Dynamic Modelling, Analysis and Design of Smart Hybrid Energy Storage System for Off-grid Photovoltaic Power Systems

by

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Dedicated to…

*my beloved Parents, Teachers, Partner, Family & Friends*
Battery technology has been widely utilized in different energy storage applications. However, limitations and challenges such as heat dissipation, low power density, unsatisfactory lifetime characteristics, environmental impacts, and high cost hinder its development in many key areas, for instance, the residential energy storage applications. To address the issue of the short service life of the battery, hybrid energy storage system (HESS) of various designs have been reported in the literature. However, the limited focus has been put on the case of the stand-alone residential energy system, especially for remote rural electrification. This thesis aims at proposing suitable battery-supercapacitor HESS designs and control strategies that can effectively extend the battery service lifetime via mitigating its operation stress, thereby realizing the cost reduction on the installing construction and operating costs of the stand-alone photovoltaic (PV) power system. For such systems that is planned to be installed in rural areas, potential suitable battery-supercapacitor HESSs are designed and discussed. To leverage on existing infrastructure in installed standalone PV-battery power system, novel smart supercapacitor/Li-ion HESS plug-in module (SHESS) is proposed to relieve the main battery operation stress. Theoretical analysis and numerical simulations for the designed HESSs and the SHESS are conducted, and their effectiveness in mitigating battery stress are investigated and compared via pulse load testing and case studies with actual data of solar irradiance and load profile from a remote community in Sarawak, Malaysia. A battery health cost model is formulated to qualitatively evaluate the impact of battery current on battery health, thus enabling the estimation of service life improvement as well as the assessment on the economic impact of the remote stand-alone microgrid. A down-scaled prototype of the proposed HESS is designed and developed to verify the theoretical analysis and analytical findings. Experiments have been carried out to test the feasibility and performance of the proposed system in terms of power-sharing capability in stand-alone PV power system operations. The experimental results demonstrate the feasibility of the proposed HESSs in retrofitting existing installed PV power systems and support the theoretical analysis and simulation outcomes.
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Declaration

I hereby declare that, to the best of my knowledge, this thesis contains no material which has been accepted for the award to the candidate of any other degree or qualification in this, or any other University and contains no material previously published or written by another person except where due reference is made in the text of this thesis. Furthermore, any idea, technique, quotation, or any other material from other people’s work included in this thesis, published or otherwise, are fully acknowledged in accordance with the standard referencing practices.

Wenlong JING
January 2019
Publications arising from this study

Journal Papers


Conference Papers


- **Wenlong Jing**, Chean Hung Lai, Wallace SH Wong, and ML Dennis Wong, “The Comparison between Two Types of Bidirectional Dual Active Bridge DC/DC Converter for Photovoltaic Application”, *(In progress)*
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# Nomenclature

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<th>Description</th>
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<tbody>
<tr>
<td>ADC</td>
<td>Analog to Digital Converter</td>
</tr>
<tr>
<td>BANP</td>
<td>Batang Ai National Park Headquarter</td>
</tr>
<tr>
<td>C-Rate</td>
<td>Charge and Discharge Rate</td>
</tr>
<tr>
<td>CAES</td>
<td>Compressed Air Energy Storage</td>
</tr>
<tr>
<td>DoD</td>
<td>Depth-of-Discharge</td>
</tr>
<tr>
<td>DAC</td>
<td>Digital to Analog Converter</td>
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<tr>
<td>EMS</td>
<td>Energy Management System</td>
</tr>
<tr>
<td>EMU</td>
<td>Energy Management Unit</td>
</tr>
<tr>
<td>ESS</td>
<td>Energy Storage System</td>
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<tr>
<td>FBC</td>
<td>Filtration-Based Controller</td>
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<tr>
<td>FES</td>
<td>Flywheel Energy Storage</td>
</tr>
<tr>
<td>GPMES</td>
<td>Gravity Power Module Energy Storage</td>
</tr>
<tr>
<td>HVAC</td>
<td>Heating, Ventilation, Air-Conditioning</td>
</tr>
<tr>
<td>HESS</td>
<td>Hybrid Energy Storage System</td>
</tr>
<tr>
<td>IEA</td>
<td>International Energy Agency</td>
</tr>
<tr>
<td>LA</td>
<td>Lead-Acid</td>
</tr>
<tr>
<td>LCOE</td>
<td>Levelized Cost Of Energy</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
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<tr>
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<tr>
<td>LCOS</td>
<td>Levelized Cost Of Storage</td>
</tr>
<tr>
<td>LCIA</td>
<td>Life Cycle Impact Assessment</td>
</tr>
<tr>
<td>LPF</td>
<td>Low-Pass Filter</td>
</tr>
<tr>
<td>MPP</td>
<td>Maximum Power Point</td>
</tr>
<tr>
<td>MPPT</td>
<td>Maximum Power Point Tracking</td>
</tr>
<tr>
<td>PV</td>
<td>Photovoltaic</td>
</tr>
<tr>
<td>PSB</td>
<td>Polysulphide Bromide</td>
</tr>
<tr>
<td>PAC</td>
<td>Power Allocation Controller</td>
</tr>
<tr>
<td>PCU</td>
<td>Power Conditioning Unit</td>
</tr>
<tr>
<td>PI</td>
<td>Proportional-Integral</td>
</tr>
<tr>
<td>PWM</td>
<td>Pulse Width Modulation</td>
</tr>
<tr>
<td>PHS</td>
<td>Pumped Hydro Storage</td>
</tr>
<tr>
<td>RES</td>
<td>Renewable Energy Sources</td>
</tr>
<tr>
<td>SHESS</td>
<td>Smart Hybrid Energy Storage System</td>
</tr>
<tr>
<td>NaS</td>
<td>Sodium-Sulphur Battery</td>
</tr>
<tr>
<td>SoC</td>
<td>State-of-Charge</td>
</tr>
<tr>
<td>SC</td>
<td>Supercapacitor</td>
</tr>
<tr>
<td>SMES</td>
<td>Superconducting Magnetic Energy Storage</td>
</tr>
<tr>
<td>TES</td>
<td>Thermal Energy Storage</td>
</tr>
<tr>
<td>VRB</td>
<td>Vanadium Redox</td>
</tr>
<tr>
<td>VAR</td>
<td>Voltage-Ampere Reactive</td>
</tr>
<tr>
<td>ZnBr</td>
<td>Zinc Bromine</td>
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</tbody>
</table>
Chapter 1
Introduction

1.1 Research background

Modern electrical grid is required to provide reliable power supply that matches the varying electricity demand from all sectors at all times. Aligning different sources of power generation and varying load demand in an electricity network is one of the biggest challenges for the utility company [1]–[3]. The unbalanced generation-demand would potentially cause serious negative impacts on power quality such as voltage variation, random frequency difference or sudden blackouts [4]–[7]. In addition, the surplus electricity generated cannot be practically and economically stored which requires it to be consumed at the instant when it is generated [8].

Ideally, energy storage system (ESS) as an intermediate buffer could potentially alleviate some of the existing challenges such as frequency regulation, load levelling, peak shaving and spinning reserve [9]. The key idea of energy storage integration is to absorb excess energy when available, and to release the stored energy during peak demand, which improves the flexibility and resilience of the electrical grid [10], [11]. There are numerous energy storage technologies available nowadays, which can be broadly classified based on the form of energy stored: (1) mechanical (pumped hydro storage, compressed air energy storage and flywheels), (2) electrical (supercapacitor and superconducting magnetic energy storage), (3) electrochemical or battery (conventional rechargeable batteries and flow batteries), thermal (latent heat storage and sensible heat storage), (4) chemical (hydrogen fuel cells and thermochemical energy storage) and (5) thermal energy storage (sensible heat storage and latent heat storage) [12].
ESS is also a vital tool for enabling integration of Renewable Energy System (RES) in the electrical grid and distributed residential energy storage solution [13], [14]. Typical renewable sources, such as solar, wind, biomass, geothermal, and tidal, are highly intermittent in nature and often generate unstable and unpredictable electricity over time. The undesirable fluctuating power generation from RES creates several issues such as power safety, power quality, and reliability as well as islanding protection. Over recent decades, solar photovoltaic (PV) technology has become one of the most prominent RES due to many advantages such as modular, easy to install, mature technology and most importantly low operating cost [15].

PV based power generation system can be categorized into grid-connected PV power system and stand-alone PV power system. Low capacity stand-alone PV systems are primarily used to supply electricity in off-grid communities such as remote rural areas, to provide basic electricity needs for example lighting, food refrigeration and other basic electrical appliances [16], [17]. Fig. 1.1 illustrates a typical profile of PV power generation in tropical rainforest climate (red line) and the estimated load demand (blue line) of rural communities. The nonlinear electrical characteristic of PV cells and intermittency of solar irradiance require integration of intermediate ESS in order to provide stable electricity supply, especially in stand-alone PV power system. ESS absorbs the generation-demand mismatch and fluctuating power exchange in the system through charge and discharge processes.

![Fig. 1.1 Typical PV power generation and load profile in Sarawak, Malaysia](image-url)
Lithium-ion and Lead-acid batteries are the two most commonly used energy storage technologies in residential ESS [18]. The Lithium-ion battery has a higher energy density, round-trip efficiency, and longer cycle lifetime compared to the Lead-acid battery, but is relatively more expensive and immature in large-scale packaging. In contrast, the Lead-acid battery is more suitable for off-grid PV power systems, particularly in rural electrification due to its lower initial cost and excellent thermal stability. Despite many advantages of integrating battery in stand-alone PV power system, the highly dynamic fluctuations in generation and demand from the low-capacity energy accelerate the battery aging process, which will significantly increase the operating cost of the system [19], [20].

Hybridization of different energy storage technologies turns out to be one of the promising solutions to mitigate the battery charge-discharge stress by directing the short term power fluctuation to another form of energy storage such as the supercapacitor (SC) [21]–[25]. Compared to electrochemical batteries, SC has very high power density, fast response time and nearly infinite cycle life, which make it a good complement to the Lead-acid battery bank in absorbing fluctuating power exchange [26]. Thus the concept of Battery-SC Hybrid Energy Storage System (HESS) has been proposed by many researchers aiming to mitigate the impact of fluctuating power on battery’s lifespan [27]–[29]. In Battery-SC HESS, the net current flowing in and out of the HESS will be divided into two or more components with varies frequencies. The SC absorbs the high frequency and surge power exchange, while the battery bank responses to the smoothed average power demand. The combination of battery and SC can provide a wide range of power and energy requirements in stand-alone PV power systems. Besides having correct combination and appropriate sizing of energy storage devices, the design of Energy Management System (EMS) is another key to achieve better efficiency, operation and maintenance costs reduction, and most importantly prolonged battery service life [30]–[34].

1.2 Problem statement

In the perspective of rural electrification, the stand-alone PV power system is usually installed to the places that are geographical dispersal, decentralized, low population
density and geographically isolated from the national grid, thus simple, stable and inexpensive design of HESS will be of crucial useful than the high efficiency but a costly and complex system [35]–[37]. Many research studies focused mainly on proposing advanced and innovated HESS in aspects of novel topologies or complicated EMS with hierarchical control, supervisory monitoring, adaptive droop moderate scheme or control strategy based on the artificial intelligence algorithms [38]–[41]. These HESS designs are generally intended to serve large-scale utilities, smart-grid, electric vehicles and other high power applications that require extensive sensing, computation, and communication, this leads to increased system complexity and implementation, and are not suitable in the rural area. However, the study on HESS for off-grid residential energy system especially in rural electrification application is limited, and their design considerations have not been systematically discussed. To address this gap in the literature, this thesis conducted a study on the applications of HESS in stand-alone PV power system for rural electrification.

1.3 Research contributions

The primary objective of this study is to enhance the service life of the Lead-acid battery in stand-alone PV-battery power systems by mitigating life-limiting factors such as current fluctuations and surge current. Thus, improving the system reliability and power quality and most importantly reducing the system operating cost. To achieve this aim, the research major works, methodology, contributions and outcomes are summarised in Fig. 1.2 and as follows:

<table>
<thead>
<tr>
<th>Major Work</th>
<th>Methodology</th>
<th>Contribution</th>
</tr>
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<tbody>
<tr>
<td>• Battery-SC HESS study</td>
<td>• Propose selection methodology based on the overview of ESS</td>
<td>• ESS selection methodology</td>
</tr>
<tr>
<td>• Lead-acid battery lifetime enhancement in standalone PV power system</td>
<td>• Standalone PV power system study and application of lead-acid battery</td>
<td>• Load profile estimation</td>
</tr>
<tr>
<td></td>
<td>• Discuss HESS topology and select suitable topologies for standalone PV Power system</td>
<td>• HESS study for rural applications</td>
</tr>
<tr>
<td></td>
<td>• Propose Smart HESS as a plug-in module</td>
<td>• Novel smart HESS plug-in module is proposed</td>
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</table>

Battery healthy assessment system is proposed

Fig. 1.2 Content summary of the study in this thesis
• Comprehensively review the existing energy storage technologies regarding their technical merit, characteristic, economic feasibility and development trends. Technical analysis, comparison and potential applications in modern power system networks are presented. In particular, the methodology to help decision-makers in identifying optimal energy storage technologies for specific applications has been developed and discussed.

• Investigate the lifetime characteristics of Lead-acid battery bank in power system applications and identify the life-limiting factors that accelerate the performance deterioration and aging process.

• Investigate the effectiveness of hybrid ESSs in enhancing battery’s service and feasibility in stand-alone PV-based power systems. This includes the development status, operation principles, characteristics, advantages and disadvantages, energy management and control strategies, and possible application scenarios.

• Complete the literature gap of the Battery-SC hybrid ESS in remote rural applications.

• Propose a novel smart hybrid ESS plug-in module that enhances the lifetime characteristics of the primary Lead-acid battery in existing installed stand-alone PV-battery power systems by mitigating life-limiting factors such as current fluctuations and surge power demand.

• Formulate a battery health cost function to quantitatively evaluate the negative impact of charge/discharge current profile, follow with a series of battery health cost analysis to systematically evaluate the effectiveness of different hybrid ESS topologies and control schemes in mitigating battery stress, and perform economic analysis and financial feasibility study.

• Provide a complete analytical methodology for the research of the Battery-SC HESS technology, including mathematical modelling, numerical simulation and analysis, prototype design and corresponding experimental testing strategy.

1.4 Outline of the thesis

Chapter 2 presents an updated review of the currently available ESS technologies. The following energy storage technologies, Pumped Hydro Storage (PHS), Compressed Air
Energy Storage (CAES), Flywheel Energy Storage (FES), Superconducting Magnetic Energy Storage (SMES), Supercapacitor (SC), cell battery, flow battery, latent and sensible Thermal Energy Storage (TES), hydrogen fuel cell energy storage and thermochemical energy storage, will be present in terms of their operation, functionality, distinct characteristics, limitations and advantages.

**Chapter 3** introduces solar cell technology and PV power systems. A series of considerations for the design of stand-alone PV power systems, such as solar irradiance measurements, load profile estimation, and energy storage devices selection, are discussed and presented. By using local solar irradiance and an estimated load profile, a typical stand-alone PV-battery power system is modelled and simulated to show the profiles of PV output power and battery currents. A lab-scale prototype of the stand-alone PV-battery power system is constructed to show the performance experimentally.

**Chapter 4** provides a study on the latest works related to Battery-SC HESS regarding topologies, control algorithms and EMS, and the applications in PV based stand-alone power system.

**Chapter 5** discusses the potential Battery-SC HESS topologies that are suitable for the stand-alone PV power systems in rural areas. Theoretical analysis and numerical simulation in Matlab Simulink for the selected HESS topologies have been carried out, and their effectiveness in mitigating battery stress are compared. The battery health cost and financial analyses are presented to evaluate the life-extending capability of different HESSs and their cost reduction in the overall system. The lab-scale prototypes of them are developed, and their performances in stand-alone PV system are emulated to validate the simulation analysis.

**Chapter 6** proposes a smart SC/Lithium-ion HESS plug-in module that aims to extend the Lead-acid battery lifetime in installed stand-alone PV-battery power systems without reconstructing the system structure. It supposes to remove the severely current fluctuations from the Lead-acid battery current profile and direct it passively operating with a smoothing current profile. The proposed module is validated using numerical simulation and prototype experiment.
Finally, in Chapter 7, the conclusion concludes this study with a summary and provides suggestions for future research in this area.
Chapter 2
Review of Energy Storage Technologies

2.1 Introduction

Energy storage technologies store electrical, thermal, chemical and mechanical energy and release them in the form of electricity when needed. Energy storage devices have been widely used in various applications ranging from large-scale power systems to distributed generation in microgrids, to improve the operational capability of power systems, enhance power quality and reliability, and optimize power generation cost. Besides, energy storage technology is also one of the vital components that enable the adoption of RESs in the electrical power networks. Renewable energy sources, such as solar, wind, biomass, geothermal and tidal, are often intermittent in nature that tends to produce fluctuating and unstable electricity over time. The intermittent power generation from RES creates issues such as power quality and reliability, power safety and the needs for islanding protection. Energy storage technologies can be classified into five major categories based on the form of energy when stored: (1) mechanical energy, (2) electrical energy, (3) electrochemical energy, (4) thermal energy and (5) chemical energy. The following sub-sections will present an overview of the modern power system and a comprehensive review of energy storage technologies, including their electrical and lifetime characteristics, technical analysis, and comparison.

2.2 Modern power system with energy storage

Fig. 2.1 shows a typical structure of modern power system consisting of subsystems such as power generation, transmission, distribution, and end-users. The figure also
summarizes the major challenges that exist in each subsystem, and the potential applications of ESS across modern power system network [42]–[46].

The primary role of the power system is to generate electricity that matches the continually varying load demand as close as possible to avoid over-generation of electricity and power deficit which requires load shedding remedy. Secondly, the power system is required to maintain the system voltage and frequency at all times despite random failure and/or variations at the generation side. ESS is one of the promising solutions to enhance the reliability of the power system by acting as a contingency reserve to provide immediate supply or spinning reserve during supply-demand mismatch [47].

For load levelling application, ESS stores the excess energy at off-peak periods and supply the stored energy during peak demand periods as shown in Fig. 2.2 [48]. Besides, the adoption of ESS can effectively counterbalance the power fluctuations from generators to ensure frequency regulation [49]. The integration of ESS at generation side can minimize the usage of costly load following power plant as well as wastage during off-peak hours. In the case of renewable energy based generation, ESS plays an important role to smooth (capacity firming) the intermittent RESs output power [50].
Serious voltage collapse in power system due to excessive reactive power loss has been one of the causes in major blackouts and voltage instability such as voltage sags, voltage swells, frequency harmonics and flickers [51]–[53]. A stable electricity supply requires a well-balanced real power and reactive power. The centralized power generation supplies the real power and the reactive power can be generated either by local Voltage-Ampere Reactive (VAR) supply or remote generators [54]. The local VAR supply, also known as static compensation, can be the transformer tap changers, switched capacitor banks and large rotating machines which are typically located within the transmission and distribution sub-systems [55]–[57].

![Fig. 2.2 Load levelling and capacity firming in fluctuating load profile using ESS](image)

As an alternative technology, ESS can be used to effectively perform voltage regulation and VAR support function [58]. Instead of the conventional methods where VAR (up to 10MW) is installed in transmission sub-system to control the voltage dynamic behaviors and balance phase-angle difference between generation and demand sides, ESS container (up to 2MW) can be installed at the end of distribution network that acts as an energy buffer to provide stabilized high quality electricity to the loads [59].

In small-scale residential power applications, ESS can be used as a back-up power supply or uninterrupted power supply. In addition, the ESS can be controlled to simulate the time-shifting processes for which cheaper electricity at off-peak is stored and provide electricity supply during peak hours [60]. Assuming well-coordinated time-shifting processes at the demand side, the ESSs in distributed residential power system networks not only reduce the electricity cost for the households, but the cumulative
effect of time-shifting could also be an attractive alternative to replace huge centralized ESS at the generation side for load levelling.

With the rapid development of information technology and matured power electronic technology, the traditional power system is undergoing a revolutionary transformation in order to address the fast-growing global electricity demand, large-scale renewable energy penetration, and large-scale multi-regional grid integration. The concept of smart-grid has been widely accepted as one of the promising solutions for next-generation power systems, for which the ESS is one of the critical components in the modern power system network. Smart-grid incorporates the state-of-the-art technologies in power electronics, sensors, control systems, communications and networking that significantly improve the intelligence of the power system, including self-healing, consumer-friendly, optimized asset utilization, eco-friendly, improved efficiency, reliability, and safety [61].

Unlike the traditional power system, smart-grid allows seamless integration of microgrids that contain distributed generations and loads. In general, sustainable energy technologies such as solar PV, wind turbine and small hydro are often being integrated into microgrids. Microgrid works as an independent small-scale, localized power system that includes transmission, distribution, and EMS and energy storage [62]. Because of the intermittency, variation and instability of renewable energy power generation, the installation of ESS in the system will be essential to ensure power stability with acceptable power balance, power quality, and reliability between power generations and user demands.

Table 2.1 summarizes the applications of ESS in modern power system including generation, transmission, power distribution, and demand side. In general, the integration of ESS in the power system can effectively improve the electric grid flexibility, resilience, technical efficiency and economic performance [42], [63]–[69].

<table>
<thead>
<tr>
<th>Table 2.1 Applications of energy storage in the power system</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Generation (Centralised and Distributed)</strong></td>
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<tr>
<td>-------------------------------------------------------------</td>
</tr>
<tr>
<td>- 11 -</td>
</tr>
</tbody>
</table>
- Renewable energy integration
- Grid fluctuation suppression
- Capacity firming
- Ramping and Load Following
- Frequency regulation
- Seasonal energy storage
- Contingency reserve
- Black-start
- Spinning reserve
- Load Levelling / Peak shaving
- Voltage regulation
- Voltage-ampere reactive
- Transmission curtailment
- Transmission deferral
- Distribution deferral
- Transient stability
- Power quality
- Outage mitigation
- Energy management
- Time shifting
- Demand side management
- Energy arbitrage
- Uninterrupted power supply
- Vehicle-to-grid
- Microgrid

The detailed components of the modern power system are summarized in Fig. 2.3 [70]–[73]. The power system can be grid-connected or stand-alone or interchangeably with advanced control strategy and switching. The power system contains energy sources, interface components, power conversion system, control, and monitoring system, ESS and loads. The power conversion system is the interconnection between systems of different electrical characteristics, for example, the conversion from AC to DC or vice versa. The loads include the end-use customer in different sectors which can be either AC or DC.

![Fig. 2.3 The detailed components of the power system](image)

The power system with ESS integrated allows the surplus electricity to be stored in energy storage devices and dispatched during high electricity demand for improved efficiency. The ESS contains three main components that are charge/discharge module, energy storage devices, and energy management system. The charge/discharge module
manages the energy that flows in and out of the energy storage devices, while the EMS monitors, controls and manages the ESS to ensure safe operation.

2.3 Energy storage technologies

Energy storage technology can be classified into five categories based on the form of stored energy, which are (1) Mechanical, (2) Electrical, (3) Electrochemical, (4) Thermal and (5) Chemical. Fig. 2.4 shows the classifications of energy storage technologies available today. The following subsections present a comprehensive review and discussion on each ESS, including their electrical and lifetime characteristics, operating principles, system components, advantages as well as limitations.

![Energy Storage Technologies](image)

**Fig. 2.4 Energy storage technology classification**

2.3.1 Mechanical energy storage

Electrical energy can be converted and stored in the form of potential energy and kinetic energy. Pumped hydro energy storage (PHS) and compressed air energy storage (CAES) are two common potential ESSs. While flywheel technology converts and stores energy in the form of rotational energy.

a. **Pumped hydro storage (PHS)**
Fig. 2.5 Pumped hydro storage (PHS) in renewable power system

Fig. 2.5 shows the structure of PHS, where two reservoirs at different altitudes are used to achieve electrical energy storage and conversion to gravitational potential energy [74]. PHS was first implemented in Switzerland and Italy in 1890 and currently accounts for 95% of global energy storage capacity [75], [76]. There are currently more than 300 PHS plants worldwide with a total installed capacity of 169 GW. The largest PHS plant is rated at 3 GW and can last 10 hours at rated power [77]. Compared to other energy storage technologies, PHS is considered as a large-scale energy storage and is commonly used for daily load levelling and seasonal energy storage applications.

The storage capacity of PHS depends on the elevation difference between the two reservoirs and the maximum amount of water that can be stored in the higher reservoir. During off-peak hours, excess power is used to run electric pumps to transfer water from the lower reservoir to the upper reservoir. During the high power demand period, the stored water in the higher reservoir is released to run turbines to generate electricity. The round-trip efficiency of PHS is reported to be between 70% and 85%, mainly due to energy losses during pumping and generation processes. PHS is one of the most cost-effective ways to store large amounts of energy. However, the implementation of PHS is limited by high initial cost, complex geographic location requirements, long construction periods, and potential negative ecological and environmental impacts [78].
b. Compressed air energy storage (CAES)

CAES technology is highly equivalent to PHS in terms of their operation principle, application scenarios, input/output form, and storage capacity. But unlike PHS, which moves water from lower reservoirs to higher reservoirs, CAES stores energy in the form of compressed air and is usually stored in large underground caverns (aquifers, hard rock caverns, underground natural gas storage, or salt caverns) with air pressure ranging from 40 to 70 bars, as shown in Fig. 2.6 [79]–[81]. The excess power generated during off-peak hours is used to compress air, which can be released to drive the gas turbine generator to meet higher power demand during peak hours. CAES has high energy and power density, which is considered as long-term energy storage technology. CAES has been widely used in load shifting and power smoothing applications [82], [83]. However, similar to PHS, its development is mainly limited by geographical location and large initial cost. There are two common types of CAES based on how heat is handled during the compression and storage processes, namely diabatic CAES and adiabatic CAES, as shown in Fig. 2.7 and Fig. 2.8 respectively [84].
Heat will be generated during the compression process and dissipated during the expansion process. The diabatic CAES removes heat produced in the compression with intercoolers. A reheating process with a gas-fired burner is often needed before expansion in the turbines, which decreases the round-trip efficiency to about 40% to 50% [85]. If the heat generated during the compression process (charging process) can be stored and used during the expansion process (discharge process), the round-trip efficiency can be significantly improved. The adiabatic CAES storage retains the heat during compression with well-insulated heat storage and returns the heat during expansion process while running the turbine generators. The round-trip of adiabatic CAES power plant has been reported to be approximately 70% [86]–[88].
c. **Flywheel energy storage (FES)**

FES stores electrical energy in the form of kinetic energy by rotating mass, as shown in Fig. 2.9. It comprises of a flywheel (steel or carbon composite) coupled with a high-speed motor-generator and magnetic bearings that are mounted in a vacuum box in a suspended state that aims to reduce self-discharge loss [89]. The stored energy is calculated as \( E = J\omega^2/2 \), where \( \omega \) is the angular velocity and \( J \) is the moment of inertia [90]. The faster the flywheel rotates the more energy it stores. FES is considered as short-term energy storage since the discharge time is from few mins to hours.

![Fig. 2.9 The flywheel ESS](image)

There are two types of FES based on the flywheel rotating speed: (1) low speed FES (up to 6000 rpm), and (2) high speed FES (up to 60,000 rpm). The low-speed FES has a specific energy close to 10-30 Wh/kg and they are made of steel rotors and conventional bearings. High-speed FES can achieve a specific energy of 100 Wh/kg because of its lightweight and high strength composite rotors. Low-speed FES is suitable for applications that require short-term energy storage with high power capacity. On the other hand, high-speed FES aims to serve applications that require medium-term energy storage with a relatively lower power rating. During the charging process, the flywheel is accelerated by a high-speed motor to convert the electrical energy to kinetic energy of the rotating mass. When electrical energy is needed (discharging process), the rotating flywheel is used to drive the generator in order to generate electricity. FES system performs a series of good characteristics such as high power density, long cycle life (up
to 100,000 cycles), high round-trip efficiency (80% to 90%), no Depth-Of-Discharge (DoD) effect, wide operating temperature range, and environment-friendly.

