Uninterrupted power supply to BESS based microgrid system using adaptive reclosing approach

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Abstract

As more than 80% of faults on overhead lines are temporary (transient) in nature which is caused due to lightning strikes, momentary bird or tree limb contact, wind bringing conductors in contact, etc. These type of faults gets cleared by itself in a short duration. But the use of a conventional reclosing scheme results in an outage time which is much larger than the actual fault duration. This is due to the use of fixed dead times in conventional reclosing schemes. This unnecessary outage results in increased consumption of stored energy of energy storage system causing considerable losses. This paper proposes an empirical mode decomposition based adaptive reclosing technique which can sense the exact instant of fault clearance and modify the prefixed dead time to an adaptive value. Within half cycle time period after fault clearance reclosing command can be issued for the breaker. The performance of the proposed algorithm is verified in a modified IEEE 13 bus distribution network model considering a battery energy storage system and hybrid distributed generators. The simulation and modelling of the various fault cases in the microgrid structure are done using EMTDC/PSCAD software.

1 | INTRODUCTION

To maintain the uninterrupted power supply to the microgrid, various strategies have been adopted. One of the most common practices is using some energy storage System like battery energy storage system (BESS), flywheels, supercapacitors etc. to store the energy when there is a surplus of it and release it when required such as in the case of failure of grid supply [1]. In a microgrid system generally, a BESS is used as a source of backup supply during power outages. Since these energy storage units are of limited capacity, it has to be used very efficiently. If a fault occurs in a section of the microgrid then the energy storage units like BESS are utilized to maintain the uninterrupted power supply to critical loads of the isolated section [2]. However, in transient fault conditions, due to the inability of the conventional reclosing scheme to sense the exact time of fault clear - ance the reclosing is delayed for a fixed predefined dead time [3]. During this dead time, BESS often gets unnecessarily engaged even if fault gets cleared. It also causes increased outages in the other non-critical loads or sections where a backup system is not available [4]. The use of an adaptive reclosing scheme provides adaptive dead time by sensing the exact instant of fault clearance [5–7]. In the literature, several auto-reclosing schemes have been proposed for the transmission system to detect the instant of secondary arc extinction [5–21]. In [5], secondary arc current measurements are used for the calculation of adaptive dead time for real-time application in single-pole switching of high voltage lines. In [6], authors have introduced a digital algorithm for the detection of transient arcing fault and calculation of dead-time. It used zero sequence voltage measurement to differentiate between the arcing and permanent fault. Further, the third harmonic component of zero sequence voltage is used to detect the moment of secondary arc extinction. Emergency extended equal area criterion (EEEAC) is used in [7,8] to determine the optimal reclosing time to improve the transient stability and to reduce the system oscillations. In [9], a numerical algorithm is applied on a medium voltage overhead line that works on time-domain information, processing the acquired terminal data, then the least square method is used to estimate the nature of the fault. A voltage harmonic measurement based...
digital harmonic filter is applied in [10], for adaptive single-phase reclosing of extra high voltage transmission system breaker. In this context, a wavelet-based method is also proposed in [11]. Authors in [11] have used wavelet transform to extract the features from the bus voltage to calculate the Percentage of Energy (PE). This PE is further used to classify transient and permanent faults. If the fault is classified as transient then the adaptive fuzzy neuro inference system (ANFIS) utilizes the obtained PE data to detect the secondary arc extinction time. In [12], a cumulative sum energy estimated using fast sparse S-transform coefficients based fast reclosing technique is proposed for series compensated line. In a similar context, authors in [13,14] have used ADALINE neural network for training and testing. But these methods require extensive training before implementation and produce erroneous results for the unaccounted situation. Methods such as mathematical morphology [15] and dual-window transient energy ratio [16] are also used for adaptive reclosing. The former uses generalized multiresolution morphological gradient (GMMG) for the extraction of high-frequency energy of mode current and the latter employs a close-opening open-closing morphological gradient (COOCG) for the extraction of high-frequency energy of voltages. Communication aided methods which require both end data are presented in [17–19]. But such a scheme may introduce latency issues and increases implementation cost. In [20], the local bus voltage signal is fed to the adaptive cumulative sum method (ACUSUM) for the detection of successive events of fault inception, breaker opening (primary arc extinction) and secondary arc extinction. The completion of the last event gives the information of secondary arc extinction. Due to very little computational complexity, this method is very fast and gives results in about 4 ms. A similar approach is presented in [21] which works by analysing the patterns in voltage waveform for faster detection. But unfortunately, auto-reclosing techniques available for transmission systems cannot be applied directly in the distribution system because of its dissimilar network configuration, short length, lower operating voltage etc. In such low voltage grids, the secondary arcing phenomenon is hardly noticeable. However, few studies proposed some algorithms like the use of Haar wavelet transform and THD calculation [22], SODT (second-order difference of THD) [23] for the implementation of the adaptive reclosing in the distribution system. The method presented in [23] require a BESS to continuously feed the fault to detect the fault clearance instant which causes wastage of stored energy of BESS. The electrostatic induction phenomenon between the three-phase and neutral lines in an unbalanced distribution system is utilized to detect the instant of fault clearance in [24]. However, the impact of BESS is not investigated in [24].

