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RESEARCH ARTICLE

Adaptive Reclosing Technique Using Variational Mode Decomposition Algorithm in BESS-Based Microgrid

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ABSTRACT This study introduces a novel adaptive technique to accelerate the process of reclosing in a Battery Energy Storage System (BESS)-based microgrid system to provide uninterrupted power supply (UPS). Two different methodologies, Fault Current Contribution Ratio (FCCR) and Variational Mode Decomposition (VMD) are used to implement the proposed technique. First, the FCCR between the healthy and faulty phases is estimated in the relay after the occurrence of the transient. In the next stage, exact fault occurrences and clearance instances are detected using the VMD technique. The exact detection of fault clearance time will help reduce the conventional outage time. This will reduce the unwanted burden on the BESS as it can be used adaptively during the fault only. The comparative assessment is done to show the efficacy of the proposed reclosing method. The proposed technique will also help distinguish faults from switching operations. The performance of the proposed method is validated through a modified IEEE 13-bus BESS-based microgrid architecture. The EMTDC/PSCAD software is used for simulation. The algorithms are developed on the MATLAB platform. Real-time test results are also provided for the signals obtained from the Smart Grid Technology Laboratory (SGTL) lab setup. The results prove the efficacy of the proposed technique.

INDEX TERMS Variational mode decomposition (VMD), battery energy storage system (BESS), uninterrupted power supply (UPS), total harmonic distortion (THD).

I. INTRODUCTION

A. MOTIVATION AND INCITEMENT

In the current scenario and in the past decades, the development in the power sector is beyond the expectations. Today, maintaining the stability and reliability of the supply is quite difficult due to advances in the generation side, the integration of distributed energy resources (DER), the diversification of the transmission side, and the dynamic operation of distribution systems due to the penetration of power electronics-based equipment [1], [2]. Quality and continuity of supply are two aspects that must be maintained [3]. Past reports on many outages encourage the power society to develop new concepts and technologies so that the overall outage rate, as well as time, can be reduced [4]. Enhancing the resiliency of the system with battery energy storage after any major disturbance can save the economy of any country to a great extent [5].

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The conventional distribution system is currently experiencing significant reconfiguration due to the penetration of distributed energy resources, as well as energy storage systems. Primarily, the electric power systems use BESS to maintain an uninterruptible power supply. Therefore, various research has been done on the grid-connected mode of the BESS. These include its adaptive control, monitoring, integration with renewable sources, and protection schemes. This study focuses on the reclosing technique among protection issues using BESS in microgrid systems. The recloser acts as a circuit interrupter in which the magnitude of fault current is marginal for the distribution network. The conventional reclosing technique follows the operation sequence with 0.5 and 15 s (preset dead time) for the first and second reclosing instances, respectively, even if the fault has cleared before reclosing. Hence, the operation of the recloser is delayed for a preset dead time, independent of fault type. Furthermore, the conventional reclosing technique cannot determine the accurate fault clearance time. Hence, there is a need to develop some techniques to detect the exact time of fault clearance to reduce dead time.

B. LITERATURE REVIEW

In the literature, there are several articles in which the researchers present different ways to minimize the outage rate in a post-disturbance situation [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22], [23], [24], [25]. In [6], the dead time of the single-pole autoreclosing can be controlled by the secondary arc voltage in a high-voltage transmission system. In [7], the adaptive dead time has been calculated using secondary arc extinction measurements for the single-pole switching operation of high-voltage lines in real-time applications. In [8], the comparison of the reclosing application has been presented based on the behavior of the secondary arc during simulations, laboratory results, and real-time implementation. In [9], different degrees of feeder automation have also been presented to reduce outage time with remote controlled breakers that will selectively perform load shedding based on their degree of criticality. In past decades, much research has been done on fault and outage location detection algorithms as one of the most economical and efficient methods to enhance the resilience of distribution systems [10]. In [11], the implementation of the high-speed adaptive single-phase reclosing technique has been done based on the local voltage phasors. This work uses the local voltage magnitude and angle of the faulted phase to quickly identify the faulted phase and arc extinction. Machine learning classifiers are used for arc extinction detection after processing the measured fault phase voltage and extracting significant features [12]. This intelligent classifier can also be implemented to distinguish transients from permanent faults.

The proposed scheme in [13] uses frequency response analysis (FRA) as an efficient tool for fault detection. To overcome the shortcomings of multiple fault estimation, different methods such as [14] and [15] are proposed that can be used to determine the status and location of the outage area, where the optimal number and location of fault indicators are collected. To mitigate the harmful effects of a single line-to-ground fault, a single-phase auto-reclosing (SPAR)-based method has been developed [16]. This process primarily consists of opening the faulted phase, waiting for a preset dead time, and reclosing the previously disconnected phase. The proposed technique was able to correctly detect whether the system was faulty. Voltage and current waves are used in [17] to develop the Frequency-Dependent Line Model (FDLM), which must travel together with the same propagation function.

In [18], an appropriate method has been proposed to detect and locate faults using a wavelet transform. The data from the bus voltage is used to measure the energy percentage. Transient and permanent faults are discriminated against by using the differential voltage across circuit breaker contacts, which helps in auto-reclosure operation [19]. In existing work, various automatic reclosing techniques have been implemented in the transmission system to determine the secondary arc extinction time. However, unfortunately, it cannot be directly applicable to the distribution system [20], [21]. However, a few proposed techniques, including the fault current ratio calculation, total harmonic distortion (THD) analysis [22], the second-order difference of THD, and the minimization of transient using synchronism checking for the adaptive reclosing implementation in the distribution network are discussed in [23] and [24]. Several other techniques are described in the literature to support researchers and power system engineers in selecting the most suitable technique for the outage, fault detection, and reclosing operation as per their needs, the availability of data, and measurement. However, each method has its own desired functionalities and challenges.

The BESS can also be utilized for peak load management and frequency regulation. BESS is generally connected for both energy storage and backup power supply in hospitals and communication systems. However, unnecessary engagement can degrade the operating life of BESS. It is rarely possible for the breaker reclosing technique to take attempts at the exact fault-clearance time. The unnecessary burden on BESS due to the conventional dead time of the reclosing system deteriorates the battery's life. In a microgrid system, generally, a BESS is used as a UPS source during a power outage. Since the capacity of BESS components is limited, they have to be used efficiently. If any fault occurs in a part of the microgrid, then the energy storage sources like BESS are used as UPS for emergency loads on the isolated portion of the microgrid.