FES technology is theoretically suitable for energy storage applications that experience frequent charge-discharge cycle, require short to medium term energy storage and fast response. For example, uninterrupted power supply, ancillary services, peak power buffer, solar or wind power system and aerospace applications [90], [91]. The main shortcomings of FES are the high energy cost (up to 1400 US$/kW) and high self-discharge rate.

2.3.2 Electrical energy storage

Electrical ESS stores energy in the form of electrostatic or electromagnetic energy that includes SCs and superconducting magnetic energy storage.

a. Supercapacitor (SC)

SC, also known as ultracapacitor or electrochemical double-layer capacitor, stores electrical energy in the form of the static electric field. As shown in Fig. 2.10, SC consists of metal plates, polarized electrode, electrolyte, and separator (ion-permeable membrane) [26]. Due to the porous and large specific surface area, the highly activated porous carbon is used as the polarized electrodes.

![Fig. 2.10 Simplified cross-section of SC cell](image)

The two electrodes are separated by the separator and electrically connected to each other by the electrolyte. The separator serves as a physical separation between the two electrodes, which provides insulation and allows ion conduction between the two.
oppositely polarized electrodes. During the charging process, ions in the electrolyte migrate to the opposite polarity of the electrode, and the electrostatic field are formed at the interface between electrolyte and electrode on both sided of the separator that creating an electric double layer. The double layer increases the surface area that allows a relatively large amount of electrical energy to be stored and thus having a capacitance that is thousands of times larger than a conventional electrolytic capacitor. Compared to other energy storage technologies such as electrochemical batteries, SC has higher power density ranging from 800-2000 W/kg. Similar to the conventional electrolytic capacitor, SC has nearly infinite charge/discharge cycles without degradation, with an efficiency as high as 95%.

Typical single SC cell operates in the low voltage range and can be connected in series or in parallel to form modules and arrays to suit different application requirements. The relatively higher self-discharge rate and low energy density of SC limit it to only short-term applications. Short-term energy storage applications such as regenerative braking in electric vehicles have become one of the main application areas of SC arrays, where the SC array is designed to absorb and supply surge power demands during acceleration and braking events. Research and development works for the next-generation SC have been on-going and are mainly focusing on novel capacitive materials with larger capacitance, such as graphene.

b. **Superconducting magnetic energy storage (SMES)**

The concept of SMES was first proposed by M. Ferrier in 1969 [92]. SMES stores energy in superconducting magnetic conductors in the form of electromagnetic energy. Fig. 2.11 shows a schematic of SMES with the superconducting coils as a core component that placed in a helium vessel. The coils form a conductor that is made of superconducting materials, such as Niobium-Titane (NbTi) wire operating at an extremely low temperature (-270°C). The low-temperature environment allows the superconducting materials to carry the electrical current as a large inductor and generate a magnetic field with almost no resistive losses. The conductor inductance determines the capacity of SMES and the corresponding maximum allowed current. The stored energy in a typical SMES can be formulated as [93]:
$$W = \frac{1}{2} L \cdot i^2$$  \hspace{1cm} (2.1)\)

where $W$ is the stored energy inside the superconducting magnet conductor, $L$ is its inductance, and $i$ is the current flows in the coil. Under the superconducting state, the current density inside the SMES is ten to hundred times higher than conventional coil and therefore higher power density (up to 105 kW/kg), and energy density (1-10 Wh/kg) can be achieved. SMES has a series of advantages such as high efficiency of 90-95%, a large number of charge-discharge cycles, environmentally friendly, and fast response during charge-discharge processes (less than 100 milliseconds).

The installed capacity of typical SMES is generally within 10 MW and are mainly used for power quality improvement such as transient stability and spinning reserve in grid-scale applications [94]. Moreover, SMES allows the stored energy to be fully discharged, which is useful for applications that require continuously complete charge-discharge operations. Currently, the SMES is still under development stage, and some major shortcomings hinder the development, such as a complex structure in the refrigeration system and control system, and most importantly the high cost in superconducting materials.

### 2.3.3 Electrochemical battery

Electrochemical battery technology uses chemical reactions to exchange electrical energy and chemical energy. There are two types of electrochemical storage system: (1) cell battery and (2) flow battery.

#### a. Cell Battery
Cell battery stores electrical energy in the electrode materials, while the flow battery stores energy in the electrolyte. Fig. 2.12 illustrates the typical structure of the electrochemical cell battery. Cell battery is a classical solution for storing electricity in direct current form. It normally comprises of anode, cathode and the electrolyte that acts as the medium allowing electrons exchange between two electrodes. It has the rechargeable function of storing and releasing electricity via chemical reactions in alternating the charge-discharge phases. Examples of cell battery technologies include Lead-acid batteries, Lithium-ion batteries, sodium-sulphur batteries, nickel-based batteries, and metal-air batteries.

**Fig. 2.12 General structure of electrochemical cell batteries**

**LEAD-ACID BATTERY**

The Lead-acid battery was first proposed in 1859 and is considered to be the oldest and most matured cell battery technology. It composes of the lead-dioxide cathode, sponge metallic lead anode and an electrolyte in sulphuric acid. The Lead-acid battery has an energy density of up to 30 Wh/kg. As a rechargeable cell battery, it can tolerate approximately 75% DoD and has approximately 1000-2000 cycles lifetime at 72-78% efficiency. The Lead-acid battery has many advantages such as low cost, rapid electrochemical reaction, simple power system installation, low maintenance, low self-discharge rate (about 2-5% per month), and excellent thermal stability. Thus, the Lead-
acid battery is still one of the most widely used ESSs in various applications such as uninterruptible power supplies, residential energy storage, backup power supplies, automotive batteries, etc [95], [96]. Although the Lead-acid battery is the most matured cell battery technology, the relatively short service life and poor lifetime characteristics hinder its development in many application areas, such as power system and residential energy storage [97], [98].

**Lithium-ion Battery**

The Lithium-ion battery has been widely used in consumer electronics (smartphones, laptops, portable devices), and electric vehicles. It uses an intercalation lithium compound as an electrode material, allowing lithium ions to move between electrodes for charging and discharging processes. The advantages of Lithium-ion battery include negligible memory effect, long lifetime (3000 cycles at 80% depth of discharge), high power density (500-2000 W/kg), high energy density (80-190 Wh/kg), lightweight, stable, low self-discharge rate (1–3% per month), abundant, high efficiency (90-100%), and low cost cathode material [99], [100]. However, Lithium-ion batteries are more expensive compared to other electrochemical energy storage devices, ranging from $900/kWh to $1300/kWh. Other drawbacks such as sensitive to overcharge and deep-discharge, for which additional State-of-Charge (SoC) monitoring and protection system are required for safe operation [101]. The Lithium-ion battery is one of the most promising energy storage solutions for the modern power system. However, the weaknesses mentioned above must be addressed before it can be widely adopted in large-scale energy storage applications as well as residential energy storage solution.

**Sodium-sulphur Battery (NaS)**

The sodium-sulphur battery (NaS) was introduced in the 1960s and first commercially available by the TEPCO (Tokyo Electric Power Co.) and NGK (NGK Insulators Ltd.) in 2000 [102]. NaS operates at a high temperature (300°C-350°C) and uses liquid sulphur as the positive electrode and liquid molten sodium as the negative electrode, as depicted in Fig. 2.13. The high temperature ensures the electrodes (Na and S) are in liquid state with a high reactivity. The solid beta alumina ceramic electrolyte separates the two electrodes. During charging process, the sulphur forming sodium polysulfide (Na$_2$S$_n$)
release the Na\(^+\) ions to the electrolyte and combine with elemental sodium, for which electrical energy is converted to chemical energy, and vice versa during the discharging process. The free electrons flow to the current collector that is connected to the external circuit. During the operation, heat produced by the chemical reaction is sufficient to maintain the required high operating temperature. The NaS battery has an energy density of about 100 Wh/kg and allows 100% depth of discharge, performing 2,500 cycles at a high roundtrip efficiency of up to 89% [103]. High operating temperature and highly corrosive sodium polysulfide in the electrode material limit the NaS application to only large-scale energy storage solutions. NaS can be applied in the transmission and distribution sections of the power system for power quality improvement, transient stability, Transmission, and distribution deferral, and outage mitigation [104]. Another major limitation of NaS is that it requires additional auxiliary equipment to maintain the high operating temperature and to ensure safe operation.

Nickel-based Battery

The nickel-based battery uses the active material of nickel oxide hydroxide as the positive electrode and varies metal elements as the cathode. Typical nickel-based batteries include nickel-zinc (Ni-Zn), nickel-cadmium (Ni-Cd), nickel-metal hydride (Ni-MH) and nickel-iron (NiFe). The Ni-Cd and Ni-MH batteries are relatively mature.
technologies and widely used in consumer electronics [105]. Ni-Cd battery use nickel oxy-hydroxide and metallic cadmium as the electrodes. The energy density can reach up to 75Wh/kg with a cycle life of approximately 2000-2500 [106]. The shortcomings are the high self-discharge rate (5-20% per month) and the use of rare and highly toxic electrode materials. Therefore, the Ni-Cd batteries have gradually lost their dominant position in the consumer electronics market since the 1990s, and it was replaced by Ni-MH and Lithium-ion batteries.

The Battle-Geneva Research Center around 1970 first invented the Ni-MH battery, that uses metal hydride as the cathode [107]. Ni-MH battery has an energy density of up to 50 Wh/kg, the power density of up to 1000 W/kg and recorded 500 cycle life at 100% depth of discharge. Compared to Ni-Cd battery of similar size, Ni–MH battery offers 30-40% more energy capacity and power capabilities, thus making it a more affordable option for hybrid fuel-electric vehicles. Ni-MH batteries are widely used in hybrid fuel-electric vehicles, contributing to over 95% of all market shares [108]. Other advantages of Ni-MH include low maintenance, high power and high energy density, environmentally friendly, safe operation during the charging-discharging transition at high voltages.

**Metal-air Battery**

Metal-air battery uses pure metal as the anode and ambient air as the cathode from an external system, its layout is shown in Fig. 2.14. The chemical reaction occurs in a tank containing the aqueous electrolyte. Unlike the usage of aqueous in previous cell battery technologies, the metal-air battery uses the ionic liquids as the electrolyte. Many metal elements can be used as anodes, such as aluminum, calcium, barium, iron, lithium, magnesium, potassium, silicon, sodium, tin, and zinc [109]. The most mature metal-air batteries among them are the lithium–air and zinc-air batteries [110], [111], the latter is more suitable due to cheap pure metal materials and low environmental impact. Metal-air batteries are of interest to electric car companies because of their free cathode materials and simple structures that do not require heavy enclosures to hold batteries [112]. It can theoretically be designed to be ultra-lightweight and have a long-lasting regenerative cathode, which is an attractive advantage in EV applications. For future development, major limitations should be further considered, such as poor life cycle,
low roundtrip efficiency of about 50%, unstable operating environment, and relative safety issues [113], [114].

Fig. 2.14 Simplified layout of the metal-air battery

b. Flow battery

Flow battery, or redox flow battery, is a kind of electrochemical energy storage that stores energy via two chemically electroactive materials. It converts electrical energy into chemical potential energy by charging two liquid electrolytes and releasing stored energy in reverse process. As shown in Fig. 2.15, the catholyte and anolyte are externally stored in two separate electrolysis tanks/reservoirs, and the electrolyte is pumped through the ion-exchange membrane cell. The reversible electrochemical redox reaction occurs here and generates the electricity simultaneously. During charging, one electrolyte is oxidized at the anode and the other electrolyte is reduced at the cathode. The reverse process occurs during discharging. Flow battery has a roundtrip efficiency of 70% to 85%. Since the battery capacity depends on the electrolyte volume and the electrode surface area, the external electrolyte tank concept allows the battery to be independently sized from different power or energy requirements in varies applications.

Moreover, it also results in that the flow battery can be recharged almost instantaneously by recovering the spent electrolyte liquid for re-energization. In addition, it has the advantages of low self-discharge percentage, fast response time, tolerance to overcharge/over discharge, long lifetime (without phase transition during
the process), low maintenance requirements and environment-friendly [115]. Currently, the available flow batteries that has been developed over the past years contains vanadium redox (VRB), polysulphide bromide (PSB), zinc bromine (ZnBr), and cerium zinc (CeZn) [116]. They are generally considered to be an attractive technology for relatively large scale energy storage applications in the 1 kW-10 MW range.

![Simplified layout of flow battery](image)

**Fig. 2.15 Simplified layout of flow battery**

c. **Summary of electrochemical battery**

Table 2.2 presents the technical comparison among these types of electrochemical energy storage discussed above [73], [95], [101], [109], [117]–[120]. As a matured energy storage technology and lowest cost per unit energy stored, the Lead-acid battery is one of the preferred choices for small to medium scaled renewable and backup power systems. Lithium-ion battery, with superior electrical characteristics, is currently utilized in portable consumer electronic devices, the adoption in power system applications are still low due to the safety issues and higher initial cost. On the other hand, despite the excellent properties of NaS such as high energy density and small self-discharge, the technology is still in the developmental stage due to the challenges in maintaining the optimal operating temperature above 300°C. Unlike other electrochemical batteries, the flow battery allows instant recharge by refilling the spent
electrolyte liquid. The flexible capacity, long service life, and low initial cost make the flow battery an up-and-coming ESS technology in large-scale renewable power generation plants.

<table>
<thead>
<tr>
<th>Battery type</th>
<th>Advantages</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead-acid</td>
<td>Low costs, Low self-discharge (2–5% per month), Low maintenance, Most maturity technology</td>
<td>Short cycle life (1200–1800 cycles), Aging due to deep depth of charge, Environment unfriendly (Pb &amp; acid), Low power density</td>
</tr>
<tr>
<td>Lithium-ion</td>
<td>High efficiency 90–100%, High energy density, Low self-discharge rate, Low maintenance, No priming required, Variety of types available</td>
<td>Overcharge protection is required, Aging due to deep depth of charge, Very high cost ($900–1300/kW h)</td>
</tr>
<tr>
<td>Nickel-based</td>
<td>Can be fully charged (3000 cycles), Higher energy density (50–80 Wh/kg), Lowest cost/cycle, Good low-temperature performance, Available in a wide range of sizes and performance options</td>
<td>High cost, 10 times of Lead-acid battery, High self-discharge (10% per month), Sensitive to overcharge, Memory effect, Generates heat at high C-rate</td>
</tr>
<tr>
<td>Sodium Sulphur (NaS)</td>
<td>High efficiency 85–92%, High energy density (90–120 Wh/kg), No degradation to deep charge, No self-discharge, Insensitivity to ambient conditions</td>
<td>Be heated in standby mode at 325 °C (Heating consumes 14% of battery energy per day), High price in battery sealing to avoid leak</td>
</tr>
<tr>
<td>Metal-air</td>
<td>High capacity, low cost, Removal of seal enables airflow</td>
<td>Sensitive to cold heat, humidity, and air pollution, one-time use</td>
</tr>
<tr>
<td>Flow battery</td>
<td>Capacity can be modified via set tank size, Long service life (10,000 cycles), No degradation for deep charge, Negligible self-discharge</td>
<td>Medium energy density (40–70 Wh/kg), High corrosion</td>
</tr>
</tbody>
</table>

2.3.4 Thermal energy storage (TES)

As shown in Fig. 2.16, TES technology stores energy via cooling or heating storage medium materials in the insulated containers and the stored thermal energy can be used directly in the domestic buildings, district heating, the industrial process needs where consumes thermal energy, or in power generation applications via gas generator [121], [122]. There are two types of TES technologies, latent heat storage and sensible heat storage [123]. Latent TES uses the liquid-solid transition of phase change materials
(PCMs) to exchange the thermal energy. During charging, the PCMs will shift from the low internal energy state to higher internal energy state, such as solid to liquid and liquid to gaseous. During retrieval, the higher internal energy state will transit back to former state and release energy.

![Simple layout of thermal ESS](image)

Unlike Latent TES, sensible TES stores the energy via high heat capacity of bulk medium materials such as sodium, molten salt, pressurized water, etc. When the system is charging, the bulk medium materials will be heated to a higher temperature. The heat is then released to generate water vapour that drives turbo-generator system for electricity. The main drawbacks include the low efficiency due to the energy losses during heat process, weather sensitivity and require large volume or surface to get the rated power.

### 2.3.5 Chemical energy storage

Chemical energy storage technologies include hydrogen fuel cells and thermal-chemical energy storage. Hydrogen fuel cell as depicted in Fig. 2.17, comprises of electrolyze unit, electrode storage tanks, and energy conversion cell. It uses the chemical reaction between oxygen and hydrogen to generate electricity, the reaction results are water and therefore offers zero-emission [124]. Up to 65% efficiency in hydrogen fuel cell has been reported in the literatures [125]. Its benefits contain high energy density (300–
1200 Wh/kg), low maintenance requirements, easy installation and environment friendly with low toxic emissions. The main drawbacks of hydrogen fuel cells are the high cost of hydrogen containers, stringent transport requirements, and the highly flammable nature of hydrogen. Hydrogen fuel cell performs more than 20,000 lifecycles with about 15 years lifetime. Its initial cost mainly from the storage method ($2–15/kWh) and storage equipment ($500–10,000/kW) [65][126][127]. While for the hydrogen production, hydrogen production with costs in the range of 1.34–2.27 $/kg, using available electrolysers [128][129]. Another form of chemical energy storage is the thermos-chemical ESS. Similar to flow battery, thermos-chemical ESS has two separate tanks to accommodate two different electrode materials. The heat energy is stored in the endothermic chemical reaction in molecular level. The stored energy is used to break the chemical bond (dissociation reaction) during the charging process, and then the reverse reaction will release energy in the discharging process.

Based on the type of reaction within the energy conservation cell, it can be classified into sorption systems and pure chemical reaction system [130]. The thermos-chemical energy storage has a relatively high energy density, which allows a large amount of energy to be stored using small amounts of storage medium materials. The heat loss in thermos-chemical energy storage is relatively low due to two separate storage tanks at
ambient temperature. The technology is still under research and development stage, with emphasis on reactor design, heat exchangers, and vacuum control.

2.4 ESS characteristics

A comprehensive understanding of ESS characteristics is essential in the consideration and selection of suitable energy storage technologies for different application scenarios. Fig. 2.18 presents the ESS characteristics in four different aspects, which are capacity, efficiency, response, and product features.

![Fig. 2.18 Energy storage characteristics taxonomy](image)

2.4.1 Technical characteristics comparison of energy storage technologies

a. **Volumetric: power density and energy density**

The volumetric property of ESS is an important factor in many applications, such as power transmission, portable devices, automotive, and remote applications. For a given energy capacity of ESS, the higher power and energy density is often desirable. Fig. 2.19 depicts the volumetric properties of different ESSs, with the nominal values of 1000W/L and 100Wh/L set for power density and energy density respectively. The bottom left corner indicates the ESS with low energy density and power density, and vice versa for ESS located at the top right corner.
PHS and CAES are low in energy density and power density by nature, which are normally implemented in large-scale and stationary energy storage project. In the top left corner, the SC, SMES, and flywheel are having high power density but relatively low in energy density. SC has the largest power density beyond 10,000 W/L, while its energy density is in the range of 10-30 Wh/L. In general, SC, Flywheel, and SMES have speedy response times, which are typically in the range of milliseconds. As one of the oldest electrochemical battery, the Lead-acid battery has a relatively higher energy density in the range of 50-90 Wh/L among the ESS grouped in the bottom left region. Lithium-ion battery exhibits high power density and energy density among all energy storage technologies. In the bottom right corner, the Zn–air battery as an emerging energy storage technology has demonstrated superior energy density, making it one of the promising energy storage solutions in power transmission systems.

![Energy Density vs Power Density Diagram](image.png)

Fig. 2.19 Comparison of energy density and power density

**b. Gravimetric: specific power and specific energy**

Specific energy and specific power are gravimetric characteristics that indicate the energy or power per unit weight. Fig. 2.20 illustrates the technical comparison of different ESS regarding specific power and specific energy. The VRB flow cell is
located in the lower left area and performs the lowest specific power and specific energy, 160-170 W/kg and 10-30 Wh/kg, respectively. In the upper right corner, Lithium-ion and Zn-air batteries are the lightest energy storage technologies. Compared to Lithium-ion battery, the Zn-air battery has a relatively lower power density, which makes them less suitable for consumer electronic devices. On the other hand, SC, SMES, and Flywheel energy storages demonstrate the highest specific power but lower specific energy due to the electrical characteristics and energy conversion mechanism. SMES has the highest specific power of 500-2000 W/kg, while SC exhibits an exceptionally high power density in the range of 40,000–120,000 kW/m$^3$. Due to their fast response time, they are broadly applied to power quality management systems. The flow batteries of VRB, ZnBr and Lead-acid battery have moderate specific energy and specific power, which are suitable for many medium-sized stationary residential energy storage solutions. The TES and fuel cell show high specific energy but low specific power (lower right area), that are usually used for large-scale ESS projects.

![Comparison of specific energy and specific power](image)

**Fig. 2.20 Comparison of specific energy and specific power**

c. *Capacity: power rating and energy rating*
The power rating indicates that the amount of power in kW can flow in or out of the energy storage at any given moment. The energy rating, or energy storage capacity, describes the amount of energy or electricity that energy storage can be stored and measured in kWh.

Based on the individual application scenarios of each energy storage technologies, Fig. 2.21 presents a comparison in energy rating and nominal discharge time duration at the power rating. The SC, SMES, and flywheel, with the highest power density and lowest energy density, are at the bottom of the chart. Their discharge time at rated power is generally in the range of minutes. The cell battery and flow battery are middle range energy storage devices with energy rating ranges from 1kWh to 1MWh, and the discharge time can reach 10 hours at the rated power. The PHS, CAES, NaS, VRB, hydrogen fuel cell and TES are ordinarily large-scale energy storage technologies with a capacity of more than 10 MWh, and their discharge time at rated power can up to days.

![Discharge Time duration (at power rating)](image)

**Fig. 2.21 Comparison of energy rating and discharge time duration in power rating**

**d. Efficiency: discharge efficiency and roundtrip efficiency**

Discharge efficiency and round-trip efficiency are two of the standard performance indicators for energy storage technology. The roundtrip efficiency, or cycle efficiency, is a ratio of output energy to input energy in one complete charge-discharge process. The discharge efficiency represents the ability to transmit stored energy in the case of full discharge. Most of the energy storage technologies perform medium to high cycle
efficiency of above 70%, except for CAES, TES, metal-air battery and hydrogen fuel cell that generally exhibit lower efficiency below 60%. Efficiency enhancement has been one of the main focuses in ESS research, aiming to minimize system cost.

e. Self-discharge rate and storage duration

The self-discharge rate (%), or idling losses rate, is a measure of how fast one energy storage unit will lose its stored energy without being connected to load. The phenomenon of self-discharge in energy storage device is mainly caused by undesirable internal mechanical or chemical effects such as energy dissipation via heat transfer losses in TES, the chemical reaction in batteries, friction energy loss in the flywheel, air leakage loss in CAES, etc. The storage duration refers the time period that ESS can provide from full charge to zero. Fig. 2.22 presents a comparison chart based on self-discharge rate and storage duration for ESSs. The SC, SMES, and flywheel have the highest self-discharge rate, and their storage duration can only be maintained within hours. Therefore, they are limited to short-term storage applications. Large-scale energy storage devices such as PHS, CAES, NaS, hydrogen fuel cell, and VRB, and ZnBr flow battery have low self-discharge rates, which is capable of keeping the stored energy for months. While the TES and conventional cell batteries such as Lead-acid, Lithium-ion, Nickel-based batteries exhibit intermediate self-discharge rate of 0.05-5%. They are commonly used for medium storage applications such as RES distributed power systems, electric vehicles, and consumer electronics.

<table>
<thead>
<tr>
<th>Storage Duration</th>
<th>Self-Discharge (%/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>months</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>days</td>
<td>0.03-5</td>
</tr>
<tr>
<td>hrs</td>
<td>15 – 40</td>
</tr>
<tr>
<td>mins</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 2.22 Comparison of storage duration and self-discharge rate
f. **Calendar Life and Cycle Life**

The lifespan of ESS can be expressed regarding calendar life or cycle life. The calendar life of an ESS indicates the period before an ESS deteriorates to an unacceptable state. Cycle life represents the number of full charge-discharge cycles before significant performance degradation. The lifespan of energy storage is an essential factor that determines the system operating cost. In general, non-chemical based energy storage technologies including PHS, CAES, flywheel, SC, SMES, and TES typically have much longer lifetime compared to chemical energy storage technologies such as cell batteries, flow batteries, and hydrogen fuel cell, due to the chemical deterioration and corrosion phenomenon.

g. **Maturity and economic cost**

The technical maturity, memory effect, financial cost and environmental impact of energy storage products are also important evaluation factors for selecting suitable energy storage in specific projects. The maturity of energy storage technology can be classified into five levels which are (1) research and development (R&D), (2) proven/commercializing, (3) mature/commercialized, and (4) very mature/fully commercialized.
Fig. 2.23 presents the technology maturity versus energy capital cost of the different energy storage technologies [131]. The cost of energy storage includes the energy capital cost (initial cost) and maintenance and operation (M&O) cost. The former one is usually expressed in cost/per unit ($/kWh). Well-developed energy storage technologies, such as PHS and Lead-acid battery are classified as very mature, with a history of more than 100 years. The sensible TES, Lithium-ion, Zn-air and NaS battery are mature technologies that have been commercialized on the market for decades. They are technically developed and commercially available in the industry, but stability, reliability, and cost competitiveness are still evolving and need further improvement. CAES, VRB flow battery, flywheel, and latent TES are on the commercializing stage with some significant improvement before commercialization. Hydrogen fuel cell, SMES, and ZnBr flow battery are still in their early stage of development.

![Energy Storage Technologies](image)

**Fig. 2.24 Comparison of energy capital cost and M&O cost**

Fig. 2.24 shows the comparison of M&O cost versus energy capital cost of energy storage technologies under consideration. The energy capital cost and M&O cost are the crucial aspects to consider when selecting energy storage for any project to ensure long-term financial sustainability. For example, the Lead-acid battery has a relatively low energy capital cost, but it requires a relatively higher M&O cost, which makes it inappropriate for the large-scale energy storage applications. More financial analyses of
different energy storage technologies in various application scenarios such as internal rate of return, tariff reduction, price arbitrage evaluation, are reported in [132]–[134].

h. Other characteristics: memory effect, aging mechanism, environment impact

Other non-quantifiable energy storage characteristics are critical aspects to consider when selecting an energy storage device. The memory effect is a unique feature of nickel-based rechargeable batteries. It is an effect where the battery loses its maximum energy capacity when it is repeatedly not completely discharged before being recharged, which seems that the battery remembers the latest smaller capacity. While the aging mechanism refers to the process of performance deterioration due to the physical and chemical changes during operation. In general, the aging mechanism is commonly found in chemical-based batteries due to the corrosion, and in mechanical-based energy storage due to physical wear and tear.

Environmental impact is another issue to be considered when choosing energy storage products or design ESS. The PHS and CASE require large-scale infrastructure which may disturb the local ecosystem. The flywheel, SMES, and hydrogen fuel cell are considered to have the least impact on the environment because there is no apparent toxic emission or waste by-product that causes pollution. Chemical-based energy storage technologies are using potential hazardous toxifying materials such as lead, cadmium, bromine, lithium, etc. Thus the recycling process of the aged chemical battery becomes extremely important, and additional attention needs to be paid to before their implementation.