During the fault period, BESS is highly stressed which adversely affects its lifespan. At times, BESS may not be able to manage high load demands and get out of the system. The use of an adaptive reclosing scheme helps in maintaining an uninterrupted power supply in conjunction with BESS. In this work, a novel adaptive reclosing algorithm is proposed which uses the line side voltage and current measurement to extract the fault data and uses the Empirical Mode Decomposition algorithm to detect the status of the fault. The decomposition of raw signals aids to analyse the transients during fault inception and clearance. This also helps in separating the actual fault cases from the other cases like various LG faults, capacitor switching, DG switching, adjacent line tripping, islanding, change in topology, higher sampling frequency, transformer energisation and nonlinear load switching. The method does not require BESS information to confirm the fault clearance. That means after a fault detection, power can be supplied from BESS to the affected feeders and after reclosure of the breaker, the BESS can be disconnected. In this way, unwanted utilization of BESS during transient events can be avoided. Once the fault clearance is detected the auto-recloser can instantly reconnected the isolated section from the grid, hence strengthening the resilience of the microgrid.

2 ADAPTIVE RECLOSELING

The use of conventional reclosing scheme suffers from an inherent disadvantage of fixed dead time as shown in Figure 1. In a distribution system with distributed energy resources (DERs) and BESS, the reclosing scheme can be applied to provide uninterrupted power supply to end users. During any transient fault, the BESS can provide temporary supply to the affected load and after the clearance of the fault, the system configuration can be restored. However, the application of conventional reclosing scheme can impose direct effect on the life and efficiency of the storage units as well as the connected loads, causing increasing outage. The inability of detecting the exact fault clearance time can be overcome by the use of adaptive reclosing.

In Figure 1, the 1st dead time t1 is very small (0.5 s) which is supposed to provide sufficient time to any transient fault to get cleared. However, if the fault doesn’t get cleared during 1st dead time then the breaker will attempt a reclose operation and get opens for a much longer 2nd dead time t2 (10–15s). The use of auto-reclosing enables the detection of the exact time of fault clearance and hence fixed dead time of conventional recloser can be modified to an adaptive value as shown in Figure 2. Hence, the breaker can be reclosed as soon as the fault gets cleared avoiding the unnecessary outages. As fault clearance is assured, only one reclosing attempt is required therefore it eliminates the risk of damages due to unsuccessful reclosing attempts as large faults currents and surges adversely affects the line equipment. In this paper, the adaptive reclosing scheme is implemented in the distribution system with different DERs and BESS.
3 | MICROGRID TEST MODEL

Two different microgrid test systems are considered to verify the response of the proposed adaptive reclosing technique.

