Modelling of Short-Circuit Protection for A Residential Grid-Connected BESS

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Abstract

This research paper presents the power protection study on a grid-connected Battery Energy Storage System (BESS) in a typical Malaysia low-voltage (LV) residential network. The BESS model and control algorithm is developed in MATLAB/Simulink environment. The BESS model can charge and discharge its energy with an algorithm-controlled bidirectional AC/DC converter. The paper also presents two cases for BESS short circuit evaluation to investigate stability of internal and external systems of BESS. The protection level on BESS is also optimized by introducing a time-delay characteristics model to coordinate circuit breakers in compliance with standards outlined in IEEE Std 1375-1998, IEC/EN 60898-2, IEC/EN 60947-2, UL 1077, and CSA 22.2. No.235. The paper presents BESS system stability with and without overcurrent protection. As a conclusion, BESS was interrupted within stipulated time. In case of internal short circuit protection failure, a backup protection will act on isolating BESS from the grid provided

Keywords: Battery Energy Storage System, Fault analysis, Power system stability, Protection scheme, Optimized protection

1. Introduction

Lately, more than 200 energy storage demonstration projects, at megawatt level and above, have been set up across the world, indicating huge potential for further expanded application of 154 Grid-scale energy storage systems and applications energy storage technologies [1]. According to U.S. department of energy, ESS increases grid resistant to disruptions, promotes clean electricity, and increases the economic value of wind and solar power [2]. ESS is also essential to provide power at optimal response speed to overcome the intermittence of renewable sources and contribute to the mains voltage regulation [3]. There are various types of ESS technologies proposed by [4] used for transportation, emergency, and small-to-large scale power generation. BESS may be the most versatile of the several storage systems according to [5].

BESS has three primary components: an AC grid, a battery, and a battery management system [6]. The kind of battery used in the system determines the power output and energy levels of BESS. Various research has been previously conducted for modelling of BESS. In [*7*], the author has proposed a detailed modelling of BESS using various power electronic components and control modules have been discussed. On the other hand, a simplified BESS model using MATLAB/Simulink logical-numerical modelling approach has been proposed by authors in [8] that can simulate the behaviors of a typical BESS.

Several issues have been faced by BESS due to its fault behaviours. The primary issue is the high fault current contributed from BESS [9]. The second issue is the rate of current rising [10], [11]. Regarding the two issues, the power electronic switches used with BESS may also be harmed by the current and its increasing rate [12]. The sudden decline in battery state of charge (SOC), which had an adverse effect on battery lifetime, is the final issue [13]. BESS can pose a significant safety risk to both users and installers, with the potential to cause hazards such as fire, flash burns, and explosion if it suffers from short circuit or fault if installed and used improperly [14]. Short circuits are a major contributor to the electrical and temperature risks brought on by Li-ion batteries [15]. Accordingly, it is crucial to achieve power protection of BESS to ensure its proper functions during critical time. Therefore, two main areas of BESS protection are protection of BESS itself for internal fault and isolating BESS from a system for external fault [6]. Several options to protection of stationary battery systems such as circuit breakers and fuses have also been provided in [16] to DC system designer. The paper presents an LV grid-connected BESS with and without overcurrent protection of both internal and external circuit of BESS alongside with fault analysis.

2. Methodology

2.1. *System Design*

As displayed in Fig. 1, the BESS is connected to a typical Malaysia LV network. The connection between BESS and Grid is straight forward since no load is connected to the network bus. BESS consists of a battery module and a bidirectional AC/DC converter. The BESS has utilized a battery module from manufacturer's datasheet. The battery module is referred to technical specifications outlined in manufacturer's datasheet. With the aid of a converter, the BESS can charge or discharge the battery at constant voltage and current. The BESS is protected by internal and external protection units against internal and external short circuit faults respectively. Short circuit and power system stability can be analyzed through DC and AC protection breaker monitoring interface.