2.4.2 Summary table of energy storage characteristics

Table 2.3 presents the summary of characteristics, parameters and product features for each of the energy storage technologies [63], [65], [75], [135], [136]. Inside the table, the item of Energy capital costs means the rough estimation about the cost of an ESS project to a commercially operable status.

|----------------|---------------------|-----------------------|-----------------------|----------------|--------------------|-----------------------------|------------------|

- 37 -
### Energy Storage Technologies

<table>
<thead>
<tr>
<th>Energy</th>
<th>Specific Energy</th>
<th>Round-trip</th>
<th>Response</th>
<th>Lifetime</th>
<th>Environment</th>
<th>Maturity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>[Wh/L]</td>
<td>efficiency [%]</td>
<td>time</td>
<td>(Years)</td>
<td>impact</td>
<td></td>
</tr>
<tr>
<td>CAES</td>
<td>0.5–2 Not appl.</td>
<td>Small</td>
<td>hours–days</td>
<td>8000–12000</td>
<td>2–50</td>
<td>Very large</td>
</tr>
<tr>
<td>2–6</td>
<td>30–60</td>
<td>40–50</td>
<td>s-min</td>
<td>20–40</td>
<td>Medium</td>
<td>Proven</td>
</tr>
<tr>
<td>PHS</td>
<td>0.5–1.5 Not appl.</td>
<td>Very small</td>
<td>hours–days</td>
<td>10000–30000</td>
<td>10–12</td>
<td>Very large</td>
</tr>
<tr>
<td>0.5–2</td>
<td>0.5–1.5</td>
<td>70–85</td>
<td>s-mins</td>
<td>30+</td>
<td>High</td>
<td>Very Mature</td>
</tr>
<tr>
<td>FES</td>
<td>1000–5000</td>
<td>400–1600</td>
<td>20–100</td>
<td>min–hours</td>
<td>20000+</td>
<td>1000–14000</td>
</tr>
<tr>
<td>20–80</td>
<td>5–130</td>
<td>85–95</td>
<td>10–20 ms</td>
<td>15–20</td>
<td>Very low</td>
<td>Proven</td>
</tr>
<tr>
<td>SC</td>
<td>40000–12000</td>
<td>500–15000</td>
<td>20–40</td>
<td>min–hours</td>
<td>100000+</td>
<td>300–2000</td>
</tr>
<tr>
<td>SMES</td>
<td>1000–2500</td>
<td>500–2000</td>
<td>10–15</td>
<td>min–hours</td>
<td>100000+</td>
<td>1000–72000</td>
</tr>
<tr>
<td>2–6</td>
<td>0.5–5</td>
<td>&gt;95</td>
<td>&lt;100 ms</td>
<td>5–20</td>
<td>Low</td>
<td>R&amp;D</td>
</tr>
<tr>
<td>Lead-acid Battery</td>
<td>10–400</td>
<td>75–300</td>
<td>0.1–0.3</td>
<td>hours</td>
<td>500–1000</td>
<td>200–400</td>
</tr>
<tr>
<td>50–90</td>
<td>30–50</td>
<td>80–90</td>
<td>ms</td>
<td>3–10</td>
<td>High</td>
<td>Very Mature</td>
</tr>
<tr>
<td>Lithium-ion Battery</td>
<td>1500–10000</td>
<td>230–340</td>
<td>0.1–0.3</td>
<td>hours</td>
<td>10000–20000</td>
<td>900–1300</td>
</tr>
<tr>
<td>150–500</td>
<td>100–250</td>
<td>90–98</td>
<td>10–20 ms</td>
<td>5–15</td>
<td>High/Medium</td>
<td>Mature</td>
</tr>
<tr>
<td>NiCd</td>
<td>80–600</td>
<td>150–300</td>
<td>0.2–0.6</td>
<td>hours</td>
<td>2000–3500</td>
<td>500–1500</td>
</tr>
<tr>
<td>&lt;200</td>
<td>45–80</td>
<td>70–75</td>
<td>ms</td>
<td>10–20</td>
<td>High</td>
<td>Very Mature</td>
</tr>
<tr>
<td>NiMH</td>
<td>500–3000</td>
<td>70–800</td>
<td>0.4–1.2</td>
<td>hours</td>
<td>300–3000</td>
<td>270–530</td>
</tr>
<tr>
<td>&lt;350</td>
<td>60–120</td>
<td>70–75</td>
<td>ms</td>
<td>5–10</td>
<td>High</td>
<td>Very Mature</td>
</tr>
<tr>
<td>NaS</td>
<td>120–180</td>
<td>90–230</td>
<td>–20</td>
<td>hours</td>
<td>2000–4500</td>
<td>300–500</td>
</tr>
<tr>
<td>&lt;400</td>
<td>150–240</td>
<td>85–90</td>
<td>10–20 ms</td>
<td>12–20</td>
<td>Medium/Low</td>
<td>Mature</td>
</tr>
<tr>
<td>VRB</td>
<td>0.5–2 Not appl.</td>
<td>0–10</td>
<td>hours</td>
<td>12000+</td>
<td>600–1500</td>
<td>Large/Medium</td>
</tr>
<tr>
<td>20–35</td>
<td>10–30</td>
<td>75–82</td>
<td>ms</td>
<td>10–20</td>
<td>Medium/Low</td>
<td>Proven</td>
</tr>
<tr>
<td>ZnBr</td>
<td>~25</td>
<td>50–150</td>
<td>Small hours</td>
<td>2000+</td>
<td>700–2500</td>
<td>Large</td>
</tr>
<tr>
<td>30–65</td>
<td>30–80</td>
<td>60–70</td>
<td>ms</td>
<td>5–20</td>
<td>Medium</td>
<td>R&amp;D</td>
</tr>
<tr>
<td>Zn-air</td>
<td>50–100</td>
<td>~1350</td>
<td>Not appl.</td>
<td>hours</td>
<td>2000+</td>
<td>10–1000</td>
</tr>
<tr>
<td>~800</td>
<td>~400</td>
<td>60</td>
<td>ms</td>
<td>30+</td>
<td>Very low</td>
<td>Mature</td>
</tr>
<tr>
<td>Latent Heat Thermal</td>
<td>Not appl.</td>
<td>10–30</td>
<td>0.5–1</td>
<td>Not appl.</td>
<td>Not appl.</td>
<td>3–80</td>
</tr>
<tr>
<td>25–120</td>
<td>150–250</td>
<td>75–90</td>
<td>Not appl.</td>
<td>20–40</td>
<td>Low</td>
<td>Proven</td>
</tr>
<tr>
<td>Sensible Heat Chemical</td>
<td>Not appl.</td>
<td>Not appl.</td>
<td>0.5</td>
<td>Not appl.</td>
<td>Not appl.</td>
<td>0.04–50</td>
</tr>
<tr>
<td>100–370</td>
<td>10–120</td>
<td>70–90</td>
<td>Not appl.</td>
<td>10–20</td>
<td>Low</td>
<td>Mature</td>
</tr>
<tr>
<td>Hydrogen Fuel-cell Chemical</td>
<td>&gt;500</td>
<td>&gt;500</td>
<td>0.5–2</td>
<td>hours-days</td>
<td>1000+</td>
<td>500–3000</td>
</tr>
<tr>
<td>500–3000</td>
<td>800–10000</td>
<td>30–50</td>
<td>s-mins</td>
<td>5–15</td>
<td>Very low</td>
<td>R&amp;D</td>
</tr>
</tbody>
</table>

### 2.4.3 The selection of energy storage technologies

In power system, the application of ESS can be divided into five categories: large-scale energy services, transmission, and distribution infrastructure services, auxiliary services,
and residential energy storage solutions. The auxiliary service contains emergency power back-up, peak shaving, time shifting and etc. Since each type of energy storage technology has its unique characteristics, it is essential to select the optimal energy storage technology for specific applications [137]–[139]. In general, the characteristics that can be used to assess the applicability of energy storage technology for specific applications include:

- Energy rating and power rating;
- Energy density and power density;
- Response time;
- Self-discharge rate;
- Cycle efficiency;
- Rated voltage and current;
- Charge/discharge duration and ampere-hour;
- Operating temperature;
- Service life;
- Environmental impact;
- Cost, weight, and size.

The above characteristics can be sorted into three main categories: technical, economic performance and environmental standards. In most cases, the rated power and duration of discharge are the critical characteristics in selecting appropriate energy storage technology for various applications; this is mainly because that the functionality is a prerequisite and to meet the technical requirements of the targeted system is the priority. At the same time, ESS economic performance and environmental standards are also important factors that influence the final decision. A typical method of analyzing the economic performance of an ESS is the Levelized Cost Of Energy (LCOE), sometimes referred to as Levelized Cost Of Storage (LCOS) [140]–[142].

The environmental standards mainly include the impact on the environment and the life of the ESS itself. The Life Cycle Impact Assessment (LCIA) is a systematic and commonly used method to assess the environmental impact of a product or process system throughout its life cycle [143], [144]. With the various characteristics, no single energy storage technology can fulfill all desirable requirements in different energy storage applications. For example, the Lithium-ion battery is one of the best options for small-scale portable devices because of its high power density, high energy density,
high efficiency, and reasonable cycle life. However, the higher initial cost and thermal instability hinder its usage in residential energy storage applications. As an alternative, the Lead-acid battery is a mature technology with relatively low cost and superior electrical stability. It is a practical option for residential energy storage solution, especially in stand-alone power systems. At the same time, however, in large-scale situations (several kWh), the Lead-acid battery is not suitable because of its high M&O cost and inefficiency.

![Fig. 2.25 The framework of the energy storage technology selection](image)

With the growth in ESS applications and options of energy storage technologies, it is efficient for decision-makers to provide a framework that can facilitate the selection of suitable ESSs. Fig. 2.25 shows the typical framework of the energy storage selection. Technical, economic performance and environmental standards are evaluated using sub-items that need to be balanced by decision-makers. The selection aims at finding the most suitable energy storage technology that can not only meet the technical constraints imposed by the target applications but also has the best overall performance in the main criteria, for example, the one with high technology maturity, low total cost, and small environmental impact.
The main criteria in the three domains for selection normally include qualitative and quantitative features. The quantitative considerations include efficiency, lifetime, cost, power and energy densities, electrical response time, etc. A comprehensive quantitative assessment can eliminate the effects of human factors and make the selection more realistic. The qualitative considerations include the evaluation of energy storage technologies attributes such as device properties, technology maturity, reliability and safety, environmental impact, etc. Qualitative analysis will mainly base on the user features, expert experience, and government policies to meet the environmental requirements, cost requirements, and stability requirements for specific projects. Once the appropriate energy storage product has been determined, the design of ESS will follow the procedures:

1. Determination of the required size of the energy storage, such as voltage and storage duration requirements (large, medium or small);
2. Determination of the energy storage structure that is required to meet the total ampere-hour capacity (single, parallel or series);
3. Design the control system;
4. Design of construction facility at the installed site, including protection system, monitoring system, cabling and etc.

The above procedures are the main steps in most ESS design process, and the detailed design and installation steps will be sequentially expanded according to the different application scenarios. As a case study to illustrate how to select and design an ESS in a specific application, a stand-alone PV power system with energy storage will be discussed in the next chapter.

2.5 General discussion on energy storage technology and future development

The design of energy storage technology normally involves multiple forms of energy, multiple devices, multiple substances, and multiple processes. Over the past few decades, researchers and industrial practitioners are putting great efforts in developing advanced energy storage technologies to reduce economic costs while ensuring longevity, good load regulation performance, high efficiency, and long-term reliability.
The ESS plays a crucial role in many aspects, including electric power transmission, large-scale renewable energy based power plant, large-scale grid flexible interconnection, residential RES based microgrid, and one of the necessary support technologies for the smart-grid. The main applications of various types of energy storage technologies are as follows:

1. Large-scale, long-term energy storage facilities, such as PHS and CAES, can be used for large-scale power grid peaking shaving and seasonal storage. The flow battery and thermal storage with the second large energy storage capacity, a large number of cycles, and long service life can be used as load levelling devices in the grid. While Hydrogen storage can be used to store surplus wind and solar energy to power fuel cell vehicles.

2. The SC, SMES, flywheel energy storage, sodium-sulfur batteries, and other high power density ESS are mainly operated in combination with large-scale RESs. They can quickly respond to surge power generation and stabilize the fluctuations from the RESs.

3. Lithium-based batteries, Lead-acid batteries, metal-air batteries, and other battery ESSs are less suitable for large-scale power plants and are mainly used for distributed residential energy storage applications and electric vehicles.

With the continuous innovation and development of new energy storage materials, it is expected to make significant breakthroughs in extending service life, increasing energy density, fast charging time, and reducing costs. Meanwhile, the deployment of ESS in large-scale power grids and/or microgrids is still facing significant challenges, and they shape the direction of research and development roadmap of energy storage technology, which contains three key areas:

1. To enhance energy storage performance and reliability, effective supply chain and fabrication processes to enable mass production, thus overall cost reduction;

2. Energy storage technology selection and performance optimization complementary technologies for specific applications;

3. Formalization of a systematic approach in evaluating energy storage technologies for different applications.
For traditional large-scale energy storage technologies, PHS, CAES, and TES, their main challenges are low roundtrip efficiency and higher implementation costs. The refinements of the PHS system are mainly focusing on upscaling the hydroelectric turbo-machinery, optimizing the operation efficiency via installing enhanced monitoring system and advanced intelligent energy management system. In addition to improvements in existing PHS technology, similar ideas are being actively studied such as seawater usage as a reservoir, tidal barrages, and Gravity Power Module Energy Storage (GPMES) [145]. The GPMES uses two different sized water shafts to store energy. The electricity is consumed to pump water in the smaller shaft and raises the position of a heavyweight piston of the more massive shaft. When the electricity is needed, the piston is set free, and the water flow rotates the turbine to generator power. Instead of large-scale CAES, researchers have developed mini-CAES and aboveground CAES to increase their usability in many applications and to overcome the dependency of the large-scale CAES on the geographical site selection [146]. Rapid development has been found in small-scale ground CAES as an alternative to electrochemical energy storage for the applications such as uninterrupted power supply or backup power supply.

For flywheel energy storage, the core development area should aim to investigate novel materials for the rotor, high performance and low-loss bearings, a robust control system and the cost of precision manufacturing processes. Currently, the strength composite fiber materials are applied in rotor fabrication, which may have significant improvements in rotation speed, storage capacity, power density, and reliability. The latest bearing technology is using the high-temperature superconductor, which significantly increases the efficiency. However, the high production cost, operational safety issues, and high self-discharge rate still limit its usage in long-term storage applications.

The research and development in SC mainly focus on enhancing the chemical capacitive materials to improve the lifespan and storage capability. The latest in SC development includes the use of carbon graphene-based electrodes and novel nanostructured materials that can significantly improve the SC surface area and therefore storage capacity [147], [148]. For SMES, the cost reduction of superconducting coils, the development of novel low cryogenically sensitive coil materials, and EMS optimization
should be the primary issues to be addressed in order to penetrate the market share in energy storage industry.

Electrochemical energy storages or battery technologies as one of the mainstream energy storages for stationary energy storage applications require technology breakthrough in enhancing the reliability and lifespan, electrode materials, fast charging and energy management system. Among the battery energy storage technologies, Lead-acid battery are still one of the most widely used energy storage technologies. For research and development of new-generation Lead-acid batteries, it should mainly focus on electrode materials for performance improvement, extending cycling times, enhancing the deep discharge capability as well as the recycling processes of electrode materials. At present, one of the advanced Lead-acid battery is developed by adding up to 40% of activated carbon to the negative electrode composition, wherein the cycle life is significantly increased by up to 2,000 times [149]–[151].

For lithium-based battery, many research works have been initiated on the innovation of electrode and electrolyte materials to increase their power capability, energy density and lifetime. The usage of graphene in replacing the conventional electrolyte materials has claimed to revolutionary improves the storage capacity and charging time. The graphene-based lithium battery is still on the early stage of research and development, but the superior characteristics of graphene have attracted attentions from researchers and industry [152].

NaS battery is a relatively mature technology and is often used for large-scale energy storage projects. However, the high temperature operating requirements and eliminating the corresponding limitations still need to be addressed [153]. The main limitations of flow battery are the capital cost associated with electrolyte sources, battery stack manufacture and high maintenance costs. The next generation of flow batteries could be the structure with hybrid redox fuel cells. Shortly, it is possible to apply in electric vehicles which makes it easier for electric vehicles to recharge energy by refueling [118]. The hydrogen energy storage technology is still in its early stages. It requires extensive testing and validation before it can be fully commercialized. The improvements in system power conversion efficiency, safe operation, low-cost
hydrogen production, storage, and transportation processes will become the leading research and development directions for future development [154].

In general, energy storage technology provides more flexibility and optimizes the power system operations. In the macro view of future energy storage deployment, the trend that forcing energy storage technologies to become a central element of the future power system will mainly depend on the penetration level of RES, the emergence of smart-grid development and the advancement in low-cost environment-friendly materials [155]–[157]. Thus its future development could mainly focus on the following areas.

Firstly, energy storage technology needs to achieve more grid integration to improve its safety, stability, high efficiency, and reliability. With ESS integration, power electronics, and information technologies, the electric grid is anticipated to transforming into the decentralized structure and achieving two-way interaction in every node in the power system including generation, transmission, distribution, and consumers’ end. This will eventually realize the upgrade to smart-grid and form the powerful internet-style global energy grid in the future [158], [159]. Secondly, the longevity and cost of ESS must be improved, while having both high power density and high energy density, to provide the auxiliary services such as backup energy, power smoothing and peak shaving for the renewable power systems that have intermittent and unpredictable output power. Multivariate hybrid ESS with complementary characteristics and its optimized supporting control system will become the enabler in achieving both high power and energy density requirements. Finally, energy storage will be more widely used in electric powered transportation systems such as electric vehicles, hybrid vehicles, electric-driven trains, drones, and aerospace applications, etc. [160]–[162]. This is the highest technical requirement for ESSs, and it usually requires them to have higher security, longer duration, shorter charging time, faster response, lighter and cheaper.

2.6 Conclusion

The potential applications of energy storage in modern power system and residential ESS are presented in this chapter. The desired characteristics of energy storage at a
different part of the power systems are discussed to ease the selection of energy storage for optimal performance and sustainability. The energy storage technologies in various forms were comprehensively reviewed and compared, including the electrical characteristics, storage capability, efficiency, and product features. The introduced energy storage technologies include CAES, FES, PHS SC, SMES, cell battery, flow battery, TES, and chemical energy storage. The comparative analysis of available energy storage technologies was carried out based on storage and electrical properties, strengths and limitations, technology maturity as well as the potential for future development. It can be concluded that the wide spectrum of technical characteristics of current ESS technologies can meet the requirements of different power system operations, with a suitable combination of different ESS technologies. Finally, this chapter also summarizes the limitations that exist in various types of energy storage technologies and the possible future development trends. The integration of ESS technologies in modern large-scale power system and residential applications are critical for providing flexibility and ancillary services in smart-grid to handle the increasing supply-demand challenges.
Chapter 3
Solar PV Technology and Energy Storage in Stand-alone Power System

3.1 Introduction

The global climate change caused by greenhouse effect has motivated the development of renewable energy based power system to replace the traditional fossil fuel energy [163]–[165]. Among various RES technologies, solar PV technology has become one of the most prominent and widely used technologies due to its modularity, ease of installation, matured technology, and low operating costs [166]. The modularity of solar panel allows large-scale centralized PV farm (up to 50MW) to be set up, and at the same time enables decentralized PV power system such as residential building and remote area electrification. The main disadvantages of PV power generation are: (1) the intermittency of output power due to clouds, and (2) variability due to the day-night cycles as well as seasonal variation. Therefore, the PV power systems, especially for the stand-alone systems, are generally equipped with ESS to ensure stable and reliable electricity. Over the past decades, ESSs have been widely used and indispensable in stand-alone solar PV power generation systems.

This chapter presents an overview of PV technology and its application in power systems, including the considerations of PV system design, solar irradiance measurement, load profile estimation and the selection of energy storage technology. A detailed discussion and analysis of the stand-alone PV-battery power systems will also be provided that contains an introduction to the system topology, the design of its ESS,
system modelling, numerical simulation and experimental demonstration based on a lab-scale prototype.

3.2 Overview of solar PV technology

3.2.1 Background of solar cell

Solar cell, also known as PV cell, is a solid state device that converts sunlight directly into electricity. The name of PV comes from the process of converting light (photons) into electricity (voltage), which is the so-called PV effect. The PV effect was discovered by French physicist, Becquerel, in 1839 and was first applied in silicon cell by Bell Laboratories until 1954. The silicon cell is soon gained applications in U.S space programs as the power system of earth-orbiting satellites owing to its high power-generating capacity per unit weight. The space applications inspired the solar cell development and continued to spread into varies applications ranging from powering rural villages to feeding national grids globally. Fig. 3.1 shows the classification of solar cell based on the material property [167]. The family of solar cells in different primary active materials are divided into silicon solar cell, multi-compound thin film solar cell, polymer solar cell, modified electrode layers, nano-crystalline solar cell, organic solar cell and other solar cells with novel materials.

![Fig. 3.1 Solar cell classification](image_url)

Table 3.1 summarizes the efficiency of relatively mature and dominant solar cells in the market. Mono-crystalline silicon solar cells have been widely used in the large-scale PV
power system. It possesses the highest conversion efficiency and performs significantly better compared to its counterparts under medium temperature zones such as the subtropical area [168]. Polycrystalline silicon PV cells have similar properties to monocrystalline silicon PV cells but suffer from higher temperature sensitivity, which reduces conversion efficiency. Although amorphous silicon PV cells are a cheaper option, conversion efficiency is lower, in the range of 5-7%.

<table>
<thead>
<tr>
<th>Solar cells</th>
<th>Efficiency</th>
<th>Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mono-crystalline Silicon</td>
<td>14-17%</td>
<td>Higher efficiency but higher price</td>
</tr>
<tr>
<td>Poly-crystalline Silicon</td>
<td>11-14%</td>
<td>Cheaper than mono-crystalline but less efficient</td>
</tr>
<tr>
<td>Amorphous Silicon (a-Si)</td>
<td>5-7%</td>
<td>Flexible shape, cheaper, but low efficiency</td>
</tr>
</tbody>
</table>

3.2.2 Solar cell model

In solid-state physics, solar cell works as a classical diode with P-N junction. The complex PV process in solar cell can be simplified as an equivalent electrical circuit model as shown in Fig. 3.2. The summation of the output current \( I \), the diode current \( I_D \) and the shunt-leakage current \( I_{SH} \) is equal to the photo-current \( I_L \). The series resistor \( R_S \) represents the internal resistance which depends on P-N junction characteristics such as depth, impurities and contact resistance. Due to the material imperfections of solar cell, there is leakage current at the edge of each solar cell and it is characterized by the shunt resistor \( R_{SH} \) and leakage current \( I_{SH} \). For an ideal solar cell, there is no series loss \( (R_S = 0) \) and no leakage current \( (R_{SH} = Infinity) \). The efficiency of solar cell is sensitive to \( R_S \) variation and therefore, minimizing the resistance from P-N junction is one of the research directions in solar cell to improve the conversion efficiency.

![Fig. 3.2 The equivalent circuit of solar cell](image-url)
The output current of solar cell is given by the following equation:

\[ I = I_L - I_d - I_{SH} \]  \hspace{1cm} (3.1)

The diode current \( I_d \) can be calculated by the classical diode current expression:

\[ I_d = I_D e^{\frac{QV_{oc}}{AKT}} - 1 \]  \hspace{1cm} (3.2)

Where

- \( I_D \) is the diode saturation current
- \( Q \) is the electron charge which equals to \( 1.6 \times 10^{-19} \text{C} \)
- \( A \) is the curve-fitting constant
- \( k \) is the Boltzmann constant which equals to \( 1.38 \times 10^{-23} \text{J/°K} \)
- \( T \) is the temperature in °K

The shunt leakage current \( I_{SH} \) is calculated by open-circuit voltage \( V_{oc} \) and shut resistance,

\[ I_{SH} = \frac{V_{oc}}{R_{SH}} \]  \hspace{1cm} (3.3)

Where \( V_{oc} \) is obtained when there is zero load. Thus the load current is given by the expression:

\[ I = I_L - I_D e^{\frac{QV_{oc}}{AKT}} - 1 - \frac{V_{oc}}{R_{SH}} \]  \hspace{1cm} (3.4)

The electrical characteristics of solar cell can be graphically represented by the current versus voltage (I-V) curve and power versus voltage (P-V) curve, as shown in Fig. 3.3. On the vertical axis, the highest current in I-V curve occurs at zero voltage when the output terminals are connected. This is called the short-circuit current \( I_{sc} \). On the horizontal axis, the highest terminal voltage occurs when no load is connected, which is called the open-circuit voltage \( V_{oc} \). These two parameters are usually given on the solar cell datasheet. The Maximum Power Point (MPP) occurs at the knee point on the I-V curve (marked in red circle). The I-V curve in one solar cell will vary based on the sun irradiation.
Fig. 3.3 The I-V and P-V characteristics of the solar cell

Fig. 3.4 illustrates the different I-V curves of typical solar panel. It can be observed that the knee points of the I-V curves are shifting to the right and the corresponding MPP on P-V curves increases as the sun irradiation increases. Therefore, keeping the solar cell to generate electricity at MPP continually can significantly increase the overall power efficiency. There are many MPP tracking algorithms available nowadays to maximize the efficiency of solar PV power systems.

Array type: SunPower SPR-305-WHT; 2 series modules; 2 parallel strings

Fig. 3.4 V-I and P-V curves in different intensity
A single solar cell typically produces 1W of power with approximately 0.5 volts. A number of them are interconnected in series and/or parallel to generate the appropriate voltage and current levels that can be integrated to the power systems. The PV module is formed by solar cells that are typically sealed in a protective laminate as depicted in Fig. 3.5. The PV modules are then assembled as a PV panel to achieve the desired voltage and power. In a large-scale PV power system, PV panels as the fundamental unit are connected to form PV array in order to generate the desired power generation capacity. The flexibility and modularity of solar PV allows different size of PV power systems to be implemented, ranging from large-scale solar farm down to residential PV power system.

### 3.2.3 Overview of the PV power system

The typical PV power system consists of core components such as PV array, charge controller, ESS, power inverter and loads. Modern PV power system also includes smart meters, AC/DC isolator, sensors, and monitoring systems to ensure system reliability and performance optimization. In order to achieve specific goals from powering basic electrical appliances to feeding electricity to the national grid, the PV power system can be designed in many different topologies. PV power system can be configured either as a grid-connected PV system or stand-alone PV power system, with and without ESS and/or other distributed generation sources, as categorized in Fig. 3.6. Grid-connected PV power systems operate as distributed generation networks that are interconnected with the utility grid. It uses power electronic inverters, or Power Conditioning Unit...
(PCU), to convert the DC power produced by the solar cells into AC power that are synchronized with grid voltage and frequency. With ESS integrated, grid-connected PV power systems can operate in either grid-connected mode or islanded mode based on the real-time generation-demand conditions.

Conversely, stand-alone PV power system, or off-grid PV power system, is designed to operate autonomously and independently that are generally used to supply electricity in isolated or remote areas. The simplest and primitive form of the off-grid PV power system is the direct-coupled system, where the PV panel is directly connected to a DC load, and it usually is in small power capacity. Since there is no energy storage in the system, it only operates when sunlight is available and commonly applied in ventilation fans, water pumping system for agriculture, etc. A complete stand-alone PV power system contains PV panels, charge controller, power inverter, ESS and loads. Stand-alone PV power systems are widely used for rural electrification, especially in remote rural areas where grid connection is not economically viable. Hybrid PV power system is one of the solutions to compensate for the variability of PV generation, where other distributed generations such as diesel generator, wind power generator, and mini-hydro generator are integrated.