3.1 | Test system-1

A modified IEEE 13 bus microgrid model [28] is selected for testing the proposed algorithm. The model consists of a 6 MW Wind Power Plant, 2 MW PV module, 1 MW Diesel Generator and a 2 MW BESS unit. The microgrid is connected to a utility supply which is modelled by a synchronous generator with a rated short circuit capacity of 100 MVA. The rated system frequency is 50 Hz and the rated voltage level is 11 kV. Various LG faults with different parameters are simulated in the line between bus-650 and bus-632 as shown in Figure 3. The detailed system parameters are provided in the Appendix.

3.2 | Test system-2

To verify the performance of the proposed algorithm in a different topology, a distribution network of Aalborg, Denmark owned by Himmerlands Elforsyning is selected [29]. It consists of two Wind turbines, a Photovoltaic system and a Combined Heat and Power (CHP) plant. The faults are simulated between bus-9 and bus-10 as shown in Figure 4. The rated voltage and frequency are 20 kV and 50 Hz respectively. The sampling frequency is taken as 1 kHz. The detailed system parameters are provided in the Appendix.

The notations and details of the systems are as follows:

- BESS is the battery energy storage system consisting of battery and bidirectional DC-AC converter.
- PV or Photovoltaic system consists of PV panel and an inverter.
- CHP is Combined Heat and Power (CHP) plant.
- F is the fault point.
- T-1, T-2… are transformers.
- L-1, L-2… are loads connected to different buses.
- WT-1, WT-2… are wind turbines.
- CB is circuit breaker.
- PCC is the point of common coupling.

4 | METHODOLOGY

4.1 | Empirical mode decomposition

EMD is a data-driven adaptive filtering technique that can locally decompose any non-stationary time series signal into a series of zero-mean amplitude and frequency modulated signals known as Intrinsic Mode Functions (IMFs) and a residual slow trend without leaving the time domain. Superimposition of all the IMFs and residual signal perfectly reconstruct the original signal. These IMFs contain the information of various oscillatory components present in the signal at a specific time. The IMFs are extracted using the sifting process. [25] If ‘n’ empirical modes are achieved in the iterative process then the reconstructed original signal \( X(t) \) can be represented as,

\[
X(t) = \sum_{i=1}^{n} C_i(t) + r(t)
\]  

(1)

Where \( C_i(t) \) represents the \( i^{th} \) IMF and \( r(t) \) represents the residual signal. The details of the EMD algorithm are
illustrated in the literature. [25–27] As the EMD technique requires comparatively larger memory capacity, computational time and power consumption than other available algorithms, it is most suitable for offline applications. However, block-wise implementation of the EMD algorithm is also possible as it works by interpolating in between the fixed number of extremes without the requirement of entire signal data. The block-wise implementation of the EMD algorithm enables it to be applied on online or real-time applications such as in protective relaying.

4.2 | Detection principle

In the proposed method, the current and voltage signal of the faulty line is taken from the line side CT and PT. The advantage of measuring the line-side signal over measuring bus-side signals is that the former can directly measure the fault parameter irrespective of the CB operation. In case of an unsymmetrical short circuit fault in the line, the faulty section will be isolated by a single-pole operation of the corresponding breaker. The fault detection and classification can be done conventionally by the measured fault current and voltage data. In a single line to ground fault, other healthy phase conductors remain energized, this induced considerable voltage in the isolated faulty phase conductor due to mutual coupling between the phase conductors. This voltage is negligibly small during the fault period but rises to a noticeable magnitude at the instant of fault-clearance. This transition can be precisely detected by using the EMD algorithm. To capture the transients generated only at the instant of fault clearance, the voltage data is sufficient. However, to extract the information of fault occurrence as well, the current signal is used. The IMF-1 obtained from the raw signal $X(t)$ is subtracted from $X(t)$ to remove the base frequency component and get the differential signal $S(t)$ which can be mathematically represented as,

$$S(t) = X(t) - C_1(t)$$  \hspace{1cm} (2)