C. CONTRIBUTIONS AND ARTICLE ORGANIZATION

The methods discussed previously use BESS continuously to determine the fault clearance time, which leads to the loss of reserve BESS energy [24]. In this proposal, an adaptive reclosing strategy is implemented to maintain UPS in coordination with BESS. With local end current measurement, the fault current contribution ratio (FCCR) and the energy index using Variational Mode Decomposition (VMD) are estimated. VMD technique is highly immune to noise and more suitable for fault analysis as compared to other methods. The conventional reclosing technique has a fixed dead time of 0.5s which causes an unwanted burden on the storage system [24]. Most of the time-frequency approaches are used for fault detection. Here, the VMD technique is applied to detect the fault clearance instant which can further help in reducing outage time as discussed in section V. The transient component extracted using the VMD algorithm from faulted phase current is used for the calculation of the energy index. The third mode contains the most significant transient components generated during the fault. Therefore, it is considered an effective mode of analyzing the event. The integrated logic consisting of both the fault current ratio calculation and the energy index value of the signal will identify the exact fault onset and fault clearance time. The proposed method also uses an adaptive threshold value to identify the exact time of initiation and clearance of the fault. The exact time of fault clearance detection will help to reclose the system just after the fault is cleared, thereby reducing the total outage time. The energy index of the effective mode always deviates from the normalized value when any fault occurs in the system. For other switching events, too, the index may rise. But if the index remains high for more than two cycles and is generated twice, then that event can be considered a fault initiation and fault clearance instance. In other switching events, the index will increase only once. So, after the second instance, the breaker can be reclosed, and information can be transmitted to the BESS breaker to isolate itself from the system so that the power flow from the utility side can be extended. Hence, the operation of the BESS unit can be operated adaptively as per the faulty information. In this way, unnecessary use of BESS during normal situations can be avoided.

This work introduces a novel adaptive reclosing technique using FCCR and VMD techniques in a BESS-based microgrid. Section II discusses the test system using a modified IEEE 13-bus architecture. Section III presents the proposed reclosing technique that considers BESS during the fault. After the fault is detected, the proposed integrated technique will detect the exact fault start time and the fault clearance time. Section IV describes the various results and simulations performed using the EMTDC/PSCAD software to validate the proposed adaptive reclosing technique. The algorithms are developed on the MATLAB platform. The comparative analysis with the conventional technique is done in Section V. Section VI shows the validation of the proposed adaptive technique using the signals obtained from the real-time hardware experimental SGTL lab setup. Finally, the conclusions interpreted from our work are explained in Section VII.

II. MICROGRID ARCHITECTURE

The integration of DERs in distribution systems leads to the addition of severe transient during the charging and discharging of battery sources and inverter operation. The modified IEEE 13-bus test system is developed for analyzing the impact of DERs on the proposed adaptive reclosing strategy [25]. The microgrid system is shown in Fig. 1. In the modified IEEE 13-bus system, hybrid DGs, including wind turbines, photovoltaic (PV) and BESS, are included at buses 10, 12, and 13, respectively. The capacity of the PV system connected to bus-12 is 2 MW. The DFIG (doubly fed induction generator) connected to bus-10 has a capacity of 2 MVA. The capacity rating of the BESS connected to bus 13 is 2 MW. G1 and G2 are the voltage sources; BESS consists of a battery and an inverter; and L-1 to L-13 are the different loads connected to different buses. T-1 to T-9 denote station transformers. The rating of the shunt capacitor connected to bus-3 has a capacity of 1.0 μF. The relay connected to bus 3 that protects the line connected to bus-3 and bus-8 is considered when evaluating the execution of the proposed technique.

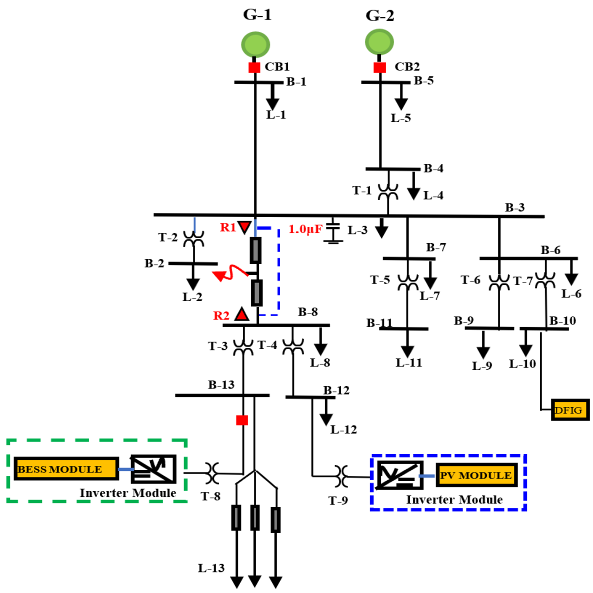

FIGURE 1. Modified IEEE 13-Bus Hybrid DG-BESS based Microgrid system.

The rated voltage of a utility supply is 115 kV, and the local plant operates at 13.8 kV. The overhead line and the capacitance of all cables are neglected. It consists of two three-phase voltage sources with a rated short circuit rating of 100 MVA and is studied at a frequency of 60Hz. The ratings of all components connected to the test system are provided in the Appendix section for reference.

III. PROPOSED METHODOLOGY

This work proposes a novel adaptive reclosing technique for microgrid systems to accelerate the reclosing process so that UPS can be used efficiently. To avoid power interruptions, BESS is installed as an UPS source. With the onset of a fault in any line, the proposed technique first detects the faulty section and isolates it from the main supply. After the separation, the BESS supplies the rest of the loads connected to the microgrid system. Hence, during the fault period, the main breaker will disconnect and the BESS breaker will be operated to connect to the faulted section.

The BESS is interfaced with the distribution system through electronic power components such as the inverter. The dynamic behavior of the inverter is different from that of synchronous or induction machines. The inertia of the inverter is negligible due to the absence of a rotating mass component. Therefore, the injection of fault current during the discharge period of a BESS is the same as that from inverter-based resources (IBRs). IBRs could produce a peak current of 1.2pu for a duration of approximately seven cycles [26]. Thus, as per this study, the contribution of the fault current from the BESS is almost 1.2pu of the full-rated current of the inverter. The injection of fault current from the BESS is marginally more than the full-load current due to the power electronics components. Thus, the over-current relay will not operate to obstruct the fault current supplied by the BESS, and the inverter will continue its operation. Therefore, the low level of injection of fault current from the BESS will not affect the distribution system. The method is tested in the microgrid system to observe smooth transition states, i.e., during isolation and reclosing of the affected line with the healthy line. During isolation from the main system, the BESS with affected phase loads will be considered a small microgrid if voltage and frequency are preserved within the steady-state limit. The different stages of the BESS-based adaptive reclosing techniques are described in the following.

A. FAULT CURRENT CONTRIBUTION RATIO (FCCR)

In the conventional microgrid system, BESS continues to supply power to the microgrid even in the event of a fault or any other disturbance. With the proposed adaptive reclosing technique, the faulted section is generally disconnected from the system, and BESS continues to maintain the power supply during the fault. In the proposed methodology, the fault current contribution ratio (FCCR) between the faulty and healthy phases can be estimated at the relay end, as in (1)

$$FCCR = \frac{Faulted\ Phase\ Current}{Healthy\ Phase\ Current} \tag{1}$$

In Fig. 1, relay R1 is considered a local end relay. For an AG fault between bus-3 and bus-8, the FCCR is estimated by changing the fault resistance values. The results are summarized in Table 1. From Table 1, it is observed that the FCCR ratio lies in the range of 1 pu to 1.2 pu. Also, for very high-resistance fault cases, the ratio may be further reduced.