**Fig. 3.6 The classification of PV power system**
Chapter 3  Solar PV Technology and Energy Storage in Stand-alone Power System

3.3 Stand-alone PV power system

Reliable and affordable electricity is of crucial importance to ensure the quality of life. However, according to the International Energy Agency (IEA), in 2015, nearly 1.3 billion people are not connected to the utility grid, and over 95% of them live in the developing countries or remote rural areas [169]. Off-grid rural communities are generally geographical dispersal, decentralized, low population density and geographically isolated from the national grid. Due to the resource and financial constraints, it is difficult to extend the national grid to these areas through the conventional power transmission and distribution approach. Thus, a typical solution to provide electricity to the remote and inaccessible area is achieved by using petrol/diesel generators which have low initial costs but high running costs, and most importantly, not environmental friendly. Therefore, using renewable energy based power system in these areas is one of the practical solutions that will bring significant benefits to the communities, especially in reducing dependence on the expensive petrol/diesel fuel and the difficulty in transporting them. Solar PV is one of the preferred choices of RES for remote rural electrification due to its excellent properties such as modular, easy to install, eco-friendly, and low operating cost [170].

3.3.1 Components and system structure

A typical configuration of stand-alone PV power system is illustrated in Fig. 3.7. It consists of PV arrays, charge controller, energy storage, power inverter and loads. The charge controller with Maximum Power Point Tracking (MPPT) or the one without will...
regulate and control the charging process from the PV arrays to energy storage [171]. In most cases, a DC/AC power inverter is needed to convert the DC power of ESS to AC electricity to power up basic electrical appliances such as lighting, television, washing machines, freezers, etc. In addition, energy storage devices are needed because of the intermittent nature of the PV output and changeable load demand. It acts as an intermediate energy buffer compensating the generation-demand mismatch.

To design an effective stand-alone PV power system, engineers need to carry out the on-site assessment. For example, solar irradiance measurement, user behaviour, electricity consumption estimation, topographical and meteorological constraints. Alongside these aspects, the social acceptance, maintenance requirement, and environmental impacts also need to be taken into consideration before installing PV power systems.

3.3.2 Solar power generation

Solar irradiance refers to the electromagnetic radiation that reaches the earth surface after being absorbed, scattered, and reflected by the atmosphere in power per unit area. The daily solar irradiance profile (sun hours) is the key parameter that determines the total output power of the PV panels, and it is used to calculate the photo-current generated from PV panels, as shown in Eq. (3.5) [172]:

\[
I_L = I_{scr} \frac{G}{G_R} [1 + \alpha_T (T_c - T_{cr})]
\]  

(3.5)

where \(G_R\) and \(G\) are the reference solar irradiation and real-time solar irradiation; \(T_{cr}\) and \(T_c\) is the reference solar cell temperature and real-time solar cell temperature; \(I_{scr}\) is the solar cell short circuit current at \(G_R\) and \(T_{cr}\); \(\alpha_T\) is temperature coefficient of photo current. In the case where the ambient temperature variation is relatively small, the real-time output current of the PV panel can be approximated from the solar radiation.

In order to evaluate and design a sustainable PV power system, it is necessary to understand the availability and quality of solar irradiance at the targeted site. Sarawak is the largest state in Malaysia with the total land area of 124,450 km\(^2\), with a daily average of ambient temperature of 26.14 °C and 12 hours average sunlight throughout
the years [173], [174]. The tropical climate with mostly cloudy weather condition provides average daily sun hours of about 4 to 5 hours. In most cases, the solar input fluctuates due to the shelter of clouds. Fig. 3.8 illustrates a 7-day solar radiation profile collected in Kuching, Sarawak, Malaysia.

![Fig. 3.8 The 7-day solar irradiance in Kuching, Sarawak, Malaysia](image)

### 3.3.3 Load demand estimation

In order to design a cost-effective off-grid residential PV power system, an accurate estimation of the load profile is vital to ensure that the system can generate sufficient energy and to prevent short battery cycling. Fig. 3.9 depicts a simple load profile estimation method used in this work. This method is based on the demographics of local households, the quantity, and characteristics of household appliances and users’ behaviour on daily energy consumption.

Firstly, a site survey was conducted to collect basic information about the population in the community, living area, public space, daily work routines and behaviours, and the types of electrical appliances. These appliances include lighting, television, refrigerator, electric fan, and consumer electronic devices. The characteristics and usage frequency of each electrical appliance are recorded during the site assessments. Secondly, aggregate the collected information into a checklist, and assign values to each item using the appropriate data. The estimated load curve will then be formed by the sum of
the values of both items. Finally, add a degree of redundancy to the results to form the final load profile estimation.

Fig. 3.9 Assessment of load profile for a non-electrified rural community

Fig. 3.10 illustrates an example of the estimated load profile for a rural community, Batang-Ai (1°14’20.5”N, 112°02’10.7”E), in the inner part of Sarawak using the abovementioned method. The target site has 6 households. It is noticed that peak energy demand occurs during noon time (between 11 AM to 2 PM) and night time (between 7 PM to 10 PM). This is because most of the power-demanding activities such as cooking and entertainment are scheduled during these times. The estimated total load demand per day is around 15kWh.

Fig. 3.10 Estimated load profiles of the target rural site in Sarawak, Malaysia
A 2kW stand-alone PV-battery-genset hybrid power system was designed and installed at the targeted site during this research work (Appendix 1). The actual load profiles were measured as shown in Fig. 3.11, and it demonstrates very similar electricity usage pattern as the one estimated using the abovementioned method.

![Actual load profiles of the target rural site in Sarawak, Malaysia](image)

3.4 Energy storage in stand-alone PV power system

ESS is the key component in stand-alone PV power system to balance the generation-demand mismatch [175]. It absorbs excess energy generated by solar panels during the off-peak period and supplies energy when PV generation is insufficient during peak time or night time. The selection and design of ESS in stand-alone PV power system is essential as it is one of the major cost components in a typical installation.

3.4.1 Discussion about the selection of ESS

As discussed in Chapter 2, no single energy storage technology can have all the desired features to fulfill the criteria in any specific application scenarios. The determination for selecting an appropriate energy storage product normally requires a series of trade-offs and considerations. Thus the selection of suitable energy storage device for stand-alone PV power system in remote areas normally needs to consider the following criteria: capacity, efficiency, availability and cost, stability, and lifespan. Ideally, in remote applications, energy storage device with small size, high efficiency, fast response,
mature technology, good stability, longevity, clean and low maintenance cost will be the preferred choice. Based on the analysis in Table 2.3, SMES and SC have relatively high efficiency, fast response, clean, and longevity, but their energy density is low and with high self-discharge rate. In addition, SMES is a relatively new technology and extremely expensive due to superconductive wiring coil usage.

On the other hand, the voltage and capacity of a single SC are minimal, and it usually requires a lot of them to connect in series and in parallel to reach the rated voltage and rated capacity. Therefore, the entire system requires power electronic converters as the controller to maintain the voltage balance and manage the power flow, which increases the complexity. Thus, neither SMES nor SC is suitable as the primary energy storage in this application. Similarly, in the hydrogen and flywheel energy storage, the issues of relatively high cost, immature technology, high self-discharge rate (Flywheel), and the difficulty in transporting the hydrogen to remote areas make them unsuitable for remote off-grid applications.

Among all ESS technologies discussed above, electrochemical energy storage turns out to be the most appropriate ESS for stand-alone PV power system. Firstly, the fluctuating and unpredictable nature of the PV output cannot allow the nickel-based battery to operate effectively without losing its capacity due to memory effects. Thus Nickel-based battery also is not suitable in PV power system. While NaS battery and flow battery provide robust lifespan and relatively low cost, but NaS battery requires high maintenance and complicated system to ensure to the high-temperature operating environment. Flow battery and metal-air battery are still under research and development stage.

Till now, the Lead-acid battery and Lithium-ion battery are the two remaining ESS options. They are both suitable for the remote applications, but Lithium-ion battery is thermally less stable than the Lead-acid battery (safety reason) and higher initial cost, which needs reliable SoC monitoring and control to avoid overcharging. Conversely, the Lead-acid battery is much stable (electrically and thermally) and robust. Thus, the Lead-acid battery is chosen as the most suitable energy storage technology for stand-alone PV energy system as its ESS.
3.4.2 Lead-acid battery and its stress factors

In a stand-alone PV-battery power system, the battery bank is often one of the most expensive components regarding initial cost and operating cost [176]–[178]. This is because the aging mechanism of Lead-acid batteries results from various stress factors caused by the intrinsic characteristics of charging and discharging processes. The life-limiting factors in the Lead-acid battery are listed below [95], [179]–[181]:

1. Prolonged low SoC;
2. Overcharging;
3. High operating temperature;
4. Frequent deep or full discharge, high depth of discharge;
5. Charging/discharging with a high C-rate;
6. Frequent charge-discharge transitions;
7. Partial cycling in low SoC.

Most of these life-limiting factors are closely related to SoC, which is the amount of remaining available energy in the battery and expressed as a percentage of rated energy [182], [183].

\[
Pb + 2H_2SO_4 + PbO_2 \xrightarrow{\text{Discharging}} PbSO_4 + 2H_2O + PbSO_4
\]

**Fig. 3.12** Electrochemical reaction of the Lead-acid battery

Fig. 3.12 shows the electrochemical reaction in a typical Lead-acid battery [180]. During the discharging process, sponge lead (\(Pb\)) is converted to lead sulfate (\(PbSO_4\)) on the negative plate and generate electrons simultaneously. The lead dioxide (\(PbO_2\)) is converted into \(PbSO_4\) on the positive plate and sulfuric acid (\(H_2SO_4\)) is consumed in the electrolyte. The \(PbSO_4\) in the process of becoming the \(PbSO_4\) will cause an increase of the battery volume. While during the charging process, the \(PbSO_4\) is converted back to
\( PbO_2 \) again, and the battery volume will shrink. When the battery undergoes repeatedly shrinkage and expansion, the inter-bonding between the \( PbO_2 \) particles will be gradually loosened, and eventually leading to shortened battery life. If the DoD can be reduced, the degree of such shrinkage and expansion will be significantly reduced, and the binding force between the lead dioxide particles will continue to be maintained, thus increasing the lifetime of the battery [184].

Another stress factor that accelerates the performance deterioration of the Lead-acid battery is the Charge and Discharge Rate (C-rate). High C-rate will cause the removal of active materials on the plate and reduces the battery rated capacity and lifetime [185]. In Fig. 3.13, the relation of the C-rate, DoD, battery rated capacity and lifecycles are presented [186], [187]. The graphs show that the performance and cycle life of Lead-acid battery be improved by carefully controlling the DoD and C-rate. Therefore, mitigating the stress factors can effectively prolong the service life of the Lead-acid battery.

![Image](image_url)

**Fig. 3.13** The curves of the Lead-acid battery healthy and stress factors

### 3.5 Case study of stand-alone PV-Battery power system

A Matlab Simulink model of a 5 kW stand-alone PV-battery power system is developed as shown in Fig. 3.14. Actual solar irradiance data recorded on typical sunny days and partially cloudy days were used to simulate PV power generation. While the estimated load profile (as shown in Fig. 3.10) is considered in the simulation and analysis.
Fig. 3.14 Matlab Simulink model of stand-alone PV-Lead-acid battery system

Fig. 3.15 Simulation current of stand-alone PV-battery power system (sunny)

Fig. 3.16 Simulation current of stand-alone PV-battery power system (cloudy)
The net power flow to and from the battery bank is illustrated in Fig. 3.15 (for sunny day condition) and Fig. 3.16 (for partly cloudy day condition). The Lead-acid battery bank (4000Ah) absorbs or supplies the net difference between the PV output and the load demand. When its current is negative, the Lead-acid battery will be charged and being discharged when net current is positive. as can be observed from the battery current profiles, severe fluctuations occur during day time where PV generation is available, even during sunny day condition.

3.5.1 Scaled prototype of stand-alone PV power system

A down-scaled prototype of stand-alone PV-battery power system was constructed to demonstrate the operating characteristics of the Lead-acid battery experimentally. The voltage on the DC bus is 12V, and the capacity of the Lead-acid battery is 30Ah. A typical commercial charge controller is used to regulate the charging process from PV to the Lead-acid battery. The experimental results in Fig. 3.17 demonstrate the battery current profiles measured during partly cloudy weather at Swinburne University Sarawak Campus, Kuching, Malaysia. The PV output current changes abruptly and fluctuates randomly. The Lead-acid battery starts to charge at around 7:00 a.m. and discharge at around 4:00 PM.
In Fig. 3.18, the 2 hours operating current can indicate that the battery closely follows the net difference in PV and load currents. There are rapid charge/discharge conditions, from -1.5A to 1.5A, as well as high current charging or discharging requirements, which has a significant adverse effect on battery life.

![Fig. 3.18 Experimental testing of stand-alone PV-battery power system (2 hours)](image)

3.5.2 The concept of SC/Lead-acid battery HESS

In stand-alone PV power system, the Lead-acid battery has to continuously charge and discharge based on the fluctuating power requirement as a result of solar intermittency and load variability. This highly dynamic charge/discharge processes are putting heavy operation stress on the battery bank, thus accelerating performance deterioration and aging process. Over the past decades, Battery-SC hybrid ESSs has been proposed by many researchers for mitigating charge-discharge stress on the Lead-acid [188]–[190].

SC as an energy storage device with excellent power density, fast response time and most importantly long cycle life, has turned out to be a great complementary energy storage device to compensate the limitations of the electrochemical battery bank. The primary idea of Battery-SC hybrid ESS is to allow the SC to absorb/supply the dynamic power exchange while letting the primary battery bank in responding to the average
power demand. Although the concept of HESS sounds promising, special consideration must be taken into accounts such as topology design, control system, and energy management strategy. The next chapter will introduce the Battery-SC HESS in details.

3.6 Conclusion

This chapter introduced solar cell technology and PV power generation systems, including literature review, working principles, classification, and typical system architecture. In rural electrification, stand-alone PV power systems have been widely installed and applied. This chapter provided an overview and discussion of system design, solar irradiance measurement, load estimation methods, system modelling, and analysis. Based on the energy storage technology discussed in Chapter 2, the selection of energy storage technology in the stand-alone PV power system is critically discussed and concluded that the Lead-acid battery is still one of the most suitable ESS for remote applications.
Chapter 4
Study on Battery-SC HESS: Topology, Control Strategy, and Application

4.1 Introduction

Lead-acid battery as one of the mainstream energy storage devices used in stand-alone PV power system suffers from short service life, despite the excellent electrical characteristics and lower initial cost. The ESS acts as an intermediate buffer to absorb excess energy and supply the stored energy when the power deficit. In addition, it also plays a vital role in regulating instantaneous power variations, power quality, and system reliability. Especially for a stand-alone PV power system, it relies heavily on energy storage to balance the unmatched generation and power consumption profiles [191]–[193]. For example, surge demand power to start motors in appliances can be 7 to 10 times larger than normal operation current [194], and the PV output fluctuates dynamically due to cloud shelter on PV arrays. The fluctuating and variable power flow could potentially accelerate the aging process of the Lead-acid battery. Thus, without proper control, the Lead-acid battery normally can only last 3-5 years which leads to higher operating cost [195]. Therefore, effectively prolonging the service life of Lead-acid battery bank will have a significant economic impact on the market of the off-grid PV power system.

Hybridization of different ESS technologies turns out to be one of the promising ways to mitigate the battery charge-discharge stress by directing the short term power fluctuation to another form of ESS such as the SC [196]–[198]. The SC stores electricity
via electrons in the static electric field and possesses high power density, has short charging-discharging time, and nearly unlimited cycle life. The battery and SC combination has been considered in most HESS developments because of their availability, similarity in working principle, relatively low cost and most importantly. They complement each other’s limitations very effectively. Recently, the development of Battery-SC HESS for residential energy storage applications is beginning to generate positive outcomes, and it typically is connected to the power system via AC or DC coupling [199]–[204]. Power electronic converters are used to control the power flow among different ESS elements [205]–[207]. Depending on the complexity of the control strategies, the use of power converters and microcontrollers can be costly [208]. Hence, the trade-off between economic feasibility and technical advantages exist, and it is crucial in determining the financial and technical sustainability of the system.

Various Battery-SC HESS topologies had been proposed in microgrid applications aiming to optimally utilize the benefits of different ESS elements [209], [210]. Besides having correct HESS topology and appropriate sizing, energy management and control strategy of HESS is another key to improve system efficiency, maximize energy throughput and prolong the lifetime of HESS [211]–[213]. This chapter presents a comprehensive review and discussion of Battery-SC HESS, including their system topologies design, electrical characteristics, energy management system, control algorithms and applications in stand-alone PV power system.

4.2 Battery-SC HESS topologies

In Battery-SC HESS, the two ESS elements can be coupled to either a common DC or AC bus. For stand-alone microgrid, common DC bus is the preferred choice due to various reasons [214], [215]. First, most ESS elements and RES based generators operate in DC voltage. Therefore, maintaining a DC bus minimizes the needs of power converter [216]. Second, DC bus does not require synchronization which greatly reduces the complexity of the overall system [217], [218]. As a result, DC coupling is more efficient and lower cost than equivalent AC bus systems [219]–[222]. In general, the topologies of the Battery-SC HESS can be classified based on the interfacing approach, as shown in Fig. 4.1. For passive connection, the terminals of energy storage
are directly connected to the DC bus for which the power-sharing mechanism and response is purely determined by the electrical characteristic of the energy storage devices. On the other hand, active HESS topologies employ active components such as bi-directional DC/DC power converter to interface the energy storage elements from DC bus and to actively control their power flow.

4.2.1 Passive Battery-SC HESS

The passive connection of battery and SC modules to DC bus offers the simplest and cheapest form of HESS [223]. It has been reported to effectively suppress transient current under pulse load conditions, increase the peak power and reduce internal losses [224]–[226].

As shown in Fig. 4.2, the battery and SC are connected to the DC bus directly, thus sharing the same terminal voltage. The DC bus voltage is purely depending on the battery SoC, and therefore it is highly influenced by the charge-discharge characteristic
of the battery. In some rural microgrid applications, the battery capacity is sized up to five days as a reserve without any external source of energy [227]. Consequently, most of the time the battery will be cycled with relatively low DoD and charged/discharged in a relatively low C-rate. As a result, the fluctuation in DC bus voltage will be minimal, ensuring a relatively stable system voltage.

However, the system current will be drawn from or feed into the battery and SC based on their respective internal resistances. Therefore, the transient power handling capability of the SC is not optimally utilized. In addition, as the voltage variation of the battery terminal is small, the SC will not be operating at its full SoC range which results in poor volumetric efficiency [228].

### 4.2.2 Semi-Active Battery-SC HESS

To make better use of the ESS elements in Passive HESS, power electronic converters are included between the ESS elements and DC bus. This allows the power flow to be actively controlled [229]. In Semi-Active HESS topology, only one of the two energy storage elements is actively controlled as illustrated in Fig. 4.3.

![Semi-Active HESS topologies](image)

Fig. 4.3(a) shows the SC Semi-Active HESS topology where the SC is connected to the DC bus through a bidirectional DC/DC converter and the battery is directly connected to the DC bus [230]. In this topology, the bidirectional DC/DC converter isolates the SC
from the DC bus and battery terminal. In this setting, the SC can be operated within a wider range of voltages, which significantly improves the volumetric efficiency. The direct connection of the battery also ensures stable DC bus voltage [231]. However, the passive connection of the battery inevitably exposes the battery to fluctuating charge/discharge current that has a negative effect on battery lifetime [232].

Conversely, the battery is interfaced by a DC/DC converter, while the SC is directly connected to DC Bus in the battery Semi-Active HESS configuration as shown in Fig. 4.3(b) [199], [233]–[235]. Unlike passive and SC Semi-Active HESS topologies, the battery current can be controlled at a relatively gentler manner regardless of the fluctuation in the power demand. The battery terminal voltage is not required to match the DC bus voltage, allowing flexible and efficient sizing and configuration of battery bank. However, the volumetric efficiency of the SC is low. The linear charge/discharge characteristic of the SC also causes large variation in the DC bus, which may result in poor power quality and system stability. To maintain a relatively stable DC bus voltage, the capacity of SC must be extremely large, which leads to high cost.

4.2.3 Full Active Battery-SC HESS

In Full-Active Battery-SC HESS topologies, the power flow of battery and SC are both actively controlled via bidirectional DC/DC converters. This enhances the flexibility of the HESS and improves the overall system performance and cycle life. Fig. 4.4 shows two of the most common Full-Active HESS topologies, namely parallel active HESS and cascaded active HESS. In Parallel Full-Active HESS, both battery and SC are isolated from the DC bus by bidirectional DC/DC converters, as shown in Fig. 4.4(a). It is one of the most common topologies in grid-scale storage applications, allowing full control of both energy storage elements [194], [236]–[238]. With this topology, the performance, battery life, and DC bus stability can be improved through a carefully designed control strategy [239]. For instance, the battery, as a high energy density ESS, can be programmed to meet the low-frequency power exchanges. The SC can be programmed to respond to the high-frequency power surges and regulate the DC bus voltage. The decoupling of battery and SC allows both ESS elements to operate at a wider range of SoC that can greatly improve the volumetric efficiency of the HESS.
In cascaded active HESS topology, two bidirectional DC/DC converters are cascaded to isolate the battery and SC from the DC bus, as illustrated in the Fig. 4.4(b) [240]. The bidirectional DC/DC converter that isolates the battery is normally current controlled to provide smooth power exchange with the battery. This releases the battery from harsh charge/discharge process due to the intermittency of renewable power generation and load. The bidirectional DC/DC converter that isolates the SC from the DC bus is normally voltage controlled to regulate the DC bus voltage while absorbing the high-frequency power exchanges [241]. Since the SC has wide operating voltage, a large voltage swing between the SC and DC bus is expected. As a result, the power losses in the DC/DC converter will be higher as it is difficult to maintain efficiency across a wide range of operating voltages.

### 4.2.4 Multi-level Battery-SC HESS

In Fig. 4.5, assuming a basic module includes either or both batteries and SC with/without DC/DC converters, hybridization beyond two energy storage modules can be configured in different combinations of passive, active, cascaded and/or parallel with unique power management system and control strategy.
The SC or battery can be modularized into a different voltage or power levels and performs a good adaptability to different system requirements. This enables a more flexible HESS in terms of system configuration and the adaptability to more sophisticated energy control algorithms for broader power and energy applications. As the number of power converters increases, the overall coulombic efficiency of the HESS will decrease due to losses from the switches among the MOSFET devices. The performance of full active HESS system is also extremely reliant on the reliability of the DC/DC converters and their control system.

4.3 Energy management system (EMS)

4.3.1 Overview of EMS

Although the hybridization of battery and SC with different characteristics have great potential in complementing the lifetime limitations of Lead-acid battery in stand-alone PV power system, it creates energy management and control problems. Especially for HESS with actively controlled DC/DC converter(s), a properly designed EMS is the key to ensuring harmonized operation while achieving the objectives and control goals of HESS implementation. As shown in Fig. 4.6, a complete EMS may include long-term
energy management, medium-term energy management, and real-time energy management. In the long-term energy management (beyond 24 hours), information such as weather conditions, load demand status, and battery SoC are collected and analyzed in order to generate reference control signals for the medium-term controller. Then the medium-term EMS will focus on monitoring hourly parameter variations and operation mode selection, as well as generating reference signals for a low-level control system for DC/DC converters.

Generally, the objectives of HESS implementation in stand-alone microgrid can be grouped into three main categories: (i) optimizing system performance, (ii) enhancing system reliability and (iii) lowering set-up and operating cost. Fig. 4.7 summarises the objectives. Active HESS topology enables each ESS elements to be optimized through an EMS.
The role of EMS is to maximize the benefits of HESS. Volumetric and coulombic efficiencies have to be maximized while maintaining system stability and power quality at the DC bus. In terms of system reliability, EMS must ensure robust system operation in all possible loading conditions, protect the ESSs from extreme conditions and extend the useful lifetime of the ESS elements. EMS also needs to ensure that cost of implementation, operation and maintenance are kept low. For instance, scheduling of diesel generator and load can be integrated into the EMS to lower the operating cost.

### 4.3.2 The design considerations of EMS

Fig. 4.8 depicts a typical EMS structure for a Battery-SC HESS in microgrid applications [242]. In general, the EMS can be divided into two levels: (i) the low-level control system regulates the DC bus voltage and controls the current flowing in and out of ESS elements based on the reference signal generated by the high-level control system. (ii) The high-level control system performs the power allocation strategy, SoC monitoring and control, and other sophisticated energy management strategies to achieve the set control goals.

*Zhou et al.* adopted the parallel active topology and proposed a modular HESS scheme that splits the single battery bank into multiple smaller battery modules [243]. The SC module and battery bank modules are interfaced to DC bus using dual-active-bridge bidirectional DC/DC converters. The authors employed a linear filtering approach to remove high-frequency power fluctuations and distribute the smooth power demands to each battery modules based on their SoC level. The SC module will respond to the high-
frequency power exchange through cascaded inner current control loop and outer voltage control loop. A simple SoC management scheme for SC module is implemented where the battery modules will charge the SC when the SoC level is lower than a pre-set threshold. The EMS mainly focuses on balancing the charge/discharge current among different battery modules. However, it does not consider the impacts of battery SoC variation in long-term operation, which may affect the system stability and longevity of the battery. Moreover, the proposed modular HESS topology requires a large number of DC/DC converters, leading to a significant increase in power loss and set-up cost.

To address the issue of high charge/discharge rate and possible response delay of the DC/DC converter, Kollimalla et. al. adopted the linear filtering approach to decompose...

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**Fig. 4.8 Typical EMS for stand-alone PV power system with parallel active HESS**
the power demand into high-frequency and low-frequency components and added a rate limiter to prevent the battery from being damaged by the high charge/discharge rate [194]. An additional compensator is implemented to compensate the slow response of battery charge/discharge. The proposed EMS mainly focuses on regulating the DC bus voltage and mitigating battery stress by limiting the battery current. The technique assumes that all ESS elements work within the acceptable limits throughout the operation. It does not take into consideration the SoC control of the battery. This may cause the battery to experience deep discharge under extreme conditions, which may lead to shorter battery lifetime.

Choi et al. presented an EMS scheme in Battery-SC HESS to achieve two objectives: (1) to minimize the energy loss due to SC internal resistance and (2) to mitigate the fluctuations of current flowing in/out of the battery pack [30]. The author mathematically formulated the two objectives in order to obtain the optimal solution to control the current flow in each ESS elements. The two objectives were formulated into convex optimization problems, which are norm approximation and penalty function approximation, respectively. The two problems are then combined into a single multi-objectives function. In order to obtain the optimal solution, boundary parameters were determined through multiplicative-increase-additive-decrease principle. The values of the boundary parameters critically determine the feasibility and optimality of the solution. This control strategy only considers the characteristics of ESS elements. It does not consider the interactions between the elements and other components within the microgrid. Thus, the resulting optimal EMS scheme tends to be for one particular system only.

The above EMS strategies for HESS mainly focus on solving the short-term power demand variations and power-sharing between SC and battery. However, the impact of SoC drift in the battery is not addressed. Specifically, in a microgrid, seasonal variations in renewable energy generation and load demand must be carefully addressed to ensure reliable operation in all possible loading conditions. To accurately monitor the battery SoC and address its long-term variations, Xue et al. proposed an actively controlled, parallel connected Battery-SC HESS in PV power system that employs a multimode fuzzy-logic power allocator to address the mismatch between supply and demand [244].
Based on the SoC conditions of battery and SC, the fuzzy-logic controller selects the appropriate operating mode to allocate the demand power to the energy storage devices. To avoid overcharging or discharging the energy storage, the controller allows the power exchange between the battery and SC and their individual power contribution to be optimally adjusted. The EMS control strategy guarantees all energy storage devices operate within their safe operating range and compensates transient mismatches between power generation and load demand.

Most EMS relies on a centralized controller to manage the power flow among different ESS elements and DC bus. Therefore, a robust communication link between components is needed. A disruption in the communication link will lead to catastrophic system failure. A hierarchical controller for HESS was proposed in [212] to address this risk. In the normal operating mode, the centralized controller allocates power to ESS modules based on their ramp rate. ESS with the highest ramp rate usually is assigned to regulate bus voltage. In the situation where the centralized controller fails, distributed control at individual ESS elements will be activated to ensure power system continuous operation.

