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Calibration and Testing Methodology of Mobile Battery Systems

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Summary:

The growing sector of high-power mobile battery systems offers flexible solutions for power delivery to diverse industrial applications at geographical locations that can vary over time. Unlike traditional stationary battery systems and electric vehicles (EVs), mobile battery systems (MBS) lack established testing frameworks tailored to their unique requirements, necessitating further research. The thesis proposes a testing framework to assess the MBS performance comprehensively. The proposal is formulated based on a meticulous exploration of fundamentals of battery technology, the distinctive properties of the MBS, existing test standards of stationary battery applications and EVs.

The proposed set of performance tests applicable for the MBS includes energy storage capacity test, energy efficiency test, duty cycle test, self-discharge test, reference signal tracking test, response time and ramp rate test, HPPC test, thermal performance test, and cycle life test.

The thesis provides illustrative examples of potential test scenarios, resembling real-world MBS configurations, along with applicable test equipment. It presents two possible test settings and detailed descriptions and procedural guidelines for conducting individual tests within this set-up.

Preface

This report presents a thesis carried out as a requirement for attaining a Master of Science degree during the spring of 2024 at the University of South-Eastern Norway (USN), Porsgrunn.

The research mainly focused to Battery system for testing to perform some experiments to develop a calibration and testing methodology of the system. This work is conducted in collaboration with Skagerak Energy.

The main supervisor of the thesis is Mohammad Khalili Katoulaei and co-supervisors are Sambeet Mishra, Thomas Øyvang, and Mohammed Yassin. Jørgen Nyhus, Håvard Hadland represented Skagerak Energy as project External partner. Their continuous supervision and support really improved my knowledge and skills throughout the project. For their instruction and invaluable time to complete the work, I am truly grateful to them. They motivated me to work in a constructive way and find solutions for any appeared problem.

I would also like to express my gratitude to the committed personnel of the USN library and the IT department for their great support. Finally, I sincerely thank Skagerak Energy for enabling a new generation of professionals to acquire skills and knowledge in the field so that we can influence the future.

Porsgrunn, 15 May 2024

Md Nazrul Islam

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Nomenclature

Symbols	Expressions	Unit
Ah	Ampere-hours	
E_c	Charging energy	Ah
E_d	Discharging energy	Ah
I_{max}	Maximum Current	A
I_{min}	Minimum Curren	A
$I_{\max\_pulse}$	Maximum pulse Current	A
$I_{\min\_pulse}$	Minimum pulse Current	A
V_{max}	Maximum voltage	V
V_{min}	Minimum voltage	V
$V_{\max\_pulse}$	Maximum pulse voltage	V
$V_{\min\_pulse}$	Minimum pulse voltage	V
V_{ocv}	Open circuit voltage	V
R_b	Battery resistance	Ω
P_{rated}	Rated power	W
P_{signal}	Signal power	W
Q_{rated}	Rated capacity	Ah
$Q_{remaining}$	Remaining capacity	Ah
$T_{response}$	Response time	s

Abbreviations

AC	Alternative current
BMS	Battery management system
CCCV	Constant current and constant voltage
CC	Constant current
CV	Constant voltage
CP	Constant power
DC	Direct current
DoD	Depth of discharge
DVA	Differential voltage analysis
EOL	End of life
EES	Electrical energy storage
EV	Electric vehicles
HPPC	Hybrid Pulse Power Characterization
ICA	Incremental capacity analysis
MBS	Mobile battery systems
OCV	Open circuit voltage
PV	Photovoltaics
SBS	Stationary battery systems
SEI	Solid electrolyte interface
SOC	State of charge
SOH	State of health

1 Introduction

The introduction chapter presents the background of the thesis. It also describes the objectives of the work along with research scopes. Then thesis Organization is detailed, outlining the sequential arrangement and sections of this thesis report.

1.1 Background

The ever-growing demand for electricity and together with the diverse and dynamic nature of its operations, has reasoned for a search of innovative technology aimed optimal solution. Traditional power generating and distribution systems are being reevaluated for sustainability and efficiency in the face of ever-increasing energy needs. It is possible to make the electrical infrastructure more adaptable and resilient using emerging technologies such as demand-side management, energy storage, and smart grids.

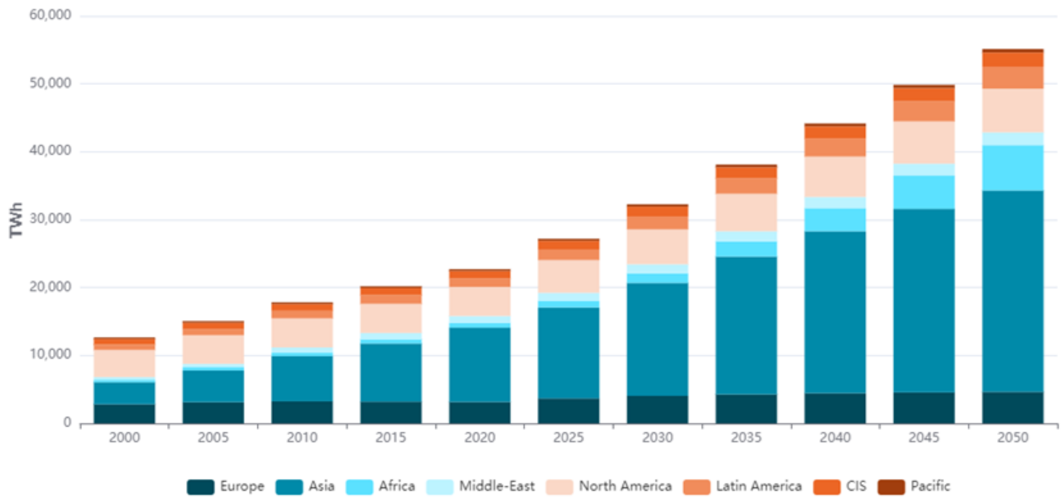

Figure 1.1: Global electricity demand and its forecast [1].

Electrical energy storage (EES) systems have proven to be exceptionally adept at handling a number of crucial features of the power industry, such as hourly variations in pricing and demand[2].There is increasing focus on EES due to rising attention about the environmental consequences of fossil fuels used to generate electricity worldwide. The applications of EES can provide better balance between the demand and the supply. The EES system is considered as an optimal solution for load and generation balance, operating reserve, Frequency regulation, Voltage support, Peak Shaving and many more[3]. There are several ways to store energy like pumped hydro, Compressed air, electro-chemicals energy storage referred as battery. They are used in different areas based on the nature of their applications.

Electrochemical devices that facilitate the conversion of chemical energy into electrical energy are known as batteries. Technological advancements have tremendously benefited batteries, providing appropriate power density for use in electric drive cars, including Plug-In and Hybrid electric vehicles, power electronics devices and many more. The developing processes of battery started very rapidly in the late 19th century. Several types of battery have been invented for example, lead-acid, nickel-cadmium (NiCd), nickel-iron (NiFe), lithium-ion and many more [4].

Lithium-ion (Li-Ion) batteries are superior to previous battery technologies in a number of ways, including longer lifespans and higher energy density [5]. Lithium-ion batteries have transformed our everyday lives by powering portable devices for almost the last thirty years.

The demand for batteries is on the rise due to potential new applications and prospects. Therefore, the high-power battery sector is growing all over the world [6].

Appropriate management, monitoring, healthy operating conditions, and control techniques are required in order to enhance battery performance, efficiency, safety, dependability, and durability. For this purpose, The State of Charge (SOC), State of Health (SOH), cell aging, Depth of Discharge (DoD) of batteries must be accurately estimated in real time by field or lab observations.

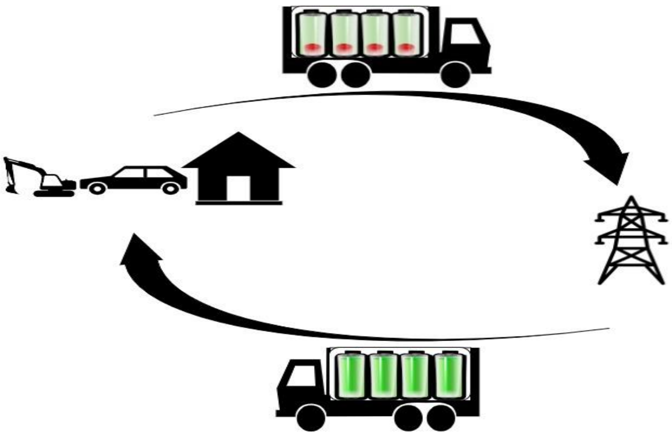

Figure 1.2: Operation of mobile battery systems.

The utilization of high-power mobile battery systems offering flexible solutions for power delivery for charging industrial installations and machinery is experiencing a notable surge [7]. This shift signifies a transformative trend, moving industrial equipment away from fossil fuel reliance toward electrification, which will help create a more environmentally friendly and sustainable operating structure. A considerable amount of research has been conducted to determine optimal operating parameters for this system taking into account variations in voltage, capacity, and charging methods. However, the sector lacks a standard testing system to evaluate their overall performance. The diverse possible applications and the scope of improvement in the gap with a focus of learning are the facts considered for the Thesis. Therefore, it becomes clear that the question of this research is always relevant.

1.2 Objective

The thesis intends to investigate how different load cycle properties affect the cycle life and ageing processes of Li-ion battery developed for high-power mobile battery systems for charging heavy equipment with focusing points on challenges and requirements for different configuration in voltage, capacity, and charging methods of the system. The high-power mobile battery systems should be operated within a standardized control technique. To confirm this, regular monitoring and testing protocol should be maintained. However, it does not still have any standard performance testing system like IEC62660 for Electrical Vehicles. Therefore, the specific aim of the research work is to formulate a standardized testing protocol. Most of the work in this thesis is carried out within the framework of a co-operation between University of South-Eastern Norway (USN) and Skagerak Energi, a Norwegian company.

The research project has mainly two parts: review of state-of-the-art mobile battery systems and proposing a test system for the mobile battery system. The key focus points of the thesis are listed below.

- Review battery technology types and the degradation mechanism in the battery storage systems.
- Conduct an in-depth review of state-of-the-art mobile battery systems utilized in charging installations, industrial machinery, and relevant applications. Identify specific challenges and requirements associated with these systems considering variations in voltage, capacity, and charging methods.
- Review the testing and testbeds used for characterization of mobile battery storage system.
- Propose relevant test procedures for the evaluation of mobile battery storage systems, encompassing parameters, test frequency, and test conditions.
- Design an experimental setup to conduct performance testing of mobile battery systems. If time allows measure and analyze the behavior of the batteries under various loads and charging conditions (focusing on key parameters such as capacity, cycle life, charge/discharge efficiency, voltage, and current characteristics).

1.3 Thesis Organization

Chapter 2 summarizes a limited literature review concerning the fundamentals of battery. different battery chemistries, state of charge (SOC) and state of health (SOH), aging and degradation process of battery. A detailed review of mobile battery systems, their configurations, a comparative study between MBS and other battery systems, and its challenges are presented in Chapter 3. Chapter 4 gives an analysis of existing battery testing standards utilized in stationary battery systems and EVs. Chapter 5 describes a proposal of testing system for the mobile battery system and test methodologies. Then Chapter 6 contains the conclusion and some suggested future works.

2 Battery Fundamentals

This chapter aims to provide theoretical background of battery fundamentals, the basic working principles of the battery, different battery chemistry, energy storage capacity and their applications. Battery state of charge (SOC), state of health (SOH), aging and degradation mechanisms are also part of the chapter.

2.1 Working Principle of Battery

The operational principle of the lithium-ion battery relies on the continuous movement of lithium ion between the anode and the cathode due to internal electrochemical reaction. Consequently, it is classified as an electrochemical energy storage device which converts chemical energy into electrical energy and vice versa. Lithium is the lightest metal with an atomic number of three and a density of just 0.53 g/cm3. Compared to Standard Hydrogen Electrode (SHE), Li+/Li couple -3.05 which indicates that it has a very low standard reduction potential. Therefore, it is considered suitable for high density, high-voltage battery cells [8]. A cell of a lithium-ion battery has mainly an anode, cathode, electrolyte, and separator. The anode and cathode among them indicate the electrically conducting components. Typically, anode and cathode are referred to as positive and negative electrodes, respectively. The electrolyte is an ionically conductive medium which allows lithium ions to shuttle between the anode and cathode. An electrically non-conductive membrane works as a separator between the anode and cathode electronically. However, it allows lithium ions to transport through it while it blocks any electrons from passing through. Figure 2.1 shows the main components of a lithium-ion battery.

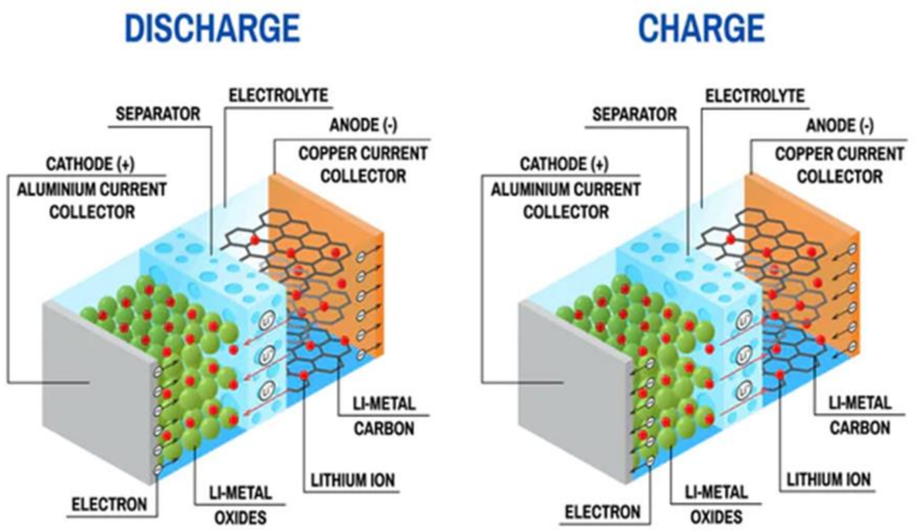

Figure 2.1: Schematic diagram of intercalation mechanism in Li-ion batteries during charge and discharge [9].

Materials of anode and cathode of lithium-ion batteries experience an insertion reaction for the charging and discharging process. The process of the reaction is the movement of Li+ cations into the cathode and anode materials (insertion, intercalation) and out of them (extraction, deintercalation), both of which frequently have a layered or tunnel structural pattern. During the discharging process, Li+ ions travel from the Li containing anode, through the separator soaked in electrolyte, and eventually intercalate into the cathode host structure. As a result, the electrons flow through the external circuit in the opposite direction where it can power a device and perform work. The opposite process takes place during the discharging response.