The FCCR exceeds the normal value after the initiation of any fault and remains above it up to the clearance of the fault. Once the fault is cleared, it returns to the original ratio. The typical time period required to clear the fault is within 4 cycles, depending upon the arc quenching medium and detection algorithms. During other switching events, except for faults, the FCCR can increase beyond its normal value, but the persistence time may vary and can be less than one cycle. This is the first criterion for the adaptive reclosing technique to detect and discriminate any switching event

TABLE 1. Simulation result of FCCR during A-G fault.

Fault resistance (Ω)	Faulted phase current (kA)	Healthy phase current (kA)	Ratio in pu
0.1	0.88	0.74	1.18
1	0.48	0.40	1.2
10	0.41	0.35	1.17
100	0.45	0.40	1.12

from a fault. In the next stage, exact fault occurrences and clearance instances are detected using an estimated index. The application of the VMD algorithm to detect the exact fault initiation time and fault clearance time is discussed. After fault detection, the main supply will be isolated from the system, and the BESS breaker will be closed to supply backup power during the fault.

B. APPLICATION OF VMD ALGORITHM FOR DEVELOPING THE ADAPTIVE RECLOSING TECHNIQUE

At the instant of fault initiation, the presence of different frequency components is significant, along with the DC component of decaying nature. Such signals can be estimated using an efficient time-frequency approach to analyze the event. The variational mode decomposition technique is an efficient and effective time-frequency approach that is used in this work to decompose the faulted phase current signal.

The implementation of the proposed VMD technique is simple when using the raw decomposed signal. The switching operation and faulted event can be judged accurately since the presence of a transient in the signal is effective only for a few cycles. Such transients are produced due to the sudden discharge of the magnetic energy elements and are termed decaying DC transients. With the use of the signal decomposition method, useful signals can be extracted to perform the event detection process. In this work, the VMD technique is implemented on current signals to obtain useful data and further tested to distinguish other switching events from a single line to ground fault. The detailed process is discussed here. Variational Mode Decomposition (VMD) is a novel non-recursive adaptive multi-resolution decomposition technique [27], [28]. The objective of VMD is to decompose a real-valued input signal x(t) into a discrete number of band-limited sub-modes (signals) u_k, where each sub-signal is developed to compact around a center pulsation ω_k considered along with the decomposition. This sub-mode has sparsity properties while replicating the input signal. Here, the pre-sparsity value is selected to be its bandwidth in the spectral domain. In other words, the considered sub-mode is mostly compact near a center pulsation, which is to be calculated along with the decomposition. The bandwidth of each mode can be determined by the following proposed schemes:

- For sub-modes u_k, with the help of the Hilbert transforms, calculate the associated analytic signal in order to produce a unilateral frequency spectrum.

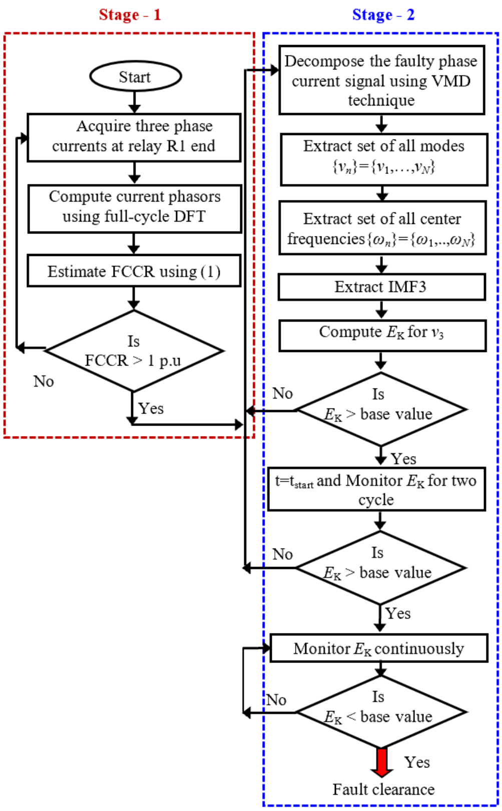

FIGURE 2. Flow chart of the proposed adaptive reclosing technique.

- The sub-modes are then mixed with an exponential term for tuning them to their respective estimated center frequency by shifting the sub-mode u_k frequency spectrum to the "baseband" value.
- The bandwidth of u_k is now calculated with the Gaussian smoothness H^1 of the demodulated signal, that is, the squared norm (L^2-norm) of the gradient is used.

The output of the constrained variational decomposition problem is as follows in (2):

$$\underset{\{u_k\},\{\omega_k\}}{\text{minimize}} \left\{ \sum_k \left\| \partial_t \left[\left(\delta(t) + \frac{j}{\pi t} \right) * u_k(t) \right] e^{-j\omega_k t} \right\|_2^2 \right\}$$
$$\text{subject to } \sum_k u_k = x \tag{2}$$

where δ is the Dirac distribution and $*$ represents the convolution operation. $[u_k]$ denotes the set of submodes $[u_1, u_2 \ldots\ldots\ldots u_k]$ and $[\omega_k]$ indicates the set of center pulsations $[\omega_1, \omega_2 \ldots\ldots \omega_k]$.

The reconstruction constraint can be represented in different ways. Here, we recommend making use of both a quadratic penalty factor and a lagrangian multiplier term in order to represent the problem of unconstrained optimization as a constrained variational problem. The combination of the two terms has the advantage of both the great convergence properties of the quadratic penalty at the finite weight and the strict implementation of the constraint by the Lagrangian multiplier.

TABLE 2. FCCR values in pu.

Cases	FCCR in pu
AG Fault	2
AG Fault with White Gaussian Noise	1.1
Capacitor Switching	1.3
Load On	1.4
Load Off	1.3
Induction Motor Switching	1.6
Generator Failure	1.2

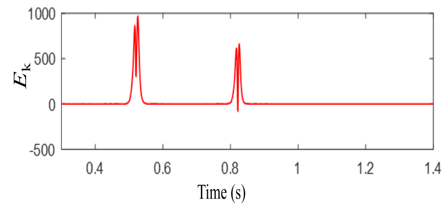

FIGURE 3. Response for AG fault case.

Thus, we represent the Augmented Lagrangian as follows in (3). The solution to (3) is found as the saddle point of the Augmented Lagrangian in a sequential iterative sub-optimizations process called the Alternate Direction Technique of Multipliers (ADTM). As a result, the solutions for u_k and ω_k can be represented as follows in (4) and (5):

$$\mathcal{L}(u_k, \omega_k, \lambda) = \alpha \sum_k \|\partial_t[(\delta(t) + \frac{j}{\pi t}) * u_k(t)]e^{-j\omega_k t}\|_2^2 + \|x(t) - \sum_k u_k(t)\|_2^2 + \langle \lambda(t), x(t) - \sum_k u_k(t) \rangle. \tag{3}$$

$$\hat{u_k}^{n+1}(\omega) = \frac{\hat{x}(\omega) - \sum_{i \neq k} \hat{u}_i(\omega) + \frac{\hat{\lambda}(\omega)}{2}}{1 + 2\alpha(\omega - \omega_k)^2} \tag{4}$$

$$\omega_k^{n+1} = \frac{\int_0^\infty \omega |\hat{u}_k(\omega)|^2 d\omega}{\int_0^\infty |\hat{u}_k(\omega)|^2 d\omega} \tag{5}$$

where, $\hat{x}(\omega)$, $\hat{u}_i(\omega)$, $\hat{\lambda}(\omega)$, and $\hat{u}_k(\omega)$ denotes the Fourier transform of $\hat{x}(t)$, $\hat{u}_i(t)$, $\hat{\lambda}(t)$, and $\hat{u}_k(t)$, respectively, and n indicates the number of iteration.