4.3.3 Advanced algorithm in EMS

Due to the complex and non-linear characteristics of battery and SC during the charging/discharging operation, simple power allocation method such as linear filtering may not be sufficient to effectively allocate the power demand among the energy storage elements in HESS. Therefore, advanced supervisory control algorithms for EMS have been developed. A number of different intelligent and sophisticated control algorithms, such as deterministic rule-based strategy, fuzzy logic control, linear programming, genetic algorithms, dynamic programming, neural network, self-adaptive algorithms, etc. have been reported in the literature [155], [245]–[247]. Fig. 4.9 illustrates an overview of the classification of existing EMS algorithms in HESS. The EMS algorithms are generally categorized into two main classes which are rule-based approaches and optimization-based approaches [248]–[250].
(1) Rules-Based Approach

Rule-based approach controls the power exchange of HESS based on rules that are derived from mathematical models and experiences [251]–[253]. The rule-based approach is an effective method for real-time energy management widely used in HESS applications. In thermostat control strategy, the battery operates with constant power at its optimal efficiency point, and it will be turned on or off according to the lower and upper SoC limits. In power follower control strategy, the battery is set as the primary energy storage, and the EMS will adjust the battery charge/ discharge power that follows the power demand. As a secondary ESS, the SC covers the difference between the power demand and battery response.

Unlike thermostat and power follower control strategy, the state machine control strategy uses multiple rules to control the power flow in HESS. The pre-defined rules can be designed based on the allowable upper and lower SoC limits of SC and battery, maximum charge and discharge rates, load and generation powers, etc. Based on the real-time operational states of the HESS, power generation and power demand, the algorithm selects the appropriate operation mode to optimize the power distribution between SC and battery.
The deterministic rule-based control strategies are widely adopted due to its simplicity, less computationally intensive and great reliability [251], [254]–[257]. However, the rules are generally designed based on the initial state of the ESS elements. This may not accurately reflect the actual conditions of the elements in the long run. Therefore, the fuzzy logic control strategy as shown in Fig. 4.10 is introduced. Similar to the deterministic approaches, the rules in fuzzy control are also pre-defined based on mathematical model and empirical data. The transition between different rules is determined by the fuzzy-rules and membership functions which results in smoother, more flexible and logical operation compared with deterministic rule-based approaches [244], [258]–[260]. Fuzzy rule-based control algorithms can be integrated with other intelligent algorithms to form a hybrid control strategy which further improves the performance of EMS in HESS [236], [261]–[263].

![Fuzzy logic flowchart](image)

**Fig. 4.10 Fuzzy logic flowchart**

(2) Optimization-Based Approach

Optimisation-based EMS employs modern optimization algorithms, such as linear programming (if the system is convex and could be mathematically represented via a set
of linear functions), dynamic programming (both deterministic and stochastic), evolutionary methods such as genetic algorithm, simulated annealing, and particle swarm optimisation [264]–[269]. These algorithms can be classified into global optimization (offline) and real-time optimization (on-line). Unlike the rule-based approaches, modern optimization algorithms and their associated optimization processes are often sophisticated that require heavy computation capability [248]. In genetic algorithms, optimal power allocation in HESS can be achieved by analyzing the genetic processes as shown in Fig. 4.11. Based on the pre-defined fitness functions, the determined percentage and mutation rate, the genetic algorithms controller will iteratively search for optimal solutions until the number of iteration exceeds the pre-set values.

![Genetic algorithm flowchart](image)

Linear programming optimization approach is commonly used for systems that are convex and could be mathematically represented via a set of linear functions. Conversely, dynamic programming employs multiple iteration loops that are designed...
to execute the backward iteration from time step N to 1, as shown in Fig. 4.12 [252]. Every loop is employed to calculate the corresponding value as shown in the flowchart. The cost-to-go function will be updated at each time step, and the iterative processes will end when optimal solution of the objective function is obtained. One computation cycle will generate one state, and the whole process can be called state iterations. Finally, the dynamic programming approach will generate a look-up table that contains the optimal decision variable at each state. In general, trade-offs in technical requirements and economic feasibility need to be carefully considered in the design and development of HESS control algorithms. Advanced EMS can provide high power quality and improve system stability. However, system complexity and hardware requirements will add to the overall system cost.

![Fig. 4.12 Dynamic programming flowchart](image)

### 4.4 Analysis and discussion

There are varieties of HESS topologies and the associated energy management and control strategies used in the microgrid applications aiming to improve the system
operation from multiple aspects. However, there is no single unique HESS solution suitable for all microgrid applications. To determine an ideal HESS design and control strategy, a detailed analysis of the system requirements, end-user expectations, physical/environmental constraints, and both technical and economic feasibilities have to be considered.

4.4.1 HESS topologies and EMS

The development of HESS is expected to progress in two directions: (i) robust and reliable HESS in small-scale stand-alone microgrids specifically for remote or isolated sites, (ii) independent and intelligent medium in the large-scale grid-connected power system that is part of the smart-grid architecture. Most researches on HESS are focused at reducing the stress on the batteries while maintaining power quality, improving HESS efficiency and lowering set-up cost. For greater controllability, active HESS topology is commonly used. However, this increases the system complexity and most importantly, creating additional uncertainty and making the power system more vulnerable to components failures [270].

On the contrary, as the most straightforward HESS structure, passively connected Battery-SC HESS provides a simple and robust way to relieve battery operating pressure, but at the same time reduces system efficiency and controllability. In this topology, the SC acts as a Low-Pass Filter (LPF) for battery, and the filtering effect is inherently dependent on the internal resistance of the Battery-SC HESS as well as the installed SC capacitance, which also implies the low volumetric efficiency of the SC. Between the Full-Active and Passive HESS topologies, Semi-Active HESS enables active control of power flow with less active components used.

For the Multi-level HESS topologies, there exist many sophisticated designs and control strategies in the literature. In [271], the battery bank is made up of micro-bank modules, each with its own DC/DC converter and EMS. A control strategy that dynamically configures the battery modules is put in place to optimize the use of the modules and for greater system efficiency. A similar concept was also proposed in [272], where banks of varied energy storage elements and battery types were used with a global charge
allocation algorithm that controls the power flow between the storage banks. With the careful use of power electronic converters, the configurable and modular HESS could be one of the future trends in the development of EMS in microgrid applications.

### 4.4.2 Summary of the advantages of Battery-SC HESS

The Battery-SC HESS was initially designed to take the benefits of SC such as fast response, long life, and high power density and make it absorb high-frequency currents, thereby protecting the battery from the surge, intermittent, variable currents and effectively increasing its service lifetime. The advantages are listed below:

**a) Battery lifetime extension**

The integration of SC helps to reduce transient fluctuations in the battery power profile which releases its operation stress. This enables the battery lifetime extension owing to the reduction in the peak power requirement. In the battery-only system, it needs to cover peak power demand, leading to increased temperature which also results in lifetime reduction.

**b) Higher energy efficiency**

The relatively low ramp rate of traditional chemical battery could result in the mismatch in surge power demands, which can have a negative impact on power quality and energy efficiency. In HESS, the SC acts as a load balancing device for the battery when the SC transmits or receives energy at peak power. The battery current profile will become closer to the average or smooth power, with small RMS value and fewer peaks. Consequently, the HESS satisfies all power demands with higher energy efficiency, while the battery operates in a much healthy current profile.

**c) Size reduction**

For the same power requirements, the battery-only system needs to oversize the battery capacity to cater for the short term surge demand [273].

**d) Less environmental impact and cost saving**
As the lifespan of the battery increases, the operating cost of a stand-alone PV-battery system can be significantly reduced, thus minimizing the needs to recycle the battery frequently.

4.4.3 AC coupled and hybrid AC/DC PV-HESS power system

The aforementioned HESS configurations in this chapter are mainly based on the DC bus. In the rural area, the remote distance for connection to the grid and lack of advanced control hardware maintenance requires the power system to have a robust control solution [274]–[276]. DC coupled stand-alone PV-battery power system is ideally suited for remote rural electrification, and they are generally small-scale in the range of 2-10kW [277]–[280]. In the large-scale microgrid, AC coupling is common to allow seamless integration with utility grid and minimize losses in power transmission effectively [217].

![Diagram of AC coupled and hybrid AC/DC PV-HESS power system](image-url)

Fig. 4.13 The stand-alone PV-HESS power system expansion
Fig. 4.13 demonstrates a hybrid AC-DC PV power system that consists of both DC and AC buses [202], [267]. For possible future requirement, the hybrid AC-DC bus coupling architecture allows integration of AC-based renewable generation technologies (such as wind turbines and hydropower), distributed generations as well as the utility grid. The connection of two buses is the interlinking converters. In the DC-coupled part, the control system will be designed to regulate the voltage and manage the power flow within HESS. The situation is different in AC bus, where the HESS is required to control the frequency and voltage simultaneously and transfer the energy between the DC and AC in a bidirectional way.

4.4.4 HESS topologies and EMS in rural electrification

Rural communities are usually located far from the grid where technical support is usually limited. Therefore, the implementation of power systems in these areas prioritizes simplicity, stability, robustness, and low maintenance requirements, rather than efficiency, intelligence, and functionality. Thus simple, inexpensive, and robust HESS are desirable and shall be prioritized in the design process for remote application. Therefore, the Battery-SC HESS structure with fewer DC/DC converters will be more favorable, such as Passive HESS and SC Semi-Active HESS configurations. The next chapter will provide a comprehensive discussion and analysis on Battery-SC HESS in stand-alone PV power systems, including system topology, control system, mathematical modelling, numerical simulation, and experimental verification.

4.5 Conclusion

This chapter introduced the concept of Battery-SC HESS, including the system topologies, control strategies and possible applications in the stand-alone power system. The existing HESS topologies are categorized into four main categories, which are Passive HESS, Semi-Active HESS, Full-Active HESS, and Multi-level HESS. Their corresponding characteristics, strengths, weaknesses and possible applications were discussed and compared. The availability of actively controlled components enabled the use of EMS to manage the power exchange within the HESS. The operation stress of the battery can be reduced while maintaining a high level of power quality and reliability.
Chapter 5
Battery-SC HESS for Stand-alone PV Power System in Rural Electrification

5.1 Introduction

In Battery-SC HESS, the net current exchange is decomposed into two or more frequency components. Ideally, the primary large battery bank will supply the low-frequency component which often represents the nominal current profile. As a high power density ESS, the SC absorbs the high-frequency power exchange from the intermittency of solar power generation and sudden change in load demand. As discussed in Chapter 4, many variations of Battery-SC HESS designs and their associated EMS have been proposed by researchers over the past decades. These HESS designs are generally intended to serve large-scale utilities, smart-grid, electric vehicles, and other high power applications, and they normally require extensive sensing, computation, and communication, which significantly increase the system complexity and implementation.

This chapter presents a comprehensive study and discussion on the potential Battery-SC HESS topologies and energy management strategies in stand-alone PV power system, especially for rural electrification purposes. The targeted HESS topologies are presented and discussed in sequence from the simplest passive HESS structure to complex active topology. Theoretical analysis and numerical simulation of the HESS under consideration are presented to demonstrate the feasibility and effectiveness of mitigating battery stresses in stand-alone PV power system based on case studies of a remote
community in Sarawak, Malaysia. Novel evaluation method based on a battery healthy cost model is proposed to perform technical comparison and to demonstrate the improvement in primary battery health, thus the economic impact study. Experiments have been carried out and presented to verify the theoretical analysis.

5.2 Selected HESSs for stand-alone PV power system in rural electrification

Based on the discussion in Chapter 4, HESS topologies can be categorized regarding the number of ESS elements, the strategies of power-sharing among ESS elements and the interfacing methods, as summarised in Fig. 5.1.

![Fig. 5.1 Classification of the Battery-SC HESS topologies](image)

In rural electrification, most stand-alone PV power systems are geographically isolated [281], [282]. As a result of the high maintenance cost and limited technical support, system robustness turns out to be one of the most important considerations when designing HESS. Therefore, fully active HESS topologies may not be suitable for this rural electrification application. Conversely, HESS that can perform basic power management with minimal active components interfacing secondary ESS module(s) will
be the preferred choice. Among all HESS topologies presented above, the Passive HESS (Fig. 5.1(a)) and SC Semi-Active HESS (Fig. 5.1(d)) are two potential configurations for stand-alone PV power system in rural electrification. However, the two topologies have a common weakness that both of them require installing a large capacitance of SC to effectively absorb the fluctuating current, which leads to higher costs. Thus, based on Fig. 5.1(f), a novel Multi-level HESS configuration with passively connected primary ESS (extended from the SC Semi-Active HESS) is proposed, as illustrated in Fig. 5.2. This topology can have both benefits of passive HESS and semi-active HESS, the installed 2nd battery can replace part of SC which contribute an economic save. Their operation characteristics and control strategy in stand-alone PV power system will be discussed and compared in the following subsections.

![Multi-level HESS topology](image)

**Fig. 5.2 Multi-level HESS topology**

### 5.3 Stand-alone PV power system with selected HESSs

To evaluate and compare the power-sharing capability of the selected HESS designs for rural applications, the responses of different ESS elements are investigated with pulse current loads. Matlab Simulink models of the respective HESS topologies and their control algorithm are developed, and the integration of these HESSs in stand-alone PV power system are discussed and demonstrated.

#### 5.3.1 With Passive HESS

As the simplest topology of HESS, the Passive Battery-SC HESS can help to smooth the original current curve of Lead-acid battery directly and is the easy to install in
standalone PV power system. The Passive HESS can be modelled by an equivalent circuit model as shown in Fig. 5.3 [283]. The SC is modelled as a large capacitance $C$ with an equivalent series resistance $R_{sc}$ with a finite initial voltage $V_{sci}$ in SC. The Lead-acid battery is modeled as a constant voltage source $V_{LA}$ with an equivalent series resistance $R_{LA}$, where Lead-acid is its short name.

The passive HESS can be modelled by an equivalent circuit model as shown in Fig. 5.3 [283]. The SC is modelled as a large capacitance $C$ with an equivalent series resistance $R_{sc}$ with a finite initial voltage $V_{sci}$ in SC. The Lead-acid battery is modeled as a constant voltage source $V_{LA}$ with an equivalent series resistance $R_{LA}$, where Lead-acid is its short name.

The Thevenin equivalent voltage $V_{Th}(s)$ and impedance $Z_{Th}(s)$ in frequency domain are [222], [228]:

$$ V_{Th}(s) = \frac{R_{LA}}{s} + \frac{R_{LA}}{R_{LA} + R_{sc}} \frac{s + 1}{s + (R_{LA} + R_{sc})C} $$  \hspace{1cm} (5.1)

$$ Z_{Th}(s) = \frac{R_{LA}R_{sc}}{R_{LA} + R_{sc}} \frac{1}{s + (R_{LA} + R_{sc})C} $$  \hspace{1cm} (5.2)

where $s$ is the complex variable. In order to study the behavior of the HESS when there is a source/load, and suddenly fluctuate from one level to another, this study assumes a pulse source. The analysis method is as follows. For repetitive pulse load input, the periodic load current, $i_{Bus}(t)$ can be expressed as:

$$ i_{Bus}(t) = I_{Bus} \sum_{k=0}^{N-1} [\phi(t - kT) - \phi(t - (k + D)T)] \hspace{1cm} (k = 0, 1, 2, \ldots) $$  \hspace{1cm} (5.3)

where $D$ is the duty ratio of the input signal, $\phi(t)$ is the step function. To transfer the function with variable time to its frequency domain with complex variable $s$, the corresponding Laplace transform of $i_{Bus}(t)$ is:
\[ I_{Bus}(s) = I_{Bus} \sum_{k=0}^{N-1} \left[ \frac{e^{-skT}}{s} - \frac{e^{-s(k+D)T}}{s} \right] \quad (k = 0, 1, 2, \ldots) \] (5.4)

Then the voltage drop across the impedance \( Z_{TH}(s) \) for the given current \( I_{Bus}(s) \):

\[ V_2(s) = I_{Bus}(s) \ast Z_{TH}(s) = \frac{R_{La}R_{sc}I_{Bus}}{R_{La} + R_{sc}} \sum_{k=0}^{N-1} \left[ \frac{s + \frac{1}{R_{sc}C} e^{-skT} - e^{-s(k+D)T}}{s + \left( \frac{1}{R_{La} + R_{sc}} \right)} \right] \] (5.5)

The terminal voltage in the frequency domain can be expressed as:

\[ V_{Bus}(s) = V_{TH}(s) - V_2(s) \] (5.6)

\[ V_{Bus}(s) = \frac{V_{LA}}{s} + \frac{R_{La}R_{sc}}{R_{La} + R_{sc}} \ast \frac{v_{sci} - v_{LA}}{s + \left( \frac{1}{R_{La} + R_{sc}} \right)} - V_2(s) \] (5.7)

and its expression in the time domain via inverse Laplace transforms:

\[ v_{Bus}(t) = v_{LA} + \frac{R_{La}}{R_{La} + R_{sc}} \ast (v_{sci} - v_{LA}) \ast e^{-\left( \frac{t}{(R_{La} + R_{sc})C} \right)} \\
- R_{La}I_{Bus} \sum_{k=0}^{N-1} \left[ \left( 1 - \frac{R_{La}}{R_{La} + R_{sc}} e^{-\left( \frac{t-kT}{(R_{La} + R_{sc})C} \right)} \right) \varphi(t - kT) - \right] \\
- \left( 1 - \frac{R_{La}}{R_{La} + R_{sc}} e^{-\left( \frac{t-(k+D)T}{(R_{La} + R_{sc})C} \right)} \varphi(t - (k + D)T) \right) \] (5.8)

Finally, the battery current \( i_{LA}(t) \) and SC current \( i_{sc}(t) \) can be obtained as:

\[ i_{LA}(t) = \frac{v_{LA} - v_{Bus}(t)}{R_b} \]

\[ = \left( \frac{v_{sci} - v_{LA}}{R_{La} + R_{sc}} \right) \ast e^{-\left( \frac{t}{(R_{La} + R_{sc})C} \right)} \]

\[ + I_{Bus} \sum_{k=0}^{N-1} \left[ \left( 1 - \frac{R_{La}}{R_{La} + R_{sc}} e^{-\left( \frac{t-kT}{(R_{La} + R_{sc})C} \right)} \right) \varphi(t - kT) - \right] \\
- \left( 1 - \frac{R_{La}}{R_{La} + R_{sc}} e^{-\left( \frac{t-(k+D)T}{(R_{La} + R_{sc})C} \right)} \varphi(t - (k + D)T) \right) \] (5.9)

\[ i_{sc}(t) = i_{Bus}(t) - i_{LA}(t) \] (5.10)

Since the SC and battery will share the same terminal voltage with DC bus at steady states, where \( v_{sci} = v_{LA} \), then their current in steady state are:

\[ i_{LAss}(t) = I_{Bus} \sum_{k=0}^{N-1} \left[ \left( 1 - \frac{R_{La}}{R_{La} + R_{sc}} e^{-\left( \frac{t-kT}{(R_{La} + R_{sc})C} \right)} \right) \varphi(t - kT) - \right] \\
- \left( 1 - \frac{R_{La}}{R_{La} + R_{sc}} e^{-\left( \frac{t-(k+D)T}{(R_{La} + R_{sc})C} \right)} \varphi(t - (k + D)T) \right) \] (5.11)
\[ i_{SCSS}(t) = \frac{R_{LA}I_{Bus}}{R_{LA} + R_{sc}} \sum_{k=0}^{N-1} \left[ e^{-\frac{t-kT}{R_{LA}+R_{sc}C}} \phi(t-kT) - e^{-\frac{t-(k+1)T}{R_{LA}+R_{sc}C}} \phi(t-(k+1)T) \right] \]  \hspace{1cm} (5.12)

At time \( t = (D + k)T \), the pulse load current steps from low to high resulting in a net change in HESS current. Assume the maximum current occurs at \( N \) approaching infinity, the battery peak current can be simplified as:

\[ i_{LAp} = I_{Bus}(1 - \varepsilon) \]  \hspace{1cm} (5.13)

The parameter \( \varepsilon \) defines the current allocation relationship between the battery and the SC at the peak current, and its expression is:

\[ \varepsilon = \frac{R_{LA}}{R_{LA} + R_{sc}} + e^{-\frac{DT}{R_{LA}+R_{sc}C}} \frac{1 - e^{-\frac{(1-D)T}{R_{LA}+R_{sc}C}}}{1 - e^{-\frac{T}{R_{LA}+R_{sc}C}}} \]  \hspace{1cm} (5.14)

The parameter also indicates that the peak current from the battery will always be less than \( I_{Bus} \) when SC is connected. If there is no SC, \( \varepsilon = 0 \), and then \( i_{LAp} = I_{Bus} \), which means that there is no enhancement and the battery alone absorbs all the charging current. Eq. (5.13) also expresses the relation between the battery current and DC bus current at specific time. In the case where the Lead-acid battery operates under a rated current, the DC bus current can be calculated as:

\[ I_{Bus} = \frac{1}{(1 - \varepsilon)}I_{LRated} = \partial \cdot I_{LRated} \]  \hspace{1cm} (5.15)

To evaluate the peak power enhancement in HESS, assuming the instantaneous HESS peak power occurs at rated current:

\[ P_{HESSp} = I_{Bus} \cdot V_{Bus} = \partial \cdot I_{LRated} \cdot V_{Bus} = \partial \cdot P_{LRated} \]  \hspace{1cm} (5.16)

Eq. (5.16) shows the peak power in the HESS increases as the parameter \( \partial \) is greater than 1, while the SC passively connects in parallel.

The computation model of Passive HESS in Matlab Simulink is shown in Fig. 5.4. A 12Ah Lead-acid battery and 10 Farad SC are connected in parallel to the pulsed current load. The input pulsed current load is set to 5 amps, 50% duty cycle and cycling period of 10s. Fig. 5.5 presents the simulation results of the capability of power sharing between the Lead-acid battery and SC for Passive HESS topology. At the rising edge, the SC
responses rapidly due to the relatively low time constant. The SC will be discharged immediately once the step current drop to zero and it allows the battery discharge in relatively smooth curve. On the other hand, the battery slowly picks up over time and supply the demanded current. The results show minor effect on the power-sharing in the passively connected Battery-SC HESS for which the power-sharing only occurs within fractions of seconds. Additionally, the power-sharing capability of Passive HESS is fixed based on the internal parameters of the two ESS elements.

Fig. 5.4 Matlab Simulink model of Passive HESS

Fig. 5.5 Pulse load response of Passive HESS
A schematic diagram of the integration of a passive Battery-SC HESS in a typical stand-alone PV power system is illustrated in Fig. 5.6. The Lead-acid battery is usually the primary energy storage. The charge controller is modeled as a unidirectional DC/DC converter with a MPPT system and two control switches for interfacing the HESS and the load. A diesel/petrol generator usually is integrated as a backup and dispatchable power source in case of system failure or when additional energy is required.

![Diagram of stand-alone PV power system with Passive HESS](image)

**Fig. 5.6 Stand-alone PV power system with Passive HESS**

### 5.3.2 With SC Semi-Active HESS

For SC Semi-Active HESS (Fig. 5.1(d)), the equivalent circuit model in the time domain and frequency domain are presented in Fig. 5.7.

![Diagram of the equivalent circuit of the SC Semi-Active HESS](image)

**Fig. 5.7 The equivalent circuit of the SC Semi-Active HESS**
By neglecting the dynamic characteristics, the DC/DC converter is simplified and represented as parameters of efficiency $\eta_{sc}$ and voltage transfer rate $K_{sc}$ [222]. Thus the SC terminal voltage and current in real time before DC/DC converter is expressed as:

$$i_c(t) = \frac{K_{sc}}{\eta_{sc}} i_{sc}(t) = i_{bus}(t) - i_{bus}(t)_{LPF}$$

(5.17)

$$v_c = \frac{v_{sc}}{K_{sc}} = \frac{v_{bus}}{K_{sc}}$$

(5.18)

where the $i_{bus}(t)_{LPF}$ is the filtered $i_{bus}(t)$. When pulse signal $i_{bus}(t)$ is loaded, the SC current and the battery current on DC bus are:

$$i_{bus}(t) = I_{bus} \sum_{k=0}^{N-1} [\phi(t - kT) - \phi(t - (k + D)T)] = i_{sc}(t) + i_{LA}(t)$$

(5.19)

$$i_{sc}(t) = \frac{\eta_{sc}}{K_{sc}} i_c(t) = \frac{\eta_{sc}}{K_{sc}} [i_{bus}(t) - i_{bus}(t)_{LPF}]$$

(5.20)

$$i_{LA}(t) = I_{bus} \sum_{k=0}^{N-1} [\phi(t - kT) - \phi(t - (k + D)T)] - \frac{\eta_{sc}}{K_{sc}} [i_{bus}(t) - i_{bus}(t)_{LPF}]$$

(5.21)

Assuming the peak current will occur at the end of the pulse duty cycle, when $t = (k + D)T$. Considering the efficiency factor of DC/DC converter, $\eta_{sc}$, then the maximum current drawn from the battery can calculated by the following expression,

$$i_{LA_{p}} = I_{bus} - \frac{\eta_{sc}}{K_{sc}} [i_{bus}(t) - i_{bus}(t)_{LPF}]$$

(5.22)

Thus the peak current of battery is reduced by the SC current which is actively controlled by DC/DC converter. As a result, mitigation in battery stress due to surge current can be achieved.

The Matlab Simulink model for SC Semi-Active HESS was constructed as shown in Fig. 5.8. The parameters for SC, Lead-acid battery and the input pulsed current are set identical to those in Passive HESS (Fig. 5.4). A LPF is used to decompose the pulse load into two different frequency components. The generated signal from the higher one is used to control the DC / DC converter. Inside the grey box, the Proportional-Integral (PI) controller is implemented to track the reference signal, while the remaining of the current demand will be responded by the passively controlled Lead-acid battery. The
advantage of actively controlled SC module is that the time constant of the response can be adjusted to utilize the SC module better. Also, the isolation of the SC module from the DC bus allows wider variation in SoC that significantly improves the volumetric efficiency.

Fig. 5.8 The Matlab Simulink model of the SC Semi-Active HESS

Fig. 5.9 Pulse load response of the SC Semi-Active HESS
Fig. 5.9 shows the simulation results for power-sharing between Lead-acid battery and SC in the Semi-Active setting. The pulse load is successfully decomposed into two different frequencies by the LPF. Since the introduction of DC/DC converter and simulation limitation, the current profile is changed into the shape with minor high frequency oscillation, which is different in Passive HESS. When the pulse load becomes 5A, the SC is discharged immediately to meet the pulse requirement. When the pulse becomes 0A, then the SC is quickly charged to absorb excess power. Throughout the process, the battery can be slowly discharged and charged at its own rate. The sum of the charge and discharge from the two energy storage elements is equal to the value of the pulse load. However, due to the unavoidable time delay of the active component and controller, there is an inrush current when there is a step change in load current.

Fig. 5.10 depicts the same stand-alone PV power system with SC Semi-Active HESS as the energy storage. The Lead-acid battery is directly connected to the DC bus, while the SC is interfaced with a bi-directional DC/DC converter. The net change in current is measured and a Pulse Width Modulation (PWM) signal with the appropriate duty cycle \( D_{SC} \) is generated by the controller to control the power flow of SC.
Its control scheme is illustrated in Fig. 5.11 where the demanded power $P_{HESS}$ is resolved by using decomposition methods such as LPF, and the high-frequency component of the power exchange will be used as the reference signal $P_{SC(ref)}$ for SC. A carefully tuned current tracker (PI controller) is used to control the power flow from SC. When selecting the bandwidth of the LPF, a trade-off exists between the smoothness of battery current $I_{Batt}$ and the capacity of SC. For instance, a relatively low cut-off frequency in LPF will generate a smoother $I_{Batt}$ but requires larger SC capacity as well as higher power rating of active components in DC/DC converter.

