detailed parameters of the UL-1741 test bed and the cases performed on UL-1741 are shown in TABLE 1.

The NDZ analysis is performed on various load and system parameters variation conditions to validate the efficacy of the proposed scheme the results are depicted in FIGURE 12, the proposed CKFA-based scheme depicts suitable performance with a very low power mismatch of 0.002 MVar and 0.002 MW. Moreover, the comparison of NDZ of the proposed method with some existing benchmark schemes as depicted in FIGURE 13, the Proposed CKFA-based scheme shows better performance. The proposed scheme is also compared with existing schemes in terms of time of operation, noise consideration, accuracy, and computational latency, as illustrated in TABLE 2. proposed method depicts better performance. Hence, the proposed method is better in performance than some existing benchmark schemes.

VII. CONCLUSION

This study suggested a novel approach utilizing the Cubature Kalman Filtering Algorithm for the detection of islanding events within ACMGs. By leveraging voltage signals at the point of common coupling, the proposed method demonstrates remarkable efficacy in accurately identifying islanding occurrences under various load/generation conditions, both balanced and unbalanced. Through extensive simulations on MATLAB/Simulink-based IEEE 13-bus test bed and UL-1741 test bed, the effectiveness of the proposed scheme is validated, achieving an impressive accuracy rate of 99.9%. Additionally, the method exhibits low computational latency and a minimal NDZ, ensuring timely and reliable detection without false operations. With a time of action of less than 1 millisecond, the proposed scheme emerges as a practical and efficient solution for islanding detection in ACMGs, offering significant contributions to the advancement of distribution system reliability and stability.

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