C. ENERGY INDEX VALUE CALCULATION

The energy index value is a measure that is widely used in a majority of fields to present the complexity of the signal. In the energy index calculation process, when any transient occurs in the power distribution network, the stable state of the signal will be discontinued during the period. If the distorted signal is divided into different sub-modes and the energy of each sub-mode is estimated, then the energy will be different for each sub-mode, which essentially depends on the type of power quality issue. Next, the feature for

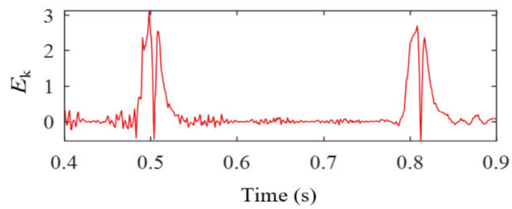

FIGURE 4. Response with white gaussian noise.

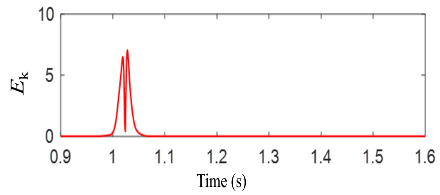

FIGURE 5. Response for capacitor switching.

fault detection is extracted by calculating the energy E_k of a significant mode u_k. It is taken as the energy index value with the M number of modes and is expressed as in (6).

$$E_k = \sum_{m=0}^{M-1} |u_k(m)|^2 = \frac{1}{M} \sum_{q=0}^{M-1} |F\{u_k(m)\}|^2 \tag{6}$$

D. BASE VALUE CALCULATION

For power system security reasons, an adaptive base value is calculated for the proposed method using (7).

$$base\ value = \sqrt{\frac{\sum (E_k - \overline{E_k})^2}{M}} \tag{7}$$

The relay R1 will compare the value of E_k with the base value to start counting the number of cycles. It is to be observed that the base value settings are not dependent on the system configuration.

In this work, the energy index E_k of the decomposed signal is estimated and used to implement the detection operation of the exact fault initiation time and fault clearance time. At the time of the transient, the high-frequency component is injected into the current signals, and the energy index value of the current signal increases sharply. Therefore, the energy index can be used as a sign of the fault onset and fault clearance time. The flow chart of the proposed reclosing technique is shown in Fig. 2.

The operational steps of the proposed adaptive reclosing technique are given below:

1) Determination of the FCCR for three-phase currents measured at the relay R1 by using the full-cycle discrete Fourier transform (DFT).
2) Check whether the FCCR is greater than 1 p.u. or not. If 'Yes', then go to Step 3. Otherwise, go to Step 1.
3) Decompose the faulty phase current signal using the VMD technique.
4) Extraction of all the decomposed modes sets $[v_n] = [v_1, v_2, v_3]$.

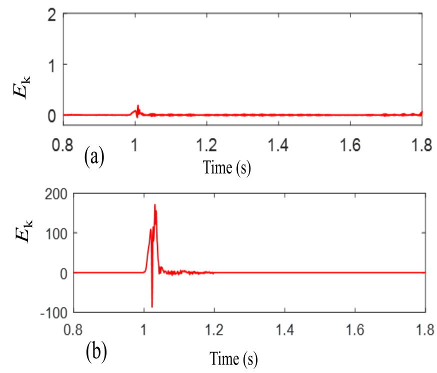

FIGURE 6. Results for load switching cases. (a) load ON. (b) load OFF.

5) Choose the most significant decomposed mode v_3 for the feature extraction.
6) Computation of the energy-based index E_k using (6).
7) Calculate the base value using (7).
8) Comparison of E_k with the base value If E_k is greater than the base value, then go to Step 9. Otherwise, go to Step 3.
9) Monitor E_k continuously for two cycles. Again, compare E_k with the base value. If E_k is greater than the base value, then go to Step 10. Otherwise, go to Step 3.
10) Monitor E_k continuously. Again, compare E_k with the base value. If E_k is less than the base value, then the fault clearance is detected. Otherwise, monitor E_k continuously.

The first step of the proposed method detects the FCCR value at the local end relay. Once the value rises above 1 pu, then the energy index is estimated, which is basically the second step. In this second step, the faulted phase current is decomposed using the VMD approach to extract the most effective mode, i.e., the third mode. When a fault occurs in the system, the energy index of the effective mode always deviates from the normalised value. If the index remains high for more than two cycles and is generated twice, then that can be considered a fault initiation and fault clearance instance. In other switching events, the index will rise only once. Then, after the second instance, the main breaker can be reclosed, and information can be transmitted to the BESS breaker to isolate it from the system so that the power flow from the utility side can be extended, which ultimately will reduce the unwanted stress on the BESS.

IV. SIMULATION RESULTS AND DISCUSSION

The efficiency of the proposed reclosing technique is tested on the BESS-based microgrid system shown in Fig. 1 and is considered and simulated for several cases with EMTDC/PSCAD software. The algorithms are developed on the MATLAB platform. The local distribution voltage is 13.8kV and the frequency is 60 Hz. The three-phase current signals are observed by the R1 relay connected to bus-3. Then, the full-cycle DFT of the three-phase current phasor

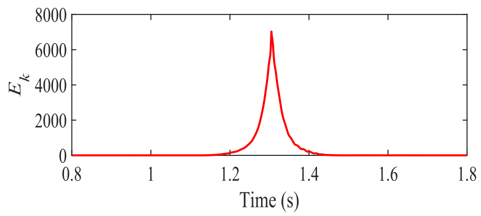

FIGURE 7. Result for induction motor switching.

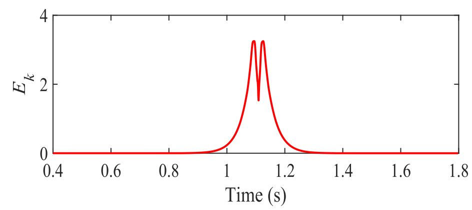

FIGURE 8. Result for generator failure event.

is calculated. The simulation results for different cases are described below:

A. FCCR FOR DIFFERENT CASES

For different simulated cases, the FCCR is calculated and provided in Table 2. The FCCR ratio is lower for other switching events in comparison to a single line-to-ground fault. For simulation, an AG fault case with a fault resistance of 2Ω and a fault location in the middle of the line is considered. For other generated switching cases, the values of FCCR are very low, well below 1.5pu. By varying the fault resistance, the FCCR may go further below and lie in the same range as other switching events. In the following subsection, different cases are simulated, and the generation of an energy index is verified to perform the reclosing process and detect the exact fault clearance time.