### 5.3.3 SC/Lithium-ion/Lead-acid battery Multi-level HESS

![Diagram](image-url)

**Fig. 5.12** The equivalent circuit model of the Multi-level HESS
To maximize the advantages of the previous two topologies, this study proposed the novel Multi-level HESS topology, and the equivalent circuits are illustrated in the Fig. 5.12. The three types of ESS elements are Lead-acid battery, Lithium-ion battery, and SC. The Lead-acid battery is the main energy storage component, Lithium-ion battery is the intermediate battery, and SC is the third one. The terminal voltage of SC and its current can be expressed as:

\[
v_{sc} = \frac{v_{sc}}{K_{sc}} = \frac{v_{bus}}{K_{sc}} \quad (5.23)
\]

\[
i_{c}(t) = \frac{K_{sc}}{\eta_{sc}} i_{sc}(t) = i_{bus}(t) - W_1 \ast i_{Bus}(t)_{LPF1} - \{[i_{Bus}(t) - w_1 \ast i_{Bus}(t)_{LPF1}]\}_{LPF2} \quad (5.24)
\]

and for the Lithium-ion battery,

\[
v_{Li-ion} = \frac{v_{r}}{K_{Li-ion}} = \frac{v_{bus}}{K_{Li-ion}} \quad (5.25)
\]

\[
i_{r}(t) = \frac{K_{Li-ion}}{\eta_{Li-ion}} i_{Li-ion}(t) = \{[i_{Bus}(t) - w_1 \ast i_{Bus}(t)_{LPF1}]\}_{LPF2} \quad (5.26)
\]

where the \(\eta_{sc}, \eta_{Li-ion}, K_{sc}\) and \(K_{Li-ion}\) are the efficiencies and voltage transfer rates of the corresponding DC/DC converters respectively, \(W_1\) is the scaling factor that set the proportion of Lithium-ion battery capacity in total power demand. For pulse load response, the pulsed input current, Lead-acid battery, Lithium-ion battery and SC currents on are:

\[
i_{Bus}(t) = I_{Bus} \sum_{k=0}^{N-1} [\emptyset(t - kT) - \emptyset(t - (k + D)T)] = i_{LA}(t) + i_{Li-ion}(t) + i_{sc}(t) \quad (5.27)
\]

\[
i_{sc}(t) = \frac{\eta_{sc}}{K_{sc}} i_{c}(t) \quad (5.28)
\]

\[
i_{Li-ion}(t) = \frac{\eta_{Li-ion}}{K_{Li-ion}} i_{r}(t) \quad (5.29)
\]

\[
i_{LA}(t) = I_{o} \sum_{k=0}^{N-1} [\emptyset(t - kT) - \emptyset(t - (k + D)T)] - \frac{\eta_{sc}}{K_{sc}} i_{c}(t) - \frac{\eta_{Li-ion}}{K_{Li-ion}} i_{r}(t) \quad (5.30)
\]

Similarly, assuming the peak power demand still occurs at the moment \(t = (k + D)T\), and the maximum current drawn from the Lead-acid battery can be expressed in Eq. (5.31) when \(N\) tends to infinity,
\[ i_{LAp} = I_{Bus} - \frac{\eta_{SC}}{K_{SC}} i_{c}(t) - \frac{\eta_{Li-ion}}{K_{Li-ion}} i_{r}(t) \]  

(5.31)

Fig. 5.13 depicts the Matlab Simulink model of Multi-level HESS and its EMS. The parameters for Lead-acid battery module, SC module, and pulse load are kept identical as the one in Passive HESS and SC Semi-Active HESS. The additional Lithium-ion battery module has a capacity of 2 Ah, and the scaling factor \( W_i \) is set to 0.85. This value is set as an example in this section, but in different applications, it can be dynamically changed according to specific needs.

The responses of the Lithium-ion battery, Lead-acid battery, and SC are depicted in Fig. 5.14. SC is programmed to respond to transient currents, while the Lithium-ion battery responses to the medium frequency component during current variation and supplying a small portion of the current demand. Due to the discrete simulation steps, high frequency ripples are observed in simulation results. The DC/DC converters controls...
current variation and allow the SC/Lithium-ion operate at their corresponding curve. When the pulse load suddenly rises to 5A, the SC is rapidly discharged to 5A to provide this instantaneous power, and then slowly reduce the discharge rate until 0A. At this time, the Lithium-ion battery starts to discharge and faster than the Lead-acid battery. After the Lead-acid battery is slowly discharged to a certain value, the Lithium-ion battery begins to reduce the discharge rate. When the pulse load suddenly drops to 0A, the SC instantaneously absorbs the 5A currents from the Lead-acid battery and Lithium-ion battery. Meanwhile, the Lithium-ion battery changes its status from the discharged state to the charged state. The Lead-acid battery slowly reduces the discharge rate until the next pulse period. The series of above actions enable the reduction in peak current for the passive Lead-acid battery bank which contributes to the cycle life of the battery. Since the DC/DC converter controls the Lithium-ion battery and the SC, the inrush current still exists as the one in the Semi-Active HESS. However, in the pulse load test, the instantaneous increase of the current is the extreme conditions and rare in the actual system. In a stand-alone PV power system, such a situation is not going to occur, so the problem of inrush current will not affect the operation of the HESS.

![Graph showing current variation](image)

*Fig. 5.14 Pulse load response of the Multi-level active HESS*

Fig. 5.15 illustrates the stand-alone PV power system with Multi-level Battery-SC HESS in which three different energy storage devices are utilized for better stress mitigation. In this setting, two actively controlled complementary ESS elements (SC and Lithium-ion battery) are connected in parallel with the passively connected primary Lead-acid battery.
The combination of SC and Lithium-ion modules enhances the stress mitigation capability by covering a wider spectrum of current fluctuation as well as supply part of the nominal current demand, which enables a more stable charge-discharge process and peak current reduction in the primary Lead-acid battery bank.

![Battery-SC HESS for Stand-alone PV Power System in Rural Electrification](image)

Fig. 5.15 Stand-alone PV power system with Multi-level HESS

![Diagram of Power Allocation Strategy and Linearized Model of the Current Control Loop](image)

Fig. 5.16 Power allocation strategy for the Multi-level HESS
The associated power allocation strategy is shown in Fig. 5.16. Two LPFs are cascaded to decompose the net power demand into three different frequency ranges. The highest frequency $P_{SC(\text{ref})}$ will be used as the reference signal to control the power flow of the SC module. While the medium frequency component $P_{\text{Lithium-ion(ref)}}$ will be the reference for Lithium-ion battery module. A scaling factor $W_1$ is proposed to set the proportion of Lithium-ion battery load in total power demand.

5.4 Numerical simulations in stand-alone PV power system

To evaluate the effectiveness of the selected HESS in mitigating battery stress in stand-alone PV power system, Matlab Simulink models of 5kW stand-alone PV power system with different HESS are developed, and simulations have been carried out with actual solar irradiance data and estimated load profile from the targeted site.

5.4.1 Solar irradiance and load profiles for case studies

Fig. 5.17 and Fig. 5.18 show the PV output based on the 24-hour solar irradiance data recorded for a typical (a) sunny day and (b) cloudy day at Kuching Sarawak.

![Fig. 5.17 The PV output in sunny day](image-url)
Fig. 5.18 The PV output in cloudy day

This section uses the forecasted daily scaled-up load profile that using the methodology in Chapter 3 as load demand in the following numerical simulations. The simulation is executed in 5kW stand-alone PV power system, and thus the estimated load profile is scaled up into Fig. 5.19 where will have 12 households for 30 people with similar electricity usage pattern, same place in Batang-Ai (1°14’20.5”N, 112°02’10.7”E). The peak power demand is around 2.7kW and total load demand per day is around 30kWh.

Fig. 5.19 Estimated load profiles of the target rural site in Sarawak, Malaysia
5.4.2 Results of simulations

Chapter 3 has introduced the simulation results of the battery-only in a stand-alone PV power system, showing the PV output characteristics and current profiles of the battery in sunny and cloudy weather conditions. With the same stand-alone PV power system, the selected HESS topologies will be simulated and analyzed individually under the same PV output and load profile in the following section.

Table 5.1 lists the parameters of the Matlab Simulink model used in the simulation. For a fair comparison, the primary Lead-acid battery was kept identical for the four different cases, and the rated voltage is 12 volts, and the installed Lithium-ion battery module is 400Ah with 12V rated voltage.

<table>
<thead>
<tr>
<th>HESS System Topology</th>
<th>Primary Battery Capacity (Ah)</th>
<th>Complimentary Energy Storage Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery-only</td>
<td>4000Ah (Lead-acid)</td>
<td>-</td>
</tr>
<tr>
<td>Passive HESS</td>
<td>4000Ah (Lead-acid)</td>
<td>1000F (SC)</td>
</tr>
<tr>
<td>SC Semi-Active HESS</td>
<td>4000Ah (Lead-acid)</td>
<td>1000F (SC)</td>
</tr>
<tr>
<td>Multi-level HESS</td>
<td>4000Ah (Lead-acid)</td>
<td>400Ah (Lithium-ion) + 200F (SC)</td>
</tr>
</tbody>
</table>

a. Passive HESS

Fig. 5.20 Matlab Simulink model of Passive HESS
Fig. 5.20 illustrates the Matlab Simulink model of stand-alone PV power system with Passive HESS. An ideal PV array with MPPT charge controller is considered in the simulation of PV power generation. The simulation results for sunny and cloudy weather conditions are shown in Fig. 5.21 and Fig. 5.22, respectively. The SC in sunny day condition shares a small portion and normally operates between -5A to 5A. While in cloudy day condition, the SC operates within a larger range between -20A to 20A. With SC integrated, the Lead-acid battery current profiles show insignificant improvement compared to the battery-only system (Fig. 3.15 and Fig. 3.16).
b. Semi-Active HESS

The Matlab Simulink model for the SC Semi-Active HESS is developed as illustrated in Fig. 5.23. Identical SC with 1000F is connected to DC bus with a bidirectional buck/boost DC/DC converter. For power allocation, the LPF with a time constant T=300s is employed to decompose the power demand from the DC bus. The LPF divides the net power demand into high and low-frequency components. The low-frequency parts are passively covered by the primary Lead-acid battery, while the SC is programmed to respond to the high frequency fluctuating current actively.

Fig. 5.23 Matlab Simulink model of SC Semi-Active HESS

Compared to results in Passive HESS, the current profiles in Fig. 5.24 and Fig. 5.25 are significantly smoothed. In sunny day, the SC operation range is extended to ±20A. The effectiveness of actively controlled SC module is even more apparent in cloudy day condition, as shown in Fig. 5.25. The sharp change in solar irradiance due to cloud shelters caused the PV generated current to vary severely throughout the day. The operating range of SC current is about ±60A under cloudy day condition. This significantly improved the SC utilization rate compared to Passive HESS.
Fig. 5.24 Current profiles of sunny day

Fig. 5.25 Current profiles of cloudy day

c. **Multi-level HESS**

The Matlab Simulink model with Multi-level HESS is shown in Fig. 5.26. The Lead-acid battery remains identical as in Passive HESS and Semi-Active HESS. The SC capacity is reduced to 200F, and the additional Lithium-ion battery module is sized at
400Ah. The net power demand is split into three frequency components with two cascaded LPF (see Fig. 5.16). The time constants are set to 300s and 150s, respectively. The scaling factor $W_1$ is set to 0.85 which indicates that the Lithium-ion battery module is designed to cover 15% of the average power demand, while absorbing the medium frequency fluctuation.

The SC module is programmed to absorb the highest frequency component, while the primary Lead-acid battery bank will passively cover the remaining power demand. Significantly smoothed primary Lead-acid battery current profiles can be observed in Fig. 5.27 and Fig. 5.28. The SC handles the rapid oscillations and Li-ion battery handles great oscillations. While the Lead-acid battery takes care of the averaged nominal current demand. The SC operates within ±60A during the daytime, while the Lithium-ion battery absorbs part of the fluctuations (±20A) and at the same time shares a portion of the nominal load. The Lead-acid battery is significantly smoothed with a reduction in peak current as a result of the power-sharing capability of the Lithium-ion battery module.

![Fig. 5.26 Matlab Simulink model of Multi-level HESS](image-url)
d. SoC variation in SC

Fig. 5.29 and Fig. 5.30 present the SoC variation in SC for Passive HESS, Semi-Active HESS, and Multi-level HESS, respectively. With the capacity of 1000F in Passive HESS, only less than 10% of the SoC is utilized because of the shared terminal voltage with
battery. Conversely, with the same 1000F capacitance, the decoupled SC terminal voltage with DC/DC interface in Semi-Active topology, approximately 55% of the SoC is utilized for both sunny and cloudy conditions.

Fig. 5.29 SoC variation of SC in three different scenarios (sunny day)

Fig. 5.30 SoC variation of SC in three different scenarios (cloud day)
As for the Multi-level HESS, the SoC variation ranges from 25% for the sunny day and 55% for the cloudy day, with a much-reduced capacity of 200F. Since the lifetime of SC usually is much longer than Lithium-ion battery, and its initial cost is also higher, there is a tradeoff about the installation of SC between Semi-Active HESS and Multi-level HESS. In long-term applications, the Multi-level HESS needs to replace Lithium-ion battery regularly while Semi-Active HESS would not need it. On the other hand, in short-term applications, the lifetime of Lithium-ion battery would satisfy the requirements and effectively prolongs the primary battery lifetime similar to Semi-Active HESS which requires 5 times more SC installation with a much higher price.

5.4.3 Battery health assessment and financial analysis

a. Cost function

The simulation results presented above demonstrate the effectiveness of different HESSs in mitigating the Lead-acid battery stress compared to the conventional battery-only system. Based on the phenomenon in Lead-acid battery current profile, the charge/discharge rate, surge and fluctuating current, deep discharge effect and charge/discharge transition rate will be the main life-limiting factors. To quantify the effectiveness and extend the improvements of the selected HESS topologies for the Lead-acid battery operation environment under different weather conditions, a battery health cost function is proposed in this study as shown in Eq. (5.32), including the sum of real-time current square, the differential of current, square of DoD, times count of charge/discharge transition and the calendar lifetime of battery:

\[
\text{Cost}(T) = \sum_{t=0}^{T} n_1 |i_b(t)|^2 + \sum_{t=0}^{T} n_2 \left| \frac{di_b(t)}{dt} \right| + n_3 \left[ \max(b(t)) - \min(b(t)) \right]^2 + \sum_{t=0}^{T} n_4 \left[ \begin{array}{c}
1 ; \text{if } [i_b(t) \cdot i_b(t-1) < 0] \\
0 ; \text{if } [i_b(t) \cdot i_b(t-1) \geq 0]
\end{array} \right] + n_5 T_{\text{year}} \quad (5.32)
\]

where \( T \) is the total operating time, \( i_b(t) \) is the battery current, \( b(t) \) is the SoC of battery, while the \( n_1, n_2, n_3, n_4 \) and \( n_5 \) are positive constants. Five life-limiting factors are considered based on the lifetime characteristics of Lead-acid battery. The first term quantifies the negative impact of charge/discharge rate (C rate). The second term
evaluates the accumulation of the negative extent on Lead-acid battery when subjected to surge and fluctuating current. The third term quantifies the impact of deep discharge. During the day, due to unpredictable power demand from PV output or load users, Lead-acid battery may frequently switch between charging state and discharging state, which accelerates the cycle life of Lead-acid battery. Therefore, the fourth term penalizes the impact of the charge/discharge transition. The last term indicates the calendar life of the battery, which is assumed to be constant over time. The aging process of Lead-acid battery is a fairly complex chemical phenomenon caused by many factors. It is very difficult to establish an accurate mathematical model and quantify the extent of their impact. The formulated cost function intends to relatively measure the impact on battery health for comparison among the HESS under consideration.

b. Battery health assessment in different weather conditions

This section will conduct a health assessment of the Lead-acid battery based on the current profiles in different HESSs. The coefficient $n_2$ and $n_4$ are set to 0.3 indicating the strong negative impact of current fluctuation and frequent charge-discharge transitions due to the intermittent solar power. While $n_1$ and $n_3$ are set to 0.15 and 0.2 respectively to quantify the damaging impacts of the charge/discharge rate and deep-discharge. The effect of calendar life $n_5$ is usually much lower compared to the other factors, and therefore it is set to 0.05. The assessment is executed under two different weather conditions, which thoroughly presents the improvement of battery health with different HESS topologies. Different load profile will be used during these two days.

1. Sunny day condition

The cumulative impacts (24 hours) of the life-limiting factors for different HESS are shown in Figs. 5.31-5.33, respectively. The impact of calendar life is not presented because they are assumed to be identical for the Lead-acid batteries of similar size. In Fig. 5.31, the Multi-level HESS performs the lowest value while the other three systems have almost the same value. This is because the Lithium-ion battery shares a part of the current so that the Lead-acid battery can work under the lower charge/discharge rate. Fig. 5.32 shows the extent to which HESS reduces drastic current fluctuations, or dynamicity, in Lead-acid battery throughout the day. In general, a significant reduction in battery
health cost can be observed in Semi-Active HESS and Multi-level HESS. The Multi-level HESS with 200F SC performs equally well compared to SC Semi-Active HESS with 1000F SC. In the case of Passive HESS, since the terminal voltage of the SC is limited by the terminal voltage of the Lead-acid battery, the power-sharing capability is insignificant. As for the penalty on DoD (Fig. 5.33), Multi-level HESS demonstrates the least impact on battery health cost due to the power-sharing capability of Lithium-ion battery module.

Fig. 5.31 The results of the charge/discharge rate (sunny day)

Fig. 5.32 The results of the dynamicity (sunny day)
Fig. 5.33 The results of the SoC (sunny day)

Fig. 5.34 shows the impact of charge-discharge transitions on battery health. It can be seen that SC Semi-Active performs slightly better than the Multi-level HESS. Generally, both Semi-Active HESS and Multi-level HESS significantly reduce the impact of fluctuating current compared to systems with battery-only and Passive HESS.

The normalized cumulative battery health costs of the different HESS settings in sunny day condition are shown in Fig. 5.35. The results indicate that the Multi-level HESS reduces about 50.1% of the battery health cost compared to conventional battery-only PV.
power system in sunny day condition. Followed by the SC Semi-Active HESS, it demonstrates 43.4% reduction in sunny day, while only 6.2% reduction in battery health cost for Passive HESS.

Fig. 5.35 Normalized results of cost function throughout the sunny day

2. Cloudy day condition

The results of the first four individual factors in cloudy day condition are presented in Figs. 5.36-5.39.

Fig. 5.36 The results of the charge/discharge rate (cloudy day)
Similar to results in sunny day, the Multi-level HESS recorded the lowest cost due to the power-sharing capability of Lithium-ion battery module.

![Graph showing dynamicity of LA battery current](image)

**Fig. 5.37 The results of the dynamicity (cloudy day)**

Similar patterns are observed on dynamicity, DoD and charge-discharge transitions.

![Graph showing LA battery State of Charge](image)

**Fig. 5.38 The results of the SOC (cloudy day)**
The normalized cumulative battery health costs of the different HESS settings in cloudy day condition are shown in Fig. 5.40.

Fig. 5.40 Normalized results of cost function throughout the cloudy day

Setting the battery health cost of battery-only setting in the sunny day as the reference, the battery-only system in cloudy day condition is 1.308 which is 30.8% more than the same setting in sunny day. This is because the relatively heavier PV power fluctuation...
in cloudy day has a larger impact on battery health, thus higher battery health cost. By comparing the battery health cost in cloudy day condition, the Multi-level HESS manages to reduce the battery health cost by nearly 62.5%, followed by a reduction of 59.6% in SC Semi-Active HESS, and 11% reduction in Passive HESS setting.

c. Financial analysis

The estimated annual battery cost (365 days) for different systems and their corresponding cost reduction are calculated and presented in Table 5.2.

<table>
<thead>
<tr>
<th>Operation mode</th>
<th>Weather condition</th>
<th>Battery Capacity (kWh)</th>
<th>Initial Cost $</th>
<th>Battery Health Cost $/cycle</th>
<th>Cost / cycle ($)</th>
<th>Estimated Annual Battery Cost ($)</th>
<th>Cost Reduction %</th>
</tr>
</thead>
<tbody>
<tr>
<td>LA Battery-only</td>
<td>Sunny</td>
<td>48 (LA)</td>
<td>12288</td>
<td>1.000</td>
<td>500</td>
<td>24.58</td>
<td>8971.70</td>
</tr>
<tr>
<td></td>
<td>Cloudy</td>
<td>48 (LA)</td>
<td>12288</td>
<td>1.308</td>
<td>382</td>
<td>32.17</td>
<td>11742.05</td>
</tr>
<tr>
<td>Passive HESS (SC 1000F)</td>
<td>Sunny</td>
<td>48 (LA)</td>
<td>12288</td>
<td>0.938</td>
<td>533</td>
<td>23.50</td>
<td>8577.5</td>
</tr>
<tr>
<td></td>
<td>Cloudy</td>
<td>48 (LA)</td>
<td>12288</td>
<td>1.164</td>
<td>429</td>
<td>28.64</td>
<td>10453.6</td>
</tr>
<tr>
<td>SC Semi-Active HESS (SC 1000F)</td>
<td>Sunny</td>
<td>48 (LA)</td>
<td>12288</td>
<td>0.566</td>
<td>883</td>
<td>13.92</td>
<td>5080.8</td>
</tr>
<tr>
<td></td>
<td>Cloudy</td>
<td>48 (LA)</td>
<td>12288</td>
<td>0.529</td>
<td>945</td>
<td>13.00</td>
<td>4745.00</td>
</tr>
<tr>
<td>Multi-level HESS (SC 200F)</td>
<td>Sunny</td>
<td>48 (LA)</td>
<td>12288</td>
<td>0.499</td>
<td>1002</td>
<td>13.26</td>
<td>4839.9 + 255.5(Lithium-ion) = 5095.4</td>
</tr>
<tr>
<td></td>
<td>4.8 (Li-ion)</td>
<td>1392</td>
<td>-</td>
<td>2000³</td>
<td>0.70</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cloudy</td>
<td>48 (LA)</td>
<td>12288</td>
<td>0.491</td>
<td>1018</td>
<td>12.07</td>
<td>4405.55 + 255.5(Lithium-ion) = 4661.05</td>
</tr>
<tr>
<td></td>
<td>4.8 (Li-ion)</td>
<td>1392</td>
<td>-</td>
<td>2000³</td>
<td>0.70</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note 1 – Initial cost of Lead-acid battery ($256/kWh) and Lithium-ion battery ($290/kWh) are considered.[269]

Note 2 – Typical life cycle / Cost of battery utilization; (typical life cycle for Lead-acid – 500 cycles, Lithium-ion – 4000 cycles and SC >100,000 cycles)[269]

Note 3 – Estimated to perform 50% of the expected lifecycles of the Lithium-ion battery when Lead-acid battery is replaced.

Note 4 – Percentage cost reduction is calculated based on battery-only system.

Since the SC lifetime is nearly infinite, it is not considered in the annual operating cost of the ESS in stand-alone PV power system. The Passive HESS reduces the battery cost by 6.3% and 10.8% respectively for sunny and cloudy days, while both SC Semi-Active HESS and Multi-level HESS demonstrate significant ESS cost reduction of about 43% on a sunny day and 60% on a cloudy day. Despite the higher upfront battery cost (Lead-acid and Lithium-ion) in Multi-level HESS, it only requires 20% of the SC capacity compared to other HESSs.
5.5 Experiment verification

5.5.1 Testbed setup

To demonstrate the feasibility of the selected HESS topologies and to verify the simulation analysis presented in the previous section, scale-down prototypes of stand-alone PV-battery power system with the selected HESSs were designed and developed as illustrated in Fig. 5.41. The test-bed is tested in campus of Swinburne University.

Inside the system, the Lead-acid battery is connected to the DC Bus through a charge controller. The three HESS modules, marked with red dashed lines, can be individually connected to the DC bus and tested. A programmable DC electronic load (BK Precision BK8500) is used to emulate the pulsed load as well as the estimated load profiles. A 15W solar panel is used to generate the PV power. The current flows in energy storage devices are measured by current sensors (ACS712) and logged by using the NI USB-6008 data acquisition device. The power allocation algorithm is controlled by Arduino (ATMEGA328P). The design and implementation of bidirectional buck-boost DC/DC converter and its control system are presented in Appendix 2.1. The parameters of the experiment testbed are summarized in Table 5.3.
Table 5.3 Experimental testbed parameters

<table>
<thead>
<tr>
<th>System Parameters</th>
<th>Passive HESS</th>
<th>SC Semi-Active HESS</th>
<th>Multi-level HESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV panel peak power</td>
<td>15W</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Daily load energy consumption</td>
<td>0.4 kWh</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lead-acid battery nominal voltage</td>
<td>12V</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lead-acid battery capacity</td>
<td>30Ah</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SC Capacitance</td>
<td>-</td>
<td>50F</td>
<td>25F</td>
</tr>
<tr>
<td>SC Equivalent Series Resistance</td>
<td>-</td>
<td>0.001Ω</td>
<td>0.001Ω</td>
</tr>
<tr>
<td>Lithium-ion Battery nominal voltage</td>
<td></td>
<td></td>
<td>12V</td>
</tr>
<tr>
<td>Lithium-ion Battery capacity</td>
<td>-</td>
<td>-</td>
<td>6Ah</td>
</tr>
</tbody>
</table>

5.5.2 Pulse load response

A repetitive pulsed current profile with amplitude of 1 Ampere, period of 120s, and 50 percent in duty ratio is generated by using BK8500. Figs. 5.42-5.44 show the responses of battery and SC currents in each selected HESSs under pulse load test.

![Experimental responses to pulsed load of Passive HESS](image)

In Passive HESS (Fig. 5.42), the SC responded instantaneously to the step change in current, while the battery picked up slowly with a time constant of about 1.5s. In SC Semi-Active HESS, an Arduino controlled bi-directional buck/boost DC/DC converter is used to control the current flow in SC module with a simple digital LPF to allocation...
current among SC and battery modules. As can be seen from Fig. 5.43, the SC responded quickly to the step change in current and allowed the battery to gently supply/absorb the current change.

![Fig. 5.43 Experimental responses to pulsed loads of SC Semi-Active HESS](image)

The current response of the Multi-level HESS is shown in Fig. 5.44. The structure enables the primary battery to gently supply/absorb the changes but with notably lower
peak current because the Lithium-ion battery module shares part of the current demand that can be determined by setting the scaling factor (set at 0.85 for this experiment). The experimental results of pulsed load responses agree to the simulation results presented in section 5.3.

5.5.3 Daily operation in stand-alone PV power system

The daily operational test with 15W stand-alone PV power system was carried out on HESSs under test separately on four different partly cloudy days in Swinburne University of Technology Sarawak Campus, Kuching, Malaysia. The net current demand \(I_{PV} - I_{Load}\), primary battery current (red line) and SC current (blue line) are depicted in Figs. 5.45 – 5.48, respectively for battery-only system, system with Passive HESS, system with SC Semi-Active HESS and system with Multi-level HESS.