The positive electrode of a Li-ion battery is usually made from a transition metal oxide and negative electrode made of graphite. The half-cell reaction, or one component of a redox (reduction-oxidation) reaction, at the positive and negative electrode can be presented by equation (2.1) and (2.2) as follows.

$$LiMO_2 \rightleftharpoons Li_1 + xMO_2 + xe^- + xLi^+ \quad (2.1)$$

For the cathode where M refers to a transition metal oxide and for the anode, respectively.

$$C_6 + xLi^+ + xe^- \rightleftharpoons LixC_6 \quad (2.2)$$

In case of the LiMO2, the transition metal oxidizes from M3+ to M4+ during charging, while there is a subsequent decrease from M4+ to M3+ during discharge[10].

The amount of charge stored per active mass or volume of a battery material is known as its specific capacity(gravimetric/volumetric). Because the crystal structure becomes unstable at a high degree of de-lithiation, the maximal usage of the theoretical specific capacity cannot be fully utilized with higher levels of de-lithiation. The state of charge (SOC) of a battery is the ratio of the remaining capacity to the theoretical capacity. Similarly, coulombic efficiency (η_c) refers as the ratio of amount of charge delivered at the discharge to the amount of charge taken by the battery for charging. The ideal value of coulombic efficiency is 100 %. Reduced coulombic efficiency values indicate electrolyte decomposition (permanent capacity losses), degradation, and side reactions [11]. To comprehend these parameters and how a battery cell works, it is crucial to understand electrochemical relations using thermodynamics.

2.1.1 Electrochemistry

Batteries indeed rely on a chemical reaction to produce electricity, and studying the electrochemical process is crucial for understanding the functioning of a battery cell. The amount of energy of a battery cell depends on its potential and the number of electrons transport during the reaction process [12]. To measure the difference in potential between two electrodes of a battery, standard hydrogen electrode is used as a reference that has the standard potential of 0 V. The equation (2.3) shows the reaction of standard hydrogen electrode (SHE) [13].

$$2H + aq \; + \; 2e^- \rightleftharpoons H_2(g) \quad (2.3)$$

The cell potential refers to the difference between the reduction potential of two half-cells and is presented in the equation (2.4).

$$E^o_{cell} = E^o_{cathode} - E^o_{anode} \quad (2.4)$$

The maximum effective work produced in a chemical process is determined by the Gibbs free energy term, in accordance with the Gibbs free energy law. Entropy change (ΔS) and absolute temperature(T) are the products of enthalpy (ΔH) and entropy, which results in Gibb's free energy. The equation (2.5) shows relations among them.

$$\Delta G = \Delta H - T\Delta S \quad (2.5)$$

The maximal electrical work that results from an electrochemical reaction is represented by the ΔG term. The equation (2.6) shows the relation between ΔG and potential difference between the electrodes. It is also known as Nernst equation[14].

$$\Delta G = -nFE \quad (2.6)$$

where n is the number of transferred electrons, F the Faraday constant (F ≈ 96485 C/mol) and E is the potential difference between the electrodes.

Researching reversible work is essential for electrochemical processes. Reversible work occurs only at equilibrium condition. Once the process moves away from the equilibrium condition, some irreversible losses happen, and the entropy rises. The losses are ohmic potential drop, charge transfer overpotential and concentration polarization overpotential. The equation (2.7) shows the sum of reversible and the three irreversible losses[15].

$$E^{rev} = E^{spont}_{cell} + rj + \eta \quad (2.7)$$

where rj is the ohmic potential drop and η accounts for the other losses.

Cell efficiency can be calculated from the equation (2.8).

$$\varepsilon_{spont} = \frac{E^{cell}_{spont}}{E^{rev}} = \frac{E^{rev} - rj - \eta}{E^{rev}} \quad (2.8)$$

2.1.2 Anode (Negative Electrode)

Anode is known as negative electrode of a battery as it is the negative side of cell and consists of active material, binder, and current collectors. Negative electrode has lower open circuit voltage (OCV) than cathode. Due to its affordable price and consistent charge and discharge capabilities, graphite is the most preferred anode material in commercial cells. Li-ions can intercalate and de-intercalate from the spaces between layers because of the graphite structure. The properties of graphite when it is embedded with lithium ions prevent change in the anode size, structure, and shape during cycling. To improve the charge and discharge performance of batteries the surface of anode is coated with carbon. There is no anode material which has both stability and energy density like graphite [16].

Many researches have been conducted to increase the performance of graphite anodes. Increase in interfacial surface area of graphite would result in an increase in battery power output. Hence the surface area for lithium intercalates and de-intercalates also rises. However, there is a possibility of consuming high amounts of lithium ions due to the larger surface to form the Solid Electrolyte Interface (SEI) layer which results in reduction of battery capacity [17].

2.1.3 Cathode (Positive Electrode)

Typically, a transition metal oxide is used for cathode also known as positive electrode, allowing lithium-ions to reversibly insert themselves into the structure. When the thermodynamically favorable reaction takes place during discharge, the cathode serves as the real sink for the lithium ions. Various research groups comprehensively analyze active materials, such as intercalation, insertion and conversion materials, among the cathodes. Despite having toxic and heavy metals, many cathode materials, such as LiCoO2 (LCO), Li(NiMnCo)O2 (NCM), or Li(NiCoAl)O2 (NCA), show extremely high reversibility during battery cycling[11]. Lithium Cobalt Oxide (LiCoO2) is the most common among the positive electrodes that manufacturers use in their Li-ion batteries. It contains a practical capacity of roughly 150 mAh/g and a layered structure. Similar to Lithium Cobalt Oxide (LiCoO2), LiNiO2 is also a traditional cathode material with better cyclic behavior, high specific charge, and high Open Circuit Voltage (OCV). However, at high temperatures, it can react adversely, posing a risk to operational safety and causing difficult environmental and financial implications during production and disposal.

One of the best materials for use as an anode is lithium iron phosphate (LiF ePO4) because of its high energy density (about 170 mAh/g), low toxicity, great thermal stability, and advantageous economic factors [18]. LiF ePO4 has a relatively high OCV of 3.0-3.5 V, although having a lower OCV than LiCoO2, LiMn2O4, and several other cathode materials. Unlike other cathode materials, LiF ePO4 keeps its OCV almost constant over a broad State of Charge (SOC) interval[19].

2.1.4 Electrolyte

Lithium salts and organic solvents are the main elements of the electrolyte placed between the electrode and the separator of a battery cell. Electrolyte is generally a liquid solvent. However, sometimes it can be a polymer gel. The most substances used include dimethyl carbonate, propylene carbonate, ethylene carbonate, LiBF4 and LiPF6. Here LiBF4 and LiPF6 are used as lithium salts. Due to their ability to boost the mobility of Li-ions traveling between electrodes, organic solvents are critical to the performance of the battery cell [20].

At low potential, the electrolyte becomes unstable, and its reduction on the graphite surface results in the SEI, an insoluble coating first described by Peled in 1979. The SEI layer is ionically conductive but electrically insulating. Therefore, electrically insulating property of the SEI layer results in slow down of the reaction rate. To extend the life of lithium-ion batteries, the stability of the SEI layer is essential. An electrolyte additive or a combination of electrolyte additives can be added to increase the stability of SEI layer. However, the additives can lead to decreasing the rate of electrolyte oxidations reactions on the surface of cathode at higher potential[21].

2.1.5 Separator

The separator plays a crucial role in the battery cell due to its impact on cycle life, safety, and energy and power densities. Plastic films made of polyolefin are used to make most separators. The separator is a porous membrane that maintains the two electrodes' physical and electrical separation. Due to this separation, internal short circuit can be prevented. The separator is also ionically conductive and electrically insulating like electrolyte. That means the separator allows lithium ions to pass through it while it blocks electrons. The pores of the separator should be big enough to move lithium ions through it, about 1 μm [20].

The addition of ceramic additives increases thermal and mechanical properties of the separator. Protecting the battery cell against internal short circuits caused by metal particle penetration can be achieved by applying ceramic coatings on the separator. Applying more thin ceramic layers to anodes can also reduce the possibility of thermal runaway and local particle penetration[22].

2.2 Different Battery Chemistry

Batteries are classified based on the materials used in their different components. The features and performance characteristics of batteries vary depending on these materials. The battery technologies commonly used in large-scale energy storage are lead-acid, nickel-cadmium (NiCd), sodium-sulfur (NaS), and lithium-ion. Each type has distinctive properties to meet the needs of diverse applications. Not every battery type is appropriate for all applications [23].

Lead-acid batteries have very low energy density compared to their volume and weight and thus bulkier and heavier. However, its low cost and its capacity to store relatively large power and provide high surge currents are suitable for automotive starting applications and storage in backup power supplies. Nickel-cadmium (NiCd) batteries using nickel hydroxide and metallic cadmium as electrodes have features of high tolerance for overcharging, deep discharging, and relatively low self-discharge rate. Even though having exceptional durability, their lower energy density compared to lithium-ion limits their use in compact, high-energy-demand devices. Sodium-sulfur (NaS) batteries have properties like high energy density, and the ability to store large amounts of energy. They utilize molten sodium and sulfur as electrodes, enabling efficient energy conversion. Despite offering attractive solutions for many large-scale electric utility energy storage applications, the batteries require careful temperature regulation and pose safety concerns due to the reactive nature of their components[24] [25] [26].

Lithium-ion batteries have a higher power density(W/Kg) and energy density (Wh/Kg). Thus, they provide the same amount of energy in a lighter, more compact design compared to other types of battery. Besides this, their characteristics like long life, low maintenance cost, low self-discharge, and high efficiency are some of the reasons making them the most favorable choice for various applications. They employ various chemistries, including lithium cobalt oxide (LCO), lithium iron phosphate (LFP), lithium manganese oxide (LMO), and lithium nickel manganese cobalt oxide (NMC)[27]. Characteristics of different types of batteries are presented in Table 1based on the research paper[23] [24] [25] [26] [27].

Table 1:Characteristics of different types of battery.

Type	Specific energy (Wh/Kg)	Specific power (W/Kg)	Cell voltage (V)	Life Cycle (80% DOD)
Lead–acid	30-50	150–250	2	400-800
Nickel-cadmium (NiCd)	35-80	150-350	1.2	500–2000
Sodium-sulfur (NaS)	100	150–200	2	2500-4500
Lithium cobalt oxide (LCO)	150-200	300- 1500	3.7–3.9	500-1000
Lithium iron phosphate (LFP)	90-170	300- 1500	3.3	2000-4000
Lithium manganese oxide (LMO)	100-150	300- 1500	4.0	300-700
Lithium nickel manganese cobalt oxide (NMC)	150-200	300- 1500	3.8–4.0	1000-2000

2.3 General Terminology

2.3.1 Capacity

A battery's electrical capacity is the maximum current it can provide over an amount of time. Battery capacity is estimated in ampere-hours (Ah). Similarly, based on the energy, capacity can be measured in watt-hours [28]. as shown in equation (2.9) and (2.10).

$$Q = I \times t \tag{2.9}$$

$$Q = \int_0^t I\, dt \tag{2.10}$$

The primary parameter for the health of a battery is indicated by its actual capacity. Comparing the actual capacity to the manufacturer's rated capacity presents a reasonable assessment of the battery's condition. Battery capacity estimation includes several factors that make it a difficult task. The discharge method is thought to be the most accurate way to determine a battery's true capacity. The discharge method involves monitoring the charge or energy during draining the charge of the battery from a fully charged condition to empty state [29].

2.3.2 C-rate

Battery charging and discharging rates are determined by the C-rate. Common battery ratings are 1C, which indicates that a fully charged battery rated at 1Ah should deliver 1A for an hour. The same battery can be charged or discharged at 0.5C rate when it will take double amount of time[30]. C-rate is calculated as the proportion of applied current and capacity of battery as shown in equation (2.11).

$$C_{rate} = \frac{Current[A]}{Capacity[Ah]} \tag{2.11}$$

2.3.3 DOD

The depth to which a battery can be discharged is known as its Depth of Discharge (DoD). It is stated as a percentage (%). Discharging the battery beyond its DOD can cause damage of the battery and reducing health and lifespan of the battery[31].

DOD is generally defined by battery manufacturers based on battery material. The cycle life of the battery can result in changing DOD. Maintaining the DOD is essential to avoid over-discharge which can lead to irreparable damage to the battery.

2.3.4 Coulombic efficiency

Columbic efficiency is defined as the ratio between discharge capacity and charge capacity of a battery. It describes the relation between the deliverable charge of the battery and its absorbing capacity. Applying equation (2.12) columbic efficiency can be calculated. It is expressed as percentage[32].

$$Columbic\ efficiency = \frac{discharge\ capacity}{charge\ capacity} \tag{2.12}$$

2.3.5 Constant Current – Constant Voltage

The charging technique for Li-ion batteries that is most frequently used is constant current constant voltage (CCCV). First, a constant current is applied to the battery at a specific rate. When it reaches a voltage limit, it changes the charging method to constant voltage. This constant voltage causes an increase of terminal voltage to open circuit voltage (OCV). In this charging method the voltage is ensured not to cross the limit, which can result in irreparable damage of the battery[12].

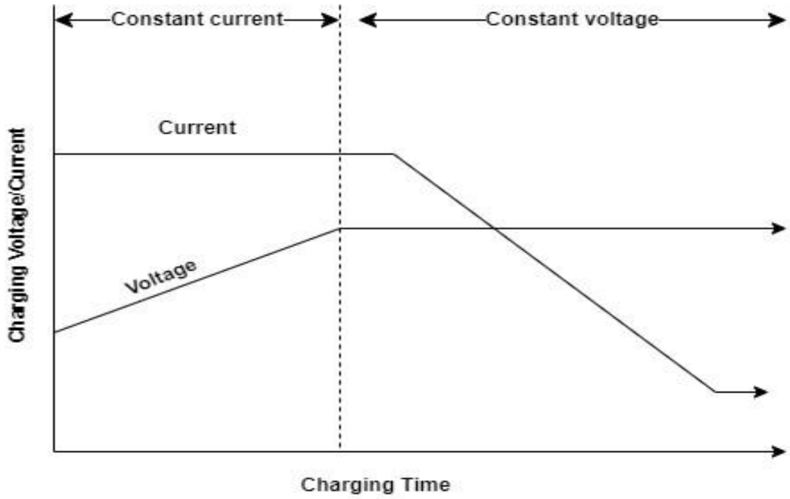

Figure 2.2: Constant current constant voltage charge.