B. OPERATION DURING SINGLE LINE TO GROUND FAULT

In the grid-connected mode, when the BESS-based microgrid system is connected to the utility grid, the performance of the proposed adaptive reclosing technique is observed for a single line-to-ground (AG) fault. AG fault is simulated on the downstream side of the relay (R_1), connected near bus-3, protecting lines between bus-3 and bus-8. AG fault is simulated at 0.5 s with a fault resistance of 2Ω. The FCCR for the AG fault case is 2pu and it can be noticed that the value of the energy index increases drastically with the initiation of the fault at 0.5s. In addition, the energy index is generated twice, indicating the fault clearance time at a second instant. Thus, the main breaker can be reclosed to connect the fault line and open the BESS after the normalization of the fault at the second instant, i.e., at 0.841 s. The response is shown in Fig. 3. In this way, BESS will provide emergency power to the critical loads and will get disconnected after the fault is cleared, thus reducing unwanted stress on BESS.

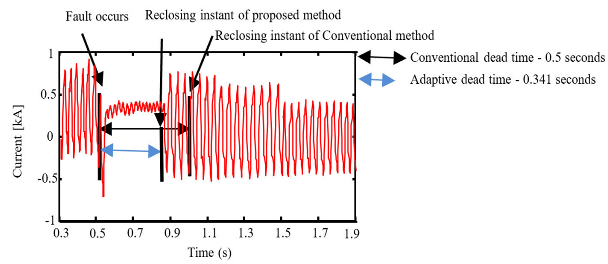

FIGURE 9. Faulted phase-A load current during AG fault.

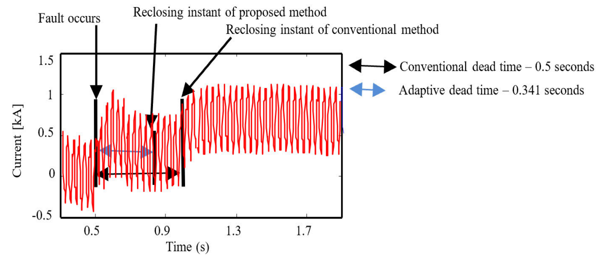

FIGURE 10. Healthy phase-B load current during AG fault.

C. PERFORMANCE WITH WHITE GAUSSIAN NOISE IN MEASUREMENT

The presence of white Gaussian noise (WGN) is more significant in the high-frequency component-based modes, due to which inaccuracies in the fault analysis may occur. To analyze the situation, a WGN of 10 dB is added to the current signal. Fault in phase-A is simulated at 0.5 s and cleared at 0.8 s. The fault resistance is 50Ω. Further, the third decomposed mode of the current signal is extracted, and the energy component is estimated using (6). The energy is then compared with the base value to detect the exact fault onset and fault clearance time. The obtained results are shown in Fig. 4.

D. CAPACITOR SWITCHING

The impact of capacitor switching is different from other switching events as it causes a relatively huge surge current and possibly an overvoltage. To simulate such a condition, a capacitor bank of 4 MVAR is switched on at 1s. The FCCR ratio is 1.3pu from which a change in system condition can be identified. But in Fig. 5, the energy index plot identifies the initiation of the transient events. The capacitor switching operation causes the system to become unbalanced by generating overvoltages in the form of a single energy index. So, the performance of the proposed adaptive reclosing technique is as expected and reliable in distinguishing the switching operation from the fault.

E. HEAVY LOAD SWITCHING

To test this scenario, a 2MW load connected to bus-8 is switched on and off at 1s. In these two cases, the response of the adaptive reclosing technique is verified. During the ON load state, the FCCR is 1.4pu, but E_k is very small,

TABLE 3. Performance comparison with previously reported reclosing techniques.

Ref.	Fault clearance detection techniques	Outage Time	Use of BESS	Threshold selection	Fault clearance time accuracy	Noise Impact Analysis
Conventional	No detection	High (0.5s)	Continuous	No	inaccurate	No
[6]	Secondary arc voltage	low	No	fixed	accurate	No
[21]	THD	low	Continuous	fixed	accurate	No
[22]	Second-order THD	low	Continuous	fixed	accurate	No
[23]	EMD	low	Adaptive	fixed	accurate	No
Proposed	VMD	lowest (0.341s)	Adaptive	Adaptive	highly accurate	Yes

TABLE 4. Component ratings.

No.	Components	Ratings
1.	Grid configurator	400V, 50Hz
2.	Number of converters	2
3.	Rated power of each converter	40 kW
4.	DC Bus voltage	700 V
5.	AC collector voltage	400 V
6.	Total active load	50 kW
7.	Total Reactive load	70 kVAR

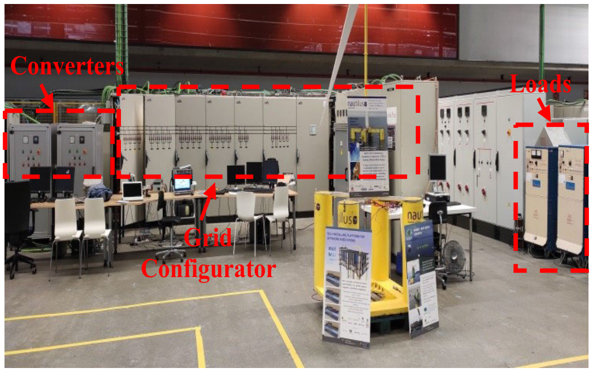

FIGURE 11. Schematic diagram of the hardware experimental test setup.

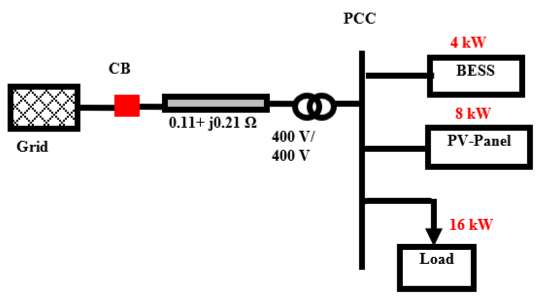

FIGURE 12. Single line diagram of the experimental test setup.

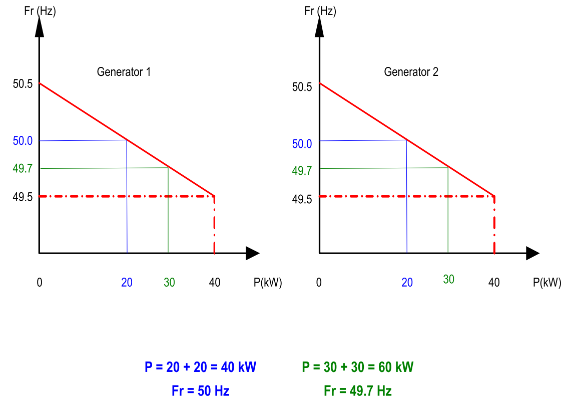

FIGURE 13. The characteristics of the droop controllers at the inverters.

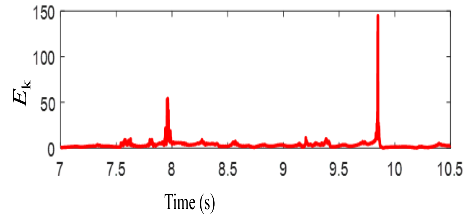

FIGURE 14. Response for algorithm validation using real-time current signal indicating fault initiation and clearance time in Grid-connected mode.