where $C_1(t)$ is the IMF-1 and the raw signal $X(t)$ is either the current signal or voltage signal data. The instantaneous magnitude of the obtained differential signal $S(t)$ along with IMF-2 and IMF-3 of the raw signals are considered to generate an index value represented by $\psi$, which can provide accurate information about the fault occurrence and fault clearance. The index can be calculated as,

$$\psi(t) = S(t) \left| C_2(t) + C_3(t) \right|$$  \hspace{1cm} (3)

where $C_2(t)$ and $C_3(t)$ are the instantaneous values of IMF-2 and IMF-3. The voltage index is computed as $\psi_v$, and the current index is computed as $\psi_c$, using (3). The index $\psi$ is substantially high only during the initiation of any transient event i.e. onset of fault, breaker operation and clearance of fault. The detection algorithm continuously monitors the current and voltage signals and computes the index $\psi$ for each phase (using Equation 3) as $\psi_c$ and $\psi_v$ respectively. During the normal operating condition, both $\psi_c$ and $\psi_v$ give no output. As $\psi_c$ reflects any transient event in the current signal, it captures the event of fault initiation and CB operation. But once the breaker contacts open and isolate the fault, the current signal and its index $\psi_c$ become zero. Since $\psi_v$ operates on line side voltage signal, $\psi_v$ captures all the three events i.e., fault occurrence, breaker operation as well as fault clearance. By using the outputs of $\psi_c$ and $\psi_v$ and removing other unwanted transients (primarily due to CB operation), the information of fault initiation and fault clearance is extracted and amplified which is represented by the indices $\psi_1$ and $\psi_2$ respectively. The complete EMD based detection algorithm is summarised in a flowchart shown in Figure 5.

![Flowchart of the proposed method](image)

In the proposed method using three phase current and voltage signal, $\psi_c$ and $\psi_v$ are computed. The indices $\psi_1$ and $\psi_2$ are generated only when an LG fault is detected. So, $\psi_1$ and $\psi_2$ correspond to the faulty phase. The index $\psi_1$ corresponding to faulty phase current distinctively shows the event of fault occurrence and the index $\psi_2$ corresponding to faulty phase voltage distinctively shows the event of fault clearance.

5 | RESULTS AND DISCUSSIONS

In the following subsections, a set of simulation studies are carried out in the EMTDC/PSCAD 4.6 version environment to investigate the performance of EMD based adaptive reclosing technique. The system as shown in Figures 3 and 4 are considered for analysis. Different LG faults, capacitor switching, DG switching, adjacent line tripping, islanding, change in topology, higher sampling frequency, transformer energisation and non-linear load switching cases are simulated using test systems 1 and
5.1 | EMD outputs

First, an unsymmetrical fault i.e. a-g fault case is considered. The fault is created at 1.3 s between the buses 650 and 632 as shown in Figure 3. At 1.33 s the fault section is isolated by opening both the breakers CB-1 and CB-2 connected at both the ends of the line. The fault resistance is 10 Ω. The fault is cleared at 1.4 s. The voltage and current outputs obtained from the EMD algorithm are shown in Figures 6 and 7 respectively. The raw signal, IMF-1, IMF-2, IMF-3, IMF-4 and residue plots are provided for both voltage and current signals.

At the instant of fault occurrence, the IMF1 of current signal is suddenly changing and at the instant of fault clearance i.e. at 1.33 s, IMF1 of voltage signal is varying. So, using Equation (3) the information about accurate fault clearance time can be detected so that the reclosing phenomena can be started adaptively.

5.2 | Impact of fault resistance

In this context, the response of the proposed method is investigated for varying fault path resistance and fault distance conditions. Two different a-g faults are created. One at 5 km with 10 Ω path resistance and another at 15 km with 100 Ω path resistance. The relay is connected near bus-650. The fault is created at 1.3 s and cleared at 1.5 s. In Figure 8, the index ψ1 starts rising after 7 ms of fault inception. So, the fault is detected in phase-a at 1.307 s. The index ψ2 starts rising after 9 ms of fault clearance. So, fault clearance is detected in phase-a at 1.509 s. Similar results are obtained for far end high fault resistance condition also. In Figure 9, the second index ψ2 detects the fault clearance at 1.508 s. So, within half cycle time period fault clearance can be detected. For both the close-in and far end fault cases the response of the proposed method is accurate and fast. Signal decomposition-based approaches provide accurate information regarding fault generated transients. So, by using such signals fault detection and clearance information can be
extracted for the operation of faster reclosing. Such an initiative can enhance the battery life as well as uninterrupted power supply can be provided to end-user in the renewable based distribution system.