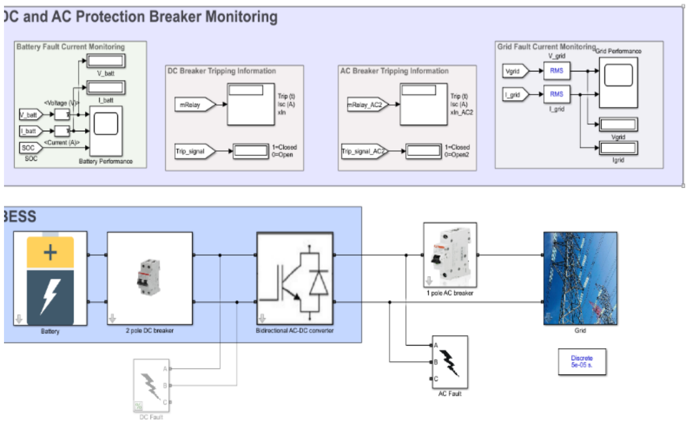

Fig. 1 Overview of BESS system protection model in Simulink

2.2. *BESS model*

The three primary components of BESS are an AC grid, a battery, and a battery management system as presented in [6]. The BESS consists of a Li-Ion battery and a bidirectional AC/DC converter. The nominal voltage and ratings of the battery are 450V and 33.33Ah respectively. The converter is designed using an average model based VSC as the converter bridge. A subsystem that consists of a series of mathematical blocks is built to generate pulse-width modulation (PWM) signal for the converter output as well as regulating the grid current. In addition, the subsystem also provides charging and discharging modes for BESS through current settings. The converter circuit has a DC link capacitor for smoothing the DC voltage as well as series parallel LCL filter to reduce the Total Harmonic Distortion (THD) of AC waveforms. Being the main charging source for BESS, AC grid is designed at 230V which is a typical LV residential network level in Malaysia. Simulation is run to analyse the behaviours of BESS when there is no short circuit.

2.3. *BESS short circuit evaluation*

According to previous research on protection of BESS in a DC microgrid, fault on the bus at BESS side and fault on DC terminals at battery side are the two fault locations as identified in [12]. Based on the project model in this research, similar fault locations have been determined in a block diagram as shown in Fig. 2. Three-phase fault blocks from MATLAB/Simulink library are placed across the identified fault locations as shown in Fig. 3. The fault blocks are set to provide line-to-line fault as F1 and line-to-line-to-ground fault as F2. F1 and F2 are identified as internal fault and external fault, respectively. The simulation is run to analyze the short circuit behaviors of BESS in terms of voltage, current, and SoC characteristics of its battery. The simulation is repeated with several short-circuit resistance adjusted in the fault block parameter settings to observe the impacts of different network short-circuit levels on system stability of BESS and AC grid.

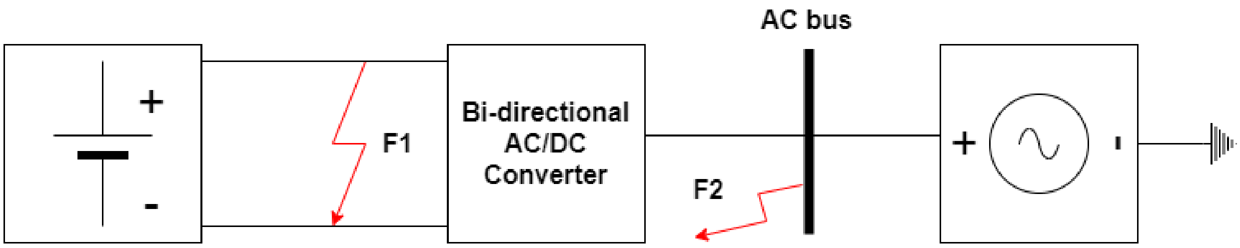

Fig. 2 Block diagram of short-circuited BESS network

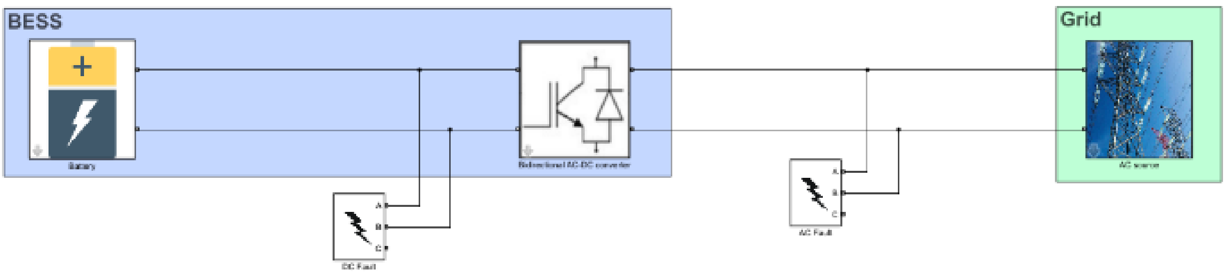

Fig. 3 A short-circuited BESS model.