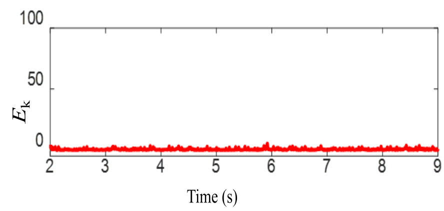

FIGURE 15. Response for algorithm validation using real-time current signal indicating load switching operation in islanded mode.

almost zero. Also, E_k is generated only once. Similarly, for the load-off state, FCCR is 1.3pu, and E_k is significantly high. As the energy index is generated only once, the proposed method will remain silent during load-switching operations. The results for both cases are depicted in Figs. 6(a) and 6(b), respectively.

F. INDUCTION MOTOR SWITCHING

To analyze the impact of induction motor switching on the proposed method, an induction motor of 4.5 MVA capacity is switched on at 1.3 s connected to bus 3. The FCCR ratio is 1.6pu from which a change can be identified in the system. In Fig. 7, the energy index plot shows the initiation of the transient event in the form of a single energy index generation. Thus, the performance of the proposed technique is satisfactory in distinguishing the induction motor switching operation from the fault.

G. PERFORMANCE DURING GENERATOR FAILURE

To observe the performance of the proposed technique during the generator failure event. Generator-2 (G-2) connected to bus-5 is intentionally tripped at 1.1 s by opening the CB-2 breaker. The response of the proposed method is recorded for this case and shown in Fig. 8. In this case, the energy index

TABLE 5. Per-unit transmission line and cable impedance data (base values: 13.8 kV, 10 MVA).

From	To	R[Ω]	X[mΩ]
BUS-4	BUS-5	0.0232	0.0461
BUS-1	BUS-3	0.0232	0.0461
BUS-3	BUS-8	0.0207	0.01729
BUS-3	BUS-7	0.0298	0.02489
BUS-3	BUS-6	0.0284	0.01189

TABLE 6. Transformer data.

From	To	Voltage [kV]	Tap	kVA	%R	%X
BUS-3	BUS-4	20:13.8	20	1500	0.4698	7.9862
BUS-1	BUS-2	13.8:0.48	13.45	1500	0.9593	5.6694
BUS-8	BUS-12	13.8:0.48	13.45	1250	0.7398	4.4388
BUS-8	BUS-13	13.8:4.16	13.11	1725	0.7442	5.9537
BUS-7	BUS-11	13.8:0.48	13.45	1500	0.8743	5.6831
BUS-6	BUS-9	13.8:0.48	13.8	1500	0.8363	5.4360
BUS-6	BUS-10	13.8:2.4	13.11	3750	0.4568	5.4810

TABLE 7. Generation, load, and bus voltage data (from power flow study results).

Bus	V_{mag} [p.u.]	δ [deg]	P_{gen} [kW]	Q_{gen} [kVAR]	P_{load} [kW]	Q_{load} [kVAR]
BUS-1	0.995	-2.39	1400	1300	460	254
BUS-2	0.995	-3.53	-	-	340	160
BUS-3	0.994	-2.40	-	-	240	110
BUS-4	0.999	-0.13	-	-	290	212
BUS-5	1.000	0.00	1200	1050	320	220
BUS-6	0.994	-2.40	-	-	384	220
BUS-7	0.994	-2.40	-	-	380	220
BUS-8	0.994	-2.40	-	-	290	212
BUS-9	0.979	-3.08	-	-	256	172
BUS-10	1.001	-4.69	250	190	171	150
BUS-11	0.981	-4.16	-	-	340	250
BUS-12	0.980	-4.72	-	-	340	250
BUS-13	0.996	-4.85	450	380	340	250

TABLE 8. Data for doubly fed induction generator.

Parameters	Values
Motor Name	Wound Rotor
Rated Power	2[MVA]
Rated Voltage	0.69[kV]
Base Angular Frequency	60[Hz]
Stator /Rotor turns Ratio	1
Angular moment of Inertia	1.7267[$kg.m^2/s$]
Stator resistance	0.0034[p.u.]
Wound rotor resistance	0.00607[p.u.]
Magnetizing Inductance	0.9 [p.u.]
Stator leakage inductance	0.0102 [p.u.]
Wound rotor leakage inductance	0.011 [p.u.]

TABLE 9. Data for photovoltaic system.

Parameters	Values
Photovoltaic array name	PV array
Nos. of modules connected in series per array	40
Nos. of module strings in parallel per array	60
Nos. of cell strings connected in series per module	108
Number of cell strings in parallel per module	4
Reference Irradiation	1000 [W/m^2]
Reference cell temperature	25[°C]

TABLE 10. Data for battery energy storage system.

Parameters	Values
Battery rating	2[MW]
Battery pack	0.5[kV]
Nominal voltage	0.12[kV]
Nominal discharge current	20%
Initial state of charge	100%

E_k exceeds the threshold only once and thus the proposed method will not get activated.

V. COMPARATIVE ASSESSMENT WITH CONVENTIONAL TECHNIQUE

With the implementation of the conventional reclosing technique [21], [22], there is a drawback of preset dead time, as depicted in Figs. 9 and 10. During a fault, the BESS will provide backup power to the end loads, and after the fault is cleared, the system will be reconnected to the normal power supply. It leads to a reduction in outage time and improves the reliability of the power supply. The AG fault with a fault resistance of 0.1Ω occurring in the line between bus-3 and bus-8 is simulated to compare the performance of the proposed adaptive reclosing technique with the conventional method. The load current of different phases is monitored for load L-13 connected to bus-13.

The faulted phase load current is shown in Fig. 9. The occurrence of a fault takes 0.5 s and the fault clearance time is detected at 0.841 s using the VMD technique. The implementation of the adaptive reclosing technique helps in the exact fault clearance time detection, and hence the conventional dead time of a recloser can be reduced to 0.341 s using the adaptive technique, as shown in Figs. 9 and 10. In the case of the existing technique, the reclosing is done at 1s after a preset time of 0.5 s which is independent of the fault clearance time. Hence, with the proposed auto-reclosing, the breaker can be adaptively reclosed as soon as the fault gets cleared, thus reducing the unnecessary outage time. After the confirmation of the fault clearance, only one reclosing operation is needed. Therefore, it reduces the risk of damage due to an unsuccessful reclosing operation, as a huge surge and fault current detrimentally affect the life of line equipment. In this work, the adaptive reclosing technique is implemented in the BESS-based microgrid system.

The healthy phase load current is depicted in Fig. 10. In the case of the proposed adaptive reclosing method, when the circuit breaker trips, the steady state current supply is supplied from the BESS to the healthy loads, and hence the system does not suffer from an outage. In the case of the conventional reclosing method, although phase B of the load is not the faulted one, it experiences the steady-state current interruption before reclosing operation, resulting in an unnecessary outage in the healthy phase. The phase current result is the same for phase C as it is for phase B.

During the transient period, the lifespan of BESS is highly stressed. At that time, BESS may be unable to fulfill a high load demand and get damaged also. The use of the adaptive auto-reclosing technique enables maintaining an uninterrupted power supply using BESS only during the fault. Also, after a fault is detected, the power supply can be maintained from BESS to the affected loads, and after the reconnection of the main breaker, the power supply from BESS can be disconnected from the system. Hence, a reduction in stress on BESS due to unnecessary outage time verifies the superiority of the proposed adaptive operation of the recloser over the conventional method and thus strengthens the resilience of the microgrid system. The summary of the performance comparison with the previously reported reclosing techniques is tabulated in Table 3.