5.3 | Impact of fault inception

In this section, the impact of fault inception time on the response of proposed method is evaluated. Because faults at voltage peak are less significant. So, c-g fault is created at a distance of 10 km from bus-650 of test system-1 with 20 $\Omega$ fault resistance. The fault inception time is 1.35 s and clearance time is 1.56 s. By index $\psi_1$, fault is detected at 1.351 s and by index $\psi_2$, fault clearance is detected at 1.565 s. The responses are shown in Figure 10. For different fault inception time also, the proposed algorithm works satisfactorily. So, half cycle time period is sufficient to initiate the reclosing process of CB by the proposed method.

5.4 | Impact of change in sampling frequency

To check whether the algorithm can work with different sampling frequencies, a b-g fault is created at mid-point of the line between bus-650 and bus-632 with 150 $\Omega$ fault resistance. Both fault initiation and clearance time are 1.3 and 1.5 s. The current and voltage data are acquired at a sampling frequency rate of 2 kHz. From Figure 11, the proposed method detects both the events after 1 and 9 ms respectively. So, within half cycle i.e. 10 ms reclosing command can be issued for the CB. From the simulation results, it is evident that the proposed algorithm can handle data sampled at any arbitrary sampling frequency.

5.5 | Impact of capacitor switching

To consider the impact of capacitor switching, a 0.25 MVAR capacitor is connected to bus-632 at 1.3 s and disconnected at 1.35 s. The output of the proposed method is shown in Figure 12. This case can be easily differentiated as it affects all the three phases therefore the index $\psi_c$ gives sustained deflection in all three phases. The indices $\psi_1$ and $\psi_2$ don’t give any output which indicates that no fault is detected in this case.
Impact of DG switching

To consider the impact of DG switching, the PV module is disconnected from the microgrid test system-1 at 1.35 s. It can be observed from Figure 13 that the current shows a sudden rise in magnitude which is sufficient to trip an overcurrent relay. But the proposed algorithm gives no output for fault detection due to rise of $\psi_c$ in two phases.

Impact of islanding

When a microgrid is islanded, the power flow in the grid is disturbed which changes the magnitude and even the direction of power flow in the line. This phenomenon may result in false tripping and therefore must be identified. Using test system-1 islanding is created at 1.35 s. Response by the method is shown in Figure 14. Both the indices are zero indicating no fault initiation and clearance. So, islanding case can be discriminated from LG fault cases.

Impact of adjacent line tripping

The tripping of an adjacent line causes a sudden change in current magnitude. This case may trigger the relays of adjacent lines. To investigate this condition, the line between bus-632 and bus-645 in test system-1 is tripped at 1.35 s. Both the indices are zero and thus the proposed logic works reliably in this case also, which is evident from Figure 15.

From the above discussed non-faulty cases it is evident that the proposed method is highly selective and dependable.

Impact of change in topology

To consider the impact of change in topology the performance of the proposed algorithm is tested on test system-2 (Figure 4). An A-g fault is simulated at the midpoint of the line between bus-9 and bus-10 with 5Ω fault resistance. The fault time is 1.3 s and clearance time is 1.5 s. By the help of both the indices, fault is detected at 1.301 s and clearance time detected at 1.509 s. Results are depicted in Figure 16. Figure shows the working of the proposed algorithm in a different microgrid with a completely different configuration and voltage level. The proposed...
algorithm can reliably work with different topologies without making any adjustments in threshold values.