2.4 State of Charge

State of charge (SoC) indicates the battery's remaining capacity at a given time and in relation to a given state of ageing [33]. It is expressed as the percentage of the amount of charge in the cell compared to the amount of charge when fully charged. SOC can be calculated applying the equation (2.14). It is important to note that a 0 SOC does not indicate that the battery is completely empty; rather, it indicates that further discharging the battery is no longer possible without resulting in irreversible chemical reactions or other permanent damage[34].

$$SOC = \frac{amount\ of\ charge}{amount\ of\ charge\ when\ fully\ charged} \times 100 \tag{2.13}$$

$$\Downarrow$$

$$SOC = (1 - \frac{Q_{discharged}}{Q_{rated}}) \times 100 \tag{2.14}$$

Here,

Q_{rated} is the rated capacity of the battery.

$Q_{remaining}$ is the remaining capacity of the battery.

$Q_{discharged}$ is the total released charge for the battery.

SOC is one of the most important factors for battery safety and management because extremely high and too low SOC due to deep discharge or overcharge can lead to permanent damage of the battery[35].

2.5 **State of Health**

The term "state of health" (SOH) refers to an abstract idea that is used to quantify a battery's condition. It indicates the cell's capacity in relation to the battery's initial capacity and is used to determine the health of the battery. SOH is typically expressed as a percentage, with 100% denoting completely healthy where 0% denoting not operable condition. The end of life (EOL) of a battery is defined by the manufacturer at a certain level of SOH where battery can be operated with very low efficiency or a fraction of its rated capacity. The general mathematical formula to calculate SOH is shown in equation (2.15).

$$SOH = \frac{Capacity\ when\ fully\ charged}{Capacity\ when\ fully\ charged\ when\ new} \times 100 \tag{2.15}$$

However, SOH estimation requires a complicated procedure. The measurements must be made at the same temperature and C-rate in order to produce accurate results and allow for value comparison. The capacity of a battery depends on several factors. Therefore, to obtain a precise and comprehensive definition of SOH, the equation (2.15) needs to applied and complemented based on the factors of battery capacity and its test conditions[36]. The most common approach for characterizing SOH is to consider the capacity fade. The reduction in battery capacity is referred to as capacity fade. Calendar life, cycle life, and battery deterioration all contribute to capacity loss. The number of cycles the battery has completed is its cycle life. The duration of the battery's total operation is known as its calendar life[37].

Because of the increasing age of battery, some internal degradation happens. This degradation causes an increase of battery internal resistance, SEI layer in anodes and overall capacity reduction (see the Degradation and Aging Mechanisms section). This factors contribute to decreasing SOH[32] [38] .

The factors that determine the SOH of a battery are mainly.

- Capacity
- Internal resistance
- Self-discharge

A large number of research has been conducted on developing different methods of SOH estimation. A comprehensive review of this studies can be found in [39] [40] [41].

Based on the research paper the following methods of SOH estimation are presented here.

2.5.1 Experimental methods

The best and most straightforward way to observe the battery’s behavior is to measure the voltage, current, and temperature of the battery. Experimental methods may offer advantages for case studies and individual analyses. This method requires a considerable number of test procedures and calculations to collect the necessary data to estimate SOH [39]. However, because of several external factors and systematic errors, it is not always possible to gather accurate information during the experiment. Internal resistance can be calculated using experimental techniques applying both direct and indirect measures. Internal resistance, impedance, battery capacity, and other tests are classified under "direct measurements." The charging curve approach, the ICA and DVA method, ultrasonic examination, and data optimization and processing to identify SOH parameters are examples of indirect methods [42].

Direct measurements

- Internal resistance measurement
- Impedance measurement.
- Capacity test

Indirect analysis

- Charge-Curves
- incremental capacity analysis (ICA) method
- differential voltage analysis (DVA) method

2.5.2 Model-Based Method

To estimate a battery's state of health using a model-based method, it requires enough experimental results for determining the dependence of essential characteristics of the battery, such as current, voltage, and capacity, on the battery's ageing. The battery's health can be calculated without destroying the battery if the model has been validated by the set of experimental findings. The technique is therefore suitable for battery management systems [42]. The following are examples of model-based SOH estimation methods.

- Equivalent circuit model
- Electrochemical model
- Mathematical fitting

2.6 Degradation and Aging Mechanisms

Degradation and aging of lithium-ion battery is a complex chemical process caused due to cycling and operating conditions. Degradation of a battery happens on a microscopic level of element used in it. Several factors contribute to the degradation and aging process of the battery. For example, loss of lithium inventory, loss of active material of anode and cathode, increasing internal impedance, growth of the SEI layer[12]. These factors lead to a reduction of battery capacity known as capacity fade.

Operating battery under extreme operating area like high temperature and high charging rate, over SOC results in an irreversible aging and cell failure [43]

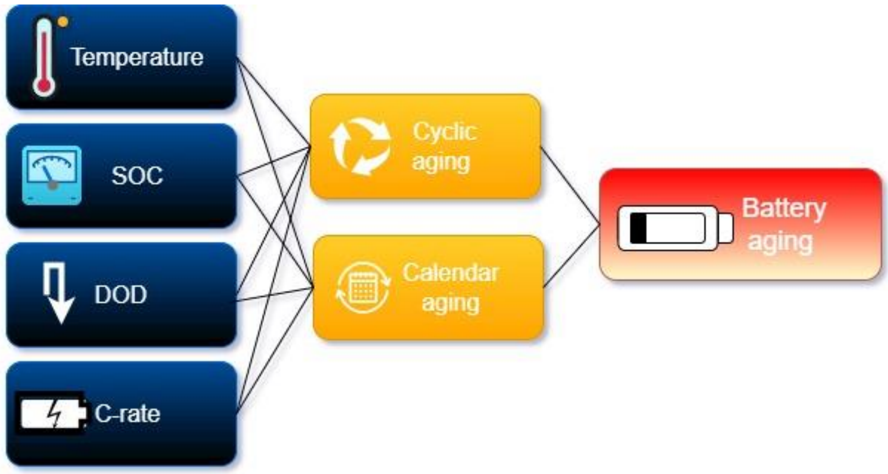

Figure 2.3: Factors affecting cycle and calendar life. Inspired by [24].

2.6.1 SEI Formation and Growth

The solid electrolyte interface (SEI) forms on the surface of negative electrode. The SEI, a coating layer, has properties of solid electrolyte. It forms first when the liquid electrolyte of a battery gets contact with the negative electrode having electron conductivity. It functions as a solid electrolyte and is usually formed at voltages lower than the electrochemical stability window of the electrolyte. Its existence, however, can expedite irrevocable redox reactions that result in electrolyte loss and breakdown [43].

Initially, during the cell's first cycle, a direct reaction between lithium and graphite produces a thin solid surface film (SEI) mainly consisting of alkyl-carbonates, polymers, and Li_2CO_3 [44]. As a result, this process causes an initial loss of 10% capacity. However, it works against further reaction of the electrolyte at the negative electrode[43]. Since the very thin thickness of SEI layer, it is electrically insulating and provides sufficient ionic conductivity for the Li-ions into the graphite particles. This too thin SEI layer allows a few numbers of electrons to tunnel through the film and results in further formation of SEI. This process continues until it grows a steady state thickness of SEI and significantly affects the internal impedance of the battery cell. The increased impedance generates heat in the battery during charging and discharging[45].

2.6.2 Lithium Plating

Lithium plating is referred to as a side reaction that results in a deposition of metallic lithium on the anode surface instead of the intended intercalation. When negative electrode becomes fully lithiated that can cause Lithium plating. In that case lithium has nowhere to go. This can happen during first charging where the rate of the side reaction in relation to the main intercalation process is increased by the high electrolyte potential. Even normal operating conditions as the cell ages and operating battery below freezing temperatures cause plating[43] [46].

Lithium plating reduces battery life by limiting intercalating and fast charging capability. It also causes further degradation that negatively affects thermal stability and safety of the battery. In some cases, it results in lithium dendrites and makes thermal runaway easier to occur [47].

Lithium plating has both reversible and irreversible components. The plated metallic Lithium increases SEI growth that can electrically isolate some lithium, forming unrecoverable dead lithium. Dead lithium and increased SEI development both result in a decrease in lithium inventory and worse conductivity due to pore blockage [43].

2.6.3 Electrolyte decomposition

All carbon-based electrodes have a feature of Electrolyte decomposition. In the operating potential range, the electrolyte is instable to the carbon material. This process causes consumption of lithium ion and reduces the number of available lithium ions to be cycled. Even after the first few cycles of the battery this process can occur and result in electrolyte decomposition. Several side reactions between lithium ions, electrolyte and electrode surface take place during operation of the battery and form a passive film referred as SEI at the negative electrode. This film prevents further reactions. This growth of SEI causes a reduction of cyclable lithium ions during the life of the battery and hence the capacity of the battery also decreases. Moreover, the battery internal impedance increases due to a lower temperature which makes lithium diffusivity more difficult. Thus, the power of the battery goes down [48] [49].

2.6.4 Particle fracture

A substantial change in volume of electrode results in stress during electrochemical reaction in the battery. This causes particle fractures in both electrodes. Due to high local current density causing larger stress, fragmentation of local particle have been noticed near the separator[43].

Particle fracture hinders electrical contract between current collectors, conductive additives, and active particles. Thus, there is a reduction in electronic or ionic conductivity in the battery which leads to capacity fade. It also enhances the formation of SEI[50].

2.6.5 Resistance Increase

Increasing battery cycles causes increased resistance which makes moving lithium ions through battery cell harder. The discharge curve moves towards lower voltage while charging curve to higher voltage due to increased resistance. This leads to less energy in battery cells. Voltage drops in the battery increase with the increase of the ohmic resistance and thus more heat generates during operation of the battery[12].

Loss of electrical contract between current collectors, conductive additives, and active particles increases internal resistance and promotes aging. Formation of SEI, Volume variations, Particle fracture, Electrolyte decomposition result in electrical contact loss in a battery cell. Similarly, Operating battery under extreme operating area like high temperature, high charging rate, over SOC, very low SOC leads to increased resistance[51].

3 Mobile Battery Systems

This chapter introduces readers to the mobile battery systems (MBS). It provides an overview of MBS and their area of application. It includes mobile battery systems size and configuration. Challenges of this system are also discussed in this chapter. After that a technical comparison between mobile battery system and other battery system applications is presented.

3.1 Introduction to Mobile Battery Systems

The MBS is defined as a truck-mounted or vehicle-mounted transportable energy storage system having standardized physical interfaces for plug-and-play operation [52]. The MBS can be installed at various power distribution network nodes to optimize efficiency and offers extremely flexible electric power delivery [53]. Similar to conventional stationary battery energy storage systems, the MBS incorporates an energy conversion system alongside battery packs. The entire system is mounted on either large vehicles or containers, enabling mobility to various locations.

The system comprises two primary components: an energy storage medium and a power conversion system. A typical MBS is depicted in the Figure 3.1

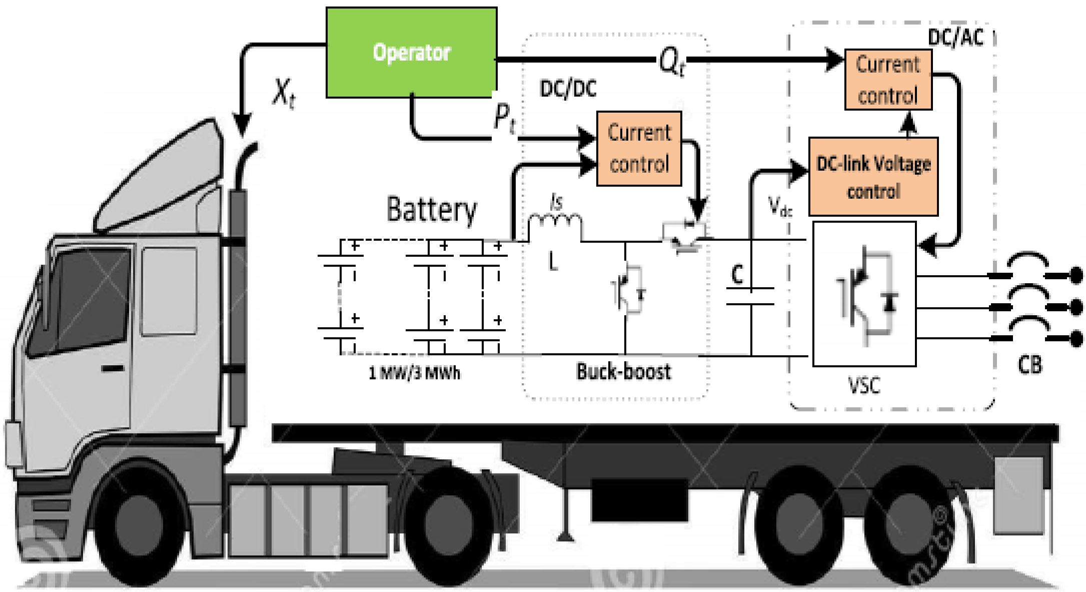

Figure 3.1: A typical mobile battery system [54].

3.1.1 Energy Storage Medium

The battery for MBS applications needs to be inherently resistant to abuse conditions including overcharge, short circuit, exposure to harsh temperatures, crush, mechanical shock, and vibration. High specific energy and power, extended cycle life, high efficiency, wide operating temperature range, and affordability are essential for this type of application in order to support commercial viability. Recent advances in lithium-ion battery technology have demonstrated substantial promise for improving specific power, specific energy, charging rate, and safety. As a result, the most common energy storage technology used in MBS is lithium-ion batteries [55] [56]. $LiCO_2$, LiNCA, LiNMC, $LiFePO_4$, $LiMn_2O_4$, LiT are examples of various electro-chemistry utilized for this type of applications. According to [53], a typical MBS features a lithium-ion battery with parameters as shown in Table 2.

Table 2 : Typical parameters of mobile battery systems

Item	Parameters
Energy density	250(Wh/kg)
Power density	500(W/kg)
Life cycle	1500(times)
Energy efficiency	85%

The battery modules are arranged in a shell formation in a container having limited space and weight carrying capacity. Consequently, the specs and technical attributes of each battery version must therefore be carefully considered during the selection process of a battery type. The critical key factors for battery selection encompass are the following.