VI. EXPERIMENTAL RESULTS

The validation of the proposed algorithm is done using real-time signals collected from a low-voltage, three-phase microgrid test set up at the Smart Grid Technologies Laboratory (SGTL) in TECNALIA, Spain. The schematic diagram of the experimental setup is illustrated in Fig. 11. A brief description of the setup and performance of the proposed approach are discussed below. The single-line diagram of the experimental microgrid setup is depicted in Fig. 12.

The method is tested offline using the recorded data. In the microgrid setup, the grid is operated at 400 volts and 50 Hz. The point of common coupling (PCC) is used to connect the line impedance and an isolation transformer to the microgrid system. Two converters are used to emulate the behavior of DGs connected as shown in Fig. 11. Converter 1 is operating in constant voltage (CV) control mode as BESS and Converter 2 is operating in constant current (CC) control mode as the Photovoltaic System. The components in the microgrid set-up and the prototype component ratings are tabulated in Table 4. The operation of both power converters is controlled using two independent control systems (CC and CV). They are as follows:

- Primary control
- Secondary control

In the primary loop, local control methods are implemented in the inverters using droop controllers for controlling active and reactive powers with the help of frequency and voltage parameters, respectively. The characteristic of the droop controller at the inverters is as depicted in Fig. 13. Since the frequency signal helps in the instantaneous sharing of load among the generators in the microgrid set-up. It is also essentially used for the conversion from the grid-connected to the island-based mode of operation.

The different services provided by the secondary control of the Smart Grid Technology Laboratory (SGTL) microgrid setup are as discussed below:

- Multi-Agent Technologies:
  modular, plug-and-play, distributed techniques are implemented based on multi-agent technologies.
- Microgrid Energy Management System:
  Under this system, different tasks can be executed, including historical storage of data, real-time visualization of data (P/Q/fr/V/I), secondary control in the grid-connected and island modes of operation, and a set of predefined power schedules for distributed energy resources (DER).
- Functions of Secondary Control:
  In grid-connected operation, it continues exchanging power with the grid to maintain the predefined values, and in islanded operation, it recovers the reference frequency, i.e., 50 Hz.
- Real Time Economic Operation:
  Each controlling device provides its own operating costs, such as generation costs, deviation costs, DSM strategies, etc., and after power coordination between generation and demand, a microgrid price is obtained. Finally, each apparatus is given a power set point as per the microgrid price.

First, the real-time three-phase current signals from the microgrid setup are collected using Opal-RT with a sampling frequency of 1 kHz. These signals are recorded and stored in MATLAB.mat format. In the next stage, this saved sampled data is utilised for the validation of the proposed algorithm developed in MATLAB.

A. ALGORITHM VALIDATION USING AN EXPERIMENTAL SETUP

1) RESULT FOR SINGLE-LINE TO GROUND FAULT

The response of the proposed VMD algorithm has been tested on the real-time current signal by signal decomposition into a different set of modes. The computation of energy (E_k) is used as an energy index value to check the fault detection time and its clearance time.

The performance of the proposed algorithm for the fault occurrence time at 7.98 s and the fault clearance time at 9.89 s is as shown in Fig. 14. The energy index is generated twice, indicating the fault onset and fault clearance times. As a result, fully utilizing the VMD characteristic and developing the detection algorithm proves to be an appropriate idea. The proposed method promises to overcome the problem of accurate fault detection and successful detection of the exact fault clearance time using the adaptive reclosing implementation.

2) RESULT FOR LOAD SWITCHING IN ISLANDED MODE OPERATION

The response of the proposed technique is tested for the load switching case in islanded mode, and the obtained response is presented in Fig. 15. From the plot for load switching at different instances, the index is negligible, and the proposed method will not take any action or remain silent for this case in islanded mode. Thus, it is verified that the energy index is very high only at the instant of initiation of the fault and changes significantly during fault clearance. So, considering the pattern of the initiation and the clearance time of the fault, it can be detected. Hence, the detector will not take any action for load switching in island mode. This logic helps to develop a more reliable algorithm in the practical domain to accelerate the process of reclosing function.

VII. CONCLUSION

In this proposed approach, an adaptive reclosing technique is developed to accelerate the breaker's reclosing process in a post-fault condition. Using the VMD technique, the energy index is continuously estimated and monitored. At the fault onset and fault clearance times, the energy index is very high. Two consecutive peaks after fault detection can only be considered as fault onset and fault clearance instances. The accurate determination of fault clearance time will reduce the dead time as compared to the conventional technique. This will reduce the total outage time. Hence, the unwanted burden on BESS will be reduced. This adaptive technique can save the energy stored in the BESS system for emergency situations, and the life of the battery can also be improved using the proposed methodology.

The modified IEEE 13-bus with a BESS-based microgrid was developed and simulated in PSCAD/EMTDC to verify the efficiency of the method. Real-time validation of the proposed technique is also done using data collected from the hardware microgrid set-up present in TECNALIA, Spain. The results of single-line to ground faults and load switching during islanded mode are tested considering the practical network. The proposed technique using VMD will also help in distinguishing faults from switching events such as capacitor switching and load switching. The proposed method also performs well with white Gaussian noise in the measured signal. Comparison analysis is done to show the efficiency of the proposed method over the conventional reclosing method. In the future, the adaptive reclosing algorithm considering BESS in the system can be analyzed by varying the fault type, fault resistance, and fault location. Also, the quantitative estimation of BESS energy saving can be explored.

APPENDIX

The data for the modified IEEE 13-bus hybrid DG-BESS-based Microgrid system are tabulated in Tables 5-10. This test case consists of 13 buses and is representative of a medium-sized distribution system. The plant is fed from a utility supply at 115 kV and the local plant distribution system operates at 13.8 kV. Due to the balanced nature of this system, only positive sequence data is provided. The capacitance of the short overhead line and all cables are neglected.

The per-unit values of transmission line impedance values with base values of 13.8kV and 10MVA are tabulated in Table 5. The ratings of transformers connected in the IEEE-13 bus are tabulated in Table 6. From the results of the power flow study, the generation, load, and bus voltage data with their units are described in Table 7. The rating of the DFIG wind turbine connected to bus-10 has a capacity of 2 MVA, 0.69kV as tabulated in Table 8. The capacity of the photovoltaic system connected on bus-12 is 2 MW, and other parameters are detailed in Table 9. The data for the BESS are given in Table 10 with a capacity of 2 MW and a nominal voltage of 0.12 kV.

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REFERENCES

[1] M. Faisal, M. A. Hannan, P. J. Ker, A. Hussain, M. B. Mansor, and F. Blaabjerg, "Review of energy storage system technologies in microgrid applications: Issues and challenges," *IEEE Access*, vol. 6, pp. 35143–35164, 2018.