2.4 Proposed design of BESS protection scheme with optimization method

Circuit breaker as a main protection scheme has been provided in [6]. However, AC breaker for DC use must be modified by adjusting the magnetic trip characteristics of an AC circuit breaker [16]. In this paper, a combination of AC breaker (ACCB) and DC breaker (DCCB) are used for the external and internal power protection of BESS, respectively as shown in Fig 4. During an external fault, F2, BESS will be isolated from AC bus whereas during an internal fault, F1, battery will be isolated within the BESS system. An ideal switch is used as a basic circuit breaker to isolate battery or BESS from the short circuit when the switch is opened. A circuit breaker trips according to its trip characteristics curve based on the guidelines provided in [16]. A model that simulates B and C trip characteristics curves has been developed using look-up table block from MATLAB/Simulink library. The trip characteristics used are referenced from a manufacturer datasheet for a miniature circuit breaker (MCB). As a common practice, B type curve is employed in DCCB whereas C type curve is employed in ACCB.

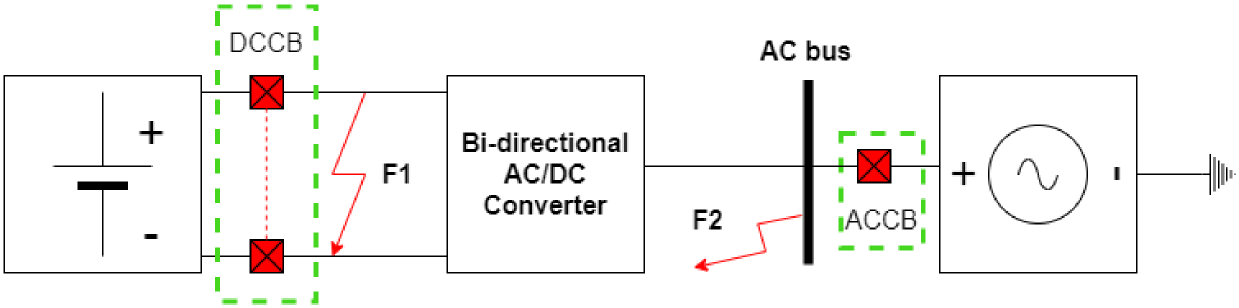

Fig. 4 Locations of circuit breaker.

Once the trip characteristics curves are verified, the curve model is employed in a subsystem. This subsystem is built to generate signal as if it was a “relay” for opening the circuit breaker. Some of the main parameters like current ratings and breaking capacity are defined in this system. Trip time limit is used to define the maximum and minimum trip time as indicated from trip curve from manufacturer datasheet. The current ratings of a circuit breaker are defined in [16]. Based on parameters of generic battery model predefined from MATLAB/Simulink, BESS can discharge current at approximate 14.5A. Whereas based on simulation, the AC bus is regulated by the converter at approximate 6A. Therefore, the DCCB and ACCB current ratings from calculation are 18.1A and 7.5A respectively. The current ratings selection should be at least or above the calculated values for common practice. From the available range of current ratings found in datasheet, DCCB and ACCB current ratings are determined as 20A and 8A respectively. In trip signal generator, MATLAB functional codes are developed to compare the current detected on the system the breaker is connected to with current multiples of the trip curve. A time-delayed signal that indicates trip will be sent to circuit breaker model to open the switch. The tripping sequence of the circuit breaker as coordinated by the trip signal generator subsystem is summarized in a flowchart shown in Fig 5. The trip curve model with trip signal generator subsystem can optimize the protection scheme by introducing delayed tripping in circuit breaker model approved with standards outlined in IEEE Std 1375-1998, IEC/EN 60898-2, IEC/EN 60947-2, UL 1077, and CSA 22.2. No.235. After installing the protection schemes in the project model, system stability with protection is analyzed.