- Smaller size and lower weight
- Temperature tolerance
- Less maintenance
- Cost of battery

3.1.2 Power Conversion System

Similar to stationary battery systems, the power conversion unit within MBS facilitates the transfer of energy between the battery and external devices or electrical systems. In an MBS this unit typically comprises two types of converters: an AC-DC converter and a DC-DC converter, the selection of which depends on the specific application requirements. The AC-DC converter functions as a bidirectional converter, enabling the conversion of alternating current (AC) to direct current (DC) during the battery charging process and vice versa during discharge. Conversely, the DC-DC converter is employed to discharge the battery power to a direct current (DC) load. The control unit includes a Human Machine Interface (HMI), Programmable Logic Controller (PLC), voltage and current sensors, temperature sensors and other sensors. The major component of an MBS is depicted in Figure 3.2

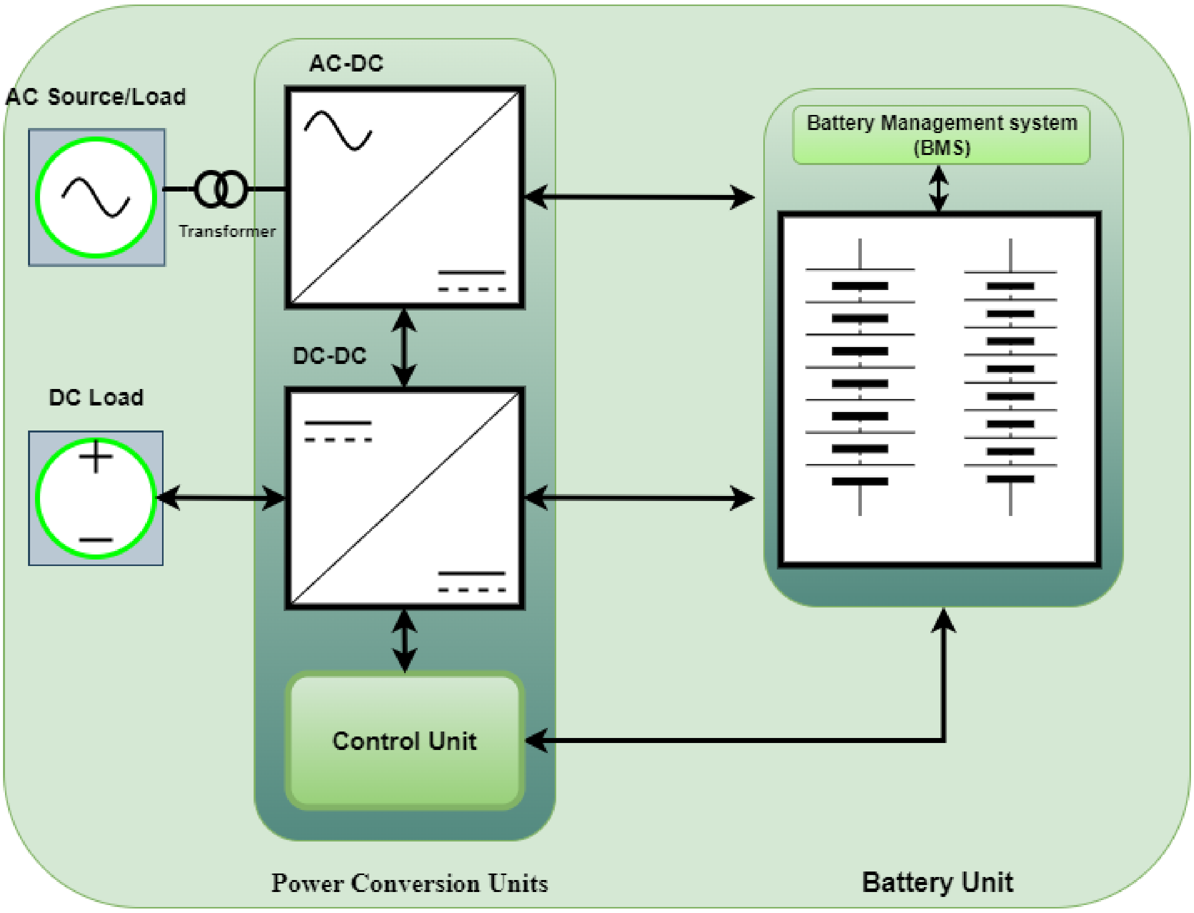

Figure 3.2: A schematic diagram of a typical mobile battery system.

3.2 Application of Mobile Battery Systems

The MBS offer portable, scalable, silently operatable ways to power various applications in different environments. The systems find a wide range of applications across industrial sectors, including emergency response, construction, entertainment, telecommunications, and remote off-grid locations. The system can operate both normal conditions and during emergency events. During normal operational condition, they can serve grid-related functions such as load leveling, peak shaving, spatiotemporal energy arbitrage, reactive power support, renewable integration, and transmission deferral[52]. Moreover, they can facilitate the charging of heavy equipment and electric vehicles (EVs). MBS can serve as essential sources of backup power for both industrial establishments and residential dwellings. Following natural disasters such as hurricanes or earthquakes, these systems can be deployed to provide essential energy support[55].

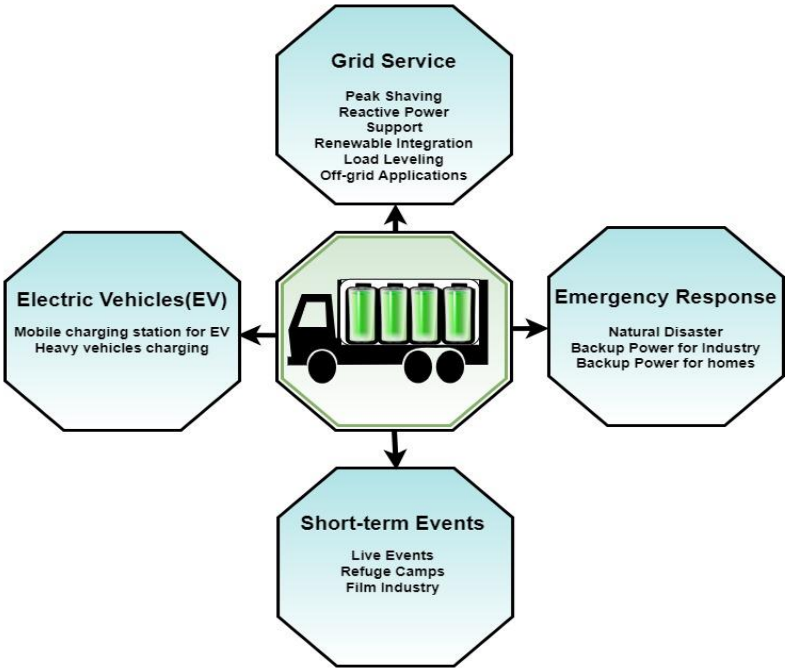

Figure 3.3: Application area of mobile battery systems.

3.3 System Size and Configuration

The size and configuration of MBS are determined by factors such as their intended applications, portability, and the type of batteries they use. Many studies have been conducted to determine the optimal dimension for these systems. For example, the optimal sizing of MBS for renewable energy integration was studied in [57] and [58]. Another study in [59] , an algorithm was introduced to determine the optimal size and location of a MBS in power distribution systems to improve voltage regulation and power losses. The study [60] presents a MBS designed to integrate with a stationery system. Many companies operate MBS with various options and configuration in the market, ranging from smaller units with a few kilowatt-hours (KWh) of capacity to larger systems with up to several megawatt-hours (MWh) capacity. A compact container can house an entire MBS with a small capacity. However, for systems with a larger capacity, it may be necessary to utilize two separate containers: one to accommodate the battery packs and another for the power conversion unit. A container with battery storage system shown in Figure 3.4

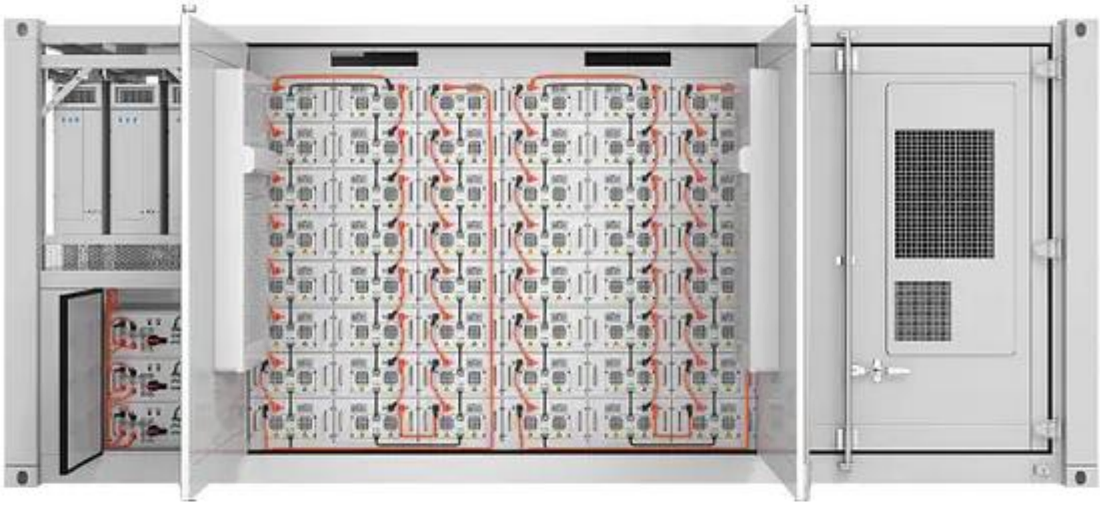

Figure 3.4: A container with battery storage system[61].

The configuration of a system with a rated power of 1MW can differ from one company to another. The specific configuration for such a system is outlined in Table 3.

Table 3: Specification of a battery system with 1MW rated power.

Manufacturer	EVESCO (Electric Vehicle Energy Storage Company)
Rated Power	1MW
Input/Output Voltage	690Vac
DC voltage Range	1075.2 – 1363.2 Vdc
Frequency	50/60 Hz
Rated Storage Capacity	2064kWh
Battery Chemistry	Lithium Iron Phosphate (LiFePO4)
Container	1(6058mm×2438mm×2591mm)
Application	PV, Micro-grid, Peak-shaving, Backup Power, EV Charging

3.4 Challenge of Mobile Battery Systems

Despite their numerous advantages and wide-ranging applications, MBS also faces several challenges that should be carefully considered. Operational boundaries, technological limitations, and regulatory requirements are some of the causes of this challenge. Addressing these issues is essential for reliable operation and high efficiency of the MBS in various environments. A survey on challenges and solution of the MBS was conducted in [62]. In another study [52] presents challenges of the systems to integrate with grid system. As per the study, the challenges confronting MBS encompass transportation logistics, grid limitations, cost-effectiveness, and integration for enhancing power grid resilience during emergency response. The primary challenges faced by these systems are outlined as follows.

- Ttransportation
- Energy storage limitations
- Environmental challenges
- High investment and charging cost.
- Grid peak demand conflicts.
- Optimal Operational Scheduling

3.5 Comparison Mobile vs Stationary Battery Systems

Even though capacity and system size of MBS is limited by transportability of the entire systems, they can serve the purpose of a stationary application also. In terms of applications, both mobile and stationary battery systems (SBS) can share common applications and operational domains. In particular, both MBS and SBS exhibit applicability in integrating with grid systems for purposes such as load leveling, peak shaving, and photovoltaic (PV) smoothing. Moreover, combination of MBS and SBS presents the potential solution for the mentioned applications [60]. MBS and SBS.

Table 4 shows the common applications of both MBS and SBS.

Table 4: Comparison regarding applications of both mobile and stationary battery systems.

Application	Mobile battery systems	Stationary battery system	Combination of both systems
Off-grid Power	✓		
Frequency Regulation	✓	✓	✓
Load Levelling	✓	✓	✓
Renewable Energy (PV)	✓	✓	✓
Peak-Shaving	✓	✓	✓
Reactive Power Support	✓	✓	✓

Technically the system configuration for both systems can be the same. And can be operated within the same operational boundary. A technical comparison between an MBS designed for 1MW rated power and a battery system for stationary applications is presented in Table 5.

Table 5: A technical comparison between same sized mobile and stationary battery systems.

Description	*Mobile battery system [61]*	*Stationary battery system [63]*
Battery Chemistry	LiFePo4	LiFePO4
Rated power	1000kW	1000kW
Nominal Energy	1106 kWh	1200kWh
Nominal capacity	1440Ah	280Ah
DoD	95%	80%
Nominal DC Voltage	768 V	716.8V
DC voltage range	672 – 852 V	627V – 817V
Nominal AC Voltage	480V	400V
AC Voltage range	423- 528 volts	-
Maximum C-rate	1C	1C
Temperature range	-20°C to 55°C	0°C to 55°C

It is possible to see MBS as transportable versions of SBS due to the similarities between the two systems' applications operational domains, battery technology, and technical requirements.

While MBS and SBS share certain features and objectives, a detailed examination reveals significant differences in system size, energy density, mobility, and operational scope. Due to transportation limitations, MBS prioritizes compactness and lightweight construction. Consequently, battery chemistry in these systems necessitates high energy density (Wh/kg) and power density (W/kg) to maximize achievable system size. In contrast, stationary battery systems can afford to be larger and heavier, as they are intended for fixed installations and are not subject to the same mobility constraints. The largest stationary battery system has an energy storage capacity of 3287 MWh whereas 12MWh capacity is recorded as the largest MBS[64] [65]. Stationary systems prioritize characteristics like lifespan and cycle life because they are installed for long-term solutions and primarily serve large-scale power demands. Compared to their stationary counterparts, MBS have a wider range of applications and can meet power needs in locations that are inaccessible to stationary systems.

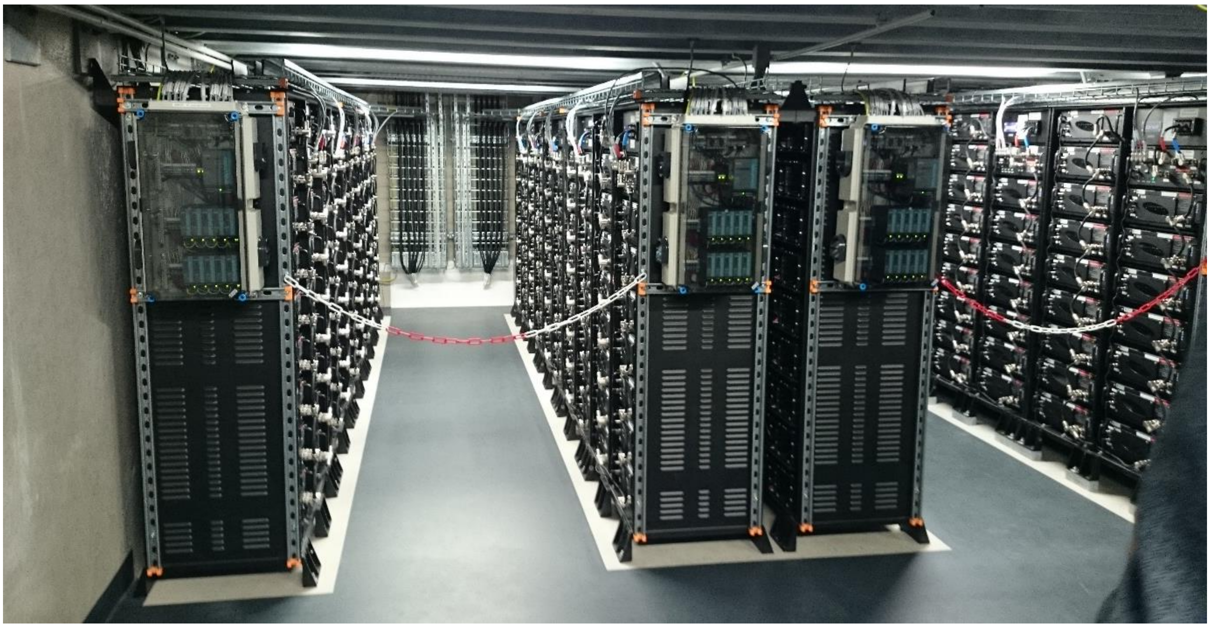

Figure 3.5: Interior view a battery storage power plant [64].