5.10 Impact of transformer energisation

The inrush phenomenon during transformer energisation can result in relay maloperation. To investigate this condition, the primary side of a 10MVA transformer connected in bus-10 of test system-2 is charged at 0.5 s. The index $\psi_c$ shows large deflection in all three phases and the indices $\psi_1$ and $\psi_2$ show no deflection. Therefore, the proposed algorithm works reliably for such a condition, as shown in Figure 17.

5.11 Impact of nonlinear load switching

To consider the impact of nonlinear load switching, a 0.5 MW nonlinear load connected to bus-10 of test system-2 is switched on at 0.5 s. In this case, the index $\psi_c$ shows sustained deflection in all three phases as shown in Figure 18. As the proposed method is only sensitive to single phase events and monitors deflection in the single-phase indices, any simultaneous rise in all the three phase indices cannot excite the response of the
proposed method. So, the proposed method doesn’t respond to nonlinear load switching and can differentiate it from the actual fault case.

5.12 Effect of the adaptive reclosing scheme on BESS

To investigate and compare the operation of BESS with the conventional and adaptive reclosing scheme, the BESS is used to supply 0.4 MW critical loads in the event of a fault and the power output as well as the state of charge (SOC) of the battery for both the cases, are shown in Figure 19. Considering a fixed dead time $t_2$ (illustrated in Figure 1) of 10 s, the BESS is engaged at 5 s and the fault clearance is detected by the proposed method at 9 s. The adaptive reclosing scheme recloses the breaker contacts around 9 s. But with the conventional scheme, reclosing is attempted at 15 s (after fixed dead time of 10 s). Once the grid supply is restored, BESS switches from discharging mode to charging mode. The area in between the blue (dotted) line and red (dashed) line signifies the savings in energy and reduced burden on BESS with the adaptive reclosing scheme.

So, from the various results for fault and no-fault cases it is found that the method is capable of detecting the exact fault detection and clearance time within half cycle time period. The overall response of the above simulated cases is summarised in Table 1.

### COMPARATIVE ANALYSIS

For comparison, the response of proposed method is compared with the wavelet and THD calculation-based method used in [22] for fault clearance detection. The response of both the methods for an a–g fault with 10Ω fault resistance are shown in Figure 20. Fault inception and clearance time are 1.3 and 1.5 s respectively. It can be seen from the plots that the proposed method gives a crisp output for the faulted phase without containing any nearby disturbances therefore it doesn’t require any threshold setting. The other method catches various disturbances and the change in percentage THD value at the time of fault clearance is very less therefore it requires a precise threshold value setting.

Efficient utilization of storage devices and quick restoration system can help in providing uninterrupted power supply to multiple DG and BESS based distribution network. Quick isolation of fault also helps in improving the battery life. Such a proposal is provided in the proposed work. The main motive of

### TABLE 1 Response of the Proposed Method for Different Fault and No-Fault Cases

| Simulation conditions          | Initiation of event | End of event |
|-------------------------------|---------------------|--------------|
|                               | Actual time         | Detected time| Actual time | Detected time |
| a) Fault cases:               |                     |              |             |               |
| 10Ω AG fault at 5 km          | 1.3                 | 1.307        | 1.5         | 1.51          |
| 100Ω AG fault at 15 km        | 1.3                 | 1.315        | 1.5         | 1.508         |
| 150Ω BG fault at 10 km        | 1.3                 | 1.301        | 1.5         | 1.51          |
| 20Ω CG fault at 10 km         | 1.35                | 1.351        | 1.56        | 1.565         |
| b) No fault cases:            |                     |              |             |               |
| Capacitor switching           | 1.3                 | No output    | 1.5         | No output     |
| DG switching                  | 1.3                 | No output    | -           | -             |
| Islanding                     | 1.35                | No output    | -           | -             |
| Adjacent line tripping        | 1.35                | No output    | -           | -             |
| Transformer energisation      | 0.5                 | No output    | -           | -             |
| Nonlinear load switching      | 0.5                 | No output    | -           | -             |
this work is to present an efficient solution for faster reclosing of circuit breaker during transient faults.