[2] E. Reihani, S. Sepasi, L. R. Roose, and M. Matsuura, "Energy management at the distribution grid using a battery energy storage system (BESS)," *Int. J. Electr. Power Energy Syst.*, vol. 77, pp. 337–344, May 2016.

[3] A. Bani-Ahmed, M. Rashidi, A. Nasiri, and H. Hosseini, "Reliability analysis of a decentralized microgrid control architecture," *IEEE Trans. Smart Grid*, vol. 10, no. 4, pp. 3910–3918, Jul. 2019.

[4] Z. Guo, W. Wei, L. Chen, Z. Y. Dong, and S. Mei, "Impact of energy storage on renewable energy utilization: A geometric description," *IEEE Trans. Sustain. Energy*, vol. 12, no. 2, pp. 874–885, Apr. 2021.

[5] H. Lee, G.-S. Byeon, J.-H. Jeon, A. Hussain, H.-M. Kim, A. O. Rousis, and G. Strbac, "An energy management system with optimum reserve power procurement function for microgrid resilience improvement," *IEEE Access*, vol. 7, pp. 42577–42585, 2019.

[6] S.-P. Ahn, C.-H. Kim, R. K. Aggarwal, and A. T. Johns, "An alternative approach to adaptive single pole auto-reclosing in high voltage transmission systems based on variable dead time control," *IEEE Trans. Power Del.*, vol. 16, no. 4, pp. 676–686, 2001.

[7] J. Vogelsang, C. Romeis, and J. Jaeger, "Real-time adaption of dead time for single-phase autoreclosing," *IEEE Trans. Power Del.*, vol. 31, no. 4, pp. 1882–1890, Aug. 2016.

[8] O. Dias, F. Magrin, and M. C. Tavares, "Comparison of secondary arcs for reclosing applications," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 24, no. 3, pp. 1592–1599, Jun. 2017.

[9] D. Michaelson, H. Mahmood, and J. Jiang, "Reduction of forced outages in islanded microgrids by compensating model uncertainties in PV rating and battery capacity," *IEEE Power Energy Technol. Syst. J.*, vol. 5, no. 4, pp. 129–138, Dec. 2018.

[10] W. A. Khan, T. Bi, and K. Jia, "A review of single phase adaptive auto-reclosing schemes for EHV transmission lines," *Protection Control Mod. Power Syst.*, vol. 4, no. 1, p. 18, Dec. 2019.

[11] F. Zhalefar, M. R. D. Zadeh, and T. S. Sidhu, "A high-speed adaptive single-phase reclosing technique based on local voltage phasors," *IEEE Trans. Power Del.*, vol. 32, no. 3, pp. 1203–1211, Jun. 2017.

[12] S.-A. Ahmadi, M. Sanaye-Pasand, P. Jafarian, and H. Mehrjerdi, "Adaptive single-phase auto-reclosing approach for shunt compensated transmission lines," *IEEE Trans. Power Del.*, vol. 36, no. 3, pp. 1360–1369, Jun. 2021.

[13] M. Bigdeli, P. Siano, and H. H. Alhelou, "Intelligent classifiers in distinguishing transformer faults using frequency response analysis," *IEEE Access*, vol. 9, pp. 13981–13991, 2021.

[14] B. Pickett, P. Elkin, C. Benner, P. Carroll, G. Hataway, K. Houser, Y. Liao, A. Martin, A. Mulawarman, P. Mysore, M. Ranieri, C. Sufana, J. Tengdin, J. Vico, and D. Ware, "Reducing outages through improved protection, monitoring, diagnostics, and autorestoration in transmission substations—(69 kV and above)," *IEEE Trans. Power Del.*, vol. 31, no. 3, pp. 1327–1334, Jun. 2016.

[15] J.-H. Teng, W.-H. Huang, and S.-W. Luan, "Automatic and fast faulted line-section location method for distribution systems based on fault indicators," *IEEE Trans. Power Syst.*, vol. 29, no. 4, pp. 1653–1662, Jul. 2014.

[16] L. M. N. de Mattos, M. C. Tavares, and A. M. P. Mendes, "A new fault detection method for single-phase autoreclosing," *IEEE Trans. Power Del.*, vol. 33, no. 6, pp. 2874–2883, Dec. 2018.

[17] J. R. Martí and A. Tavighi, "Frequency-dependent multiconductor transmission line model with collocated voltage and current propagation," *IEEE Trans. Power Del.*, vol. 33, no. 1, pp. 71–81, Feb. 2018.

[18] D. K. J. S. Jayamaha, N. W. A. Lidula, and A. D. Rajapakse, "Wavelet-multi resolution analysis based ANN architecture for fault detection and localization in DC microgrids," *IEEE Access*, vol. 7, pp. 145371–145384, 2019.

[19] J.-Y. Heo, Y.-S. Oh, H.-C. Seo, and C.-H. Kim, "An adaptive autoreclosure scheme with reference to transient stability for transmission lines," *J. Electr. Eng. Technol.*, vol. 10, no. 3, pp. 795–803, 2015.

[20] Z. Radojevic, V. Terzija, G. Preston, S. Padmanabhan, and D. Novosel, "Smart overhead lines autoreclosure algorithm based on detailed fault analysis," *IEEE Trans. Smart Grid*, vol. 4, no. 4, pp. 1829–1838, Dec. 2013.

[21] X. Xie and C. Huang, "A novel adaptive auto-reclosing scheme for transmission lines with shunt reactors," *Electr. Power Syst. Res.*, vol. 171, pp. 47–53, Jun. 2019.
[22] B. Sahoo and S. Samantaray, "Fast adaptive auto reclosing technique for series compensated transmission lines," *IET Gener., Transmiss. Distrib.*, vol. 13, no. 15, pp. 3272–3280, Jul. 2019.
[23] H.-C. Seo, "New reclosing technique in distribution system with battery energy storage system," *J. Korean Inst. Illum. Electr. Installation Eng.*, vol. 30, no. 1, pp. 21–27, Jan. 2016.
[24] H.-C. Seo, "New adaptive reclosing technique using second-order difference of THD in distribution system with BESS used as uninterruptible power supply," *Int. J. Electr. Power Energy Syst.*, vol. 90, pp. 315–322, Sep. 2017.
[25] S. Ghore, P. Das, and M. Biswal, "Uninterrupted power supply to BESS based microgrid system using adaptive reclosing approach," *IET Gener., Transmiss. Distrib.*, vol. 15, no. 7, pp. 1203–1213, Apr. 2021.
[26] X. Wang, J. Yung, P. Liu, W. Liu, J. Yan, Y. Tang, and H. He, "The optimal reclosing time of transmission lines," *Electr. Power Compon. Syst.*, vol. 44, no. 17, pp. 1904–1916, 2016.
[27] Y. Guo and Z. Zhang, "Generalized variational mode decomposition: A multiscale and fixed-frequency decomposition algorithm," *IEEE Trans. Instrum. Meas.*, vol. 70, Apr. 2021, Art. no. 3516013.
[28] P. D. Achlerkar, S. R. Samantaray, and M. S. Manikandan, "Variational mode decomposition and decision tree based detection and classification of power quality disturbances in grid-connected distributed generation system," *IEEE Trans. Smart Grid*, vol. 9, no. 4, pp. 3122–3132, Jul. 2018.

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