MBS, lacking fixed installed structures, are subject to exposure to diverse environmental conditions, necessitating robust thermal management systems to ensure optimal performance and safety. Indoor installation setups simplify the maintenance of consistent environmental conditions in SBS.

For MBS, frequent mobility means higher operating expenses. This results in higher per unit ($/kWh) energy cost compared to SBS [53]. Additionally, transportation requirements necessitate additional safety measures to mitigate the risk of system damage from vibrations. In order to reduce the possibility of damage during mobility, additional safety precautions are also required, for example vibration monitoring, use of anti-vibration mountings for battery racks and inverters.

Table 6:A general comparison between mobile and stationary battery systems.

Description	*Mobile battery system*	*Stationary battery system*
Purpose	Short-term power supply	Long-term power supply
System size range	Few kilowatts (KW) to several mega-watt (MW)	Few kilowatts (KW) to several giga-watt (MW)
The recorded largest system	12MWh	3287 MWh
Prioritize factor	High energy density (Wh/kg), power density (W/kg)	Lifespan, cycle life, cost of energy
Mobility	Transportable	Non-transportable

Battery technology	Mainly Lithium ion	Several types of battery (lithium ion, lead-acid)
Environmental barrier	It is subject to exposure to diverse environmental conditions	It is not exposed to a variety of environmental factors.
Cost	Higher per unit energy cost	Lower per unit energy cost
Safety requirement	Additional safety precautions required due to frequent mobility	Fixed installation and thus requires fewer safety precautions.

Comparison Mobile Battery Systems vs. EV

Battery systems for electric vehicles (EV) is a complex concept. It requires higher power delivery in short intervals to meet motor demands while ensuring vehicle safety. This necessitates an efficient packing of the battery system within the vehicle's framework to maximize power storage capacity to support extended driving distances without frequent recharging. Compared to MBS, the EV battery system's size is relatively lower ranging from 0.5 kWh to 100kWh. The voltage range is 100v-200V for hybrid/plug-in hybrid vehicles and 400-800V for electric-only vehicles. DC-DC boost/ buck boost converter is used to this system[66].

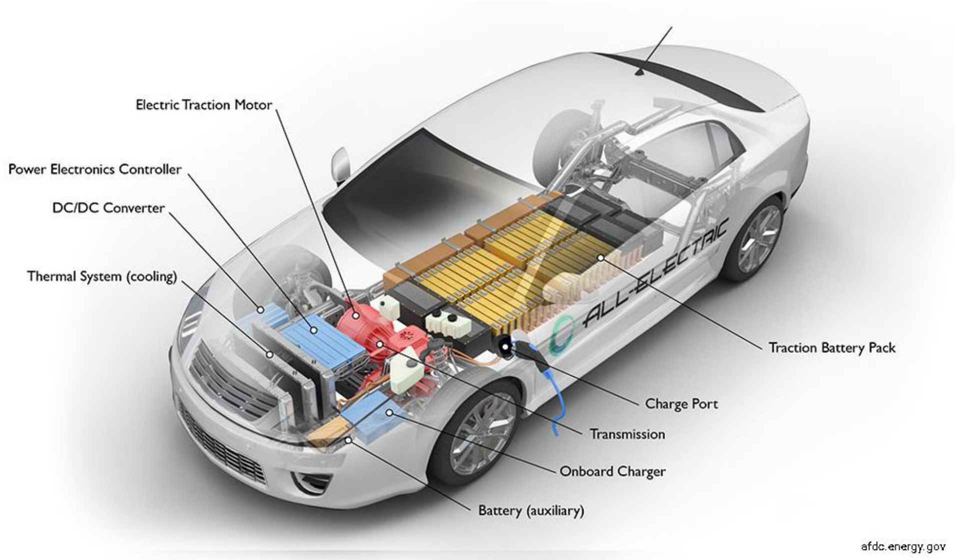

Figure 3.6: A electric vehicle (EV) battery system [67].

Table 7 provides a technical comparison between the configurations of Tesla electric vehicles and an equivalently sized transportable MBS.

Table 7:Technical comparison between an MBS and battery system of Tesla EV car.

Description	Mobile battery system	Tesla Model 3
Battery	3.2V 90Ah LiFePO4	LiFePO4
Rated Power	60 kW	-
Nominal Energy	128kWh	60.0 kWh
Nominal Voltage	400 Vac	No
Voltage Range	314 - 398 Vdc	355V DC
Power converter	Bi-directional conversion	DC-DC converter
Operating Temperature Range	-20°C to 40°C	-30°C to 60°C
Cooling	Forced air cooling	Forced cooling liquid (Water and glycol)

Differences in purpose, system size, applications, and operating circumstances are evident between the MBS and electric vehicles (EVs). MBS works as substitutes for SBS and have a wide range of applications. While the battery system for electrical vehicles has fixed application to supply power to motor of the vehicles. The above thorough analysis of MBS, SBS and battery system of EVs reveals that MBS bear greater resemblance to SBS than to battery systems designed for electric vehicles (EVs) [26] [68].

4 Battery System Testing Methodology

This chapter presents an overview of performance tests and testing methodology applied in battery system for both Electric vehicles (EV) and stationery application. It includes a generalization of testing requirements and challenges. A summary of different test standers is shown in this chapter. Based on the overview of battery system testing in this chapter a testing proposal for MBS will be given in the next chapter.

4.1 Battery Testing

There is no uniform testing method that exists to quantify all the characteristics and conditions of a battery in a single comprehensive test. Since technical characteristics like SOC, SOH cannot be measured directly from a test, different methods are applied to estimate these conditions using test results conducted in various degrees [69]. The battery tests can be conducted in three levels like cell, module, and pack level. Every testing level presents different information about the condition and performance of the battery.

4.1.1 Cell Testing

Battery cell testing examines the behavior of chemical reactions to comprehend electrochemical performance attributes and predict the viability integration into a battery module or pack [70]. In the cell testing, the internal chemical reactions, properties of cell materials, cell performance, energy storage capacity are some of the main focus points of study. The testbed for cell testing requires a small setup compared to module and pack testing. A thermal chamber and a cell cycler are enough to conduct performance test of a battery cell. Even though battery cell testing is easier and requires small test setup, it does not represent the entire battery system in high power applications, for example EV.

4.1.2 Module Testing

Module testing investigates the behavior of battery as a unit consisting of many cells. Based on the application of the module battery module testing is selected. The testing focuses on the overall battery performance, cell balancing, safety, internal heating characteristics and many more under different environmental conditions. Module testing requires a bigger test setup compared to cell testing and thus more expensive than cell testing. Even though it is cheaper and less risky than testing battery pack or an entire system, it also does not reflect the testing of the entire battery system.

4.1.3 Pack/ System Testing

Since cell and module level testing does not present overall behavior of entire system, pack testing is needed. Testing battery pack or entire system is carried out after final assembly. However, some tests are conducted just before the final assembly. To verify that every pack subsystem operates as intended, including the safety features, external hardware, and BMS communications, a comprehensive set of tests must be performed. The pack testing includes measuring SOC, direct current internal resistance (DCIR), SOH, internal resistance. As the pack consists of some other electronic components and systems that are attached to the battery like BMS, additional testing is required[70]. This thesis focuses on battery testing in pack and system level mainly.

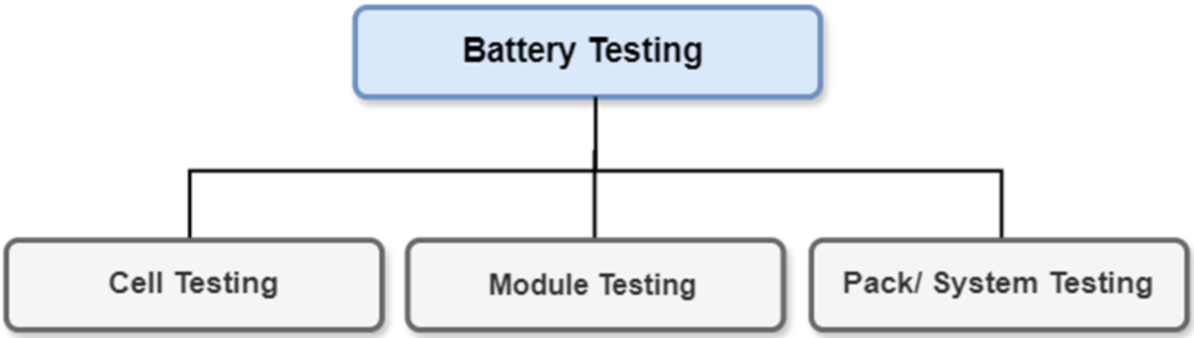

Table 8: A comparison among battery cell, module, and pack testing.

Test level	Key focus points	Benefit	Downside
Cell	Cell performance	Compared to other testing levels, cell testing is easier, cheaper, and safer	It does not represent the entire system
	Properties of cell materials		
	Chemical reactions		
Module	Cell balancing	Modules testing gives some idea of how the cells will interact with other cell	It does not represent the entire system
	Thermal characteristics	This testing is cheaper than testing the entire system	Compared to cell testing, it is more expensive
		It has less risk of thermal runaway than in a system	
Entire System/Pack	Overall system performance	The best picture on the entire system respond are reflected on the testing	It requires additional testing for external electronics components.
			More expensive than cell and modules testing

4.2 Test Conditions and Scaling

Test conditions and scaling are determined based on factors including battery test types, application, system size, configuration and battery technology. Before conducting tests, it is essential to create a proper environment for the tests considering some technical boundaries and limitations for test efficiency and safety. The research papers [71] [72] present an overview of test conditions including voltage limit, temperature and pressure control, pretest charging and discharging procedure.

4.2.1 Voltage Limits

The electrochemical voltage range of battery between 100% SOC and 0% SOC are referred to as the maximum and minimum operating voltage respectively. The operating voltage limit is recommended by the manufacturer based on the battery type and material used in it. Operating under or over the limit reduces the performance and life span of the battery. Various tests necessitate different levels of SOC, thereby leading to different voltage levels within the battery's operational window. For initial static capacity test the battery needs to be discharged for maximum voltage (V_{max}) to minimum voltage (V_{min}) to ensure stability in rated capacity. Every test should be carried out between V_{max} and V_{min} within the operating window. Beside the operating voltage limits, the manufacturer of the battery provides the specification for the maximum ($V_{\max\_pulse}$) and minimum ($V_{\min\_pulse}$) pulse voltage limit for short duration charge and discharge[73] [72].

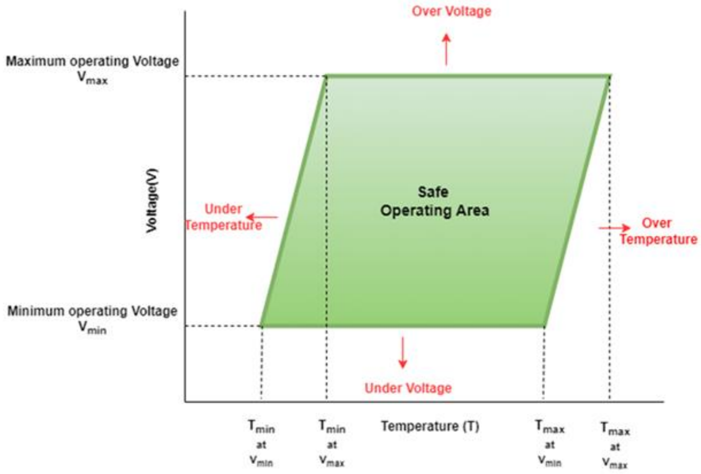

Figure 4.1: Safe operating boundary of battery system.

4.2.2 Temperature Control

The battery system must undergo testing across a range of temperatures to assess its performance under diverse environmental conditions. Tests like static capacity, thermal performance test energy are performed under various thermal conditions (-30°C to +52 °C) where high-rate charge, self-discharge tests require ambient temperature (30 °C). To control the temperature, all testing should be conducted in thermal chamber for EV application. During a long rest time to allow the battery to reach stable condition, voltage and temperature in the chamber should be monitored [73].

4.2.3 Scaling

Performance and cycle life test profiles are determined based on full size system levels. A technique for adjusting these test profiles to the device's size is necessary for testing any device that is smaller than a full-scale system. In the battery system performance test, the scaling is done applying a battery size factor specified by manufacturer. However, this factor can be determined from the beginning of life low current HPPC test using rated c-rate[71].

4.2.4 Charging and Discharging Procedure

As different % SOC, voltage and power level are prerequisites of various tests, the battery system needs to be charged or discharged to bring the level to the required state. A specific charging and discharging method are applied for maintaining the state level. Generally, C/1 rate charging current is applied to charge the battery when C/3 discharging current is applied to drain the battery. Battery manufacturers specify the charging and discharging procedure and resting period for every charge cycle [73].

4.3 Pre-test Parameters and Mathematical Model

Pre-test parameter identification is a crucial stage in the testing process that makes it easier to analyze battery systems accurately and quickly. Test parameters are identified according to the test types and mathematical models. To estimate the SOC of battery, different methods are applied like coulomb counting, open circuit voltage, and the Kalman filter method. Based on the SOC estimation method HPPC test requires parameters for internal resistance, open circuit voltage (V_{ocv}), maximum and minimum pulse current ($I_{\max\_pulse}; I_{\min\_pulse}$). According to[74] the battery system performance testing method should cover the following unit parameters in general as shown in

Table 9.

Table 9: General parameters for battery system performance testing.

Parameters for battery system
Actual energy capacity
Input and output power rating
Round trip energy efficiency
Expected service life
System response
Auxiliary power consumption
Self-discharge of battery systems
Voltage range
Frequency range

4.4 Battery Testing Challenges

Due to complexity and hazardous nature of battery, testing a battery system is a complex and time-consuming process. Battery system testing requires real-world situations to be replicated by adapting to communication signals from the system, batteries, or other devices. Challenges of battery system testing include test complexity, test set-up, long time testing process, addressing safety issues. Battery testing and its preparation takes a very long time to understand the intricate behavior of the battery. It becomes imperative to rerun the tests to acquire a comprehensive understanding of the battery system's response over time. According to [70] and [75] the main challenges of battery system testing are as following.