7 | CONCLUSION

The proposed method can precisely detect the time of fault initiation and fault clearance and the algorithm can differentiate fault phenomenon from other events in the line such as capacitor switching, DG switching, adjacent line tripping, islanding, change in topology, transformer energisation and non-linear load switching. The proposed algorithm can work efficiently within half cycle time period and higher sampling rate has no such impact on the response of the method. Using PSCAD/EMTDC simulation, the performance of the detection algorithm has been verified under different LG fault conditions. The line-side placement of measuring units allows continuous monitoring of faulty line voltages used to track the status of the fault which is not possible with bus-side measuring units. Once the fault clearance is detected by the adaptive reclosing algorithm, the auto-recloser can immediately reconnect the isolated section with the microgrid thus avoiding unnecessary outage and losses. This reduces the burden on BESS and other backup generators, which results in appreciable savings in cost and energy.

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APPENDIX

Test system-1 is modelled using the IEEE-13 bus structure. The line length is taken as 10 km between each bus except between bus-650 and bus-632 which is taken as 20 km. The line impedance values are taken as \( R = 0.1153 \) (\( \Omega \)/km), \( X = 1.053 \) (m\( \Omega \)/km). Details of system parameters data for both the test systems are provided in Tables 2–7.

| TABLE A1 | Data for diesel generator (test system-1) |
|----------|----------------------------------------|
| Parameters | Values |
| Machine type | Synchronous machine |
| Rated power | 1 MW |
| Rated voltage | 13.8 kV |
| Base angular frequency | 50 Hz |

| TABLE A2 | Data for type-4 wind turbine (test system-1) |
|----------|----------------------------------------|
| Parameters | Values |
| Machine type | Permanent Magnet Synchronous Machine |
| Rated power | 6 MW |
| Rated voltage | 0.69 kV |
| Base angular frequency | 50 Hz |
| Angular moment of inertia | 1.1511 kg.m²/s |
| Stator winding resistance | 0.00013 \( \Omega \) |
| Stator leakage reactance | 0.00287 \( \Omega \) |

| TABLE A3 | Data for DFIG type wind turbine (test system-2) |
|----------|----------------------------------------|
| Parameters | Values |
| Machine type | Wound rotor |
| Rated power | 2 MW |
| Rated voltage | 0.69 kV |
| Base angular frequency | 50 Hz |
| Stator / Rotor turns ratio | 1 |
| Angular moment of inertia | 1.7267 kg.m²/s |
| Stator resistance | 0.0012 \( \Omega \) |
| Wound rotor resistance | 0.0014 \( \Omega \) |
| Stator leakage inductance | 0.0795 mH |
| Rotor leakage inductance | 0.0833 mH |

| TABLE A4 | Line Impedance Data (test system-2) |
|----------|----------------------------------------|
| From | To | \( R \) [\( \Omega \)] | \( X \) [m\( \Omega \)] |
| BUS-5 | BUS-6 | 0.1256 | 0.4469 |
| BUS-5 | BUS-7 | 0.1344 | 0.2012 |
| BUS-7 | BUS-8 | 0.4874 | 0.7270 |
| BUS-8 | BUS-9 | 0.1346 | 0.2884 |
| BUS-10 | BUS-11 | 0.1456 | 0.3540 |
| BUS-11 | BUS-12 | 0.1309 | 0.1040 |
| BUS-12 | BUS-13 | 0.0724 | 0.0576 |

| TABLE A5 | Data for Photovoltaic System (in both test systems) |
|----------|----------------------------------------|
| 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/m² |
| Reference cell temperature | 25 °C |

| TABLE A6 | Data for BESS (in both test systems) |
|----------|----------------------------------------|
| Parameters | Values |
| BESS rating | 2 MW |
| Battery pack | 0.5 kV |
| Nominal Voltage | 0.12 kV |
| Nominal discharge current | 20% |
| Initial state of charge | 100% |