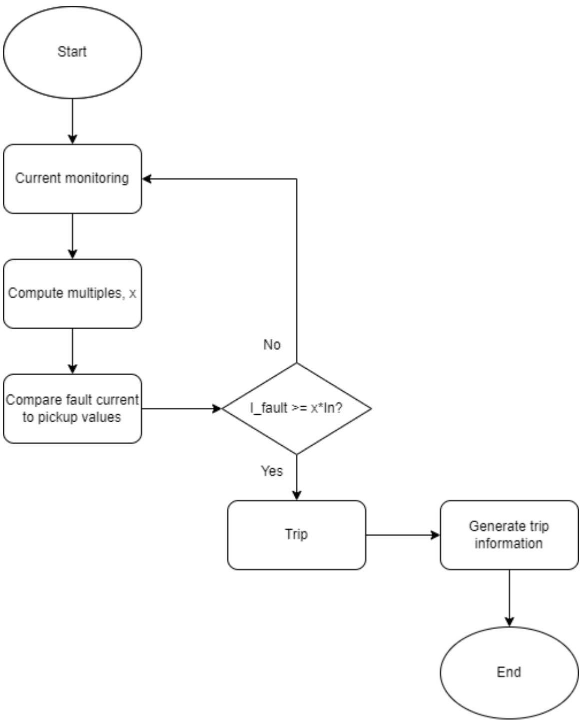

Fig. 5 Tripping sequence of a circuit breaker model.

3. Results and discussion

3.1 BESS behaviors under normal circumstances

Under normal circumstances, the voltage, current, and SoC of BESS are displayed on graphs shown in Fig 6(a) and Fig 6(b). From the graphs, BESS is operating at a constant voltage of 485V which is higher than its nominal voltage, 450V due to other settings assumed by default in generic battery model. However, the operating voltage is still within operating range based on datasheet. The BESS is also charging and discharging at 3A which is lower than current source from the grid due to impedance losses. The current when BESS is discharging opposes the polarity of current during charging as the direction of current flow differs in both states. The initial spike of current is due to initialization of the simulation. However, it does not effect on system stability as it happens only within 0.05s. SoC of BESS is increasing steadily during charging state whereas decreasing steadily during discharging state.

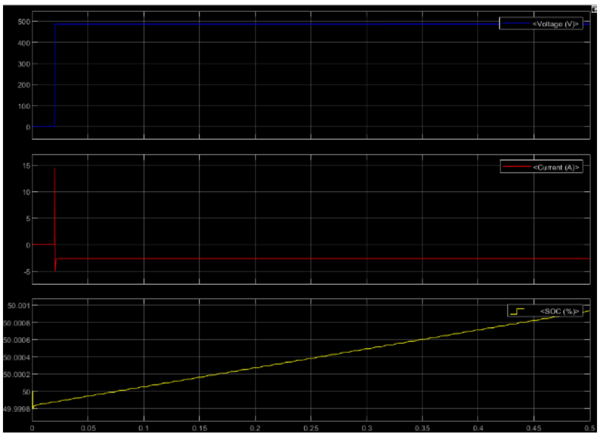

Fig. 6(a) BESS when charging.

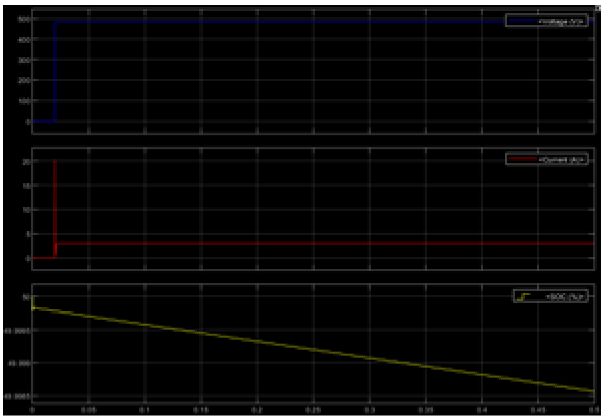

Fig. 6(b) BESS when discharging.

As seen from Fig 6(a) and Fig 6 (b), after a fault occurs at 0.1s, the battery starts to discharge quickly as observed from the graph of SoC during BESS charging and discharging states. Moreover, the voltage across the terminals of battery begins to decrease due to voltage drop through the resistance. The gradual decrease in voltage is caused by chemical changes occurring at the surface of electrodes. Furthermore, the battery current rises rapidly within 20ms to its peak at approximate 1.4kA. The gradual increase in the current is due to battery inductance.

3.2. Analysis of BESS under external short circuit

From the graphs in Fig 7(a) and Fig 7(b), voltage of battery remains stable after external short circuit effects at 0.1s. Therefore, the battery voltage does not drop due to lower resistance on external circuit of BESS. Moreover, the battery current decreases in both charging and discharging states of BESS. Furthermore, the rate of charge and discharge of BESS also decreases. Therefore, it is said that BESS does not display several issues as discussed in [9]–[13] by neither having high discharged current, voltage drop, nor sharp decrease in SoC except a decrease in power efficiency or performance of BESS. The converter shows current blocking effect by functioning as a diode rectifier and pass the current through only the reverse diodes. The grid filter between ac grid and converter then limits the fault current through the diodes [10].