- Testing takes a long time to process. Some tests and errors in testing necessitate re-running the tests.
- The hazardous nature of battery poses risks of environmental damage, toxic chemical leakage, internal short circuit thus require taking safety measurement.
- Requirement of large and expensive test set up.
- Data collection in large volume and its analysis is time consuming.
- Different applications require different tests and tests set up.
- Multiple instruments and software need to be integrated.

4.5 Battery System Test standards

Battery test standards provide guidelines for battery design, production and testing to meet requirements regarding energy efficiency, reliability, and environmental effect for different industries and applications. These standards cover a wide range of aspects including performance metrics, manufacturing processes and safety requirements. Industrial organizations and different regulatory bodies develop battery standards focusing on advancement in technology, emerging challenges in battery industry.

The international organizations for standardization that deal with battery standardization are as follows.

- International Standardization Organization, ISO
- International Electrotechnical Commission, IEC
- Underwriters Laboratories, UL

An overview of battery test standards developed by such international organizations is given for the evaluation of battery performance in Table 10

Table 10: Battery test standards for EV and stationary applications.

Application	Battery Standard
Electric Vehicles	IEC 62660-1:2010 Rechargeable Cells Standards Publication Secondary lithium-ion cells for the propulsion of electric road vehicles. Part 1: Performance testing
	ISO 12405-1:2009: Electrically propelled road vehicles -- Test specification for lithium-ion traction battery packs and system
	ISO 12405-2:2009: Electrically propelled road vehicles -- Test specification for lithium-ion traction battery packs and system
	ISO 12405-4:2018: Electrically propelled road vehicles -- Test specification for lithium-ion traction battery packs and systems -- Part 4: Performance testing
	DOE-INL/EXT-15-34184: Battery test manual for electric vehicles
	DOE-INL/EXT-07-12536: Battery test manual for plug-in electric vehicles
	SAE 2288 Life Cycle Testing of Electric Vehicle Battery Modules
Stationery Battery Systems	(DOE) PNNL -22010: Protocol for Uniformly Measuring and Expressing the Performance of Energy Storage Systems
	IEEE 1661: IEEE Guide for Test and Evaluation of Lead-Acid Batteries Used in Photovoltaic (PV) Hybrid Power Systems
	IEEE Std 1106™, IEEE Recommended Practice for Installation, Maintenance, Testing, and Replacement of Vented Nickel-Cadmium Batteries for Stationary Applications
	Electric Power Research Institute: Energy Storage Integration Council (ESIC) Energy Storage Test Manual 2016

4.6 Battery System Testing Equipment

Battery system testing conducted either at the cell, module or pack level requires precise measurement and controlling of parameters like battery terminal voltage, charging/discharging current. Some testing, particularly field testing on battery systems, involves complicated processes and necessitates gathering battery performance data continually during the execution of the tests. Therefore, it is crucial to utilize appropriate testing instruments with high efficiency to prevent errors and high testing costs.

A deep understanding of battery systems and testing activities is required for an optimal test setup and selecting suitable test equipment capable of meeting requirements for a wide range of test configurations. To evaluate the performance of battery systems, a comprehensive battery testing set-up must include testing equipment like bidirectional power supplier, battery tester, data acquisition system, thermal chamber [76].

Bidirectional power supplier: A bidirectional power supplier, also referred to as an AC/DC power converter, facilitates the suppling and controlling of the necessary charging current to a battery. It must have sufficient rated power capacity, along with the required voltage and current range. Additionally, it must be capable of integrating with grid systems and operating in constant current (CC), constant voltage (CV), and constant power (CP) charging/discharging mode functions.

Battery tester: battery tester, a measuring device used to measure the terminal voltage of battery. the battery testers must be capable of handling the voltage and current range of battery systems under test. The voltage range, accuracy, sampling time are the key factors for selecting a battery tester[77].

Data acquisition system: for collecting measurement of key parameters in real-time from sensors, storing the recode for further analysis the data acquisition system is equipped with sensors, data loggers and software. It should maintain continuous tracking of all measurements, ensuring uninterrupted flow of parameter readings, and transmit the collected data to the associated computer for real-time monitoring[78].

Thermal chamber: during tests battery systems are subject to a predefined temperature range from -40°C to 70°C [79]. The thermal chamber should provide control over this range of temperature maintaining proper humidity.

4.7 Battery System Performance Tests

Battery tests can be categorized into different types like performance, interconnection, Communications and Control test, safety and abuse test, mechanical test, environmental test [80]. However, the thesis intends to study mainly the battery system performance testing.

Battery system performance testing investigates its overall capability and operational characteristics in various conditions. The performance testing focuses on measuring and analyzing the key parameters such as energy storage capacity, efficiency, voltage response and stability, cycle life, and thermal management.

The following sections summarize the performance testing of EVs and SBS recommended by different battery test standards.

4.7.1 Battery system performance tests for EV applications

The overview of battery system performance tests for electric vehicles (EV) is presented in Table 11

Table 11: Battery system testing for EV.

Test Name	Test purpose	Test equipment	Test Condition	Parameters	Equation	Reference
Static Capacity Test	To measure device capacity in ampere-hours (Ah) and energy content as function of C-rate and temperature	Current Sensor Voltage Sensor Data Logger Temperature sensors Thermal chamber	Temperature- 0°C, 25°C and 45°C Constant discharge current	Maximum voltage limit V_{max} Minimum voltage limit V_{min} C-rate Accepted charge Energy, (E_C) Delivered discharge Energy, (E_d) Energy consumed by auxiliary loads during charge (E_{AC})	$Capacity = Time * Current$ $Capacity\ fade(\%) = 100 * (1 - \frac{Capacity_{measured}}{Capacity_{rated}})$ $Energy\ fade(\%) = 100 * (1 - \frac{Energy_{measured}}{Energy_{rated}})$ $Available\ charge\ energy = E_c - E_{Ac}$ $Available\ discharge\ energy = E_d - E_{AD}$	IEC 62660-1:2010 ISO 12405-1:2009 ISO 12405-2:2009 [73] [71]
Hybrid pulse power characterization (HPPC)	1.To determine dynamic characteristics of battery over its useable voltage range 2.To calculate SOC of battery	Current Sensor Voltage Sensor Data Logger Temperature sensors Thermal chamber	1.Starting condition: temperature (-10°, 0°, 10°, 25 °C) and 2.Fully charged battery 3. SOC at10%, 20%,30%....90 % 4. Charge and discharge current (A) I_{max} , $0.75I_{max}$	Maximum pulse voltage V_{max_pulse} Minimum pulse voltage V_{min_pulse} Pulse voltage V_{pulse} Open circuit voltage V_{ocv} Discharge current pulse I_d Battery Internal resistances R_b(Ohms) Battery capacitances C_b (F) Time constants τ_b (s)	Discharge Resistance $R_{discharge} = \frac{\Delta V_{dischage}}{\Delta I_{discharge}}$ Regen Resistance $R_{discharge} = \frac{\Delta V_{regen}}{\Delta I_{regen}}$ Discharge Pulse Power Capability $= \frac{V_{min\_puls}(V_{ocv} - V_{min\_pulse})}{R_{discharge}}$ $Regen\ Pulse\ Power\ Capability = \frac{V_{max\_puls}(V_{max\_pulse} - V_{ocv})}{R_{regen}}$	IEC 62660-1:2010 ISO 12405-1:2009 ISO 12405-2:2009 [71] [73]

Peak power	To determine dynamic pulse power capability under load conditions with respect to its operating voltage range	Current Sensor Voltage Sensor Data Logger Temperature sensors Thermal chamber	1.Starting condition: temperature (-10°, 0°, 10°, 25 °C) 2.Fully charged battery 3. SOC at10%, 20%,30%....90% 4. Charge and discharge current (A) I_{max}, $0.75I_{max}$	Maximum pulse voltage $V_{\max\_pulse}$ Minimum pulse voltage $V_{\min\_pulse}$ Pulse voltage V_{pulse} Open circuit voltage V_{ocv} Discharge current pulse I_d Base current I_{base} Battery operating capacity Q_b High test current $I_{High\ test\ current}$ Device capacityC_{device}	Same as Hybrid pulse power characterization (HPPC) and $Base\ current\ I_{base} = \frac{(12*C_{device} - I_{High\ test\ current})}{35}$	[71]
Self-discharge rate	To determine the temporary capacity loss caused by battery standing for a curtain time	Current Sensor Voltage Sensor Data Logger Temperature sensors Thermal chamber	1. Thermal stability at a temperature of 30 °C for 30 days. 2. Starting SOC at 100% 3.Constant discharge current	Maximum voltage limit V_{max} Minimum voltage limit V_{min} C-rate capacity recorded Q_b Resting time ($Time_{rest}$)	$Self\ Discharge = \frac{W_{before\ test} - W_{after\ rest\ time}}{W_{before\ test}} * 100$ $Self\ Discharge\ rate = \frac{Self\ Discharge\ power}{Time_{rest}}$	ISO 12405 1:2009 ISO 12405-2:2009 [71] [73] [81]

Thermal performance	1.To exhibit the capacity to reach a portion of the Peak Power target over a range of temperatures. 2.To design thermal management system	Current Sensor Voltage Sensor Data Logger Temperature sensors Thermal chamber	Various temperatures within the operating temperature target range (-30 °C to +52ºC).	Maximum voltage limit V_{max} Minimum voltage limit V_{min} C-rate Nominal Voltage $V_{nominal}$ Temperature t_b		[71] [73]
High-Rate Charge	To verify the capability of battery system to supply a fraction of working capacity with constant current charging from minimum voltage over a certain period.	Current Sensor Voltage Sensor Data Logger Temperature sensors Thermal chamber	Ambient Temperature 3.2 C rate	Maximum voltage limit V_{max} Minimum voltage limit V_{min} Measured open-circuit voltage $V_{measured}$ C rate Time(s)		[71] [73]
Energy Efficiency Test	1.To determine efficiency of battery 2. To construct a cycle-life pulse profile	Current Sensor Voltage Sensor Data Logger Temperature sensors Thermal chamber	1.Temperature at -20°C; 0°C; 25°C and 45°C 2. SOC range at 100%, 70%, 50%, and 35% 3. Perform 100 cycles	Measured open-circuit voltage $V_{measured}$ Accepted charge Energy, (E_C) Delivered discharge Energy, (E_d) Number of cycles(n)	$Average\ charge\ energy\ E_{C\_average} = \frac{1}{n}\sum_{i=1}^{n} E_C$ $Average\ discharge\ energy\ E_{d\_average} = \frac{1}{n}\sum_{i=1}^{n} E_d$ $Round\ Trip\ Efficiency\ (RTE) = \frac{E_{d\_average}}{E_{C\_average}} * 100$	IEC 62660-1:2010 ISO 12405-1:2009 [71] [73]

cycle life	To ensure the device can meet some specified technical characteristic targets	Current Sensor Voltage Sensor Data Logger Temperature sensors Thermal chamber	1. Thermal stability at ambient temperature (30°C)	1. Peak Power P_{peak} 2. Available Energy 3. Maximum voltage limit V_{max}	IEC 62660-1:2010 ISO 12405-1:2009 ISO 12405-2:2009 [71] [73]
Calendar life	To evaluate cell or battery degradation over lifetime.	Current Sensor Voltage Sensor Data Logger Temperature sensors Thermal chamber	1. Temperature(45°C) 2. SOC range at 100%, 50%.		IEC 62660-1:2010 ISO 12405-1:2009 ISO 12405-2:2009 [71] [73]
Cold Cranking Test	To measure power capability with 2s pulse at -30ºC temperature to compare with a specific Cold Cranking Test Profile.	Current Sensor Voltage Sensor Data Logger Temperature sensors Thermal chamber	1.Starting condition is at ambient temperature 2. Reduce the ambient temperature to –30ºC. 3. available Charge-depleting 4. available Charge-Sustaining	1. A specific Cold Cranking Test Profile by manufacturer 2. Power P(kW) 3. Time(s)	[73]

4.7.2 Battery system performance tests for Stationary applications

The overview of battery system performance tests for stationery is presented in Table 12below.

Table 12: Battery system testing for Stationary application.

Test Name	Test Name	Test equipment	Test Condition	Parameters	Equation	Reference
Stored Energy Capacity Test	To determine the stored energy capacity of battery	Current Sensor Voltage Sensor Data Logger Temperature sensors	1.Rate power 100%.75% and 50%. 2. ambient Temperature (25°C) 3.SOC at 100%,75%, 50% and 25%	Maximum voltage limit V_{max} Minimum voltage limit V_{min} C-rate Accepted charge Energy, (E_C) Delivered discharge Energy, (E_d) Energy consumed by auxiliary loads during charge	$Capacity = Time * Current$ $Capacity\ fade(\%) = 100 * (1 - \frac{Capacity_{measured}}{Capacity_{rated}})$ $Energy\ fade(\%) = 100 * (1 - \frac{Energy_{measured}}{Energy_{rated}})$ $Available\ charge\ energy = E_c - E_{Ac}$ $Available\ discharge\ energy = E_d - E_{AD}$	[81] [80]
Roundtrip Energy Efficiency Test	To determine roundtrip efficiency for validating energy delivering capability of battery	Current Sensor Voltage Sensor Data Logger Temperature sensors	1. SOC at 100%,75%, 50% and 25%	Maximum voltage limit V_{max} Minimum voltage limit V_{min} Initial test voltage $V_{initial}$ C-rate Accepted charge Energy, (E_C) Delivered discharge Energy, (E_d) Energy consumed by auxiliary loads during charge (E_{AC})	$Average\ charge\ energy\ E_{C\_average} = \frac{1}{n}\sum_{i=1}^{n} E_C$ $Average\ discharge\ energy\ E_{d\_average} = \frac{1}{n}\sum_{i=1}^{n} E_d$ $Average\ Energy\ consumed\ by\ auxiliary\ loads\ during\ charge\ E_{AC\_average} = \frac{1}{n}\sum_{i=1}^{n} E_{AC}$ $Average\ Energy\ consumed\ by\ auxiliary\ loads\ during\ discharge\ E_{AD\_average} = \frac{1}{n}\sum_{i=1}^{n} E_{AD}$ Round Trip Efficiency $(RTE) = \frac{E_{d\_average} - (E_{AD_{average}} + E_{AC_{average}})}{E_{C\_average}} * 100$	[81] [80]