Minimal mitigation of current fluctuation is demonstrated in Passive HESS (Fig. 5.46), while SC Semi-Active HESS and Multi-level HESS remove majority of the primary battery current fluctuation as can be observed from Fig. 5.47 for SC Semi-Active HESS and Fig. 5.48 for Multi-level HESS. In addition, the Multi-level HESS shares part of the current demand with Lithium-ion battery module with a pre-determined scaling factor. The experimental results demonstrate the feasibility of the HESS under test in stand-alone PV power system and validate the simulation analysis presented in Section 5.4.2.
Fig. 5.46 Experimental currents of Passive HESS in stand-alone PV power system

Fig. 5.47 Experimental currents of Semi-Active HESS in stand-alone PV power system
5.6 Conclusion

Stand-alone PV power system with Lead-acid battery has been one of the preferred choices in off-grid rural electrification. However, the nature of solar energy is causing the additional impact on the battery which accelerates the deterioration of battery performance and cycle life. This chapter presented a comprehensive study of Battery-SC HESS and their feasibility in stand-alone PV power system. Three potential HESS topologies and their associated power allocation strategy, and control system had been discussed in this chapter, followed by numerical simulation and experimental verification. The Matlab Simulink models of the selected HESSs were developed and simulated with actual solar irradiance data and estimated load profile to evaluate the effectiveness in mitigating battery stress. The simulation analysis and results had been verified by experiments with the developed lab-scale prototype of HESS under consideration. Simulation results, battery health cost and financial analyses, and empirical outcomes suggest that the combination of active secondary energy storage with the passive primary battery could be the optimal setting for stand-alone PV power system applications.
Chapter 6
Smart HESS Plug-in Module for Stand-alone PV-Battery Power System

6.1 Introduction

The structure of stand-alone PV power system, illustrated in Fig. 6.1, consists of PV arrays, charge controller, inverter, the Lead-acid battery, and AC/DC loads. This conventional stand-alone PV-battery power system has been widely installed in off-grid rural communities. Chapter 5 discussed and compared three HESS topologies that are suitable for stand-alone PV power system and the technical analysis and simulation outcomes showed that the proposed Multi-level HESS could effectively mitigate battery stress and thus leading to enhanced lifetime characteristic of the Lead-acid battery bank. However, to achieve the Multi-level Battery-SC HESS as demonstrated in Chapter 5, a complete redesign of the existing installed ESS structure is required. This may not be financially viable in most cases, especially in remote applications.

![Diagram of the stand-alone PV power system with Lead-acid battery](image_url)

Fig. 6.1 The stand-alone PV power system with Lead-acid battery
Typical stand-alone PV-battery power system consists of PV arrays, charge controller, inverter, ESS and loads. Typical solar charge controller features MPPT that maximizes the power generation, and regulates the battery charging process by monitoring the battery SoC to prevent overcharging and overly discharged [284]–[286]. However, other life-limiting factors that accelerate the deterioration of battery performance such as high C-rate, fluctuating power exchange, frequent charge-discharge transition, deep-discharging, and other external factors are often not considered in the research of the charge controllers [287]–[289].

In this chapter, a novel Smart Hybrid Energy Storage System (SHESS) plug-in module is proposed that is retrofittable on typical stand-alone PV-battery power systems, as shown in Fig. 6.1. The proposed module is designed as a plug-in that can be adopted directly in existing installed infrastructure in the installed stand-alone PV-battery power system. By design, it mitigates the principal Lead-acid battery operation stress from current fluctuations and surge demand without changing the structure of the original system. Such a scheme is simple, effective and will have a significant economic impact on the market of the installed PV system.

The proposed SHESS plug-in module consists of SC and Lithium-ion battery modules that operate in two different modes based on weather conditions: (1) light mode for operation under sunny day condition and (2) heavy mode for operation under cloudy day condition. The performance metric of the three energy storage technologies is tabulated in Table 6.1 [176], [290], [291].

<table>
<thead>
<tr>
<th></th>
<th>Lead-acid Battery</th>
<th>SC</th>
<th>Lithium-ion Battery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific Energy Density</td>
<td>30 -50 Wh/kg</td>
<td>0.1 – 15 Wh/kg</td>
<td>100 - 250 Wh/kg</td>
</tr>
<tr>
<td>Specific Power Density</td>
<td>75 - 300 W/kg</td>
<td>500-15,000 W/kg</td>
<td>230 – 340 W/kg</td>
</tr>
<tr>
<td>Life Cycle</td>
<td>500-1000</td>
<td>100,000+</td>
<td>1,000-20,000</td>
</tr>
<tr>
<td>Charge/Discharge Efficiency</td>
<td>80 – 90 %</td>
<td>&gt;90%</td>
<td>&gt;90%</td>
</tr>
<tr>
<td>Shortest Response Time</td>
<td>1 min</td>
<td>0.1 – 1 s</td>
<td>30 s</td>
</tr>
<tr>
<td>Self-Discharge/ Day</td>
<td>0.1-0.3%</td>
<td>20-40%</td>
<td>0.1-0.3%</td>
</tr>
<tr>
<td>Unit Cost ($/kWh)</td>
<td>300</td>
<td>2000</td>
<td>500</td>
</tr>
</tbody>
</table>
In sunny day condition, PV power is relatively stable for which only SC module will be activated (light mode) to complement the battery operation. In light mode, the SC will be interfaced to battery terminal by using a bidirectional DC/DC converter that is actively controlled by the microcontroller. While in cloudy day condition, the PV generates less power and fluctuates more frequently. Therefore, the heavy mode will be activated where an additional Lithium-ion battery module is activated to provide the required capacity in absorbing the current fluctuation. The current exchange will be decomposed into three frequency components (high, middle and low) and allocated reasonably to the SHESS plug-in modules of different lifetime characteristics (SC and Lithium-ion) and the primary Lead-acid battery bank.

Computational model of the proposed SHESS plug-in module is developed and evaluated in Matlab Simulink. Dynamic modelling and numerical simulations are carried out to examine the effectiveness of the SHESS plug-in module in mitigating battery stresses under different operating conditions. A scaled-down prototype of the proposed SHESS plug-in module is examined experimentally to verify the simulation outcomes and demonstrate the feasibility of the proposed system. To evaluate the technical and financial improvements of the stand-alone PV power system with SHESS, a financial analysis is presented by quantitatively investigating the lifetime improvement with battery health cost model proposed in Chapter 5.

### 6.2 SHESS Plug-in module

#### 6.2.1 System structure

The structure of the proposed SHESS plug-in module is illustrated in Fig. 6.2. The SHESS is connected to the terminal of the Lead-acid battery. A mode controller interfacing the Lead-acid battery and the SHESS plug-in module is implemented to control the mode of operation. In light mode, only the SC module is interfaced to the Lead-acid battery terminal via an actively controlled bidirectional DC/DC converter. The active connection ensures DC bus stability while allowing the SC to operate in a wide range of terminal voltages. In this mode, high-frequency current fluctuation will be directed to the SC module that is controlled by the power allocator.
Differently, both SC and Lithium-ion modules will be activated in heavy mode, where both SC and Lithium-ion modules are interfaced with actively controlled bidirectional DC/DC converters. This configuration will ensure sufficient capacity in handling severe fluctuation in current without requiring a large amount of costly SC to be installed. In this setting, the SC module will absorb/supply the high-frequency current fluctuation, while the Lithium-ion module is controlled to absorb/supply the medium frequency component of the fluctuating current, and at the same time to supply a portion of the total power demand. A power-sharing factor $W_1$ determines the proportion of power-sharing within the power allocator. The power allocator adopts the low pass filtering approach in decomposing the power demand into multiple frequency components. A power controller is used to coordinate the operation of mode controller and power allocator while generating appropriate PWM signals to operate the individual bidirectional DC/DC converters.

![Diagram of SHESS plug-in module in stand-alone PV-battery power system](image)
6.2.2 Power allocation and control strategy

The signal of power difference is collected and process via the central control system that contains Power Allocation Controller (PAC) and Energy Management Unit (EMU). The EMU is used to process the signals, determine the corresponding operating mode, and send the signal to the PAC, as well as the DC/DC converters and Mode controller. According to different working modes, the system will divide the signal into different frequency parts and send it to the control unit. Fig. 6.3 shows the mode selection process when the SHESS is operational. The mode controller can be configured as the automatic mode or manual mode. In automatic mode, the selection of mode will be made automatically based on real-time or predicted (from solar irradiance data) weather conditions. While in manual mode, the operating mode will be manually set by the user. This simple method will be attractive for the applications in remote areas.

![Mode selection process of the proposed SHESS plug-in module](image)

There are three modes of operation, namely off mode, light mode and heavy mode. In light mode, SC module will be configured to respond actively to the high-frequency power exchange while the average power demand (low-frequency components) will be supplied passively by the primary Lead-acid battery. In the heavy mode, both the Lithium-ion battery module and SC module will be parallel connected to the Lead-acid battery. The power demand will be decomposed into three frequency components, (1) high-frequency, (2) intermediate frequency, and (3) low-frequency. The high-frequency power exchange will be responded by the SC module, while the Lithium-ion battery module will cover the intermediate frequency, and lastly, the average power demand (low-frequency) will be powered by the primary Lead-acid battery passively.
In the light mode, the power allocation strategy is shown in Fig. 6.4(a). High-frequency component $P_{SC\text{(ref)}}$ is extracted from the net demand power $P_{ESS}$ ($P_{PV} - P_{load}$) using the secondary LPF. The SC actively handles the high-frequency components, and the battery responsible for the low-frequency ones in a passively way. The signal of $P_{SC\text{(ref)}}$ will be the input reference signal for the controller to generate appropriate PWM signals that operates the bidirectional DC/DC converter for the SC module as shown in Fig. 6.4(b). While the remaining smoothed power demand (low-frequency component) will be supplied by the passively connected Lead-acid battery.

**2) Heavy mode**

In the heavy mode, the SHESS utilizes two LPFs to decompose the power demand into three different frequency components as shown in Fig. 6.4(a). The highest frequency component $P_{SC\text{(ref)}}$ will be supplied by the SC module. While the middle frequency component $P_{Li-ion\text{(ref)}}$ will be covered by the Lithium-ion battery module. A weight factor $W_t$ is implemented to set the load proportion of Lithium-ion battery module with reference to the total power demand $P_{ESS}$. In this way, the load of the Lithium-ion battery
module can be flexibly adjusted according to the installed capacity, to achieve optimal power-sharing among different modules. Moreover, the \( W_i \) can be set manually or modified dynamically by advanced control algorithms to satisfy different operating conditions. In Fig. 6.4(b), it depicts the control systems for generating appropriate PWM signals to operate bidirectional DC/DC converters of both SC and Lithium-ion battery modules. Finally, the original Lead-acid battery passively absorbs/supplies the low-frequency currents.

In addition to the hybrid integration of the Lead-acid battery and SHESS, it is also critical to determine the cutoff frequency of LPF in both operation modes. In practice, the cut-off frequency needs to be carefully considered based on the capacity of the Lead-acid battery itself and the installed capacity of the SHESS. The cut-off frequencies determine the smoothness of the fluctuating current in the Lead-acid battery and can be calculated in real-time using advanced algorithms, or be manually adjusted by preset optimization values. Researchers have made considerable efforts to optimize cutoff frequency determination to maximize the benefits of HESS. The main research of this chapter is to propose the SHESS plug-in module that can extend the lifetime of the main battery in the installed PV system, and use simulation test and experimental verification to demonstrate its operating characteristics and verify its feasibility. Therefore, the algorithms for the mode selection, cut-off frequency determination, and the dynamic adjustment of weight factor will not be discussed in details in the following subsections.

6.3 Simulation analysis

In this subsection, the Matlab Simulink model and simulation results of the proposed SHESS plug-in module are presented. The model is tested with standard pulsed load and actual PV-battery PV system operational.

6.3.1 Pulse load response

The pulsed load used in simulation has a period of 10s and 5A of amplitude with a fixed 50% duty cycle. In light mode, only the SC module is activated to absorb the fluctuating current. While in heavy mode, both the SC module and Lithium-ion battery module are
activated to perform power-sharing. Fig. 6.5 shows the SHESS model developed in Matlab Simulink for pulse load test. Two switch breakers are implemented to simulate the mode controller. The EMS simulates real-time power allocation and control algorithms. The capacity of Lead-acid Battery and Li-ion Battery is set at 300Ah (12V) and 15Ah (12V), respectively. While the installed capacitance of SC is 50F.

![Fig. 6.5 Matlab Simulink model of SHESS used in pulse load testing](image)

**Light mode**

Fig. 6.6 shows the simulation result for power-sharing between the Lead-acid battery and the SC module under pulsed current load. During step change in current (from 0A to 5A), the SC module is activated and discharges rapidly to fulfill the sudden change in current, while the Lead-acid battery discharges gradually towards the current demand. In the OFF state (from 5A to 0A), the SC module absorbs the excess current and gradually reduces the Lead-acid battery current towards zero. Throughout the process, the battery can be slowly discharged and charged at its own rate. The sum of the charge and discharge from the two energy storage elements is equal to the value of the pulse load.
(2) Heavy mode

On the other hand, both of the SC module and Lithium-ion battery module are parallel connected (both switch breakers are activated) with Lead-acid battery terminal in heavy mode. Fig. 6.7 depicts the current profiles for Lead-acid battery, Lithium-ion battery module, and SC module under pulsed current load.
The pulsed current was split into three frequency components, where the SC module responded quickly to step change, while the Lithium-ion battery module took a small portion of the overall capacity and at the same time responded to the middle frequency component. As can be observed from the figure, the peak current of the Lead-acid battery is reduced due to the $W_l$ factor where the Lithium-ion battery module supplies a small portion of the current demand.

6.3.2 Operation in stand-alone PV-battery power system

Fig. 6.8 illustrates the Matlab Simulink model of the SHESS plug-in module integrated into a five kilowatts stand-alone PV-battery power system. The system model contains 5kW (peak) PV arrays, 4000Ah Lead-acid battery with 12V rated voltage, AC/DC loads, and SHESS plug-in module interfaced with two individual bidirectional buck-boost DC/DC converters. In SHESS plug-in module, the initial weight factor is set as 0.95, and the installed Lithium-ion battery module is 200Ah with 12V rated voltage. The SC capacitance is 100F. The simulations are conducted under the same daily solar irradiance data profiles of the sunny and cloudy days as shown in Figs.5.17 and 5.18 (Chapter 5) and the estimated load profile as presented in Fig. 5.19 (Chapter 5).
Multi-level LPFs are used to perform power decomposition in different operating modes. In light mode, the power allocator generates reference signal $P_{SC\text{(ref)}}$ for the controller to generate PWM signal to execute the SC module. The LPF time constant is set to 300s. In the heavy mode, the power allocator splits the power demand $P_{ESS}$ into reference signals for Lithium-ion battery module $P_{Lithium\text{-ion}\text{(ref)}}$ and SC module $P_{SC\text{(ref)}}$ by using Multi-level LPFs (as shown in Fig. 6.4(a)) with time constants of 600s and 300s, respectively. In both operating modes, the Lead-acid battery responds passively to the remaining power demand (low-frequency component).

(1) Retrofittability test

To examine the retrofittable feature of the SHESS plug-in module on the typical stand-alone PV-battery power system, the SHESS was activated halfway during the 24-hour simulation for both operating modes. Figs. 6.9 and 6.10 illustrate the 24-hour simulation results of SHESS plug-in module light mode (Fig. 6.9) and heavy mode (Fig. 6.10).

In both modes, the PV-battery power system operated without the SHESS plug-in module during the first half of the simulation time. The SHESS plug-in module was activated at 12:00 PM to perform the power-sharing for the second half of the simulation time. The plug-in action occurs at around 12:00 PM, the Lead-acid battery continuously starts to run with a smooth current curve, and the negative impact of the peak current is significantly diminished. The SHESS can adequately compensate the rapid current variation either from PV generation or load demand. When the power demand is positive ($P_{load} > P_{PV}$), the SHESS plug-in module supplies power to the DC bus, while the SHESS plug-in module absorbs excess power from the DC bus when the power demand is negative ($P_{load} < P_{PV}$).

It can be observed that the Lead-acid battery current (red line) absorbs all the current fluctuations due to intermittent PV power without the SHESS (first half of simulation time), whereas the Lead-acid battery current is significantly smoothed after the SHESS was activated (second half of simulation time). The SC current (blue line) responded effectively to absorb/supply the high-frequency current. In the light mode, the SC current varies from -20A to 20A, which covers the fastest current fluctuations and is sufficient to smooth the Lead-acid battery operating current profile. In the heavy mode, Lithium-ion
battery is utilized to mitigate power fluctuations in the middle frequency range and extend the SC current range to -50A to 50A. The Lead-acid battery still can operate under a smooth current curve. It is noted that the SC needs to reduce the current variation from approximately -80A to 80A without the integration of Lithium-ion battery module. This means that larger SC capacity is required, leading to a substantial increase in cost.

Fig. 6.9 Simulation results of plug-in testing in light mode

Fig. 6.10 Simulation results of plug-in testing in heavy mode
(2) SHESS under 24-hour operation

The results in retrofittability test presented above demonstrate integrateability of the proposed SHESS to the existing PV system and the capability to effectively reduce the current fluctuations of the primary Lead-acid battery. To further evaluate the performance of SHESS plug-in module in mitigating battery stresses under continuous operation, a daily PV-battery power system operation was simulated for both modes. The SHESS model parameters (PV and Lead-acid battery capacity) and simulation conditions (solar irradiance and load profile) were set identical. Figs. 6.11 and 6.12 show the daily Lead-acid battery current profiles under light mode (Fig. 6.11) and heavy mode (Fig. 6.12). It can be observed that the Lead-acid battery current profiles under both operating modes have been significantly smoothed with the SHESS plug-in module installed.

On cloudy days, the solar irradiance changes too violently which requires enormous SC capacity to effectively mitigate the severe current fluctuations, if SC-only HESS is implemented. In order to balance the smoothness of the Lead-acid battery current and the overall system cost, the capacity of the SHESS has to be designed to make the Lead-acid battery operates with a relatively smooth curve instead of a remarkably smooth curve.
This is also why the SC/Lithium-ion HESS mode was introduced under cloudy conditions to replace the SC-only mode. As an inexpensive ESS technology compared to SC, the Lithium-ion battery absorbs/supplies a part of the high-frequency components in the overall demand power and corporate with SC to maximally remove the Lead-acid battery current fluctuations. This approach effectively extends the lifetime of the Lead-acid battery while also ensures that the system is maintained at a lower cost range.

![Fig. 6.12 Lead-acid battery currents profile in heavy mode](image)

(3) Battery healthy cost analysis

Insert the simulation results to the battery health cost function $Cost(T)$ which was presented as Eq.(5.32) in Chapter 5, Figs. 6.13 and 6.14 show the normalized cumulative battery health cost in light mode (Fig. 6.13) and heavy modes (Fig. 6.14) respectively. In sunny day condition, the simulation results show that the SHESS plug-in module under light mode reduces the battery health cost by 26.2% compared to the Lead-acid battery-only system. In the case of cloudy day condition, the SHESS under heavy mode achieved the battery health cost of about 43.8% reduction compared to battery-only settings.
Based on the battery health cost analysis presented above, a financial analysis is presented in Table 6.2 to estimate the annual operating cost improvement with SHESS plug-in module installed. The analysis assumes that the LA battery’s life cycle is linearly proportional to the reciprocal of battery health cost. Based on the energy storage review in [85] [106], the estimated life cycle of battery for different topologies are calculated based on the typical life expectancy of 500 cycles for LA battery and 4000 cycles for Li-ion battery. In [135][292], the power capacity cost of LA battery is around 150 ~ 500 $/kWh and the Li-ion battery is around 600 ~ 2500 $/kWh for small-scale power system.
The Li-ion battery is estimated to perform 50% of the expected cycle life under fluctuating current condition. Assuming the LA battery is cycled once a day within the entire year, the estimated cost per cycle is calculated. The capacity of SC module in both light and heavy modes is set identical. Due to the extremely long service life of the SC, normally higher than 100,000 times, this paper neglects the performance deterioration of SC and assumes infinite lifetime in the economic analysis. Under these assumptions, 25.4%~25.8% annual operating cost reduction is projected under sunny day conditions, while a higher 52.4%~52.7% cost reduction is estimated under highly dynamic power fluctuation on cloudy condition.

Table 6.2 Financial analysis of SHESS under different modes

<table>
<thead>
<tr>
<th>Operation mode</th>
<th>Weather condition</th>
<th>Battery Capacity (kWh)</th>
<th>Initial Cost $</th>
<th>Cost(T) $</th>
<th>Estimated Life Cycle</th>
<th>Cost / Cycle ($)</th>
<th>Estimated Annual Battery Cost ($)</th>
<th>Cost Reduction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery-only</td>
<td>Sunny LA</td>
<td>48</td>
<td>7200–24000</td>
<td>1.000</td>
<td>500</td>
<td>14.4–48.0</td>
<td>5256–17520</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Cloudy</td>
<td>48</td>
<td>7200–24000</td>
<td>1.830</td>
<td>273</td>
<td>26.3–87.9</td>
<td>9600–32084</td>
<td>0</td>
</tr>
<tr>
<td>Light Mode (with SC)</td>
<td>Sunny LA</td>
<td>48</td>
<td>7200–24000</td>
<td>0.738</td>
<td>677</td>
<td>10.6–35.5</td>
<td>(3869–12958) + 50 (SC)</td>
<td>25.4 – 25.8%</td>
</tr>
<tr>
<td></td>
<td>Cloudy</td>
<td>48</td>
<td>7200–24000</td>
<td>0.806</td>
<td>620</td>
<td>11.6–38.7</td>
<td>(4490–15221) + 50 (SC)</td>
<td>52.4–52.7%</td>
</tr>
<tr>
<td>Heavy Mode (with SC/Li-ion)</td>
<td>Cloudy</td>
<td>48</td>
<td>7200–24000</td>
<td>2.4 (Li-ion)</td>
<td>1440–6000</td>
<td>-</td>
<td>0.7–3.0</td>
<td></td>
</tr>
</tbody>
</table>

#Note 1 – Initial cost of Lead-acid battery ($256/kWh) and Lithium-ion battery ($290/kWh) are considered.[269]
#Note 2 – Typical life cycle / Cost of battery utilization; (typical life cycle for Lead-acid – 500 cycles, Li-ion – 4000 cycles and SC >100,000 cycles)[269]
#Note 3 – Estimated to perform 50% of the expected lifecycles of the Li-ion battery when LA battery is replaced;
#Note 4 – Percentage cost reduction is calculated based on battery-only system;
#Note 5 – Assume the LA Battery: 4000 Ah with 12 volts; Li-ion Battery: 200Ah with 12 Volts (Weight factor: 0.5);
#Note 6 – Cost of 500F SC is around $50 https://item.taobao.com/item.htm?ft=t&spmu=a21m2.8958473.0.0.668ec663a19be&cid=529538036640.

6.4 Experiment verification

Fig. 6.15 Prototype of the SHESS plug-in module
In order to evaluate the viability of the proposed SHESS plug-in module in retrofitting the typical Lead-acid battery-only stand-alone PV power system, a down-scaled prototype, as shown in Fig. 6.15, has been developed and tested in laboratory settings. Experiments were carried out to examine the pulsed load response and operation in scaled stand-alone PV-battery power system. The parameters of main components are summarized in Table 6.3. The currents of the Lead-acid battery and SC and Lithium-ion battery were measured and recorded using current sensors (ACS712) and microcontroller (ATMEGA328P).

### Table 6.3 Experiment testbed parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Lead-acid Only</th>
<th>Light Mode</th>
<th>Heavy Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV panel peak power</td>
<td>15W</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Daily load energy consumption</td>
<td>0.4 kWh</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lead-acid Battery nominal voltage</td>
<td>12V</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lead-acid Battery capacity</td>
<td>30Ah</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SC Capacitance</td>
<td>-</td>
<td>25F</td>
<td></td>
</tr>
<tr>
<td>SC Equivalent Series Resistance</td>
<td>-</td>
<td>0.001Ω</td>
<td></td>
</tr>
<tr>
<td>Lithium-ion Battery nominal voltage</td>
<td>-</td>
<td>-</td>
<td>12V</td>
</tr>
<tr>
<td>Lithium-ion Battery capacity</td>
<td>-</td>
<td>-</td>
<td>2Ah</td>
</tr>
</tbody>
</table>

### 6.4.1 Pulse load response

Fig. 6.16 depicts the experimental setup and circuit diagram for pulsed load response. Two bidirectional buck-boost DC/DC converters interfacing SC and Lithium-ion battery modules are implemented and parallel connected with the Lead-acid battery through DC bus. The periodic pulsed load is generated using a programmable DC electronic load (BK Precision BK8500). The period, amplitude and duty ratio of the pulsed load are set to 120s, 1 ampere, and 50%, respectively. The EMS uses the strategies in Figs. 6.3 and 6.4 which determine the operation mode, plug-in status and controls the signals to the DC/DC converters in SHESS plug-in module. The testing is executed in the campus of Swinburne University, Sarawak, Malaysia.
Figs. 6.17 and 6.18 show the pulsed load responses of SHESS plug-in module under light mode (Fig. 6.17) and heavy mode (Fig. 6.18). In light mode (Fig. 6.17), the SC current responses rapidly to supply the step change in load, while the Lead-acid battery current responses gradually towards the demanded current.
In heavy mode (Fig. 6.18), the SC picked up the step current load as expected, while the Lithium-ion battery module supplies a portion of the remaining load demand. The Lead-acid battery current responses gradually and a portion of the demanded current is shared the Lithium-ion battery module. Thus, the experimental results of the pulse load response demonstrate the power-sharing capability of the SHESS plug-in module and verify the simulation outcomes as presented in Figs. 6.6 and 6.7.

![Graph showing current responses](image)

**Fig. 6.18 Experiment results of the pulse load testing (heavy mode)**

### 6.4.2 Operation in the lab-scale stand-alone PV-battery power system

To further verify the feasibility of the SHESS plug-in module, a down-scaled stand-alone PV-battery power system with SHESS plug-in module prototype was developed and tested under actual operating conditions. The experimental setup is shown in Fig. 6.19. The PV-battery power system includes a 15Wp PV panel, a charge controller with MPPT, a 12V 30Ah Lead-acid battery, and a programmable DC electronic load to emulate the load profile. The charge controller is kept connected the PV panels and Lead-acid battery by default. The plug-in module with two buck/boost DC/DC converters is connected, and EMS controls the operation mode according to the weather conditions. The currents of the PV panel, load, Lead-acid battery, SC and Lithium-ion battery were measured and logged by using the NI USB-6008 data acquisition device for 24-hours.
The experiment was carried out on five different days in Swinburne University (Sarawak Campus), Kuching, Malaysia, one day for battery only testing, two days for plug-in testing and two more days for one-day testing.
As a reference, the stand-alone PV-battery power system is operated independently in 24 hours in a partly cloudy day. The Lead-acid battery current profile and power demand $P_{PV-Load}$ are illustrated in Fig. 6.20, and solar irradiance is available from 8:00 AM- 17:00 PM. It is seen that high transient currents, varies from ± 1.5A, are drawn from the Lead-acid battery, which considerably reduces lifetime.

(1) Retrofittability test

In order to demonstrate the ease of being retrofit on existing installed PV-battery power system, the SHESS plug-in module was activated at 12 PM during the experiment. Figs. 6.21 and 6.22 show the current profiles of the Lead-acid battery and SHESS plug-in module. It is noted that the power-sharing process is initiated when the SHESS plug-in module was activated after 12 pm, and the Lead-acid battery current is significantly less current fluctuation. In the sunny day (Fig. 6.21), the SHESS plug-in module operated under light mode with SC current fluctuated between -0.5A to 1A. The SC module responded to the fluctuating current between 12 PM to 3 PM, while remain inactivated when the current demand was relatively stable during night time.

![Fig. 6.21 Experimental plug-in testing of SHESS plug-in module (light mode)]
On the cloudy day, as shown in Fig. 6.22, the current demand \((I_{PV} - I_{Load})\) varied heavily with rich harmonic. Despite the massive current fluctuation, the SC maintained a current variation of within 1A, while the Lithium-ion battery module shared part of the intermediate frequency current fluctuation. This allows the SHESS plug-in module to perform equally well with the same SC capacity installed. In addition, the Lithium-ion battery module shared 5% of total power demand with the weight factor \(W_1\) set to 0.95, which reduces the C-rate of the Lead-acid battery. The experimental results show that the SHESS plug-in module can reduce the Lead-acid battery stress through properly controlled power allocation.