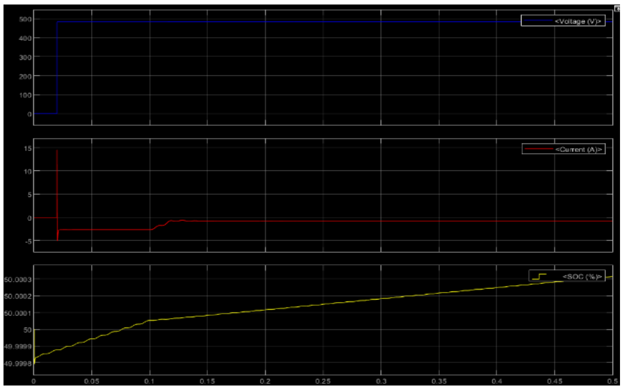

Fig. 7(a) External short circuit of BESS during charging.

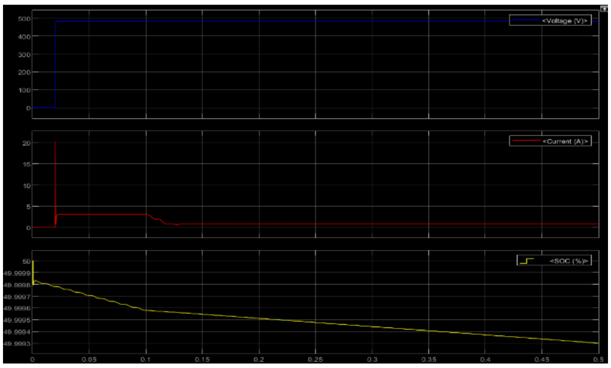

Fig. 7(b) External short circuit of BESS during discharging.

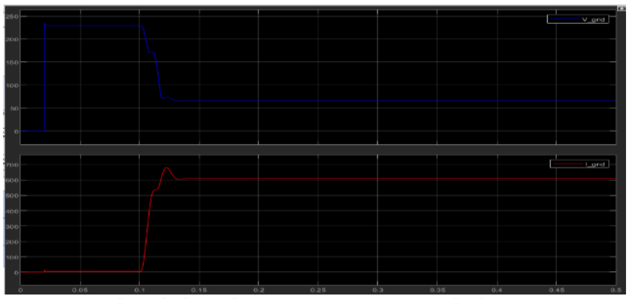

Fig. 8 Grid stability during BESS external short circuits under charging and discharging of BESS

As seen from Fig 8, grid voltage level drops to approximate 60V. Moreover, the grid current increases rapidly to approximate 600A. The gradual decrease and increase in voltage and current are due to grid impedance. The short circuit occurs on the AC bus which is also common point of coupling to the grid. Therefore, AC grid is directly affected by the short circuit.

4. Conclusion

A grid-connected BESS model applicable to a typical LV network in Malaysia has been developed in MATLAB/Simulink environment. The BESS can charge or discharge energy by adjusting the current settings in the converter block to achieve AC/DC bidirectional conversion. Short circuit analysis has also been conducted on the internal and external circuit of BESS. In the internal circuit, faults are conducted across the terminals of battery. Whereas in the external circuit, fault is conducted on the AC bus which is point of common couplings for BESS terminals and AC grid. Based on the fault analysis, internal short circuit causes high current discharged from BESS alongside with voltage drop and rapid decrease of SoC. These behaviors are damaging to the battery lifespan of BESS. On the other hand, external short circuit does not cause BESS to discharge high current but operating at lower power efficiency instead due to current blocking effect of the converter. The protection scheme using a combination of ACCB and DCCB is designed for BESS power protection. The trip characteristics curve models referenced from manufacturer datasheet are developed to optimize the circuit breakers in compliance with standards outlined in IEEE Std 1375-1998, IEC/EN 60898-2, IEC/EN 60947-2, UL 1077, and CSA 22.2. No.235 according to manufacturer datasheet. AC breaker is also adjusted for DC application in the modelling. Then, fault cases are conducted son BESS to investigate the BESS system stability with power protection. The simulation results show that BESS operation is successfully interrupted in 0.02s by DCCB during an internal short circuit event. In addition, ACCB trips with longer time delay to internal fault when DCCB fails to trip. Therefore, ACCB acts as secondary protection in case of DCCB failure. During an external short circuit event, ACCB will trip to protect BESS from AC bus fault by means of BESS isolation. DCCB will never trip because the converter diodes and AC LCL filter have limited the fault current passing through converter.

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