Reference Signal Tracking Test	To estimate the ability of the battery to track the applied reference signal	Current Sensor Voltage Sensor Data Logger Temperature sensors	1. Ambient Temperature (25°C)	Commanded Power (P_{signal}) Instantaneous output power (P_b) Rated power (P_{rated}) Number of cycles(n)	$Tracking\ error\ RMS = \sqrt{\frac{\sum(P_{signal}-P_b)^2}{n}}$ $Tracking\ error\ RMS\ \% = \frac{\sqrt{\frac{\sum(P_{signal}-P_b)^2}{n}}}{P_{rated}}$	[80] [81] [82]
Response Time and Ramp Rate	To determine the amount of time required for the battery for transition from no discharge to full discharge and no charge to full charge	Current Sensor Voltage Sensor Data Logger Temperature sensors	1. Ambient Temperature (25°C) 2. SOC at 100%, and 50%	Active Charge Power (P_{charge}) Active Discharge Power ($P_{discharge}$) Rated power (P_{rated}) Response Time ($T_{response}$) Rise Time(T_{rise}) Delay Time(T_{delay})	Response Time ($T_{response}$) = $delay + time\ to\ reach\ from\ 0\%\ to\ 100\%\ rated\ power$ $Ramp\ rate = \frac{P_{rated}}{T_{response}}$	[80] [81] [82]

Self-Discharge Rate	To determine the temporary capacity loss caused by battery standing for a curtain time	Current Sensor Voltage Sensor Data Logger Temperature sensors	1. Ambient Temperature (25°C) 2. SOC at 100%	Initial test voltage $V_{initial}$ Initial power $p_{initial}$ Power lost over the time p_{loss} Total operation Time (T_{total})	$Self\ Discharge = \frac{W_{before\ test} - W_{after\ rest\ time}}{W_{before\ test}} * 100$ $Self\ Discharge\ rate = \frac{Self\ Discharge\ power}{T_{total}}$	[80] [81]
Energy Capacity Stability	To determine Energy Capacity Stability compared to the initial stored energy capacity	Current Sensor Voltage Sensor Data Logger Temperature Sensors	1.Rate power 100%.75% and 50%. 2. ambient Temperature (25°C) 3.SOC at 100%,75%, 50% and 25%	Maximum voltage limit V_{max} Minimum voltage limit V_{min} C-rate Initial stored energy capacity ($E_{initial}$) Accepted charge Energy (E_C) Delivered discharge Energy (E_d) Energy consumed by auxiliary loads during charge (E_{AC})	$Energy\ stability = \frac{E_{storad}}{E_{initial}}$	[81]

Duty Cycle	To produce the information required in order to assess and report on a battery system operational efficacy in a specific technical application.	Current Sensor Voltage Sensor Data Logger Temperature sensors	1.Rate power 100%.75% and 50%. 2. ambient Temperature (25°C) 3.SOC at 100%,75%, 50% and 25%	Maximum voltage limit V_{max} Minimum voltage limit V_{min} Initial test voltage $V_{initial}$ C-rate Accepted charge Energy, (E_C) Delivered discharge Energy, (E_d) Energy consumed by auxiliary loads during charge (E_{AC}) Energy consumed by auxiliary loads during discharge (E_{AD}) Initial Energy ($E_{initial}$)		[80] [81]

5 Testing Proposal for Mobile Battery Systems

This chapter offers a comprehensive testing methodology applicable for mobile battery systems (MBS) analyzing well-established testing methods utilized for EV and SBS. Subsequently, the chapter outlines a proposal testing system for MBS. Within the proposal, a thorough description of applicable tests and requisite testing equipment is also presented in the chapter to evaluate the performance of the MBS.

5.1 Basis of Proposal

Developing a comprehensive performance testing method for MBS is crucial yet challenging. Several factors must be carefully taken into consideration for a proper testing method. Specifically, a critical analysis of battery basics, the distinct features of MBS, important metrics, and existing testing methods can help identify the most suitable testing approach for the MBS.

The study on fundamentals of a battery in Chapter 2 reveals that SOH of battery depends on operating voltage, SOC, internal resistance, operating temperature. Therefore, the proposed test system should measure these parameters.

The review of MBS in Chapter 3 indicates that the MBS are technically more similar to SBS than battery systems of EVs in terms of applications, system properties, system size. Therefore, the existing testing methods for stationary applications are more applicable to the MBS. However, like EVs the MBS are exposed to diverse environmental conditions, experiencing greater temperature variations compared to most SBS. Thus, existing EV battery performance tests regarding thermal condition are also pertinent to the MBS.

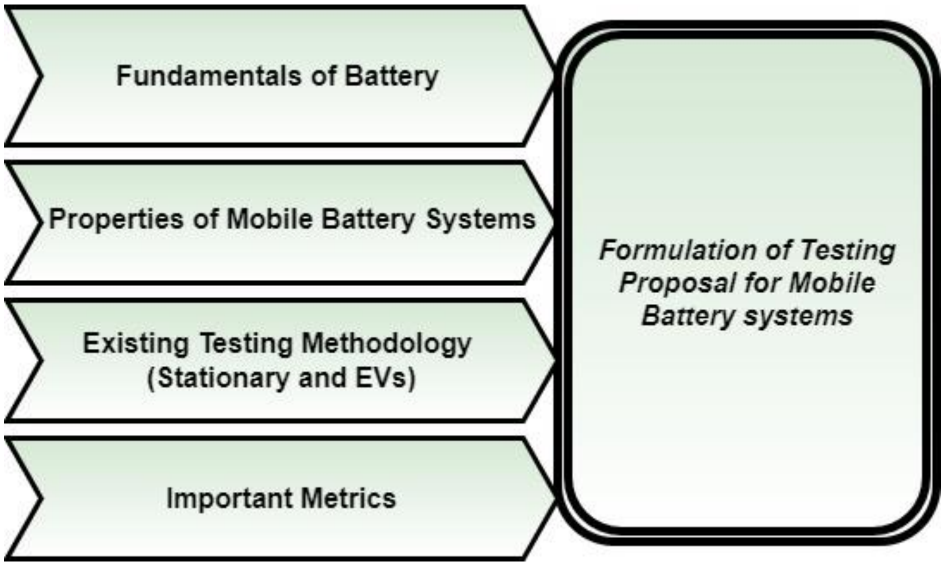

Figure 5.1: Formulation process of testing proposal for mobile battery systems.

Moreover, an in-depth review on existing testing methods derived from various battery test standards in Chapter 4 provides a guideline of battery testing system. Based on the theoretical analysis on the mentioned factors in previous chapters of the report, the test proposal for the MBS is formulated.

5.2 Applicable Tests

The applicable tests for the MBS encompass several common test practices in both stationary battery systems and electric vehicles (EVs) to determine parameters such as energy storage capacity, efficiency, state of health (SOH), and internal resistance. These tests, commonly employed in both SBS and electric vehicles (EVs), include capacity tests, energy efficiency tests, self-discharge tests, and cycle life tests. Consequently, these established testing methodologies are also relevant for evaluating the performance of the MBS.

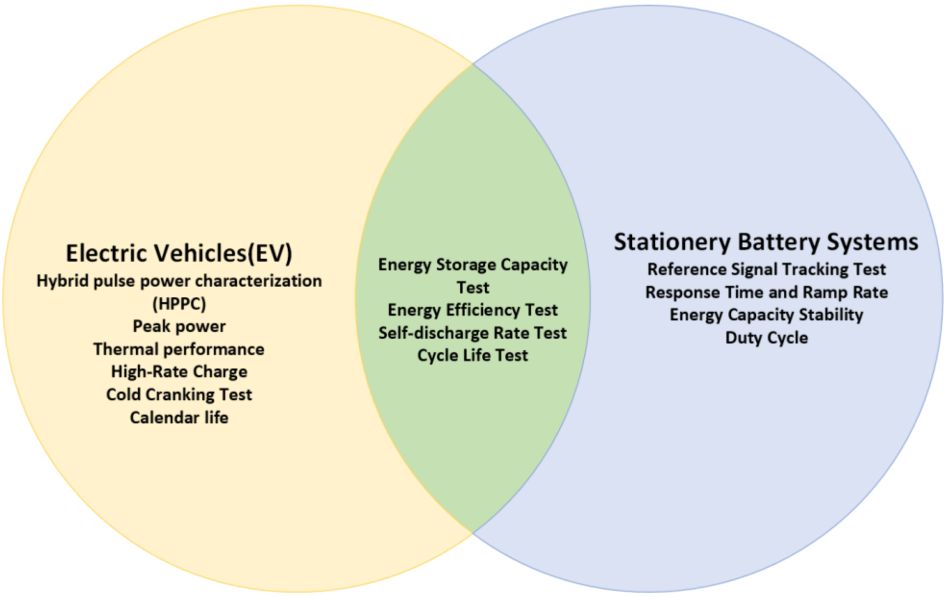

Figure 5.2: Common test practices in stationary battery systems and EVs.

As mentioned earlier, MBS can be integrated with grid systems and potentially operate alongside SBS, it's important to conduct tests like duty cycle, reference signal tracking, response time, and ramp rate tests. These tests will help determine how well an MBS performs in grid applications, tracks reference signals and responds to any change in operational settings.

To assess the dynamic power capability of the MBS, an HPPC test is necessary. Similar to EVs, thermal performance tests will evaluate the performance of the MBS across different temperature conditions. Regular practice of cycle life test will enable monitoring of key parameters of SOH of the MBS.

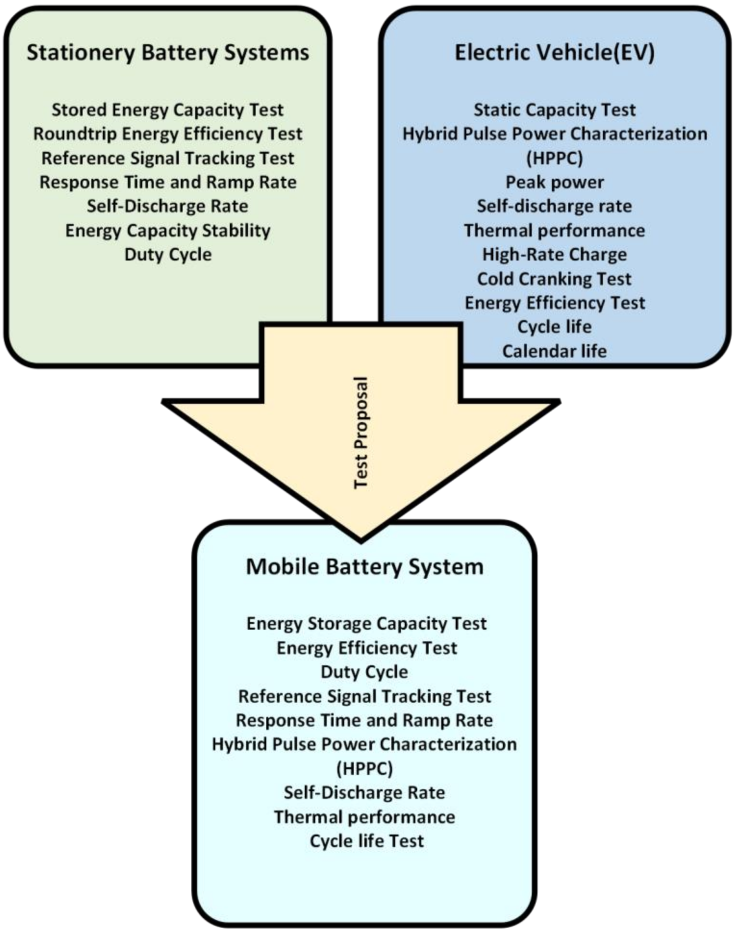

Figure 5.3: Tests proposed for mobile battery systems.

In summary, the applicable performance tests for the MBS include energy storage capacity test, energy efficiency test, duty cycle test, self-discharge test, reference signal tracking test, response time and ramp rate test, HPPC test, thermal performance test, cycle life test and.

5.3 Test Object

To illustrate a potential test scenario for an MBS, let's consider a system with a medium-size capacity with full functionality. Technical specifications of the chosen system, shown in Table 13, reflect a real system to ensure its appropriateness for laboratory settings.

Table 13: Technical specifications of chosen mobile battery system.

Specification	Value
Rated Storage Capacity	192 kWh
Input/output voltage	400Vdc
Frequency	50/60 Hz

Connection	3-phase
Nominal voltage	650Vdc
DC voltage Range	600 – 850Vdc
Maximum current output	125A
Maximum C-rate	1
Battery Chemistry	Lithium Iron
Temperature range	-25°C to 40°C

The test set up and configuration must have a capacity range that sufficiently covers the stated technical specifications of the chosen system. Additionally, the test equipment must have the capability to accurately measure values up to the specified level.

5.4 Equipment Selection

Selecting suitable test equipment necessitates a thorough understanding of testing activities and proper knowledge of the characteristics of every equipment. However, the following test equipment serves as potential options suitable for the chosen system.

5.4.1 Programable Bidirectional Power Supply

Performance testing for the selected system involves controlling charging and discharging current and voltage. This can be achieved using a programmable bidirectional power supply. The power supply should be programmable for test schedules and able to function in CC, CV, CP charging and discharging mode. It must fully integrate the system with the grid system for both charging the battery and feeding the battery power back to the grid during discharge.

Either of the programmable power inverters from ITECH and Chroma can serve as a viable solution for this purpose. Table 14 presents the technical details and a comparison between the two options.

Table 14: Technical details of ITECH and Croma power supply.

	
ITECH Bidirectional Programmable DC Power Supply	Chroma 62000 D programmable bidirectional DC power supply
Model (IT6018C-800-75)	Model (62180D-600)

18kW	18kW
800VDC	600VDC
342V-528V	380-480VAC
75A	120A
Two quadrant operation: source and load functions	Two quadrant operation: source and load functions
Response time ≤2 ms	Response time =2 ms
Current Accuracy (0.1% + 0.1%F. S)	Current Accuracy (0.1% + 0.1%F. S)
Voltage Accuracy (0.05% + 0.05%F. S)	Voltage Accuracy (0.05% + 0.05%F. S)
Operating Mode (CC,CV,CP)	Operating Mode (CC, CV,CP)

5.4.2 Battery Tester

The primary considerations for selecting a battery tester include voltage range, accuracy, and sampling time. Testing the selected MBS necessitates a battery tester capable of accurately measuring voltage within the range of 600V to 850V. The higher sampling rate allows thorough analysis of the measuring signal. A wide array of battery testers with diverse functionalities are available in the market. Here, two potentially suitable testers for the chosen MBS are presented, along with technical details and a comparison between them.

Table 15: Technical details of HIOKI and ITECH battery tester.