![Fig. 6.22 Experimental plug-in testing of SHESS plug-in module (heavy mode)](image)

(2) **Daily operation in stand-alone PV-battery power system**

The SHESS plug-in module is tested while connecting to the DC bus by running 24 hours in both operations, sunny and cloudy, as shown in Figs. 6.23 and 6.24 respectively. With the integration of the SHESS plug-in module, the Lead-acid battery current fluctuations are suppressed noticeably in both weather scenarios. In Fig. 6.23, SC module absorbed most of the high peak currents variations in a range of -0.5 A to 1A. In Fig. 6.24, the solar irradiance varies much heavy than in sunny mode and leads more power demand fluctuations with rich surge peak current components. The Lithium-ion
battery shared a portion of total power demand in a moderate variation frequency, and the SC still operated in the same range as in sunny mode. Accordingly, it is evident that the SHESS plug-in module works appropriately and efficiently releases the Lead-acid battery operate stress all over the day.

Fig. 6.23 Experimental one day testing of SHESS plug-in module (light mode)

Fig. 6.24 Experimental one day testing of SHESS plug-in module (heavy mode)
6.5 Conclusion

Typical stand-alone PV power systems with the Lead-acid battery are widely installed in remote areas. Typical charge controllers lack the considerations the life-limiting factors of the battery such as C-rate, DoD and current fluctuations, which are commonly encountered in stand-alone power systems. This chapter proposed a SHESS plug-in module that is retrofittable to existing installed PV-battery power systems to mitigate battery stress by absorbing the damaging current profile. Two operation modes are designed to face the sunny and cloudy weather conditions. Matlab Simulink model of the SHESS plug-in module has been developed and simulated to investigate the power-sharing capability. Battery health cost analysis is presented to qualitatively evaluate the improvement in battery health and reduction in system operating cost. The analysis shows that after installing the SHESS plug-in module, the annual operating cost can be reduced up to 53.7%. A lab-scale prototype of the SHESS plug-in HESS was constructed and tested under the same lab-scaled stand-alone PV-battery power system in Chapter 3, including the pulse load test, plug in/off test, and one-day test. The experiment results demonstrated the ease of being integrated into existing installed PV-battery power system and were in good agreement with the simulation results.
Chapter 7
Conclusion and Future Work

7.1 Summary

Energy storage technology provides a way to increase grid flexibility and enable the integration of intermittent, non-distributable renewable power generations. In Chapter 2, an overview of the state-of-the-art in energy storage technologies was presented, including CAES, FES, PHS SC, SMES, cell battery, flow battery, TES, and chemical energy storage. Their operation principles, technical performance, and economic aspects and the current research and development status were discussed, classified, compared and analyzed. Following this, a comprehensive comparison and potential applications analysis of the reviewed technologies were presented systematically to illustrate the advantages and limitations of various energy storage technologies in the view of different perspectives. Selection criteria and consideration that intends to help decision makers and researchers to select suitable energy storage technologies in specific applications was presented. The future development trend of different energy storage technologies was discussed.

The PV-based power system is seen to be a promising renewable energy technology in the off-grid applications in remote areas. Chapter 3 presents an introduction of solar cells and the core components in a typical PV power system. The design methodology, including site evaluation, solar irradiance measurement, load profile estimation, and system analysis were presented. Based on the collected data of solar irradiance and the estimated load profile, dynamic modelling and simulation of a stand-alone PV-battery power system were conducted in Matlab Simulink. The results show the typical
behaviour of the battery charge-discharge process under off-grid operation. With actual data of solar irradiance and estimated load profiles, the battery current is demonstrated to behave under severely fluctuating conditions, which tends to accelerate the performance deterioration and aging process of the Lead-acid battery bank.

Hybridization of battery and supercapacitor has been reported to be one of the effective ways to mitigate the operational stress on the Lead-acid battery, leading to enhanced lifetime characteristics. Energy storage elements of different electrical and lifetime characteristics complement each other up and down during the operation and thus optimize the operation and longevity. Chapter 4 reviews different HESSs, including the system topology, control strategies, and the associated energy management system. Their corresponding characteristics, advantages, disadvantages and possible applications in stand-alone PV power system were discussed and compared.

A feasibility study is presented in Chapter 5 and HESS topologies, and associated power allocation strategy that is practically applied to remote microgrid were identified, considering their system complexity, technical merits, and limitations. Theoretical analysis and numerical simulation in Matlab Simulink for the selected Battery-SC HESS were carried out, and their effectiveness in mitigating battery stress was investigated and compared. The simulation analysis and results have been verified by experiments with the developed prototype of hybrid energy storage system under consideration. A battery healthy cost function that quantitatively evaluates the impact of the damaging factors on the Lead-acid battery was proposed in this work. This allows the effectiveness of different HESSs in mitigating battery operation stress to be evaluated and compared. Furthermore, the proposed battery health cost model can be used to analyze the economic improvement of the stand-alone PV power system by estimating the extension in battery service life as a result of stress mitigation. Their performances and effectiveness in stress mitigation were examined with a lab-scaled prototype of HESS under consideration. The experimental outcomes verify the theoretical analysis and simulation results done in this work. Simulation results, battery health cost and financial analyses, and empirical outcomes suggest that the combination of active secondary energy storage with the passive primary battery could be the optimal setting for standalone PV power system applications.
To leverage on existing infrastructure in installed stand-alone PV-battery power system, a smart HESS plug-in module (SHESS) was proposed in Chapter 6 to complement the ESS operation. The design and development of the retrofittable SHESS module were systematically presented, including the control system and power allocation strategy used. The effectiveness of the proposed SHESS plug-in module in mitigating battery operation stress was simulated in Matlab Simulink with actual solar irradiance data and estimated load profile for a rural community in Sarawak Malaysia. Based on the simulation results, the battery healthy cost analysis suggests that the battery lifetime can be enhanced through mitigating damaging loading current to the primary battery bank, hence reduction in overall system operating cost can be achieved. The analysis shows that after installing the SHESS plug-in module, the annual operating cost can be reduced up to 53.7%. The prototype of the proposed SHESS was constructed, and the experimental results demonstrate the feasibility of being integrated into existing installed PV-battery power system and the effectiveness of the proposed SHESS are in good agreement with the simulation outcomes.

7.2 Future work

In this study, Battery-SC HESSs were implemented in stand-alone PV power system to mitigate the primary Lead-acid battery operating stress factors. Throughout the research and development work, progress was made in discovering promising directions which could not be achieved because of time and/or scope considerations. Based on the presented research work in this thesis, the following suggestions are provided for further explorations:

(1) EMS optimization with SoC and temperature management

In this work, the design of EMS mainly focuses on power allocation strategy and power-sharing capability without accurately evaluating and managing the real-time SoC of energy storage devices and considering the effect of battery temperature into the optimization processes. In EMS, the estimation and management of battery SoC, as well as temperature monitoring, are also two of the essential aspects to be addressed. These two parameters should be accurately monitored and controlled for performance
optimization. SoC estimation can be achieved by complementing sophisticated approximation algorithms, empirical and statistical data. Therefore, one of the main focuses of the extension of this work will be to devise an accurate and reliable battery SoC estimation method that will serve as a useful parameter for the battery performance optimization process. Moreover, at the same time, take into consideration of battery temperature into the EMS and performance optimization process.

**(2) HESS prototype in actual sized PV-battery power system**

The proof-of-concept prototypes of the proposed SHESS plug-in module were developed and tested in the lab-scaled facility. Research and development work can be extended to design and develop an actual working prototype of the proposed SHESS and to be tested in the real PV-battery power system to verify the feasibility of the proposed system further. In addition, proof-of-concept to commercialization will be one of the main aims of this research work.

**(3) Demand-side management and load prediction**

In this study, energy storage in HESS is designed to absorb/supply the power mismatch between renewable energy sources and load in real-time, without considering demand-side management such as load forecasting and demand response. If the load forecast can be included in the energy management scheme, the power allocation strategy among energy storage elements can be pre-determined (in a more optimal way) rather than passively responding to it. For HESS design, future works include integration of demand-side management into the optimization process, and daily/hourly load prediction algorithm shall be considered in order to improve the efficiency and sustainability of the overall system further.

**(4) Battery healthy cost function extension**

The battery health cost function proposed in this study considered five major life-limiting factors that would have a negative impact on battery life. Exploration of other internal or external factors that contribute to the aging process of battery should be one of the major direction of the extension of this work. This would significantly improve
the model accuracy of the complex lifetime characteristic of battery and thus, providing a more realistic battery state-of-health assessment.

(5) Battery lifetime characteristic study and evaluation

The Battery-SC HESSs in this study are designed to mitigate the operating pressure of Lead-acid battery in stand-alone PV power systems and thus extend battery lifetime. However, the exact extended lifetime of the Lead-acid battery under HESS is not given in this study. Future work could involve organizing a series of experiments to assess the Lead-acid battery operation lifetime in different HESS topologies, which provides reliable evidence on battery lifetime extension and economic improvement with HESS and thus commercialization can be realized.
Reference


Reference


Appendix

A.1. Case study

Stand-alone PV-battery Power System for Batang Ai National Park Headquarter (BANP)

A.1.1 Existing power generation and distribution system in BANP

Two major buildings are supplied with electricity namely the main office and Barrack A (staff quarter) as shown in Fig. A.1.

![Fig. A.1 Layout of BANP and current electricity supply system](image)

Barrack A is a longhouse-liked terrace that houses 6 families in total. Currently, a 5.6KVA petrol generator is used to supply electricity in BANP. In normal day, the generator will be operated on average 3 hours in between 9am-1pm to carry out routine
work on PC, and 6pm-11pm for basic electricity needs for the residents in Barrack A. Their primary source of power is diesel generators and can only be started at specific times. Based on the power consumption data collected during site visit on 28 March 2016, the power consumption pattern of the 2 main buildings is shown in Fig. A.2. The barrack A consumes on average 1.4KW at night while the office consumes an additional 300W-500W on top of the Barrack A. A summary of electrical appliances that are currently in use are tabulated in Table A.1.

Table A.1 Electrical appliances (currently in-use) of main office and barrack A

<table>
<thead>
<tr>
<th>User</th>
<th>Lighting (20W)</th>
<th>Fan</th>
<th>Entertainment</th>
<th>Portable Device</th>
<th>Refrigerator / Freezer</th>
<th>PC workstation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Office</td>
<td>5</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>3</td>
</tr>
<tr>
<td>1</td>
<td>5</td>
<td>1</td>
<td>1 Radio</td>
<td>5</td>
<td>2-door</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>1</td>
<td>1 TV + Astro</td>
<td>5</td>
<td>Freezer</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>1</td>
<td>1 TV + Astro</td>
<td>3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>4</td>
<td>1</td>
<td>-</td>
<td>1</td>
<td>1-door</td>
<td>-</td>
</tr>
</tbody>
</table>

As can be seen from the graph in Fig. A.2, the average load consumption is approximately half the rated power of the petrol generator.

Fig. A.2 Existing power consumption pattern of BANP

5.6KVA Petrol Genset
Estimated fuel consumption (½ load) = 2.1L/hr
Estimated fuel consumption (rated load)= 2.9L/hr
Estimated fuel price = RM 2.80 / L (including transportation)

~4

Rated Load (Genset)

Estimated daily fuel consumption — 16L (RM45)
Based on the estimated fuel consumption of 2.1L/hour at 50% of rated load, the site is consuming on average 16L of petrol which cost about RM45 for one ordinary day (not including the transportation cost of petrol).

A.1.2 Proposed solar-battery-generator hybrid power system

(a) Stand-alone PV power system design

Based on the power usage survey conducted, the site is estimated to consume on average 10kWh of energy per day. This power consumption estimation includes basic electricity needs for barrack A and lighting consumption of the main office only. To provide sufficient energy to this demand, a 2KWp solar array is proposed to generate on average 90% of the demand (based on average 4.5 sun hours), and the existing generator will be used to top up the remaining 10% of the energy demand. Deep cycle Lead-acid battery bank rated at 48V 600Ah will be used as the intermediate buffer for imbalance generation and load. Fig. A.3 shows the design of the proposed stand-alone PV based microgrid system to be implemented in BANP.

Table A.2 summarized the required equipment and cables. Fig. A.4 presents the connection diagram of the stand-alone PV power system.
## Table A.2 Solar installation checklist

<table>
<thead>
<tr>
<th>Sub-system</th>
<th>Device / Equipment</th>
<th>Parameters / Specifications / Configuration</th>
</tr>
</thead>
</table>
| S-1        | Promelight Polycrystalline solar panel (PT-P660250BB) | 8 x 250Wp  
Peak Power: 2kW  
V<sub>mp</sub> = 121.36V  
I<sub>mp</sub> = 16.48A |
| S-2        | Petrol Genset (existing) | Rated Power: 5.6kVA |
| C-1        | DC cable | Cable length: 25m  
Cable size: 5AWG (16mm²) |
| C-2        | AC Cable | Cable length: 80m |
| C-3        | Morning Star TriStar MPPT Charge Controller | Max Current: 45A  
Max Solar Voltage: 150V  
Max solar power: 2.2kW (48V System)  
24 x (12V 100Ah) Lead-acid Battery (4S 2P)  
Total Capacity: 28.8kWh |
| D-1        | Lead-acid Battery | 24 x (12V 100Ah) Lead-acid Battery (4S 2P)  
Total Capacity: 28.8kWh |
|            | OPTI Inverter / Charger | |
|            | MCB | 2-pole DC MCB:  
1-pole DC MCB: |
| D-2        | Main circuit breaker | |
| D-3        | RCD | |
|            | Line circuit breaker | |
| D-3        | Line circuit breaker | |

### Fig. A.4 Connection diagram of the proposed system
(b) Photos of on-site installation

Fig. A.5 PV panels installation and research team

Fig. A.6 Control system installation (MPPT + OPTI-Solar Controller)
Fig. A.7 Main switches installation (Load+PV+Battery+Controller)

Fig. A.8 2400Ah PK200-12 Lead-acid battery bank Installation
A.2. Buck-boost DC/DC converter control and codes

A.2.1 The hardware structure

Fig. A.10 illustrates the system architecture diagram of the DC-DC converter system that is based on a digital control strategy. The system includes the main power circuit, the interface circuit, and the control circuit which incorporates the microprocessor and external devices.
The main power circuit is composed of DC/DC converters and energy storage devices. The interface circuit consists of three main parts. The first part is the Digital to Analog Converter (DAC) and a peripheral circuit which contain IO ports. The second part contains the external circuits for receiving the PWM signal and the corresponding drive circuits. The third part is the feedback loop which consists of an Analog to Digital Converter (ADC) and its sampling circuits. The interface circuit acts as a bridge to connect the main power circuit to the microprocessor. The digital signal from the microprocessor will be converted into an analog signal, and then it is used to control the main power circuit. In turn, the analog signal from the main power circuit will be sampled and converted into a digital signal, which is then fed back to the microprocessor. The microprocessor will adjust the output control signal automatically and finally improve the stability of the entire system. The prototype of the buck-boost DC/DC converter is shown in Fig. A.11.

![Bidirectional buck-boost DC/DC converter](image)

**Fig. A.11 The bidirectional buck-boost DC/DC converter**

### A.2.2 Control code in Arduino microprocessor

(a) *Code for Semi-Active SC HESS Control*

```cpp
#include <PID_v1.h>
#include <PID_buck.h>
#include <PID_boost.h>
const int pwm_in = 5;
const int pwm_sd = 6;
const int current_pin = 0;
```
const int current1_pin = 1;
double amps_raw = 0; // value from acs712
double amps_actual = 0; // actual current
double amps_desired = 0; // desired current
double amps_desired_last = 0;
double amps_diff = 0;
double pwm_dc = 0; // dc = duty cycle
double pwm_dc_last = 0;
int i = 0;
int a = 0;
int b = 0;

const int sampleTime = 1; // 1714*2
const int numReadings = 20;
double readings[numReadings];
int readIndex = 0;
double total = 0;
double average = 0;

double aggKp = 0.5, aggKi = 50, aggKd = 0;
double consKp = 0.5, consKi = 50, consKd = 0;

PIDBUCK buckPID(&amps_actual, &pwm_dc, &amps_desired, consKp, consKi, consKd, DIRECT);
PIDBOOST boostPID(&amps_actual, &pwm_dc, &amps_desired, consKp, consKi, consKd, DIRECT);

void setup()
{
   // Change prescale to 1 for max PWM frequency - 62.5kHz
   TCCR0B = (TCCR0B & 0b11111000) | 0x01;

   // Declaring pin to be input or output
   pinMode(current_pin, INPUT);
   pinMode(current1_pin, INPUT);

   amps_actual = 0;
amps_desired = 0;
pwm_dc = 0;
i = 0;

**Serial.begin**(9600);
buckPID.SetMode(AUTOMATIC);
boostPID.SetMode(AUTOMATIC);
buckPID.SetOutputLimits(125,255);
boostPID.SetOutputLimits(105,255);

```
for (int thisReading = 0; thisReading < numReadings; thisReading++) {
    readings[thisReading] = 0;
}
```

```
void loop() {
    amps_actual = ((510 - analogRead(current_pin)) * (5/0.185) / 1024)*(-1);
    amps_diff = ((509 - analogRead(current1_pin)) * (5/0.1) / 1024);

    if (i < sampleTime) {
        i++;
    } else if (i == sampleTime) {
        total = total - readings[readIndex];
        readings[readIndex] = amps_diff;
        total = total + readings[readIndex];
        readIndex = readIndex + 1;

        if (readIndex >= numReadings) {
            readIndex = 0;
        }

        i = 0;
    }

    amps_desired = amps_diff - (total / numReadings);
    amps_desired = (amps_desired + amps_desired_last) / 2;
```
amps_desired_last = amps_desired;

double gap = abs(amps_desired - amps_actual);
if (gap < 0.5) {
    buckPID.SetTunings(consKp, consKi, consKd);
    boostPID.SetTunings(consKp, consKi, consKd);
} else {
    buckPID.SetTunings(aggKp, aggKi, aggKd);
    boostPID.SetTunings(aggKp, aggKi, aggKd);
}

if (amps_desired > 0) {
    if (amps_desired <= 0.04 && a == 0) {
        a = 1;
    } else if (amps_desired <= 0.1 && a == 1) {
        if (amps_desired > 0.07) {
            a = 0;
        }
    }
} else {
    TCCR0A = TCCR0A & 0b11101111;
    buckPID.Compute();
    Serial.print("buck ");
}
} else if (amps_desired < 0) {
    if (amps_desired >= -0.04 && b == 0) {
        b = 1;
    } else if (amps_desired >= -0.1 && b == 1) {
        if (amps_desired < -0.07) {
            b = 0;
        }
    }
} else {
    TCCR0A = TCCR0A | 0b00110000;
    boostPID.Compute();
    Serial.print("boost ");
}
if (pwm_dc < 0) {
    pwm_dc = 0;
}
if (pwm_dc > 253) {
    pwm_dc = 254;
}

analogWrite(pwm_in, pwm_dc);
analogWrite(pwm_sd, pwm_dc);

Serial.print(amps_desired,5);
Serial.print(",");
Serial.print(amps_actual,5);
Serial.print(",");
Serial.print(amps_diff,5);
Serial.print(",");
Serial.println(pwm_dc);

(b) Code for SC/Lithium-ion HESS Control

#include <PID_buck.h>
#include <PID_boost.h>

// Inverted signal on IN of gate driver
// Non-inverter signal on SD of gate driver
// COMnA1 | COMnA0 | COMnB1 | COMnB0
const int pwm_6 = 6;  // OC0A
const int pwm_5 = 5;  // OC0B
const int pwm_9 = 9;  // OC1A
const int pwm_10 = 10; // OC1B
const int pwm_11 = 11; // OC2A
const int pwm_3 = 3;  // OC2B
const int current_converter_sc_pin = 0;
const int current_converter_batt_2_pin = 2;
const int current_hess_pin = 1;
double amps_hess = 0; // pv - load current
double amps_batt_1 = 0;
float wf = 0.9; // weight factor

// For supercap converter
double amps_converter_sc = 0; // actual current amps_actual
double amps_sc = 0; // desired current amps_desired
double amps_sc_last = 0;
double pwm_sc = 0; // dc = duty cycle
int a = 0;
int b = 0;

// For battery 2 converter
double amps_converter_batt_2 = 0; // actual current in converter battery 2
double amps_batt_2 = 0; // desired battery 2 current
double amps_batt_2_last = 0;
double pwm_batt_2 = 0; // pwm signal for converter battery 2
int c = 0;
int d = 0;

// For battery 1 averaging (primary)
const int sampleTime_batt_1 = 1/0.055*180; // 1/0.055 = 1s
const int numReadings_batt_1 = 20;
double readings_batt_1[numReadings_batt_1];
int readIndex_batt_1 = 0;
double total_batt_1 = 0;
int i = 0;

// For battery 2 averaging (secondary)
const int sampleTime_batt_2 = 1/0.055*60; // 1/0.055 = 1s
const int numReadings_batt_2 = 20;
double readings_batt_2[numReadings_batt_2];
int readIndex_batt_2 = 0;
double total_batt_2 = 0;
int j = 0;
unsigned int time = 0;
double aggKp = 0.5, aggKi = 50, aggKd = 0;
double consKp = 0.5, consKi = 50, consKd = 0;

PIDBUCK buck_sc_PID(&amps_converter_sc, &pwm_sc, &amps_sc, consKp, consKi, consKd, DIRECT);
PIDBOOST boost_sc_PID(&amps_converter_sc, &pwm_sc, &amps_sc, consKp, consKi,
consKd, DIRECT);
PIDBUCK buck_batt_2_PID(&amps_converter_batt_2, &pwm_batt_2, &amps_batt_2, consKp,
consKi, consKd, DIRECT);
PIDBOOST boost_batt_2_PID(&amps_converter_batt_2, &pwm_batt_2, &amps_batt_2,
consKp, consKi, consKd, DIRECT);

void setup() {
    // Change prescale to 1 for max PWM frequency - 62.5kHz
    // TCCR0B = (TCCR0B & 0b11111000) | 0x01;

    TCCR1A = (TCCR1A & 0b11111100) | 0bo00000001; // _BV(WGM10)
    TCCR1B = (TCCR1B & 0b11100000) | 0b00001001; // _BV(WGM12) | _BV(CS10)
    TCCR2A = (TCCR2A & 0b11111100) | 0b00000011; // _BV(WGM21) | _BV(WGM20)
    TCCR2B = (TCCR2B & 0b11110000) | 0b00000001; // _BV(CS20)

    // Declaring pin to be input or output
    pinMode(current_converter_sc_pin, INPUT);
    pinMode(current_converter_batt_2_pin, INPUT);
    pinMode(current_hess_pin, INPUT);

    amps_converter_sc = 0;
    amps_sc = 0;
    pwm_sc = 0;
    i = 0;

    Serial.begin(9600);
    buck_sc_PID.SetMode(AUTOMATIC);
    boost_sc_PID.SetMode(AUTOMATIC);
    buck_batt_2_PID.SetMode(AUTOMATIC);
boost_batt_2_PID.SetMode(AUTOMATIC);
buck_sc_PID.SetOutputLimits(0, 255);
boost_sc_PID.SetOutputLimits(0, 255);
buck_batt_2_PID.SetOutputLimits(0, 255);
boost_batt_2_PID.SetOutputLimits(0, 255);
buck_sc_PID.SetTunings(consKp, consKi, consKd);
boost_sc_PID.SetTunings(consKp, consKi, consKd);
buck_batt_2_PID.SetTunings(consKp, consKi, consKd);
boost_batt_2_PID.SetTunings(consKp, consKi, consKd);

for (int thisReading_batt_1 = 0; thisReading_batt_1 < numReadings_batt_1; 
thisReading_batt_1++) {
    readings_batt_1[thisReading_batt_1] = 0;
}

for (int thisReading_batt_2 = 0; thisReading_batt_2 < numReadings_batt_2; 
thisReading_batt_2++) {
    readings_batt_2[thisReading_batt_2] = 0;
}

void loop() {

time = micros();
amps_converter_sc = ((512 - analogRead(current_converter_sc_pin)) * (5 / 0.185) / 1024) * (-1);
amps_converter_batt_2 = ((512 - analogRead(current_converter_batt_2_pin)) * (5 / 0.185) / 
1024) * (-1);
amps_hess = ((509 - analogRead(current_hess_pin)) * (5 / 0.1) / 1024);

if (i < sampleTime_batt_1) {
    i++;
} else if (i == sampleTime_batt_1) {
    total_batt_1 = total_batt_1 - readings_batt_1[readIndex_batt_1];
    readings_batt_1[readIndex_batt_1] = amps_hess;
    total_batt_1 = total_batt_1 + readings_batt_1[readIndex_batt_1];
    readIndex_batt_1 = readIndex_batt_1 + 1;
}
if (readIndex_batt_1 >= numReadings_batt_1) {
    readIndex_batt_1 = 0;
}

i = 0;
}

amps_batt_1 = (total_batt_1/numReadings_batt_1) * wf;

if (j < sampleTime_batt_2) {
    j++;
} else if (j == sampleTime_batt_2) {
    total_batt_2 = total_batt_2 - readings_batt_2[readIndex_batt_2];
    readings_batt_2[readIndex_batt_2] = amps_hess - amps_batt_1;
    total_batt_2 = total_batt_2 + readings_batt_2[readIndex_batt_2];
    readIndex_batt_2 = readIndex_batt_2 + 1;
}

if (readIndex_batt_2 >= numReadings_batt_2) {
    readIndex_batt_2 = 0;
}

j = 0;
}

amps_batt_2 = (total_batt_2/numReadings_batt_2);

amps_sc = amps_hess - amps_batt_1 - amps_batt_2;
amps_sc = (amps_sc + amps_sc_last) / 2;
amps_sc_last = amps_sc;

// PI
if (amps_sc > 0) {
    if (amps_sc <= 0.04 && a == 0) {
        a = 1;
    } else if (amps_sc <= 0.1 && a == 1) {
        if (amps_sc > 0.07) {
            a = 0;
        }
    }
}
} else {
    buck_sc_PID.Compute();
    output_pwm_sc();
    TCCR1A = TCCR1A & 0b10111111;
}
} else if (amps_sc < 0) {
    if (amps_sc >= -0.04 && b == 0) {
        b = 1;
    } else if (amps_sc >= -0.1 && b == 1) {
        if (amps_sc < -0.07) {
            b = 0;
        }
    } else {
        boost_sc_PID.Compute();
        output_pwm_sc();
        TCCR1A = TCCR1A | 0b11000000;
    }
}
if (amps_batt_2 > 0) {
    if (amps_batt_2 <= 0.04 && c == 0) {
        c = 1;
    } else if (amps_batt_2 <= 0.1 && c == 1) {
        if (amps_batt_2 > 0.07) {
            c = 0;
        }
    } else {
        buck_batt_2_PID.Compute();
        output_pwm_batt_2();
        TCCR2A = TCCR2A & 0b10111111;
    }
} else if (amps_batt_2 < 0) {
    if (amps_batt_2 >= -0.04 && d == 0) {
        d = 1;
    } else if (amps_batt_2 >= -0.1 && d == 1) {
        if (amps_batt_2 < -0.07) {
            d = 0;
        }
    }
boost_batt_2_PID.Compute();
output_pwm_batt_2();
TCCR2A = TCCR2A | 0b11000000;

Serial.print(amps_sc, 5);
Serial.print(amps_converter_sc, 5);
Serial.print(amps_batt_2, 5);
Serial.print(amps_converter_batt_2, 5);
Serial.println(amps_hess, 5);
Serial.print(pwm_sc);
Serial.println(pwm_batt_2);

void output_pwm_sc(){
    if (pwm_sc < 0) {
        pwm_sc = 0;
    }
    if (pwm_sc > 253) {
        pwm_sc = 254;
    }
}

analogWrite(pwm_9, pwm_sc); // inverted
analogWrite(pwm_10, pwm_sc);

void output_pwm_batt_2(){
if (pwm_batt_2 < 0) {
    pwm_batt_2 = 0;
}
if (pwm_batt_2 > 253) {
    pwm_batt_2 = 254;
}

analogWrite(pwm_3, pwm_batt_2);
analogWrite(pwm_11, pwm_batt_2); // inverted
}