	
HIOKI BATTERY HiTESTER BT3564	ITECH IT5100 Series Battery Tester(IT5101H model)
±1100.00 V	±1000.00 V
0.1µΩ -3kΩ	0. 1µ Ω -3kΩ

Resistance: ±0.5%rdg. ±5dgt. Voltage: ±0.01%rdg. ±3dgt.	Resistance: ±0.4%±0.05% FS Voltage: ±0.01%±0.01% FS
Resistance +Voltage simultaneously sampling time: 28 ms	Resistance + Voltage simultaneously sampling time < 8 ms
Single sampling time Resistance:12ms Voltage: 16 ms	Single sampling time (Resistance or Voltage) < 4 ms

5.4.3 Data Logger

Battery testing involves the continual collection of large amounts of measurement data in a short amount of time, requiring storage for further analysis. Data loggers are used to serve the purpose. The major key factors for selecting a data logger include data storage capacity, measurement type, number of measurement channels, and scalability [83]. The HIOKI MEMORY HiLOGGER LR8450 data logger, equipped with all the requisite features, can be utilized for the proposed testing.

Figure 5.4: HIOKI MEMORY HiLOGGER LR8450 data logger.

Table 16: Features of HIOKI MEMORY HiLOGGER LR8450 data logger.

Specifications	*value*
Plug-in modules	4
Measurement Channels	120

Sampling time	Voltage/ Current at kS/s (1 ms) Resistance/ Temperature at 100 S/s (10 ms)
Maximum recording time (10ms)	1 day (internal memory)

5.4.4 Battery Cycler

Instead of using the previously mentioned equipment for the test setup, selection of a compact battery cycler having all the functions of the mentioned equipment can be an advantageous alternative. Many companies offer testing tools that feature all the requisite functions for a comprehensive battery testing system within a single setup. Two such possible options are ITECH and Croma battery pack test systems. Table 17 presents technical details and a comparison between them.

Table 17: Technical details and a comparison between ITECH and Croma battery pack test system.

ITECH Battery Pack Test System	Croma Battery Pack Test System
Max Voltage range:2250V	Max Voltage range :1700V
Max current range: 2040A	Max current range: 4800A
Max power range: 1152kW	Max power range: 1200kW
Bidirectional Power supply	Bidirectional Power supply
Power regenerative efficiency up to 95%	Regenerative discharge efficiency > 90%

Max. voltage accuracy: ≤0.025%+0.025%FS	Max. voltage accuracy : ±0.02% rdg. ± 0.02% r.n.g.
Max. current accuracy: ≤0.05%+0.1%FS	Max. current accuracy: ± 0.05% of r.n.g.
Sampling rate:10ms	Sampling rate:10ms
CC / CV / CP / CC-CV / CP-CV / CR operation modes	CC / CV / CP / CC-CV / CP-CV / CR operation modes

5.4.5 Test Set-up

Now two possible pictures of test set-up have been found: 1) A set up with a single bidirectional power supply, battery tester, data logger. 2) A setup utilizing one of the two mentioned battery cyclers mentioned. Figure 5.5 and Figure 5.6 depict the connections of the devices for the two respective options.

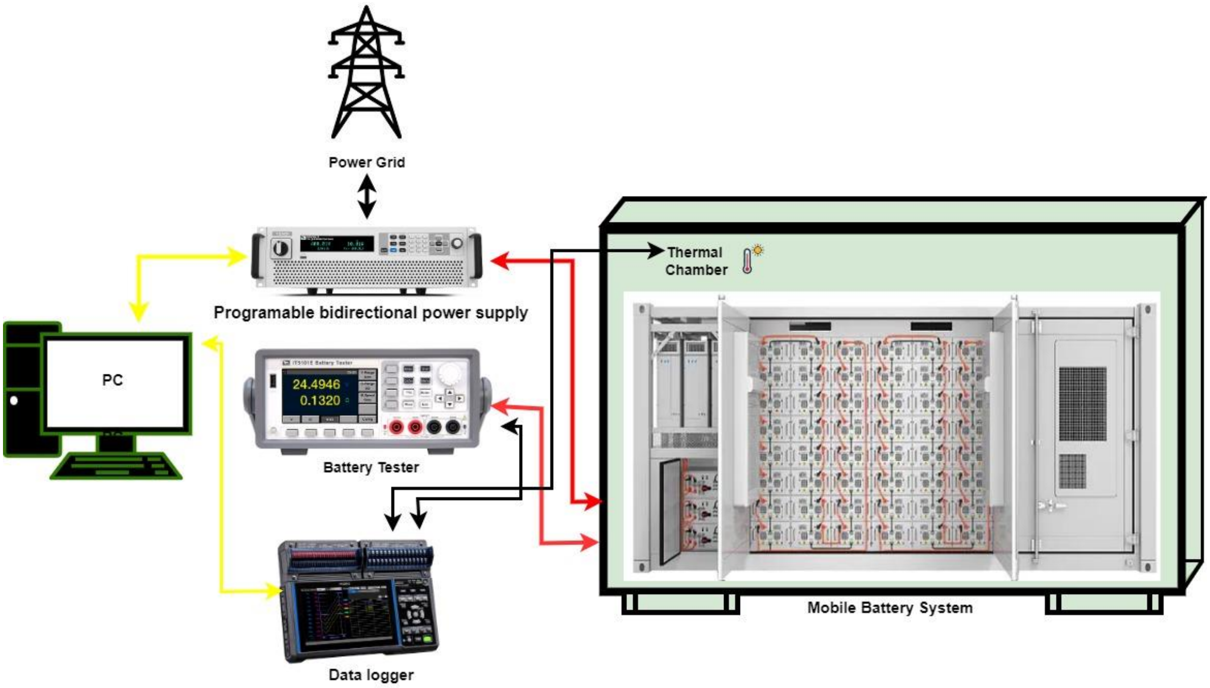

Figure 5.5: Test set up with bidirectional power supply, battery tester, data logger.

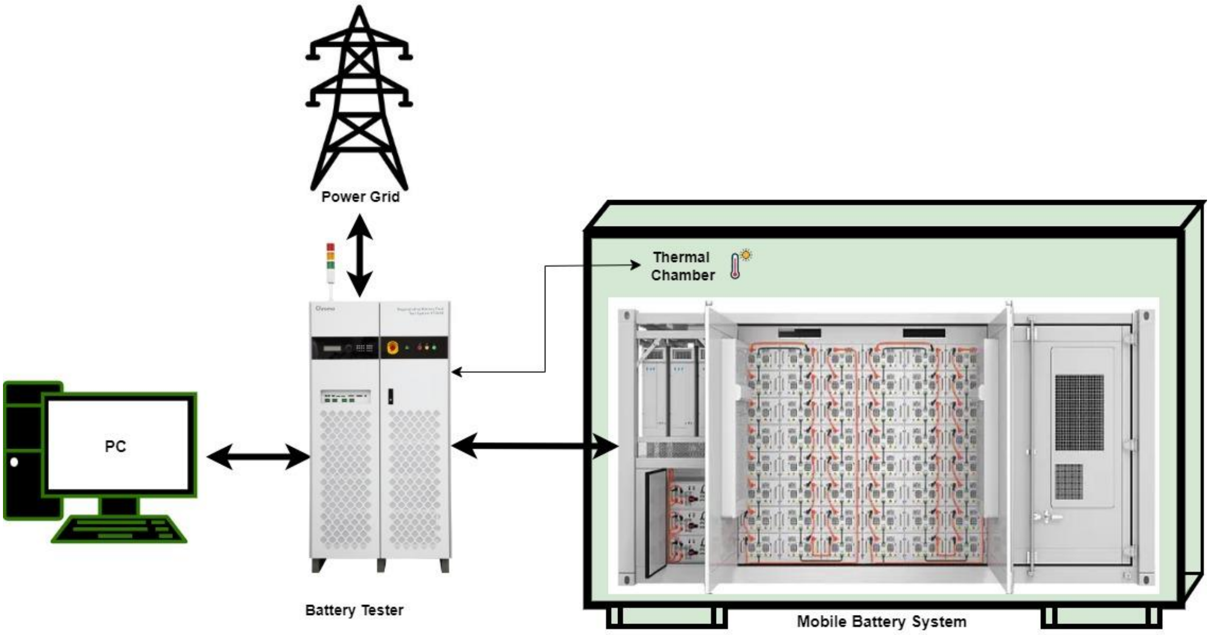

Figure 5.6: Test set up with a single battery cycler.

5.5 A General Approach of MBS Performance Testing

Depending on the test type and key metrics, the configuration and procedures of the test may vary. However, some common test frameworks can possibly be applicable to every test. The initial stage of the testing process involves selecting a test and defining its purpose. Subsequently, parameters choosing, and establishing a mathematical model, configuring the test equipment setup. Then creating test conditions, executing test procedures, taking readings from measuring devices.

Mathematical model: Even though selecting mathematical model is a theoretical aspect, depending on the mathematical model, the test parameters, test condition, and procedure are selected. And according to the mathematical model the test results and findings are calculated and analyzed.

Selecting parameters: parameters depend on the test object, properties of battery system, maximum and minimum operating voltage, required SOC, charge and discharge rate(C-rate), power limit. Some of the parameters are defined by manufacturers and need to follow their instructions.

Test conditions: Before starting an experiment, a proper environment needs to be created. Depending on mathematical model and parameters, test condition includes the initial temperature, initial voltage, and SOC level.

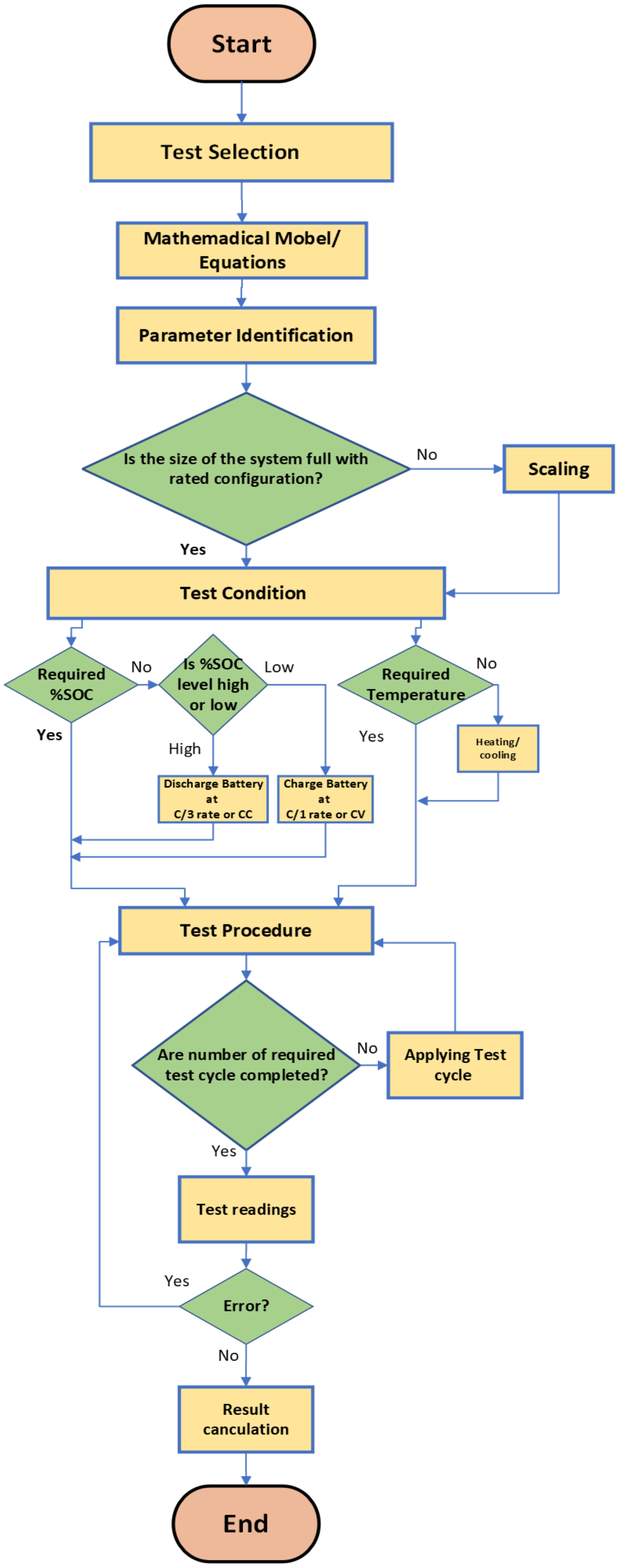

Figure 5.7: A comprehensive performance testing process of MBS.

Applying test procedure: Following the creating appropriate test conditions, the applying proper charge and discharge power rates (C-rate) is an essential point. Additionally, the duration of resting periods between charge and discharge must be in accordance with manufacturer instructions.

Measurement: Throughout each charging and discharging phase, voltage, current, power and time duration must be measured and recorded. A general approach of a comprehensive performance testing process of MBS is presented in

Figure 5.7

5.6 Energy Storage Capacity Test

The test aims to measure the storage capacity of battery systems in ampere-hours (Ah). This capacity represents the amount of energy the battery can deliver to a load during discharge at entire electrochemical range, from maximum to minimum voltage. For the chosen MBS, the maximum voltage is 850Vdc, indicating 100% state of charge (SOC), while the minimum voltage is 600 Vdc, corresponding to 0% SOC. The energy discharged by the MBS from 850 Vdc to 600 Vdc determines its capacity. Generally, this capacity is specified by the manufacturer of the MBS. During the test, the temperature at 25°C needs to be maintained.

Test Parameters

Initial voltage	850Vdc
End test voltage	600Vdc
Maximum operating voltage	850Vdc
Minimum operating voltage	600Vdc
Applied charging current	CV
Applied discharging current	CC
Temperature	25°C

Test Condition

The test is conducted at ambient temperature, thus requiring maintaining a constant temperature of 25°C. Consequently, it is important to continuously measure the temperature of the system during the test. At the beginning of the test, the voltage level must be at the maximum operating voltage(850Vdc) or maximum 100% SOC level. Hence, prior to starting the main test, the MBS must be charged to reach the required voltage level or SOC level.

Procedure

1. Measure the voltage of the MBS and check SOC level.
2. Charge the MBS at CV mode to maximum operating voltage to 850Vdc (100% SOC). Measure the voltage and charging current of the mobile battery system during charging.
3. Keep the MBS at rest in an active standby state for a certain period of time recommended by the manufacturer.
4. Discharge the MBS at CC mode to minimum operating voltage to reach 600 VDC (0% SOC). Measure the voltage and discharge current of the MBS during discharge.
5. The MBS needs to be left at rest for same period of time like step 3 at an active standby state.
6. Repeat steps from 2 to 5 for 4 times to complete a total of 5 cycles.
7. Keep a record of all measurements.
8. Maintain the temperature at 25°C.

Result calculation

Discharge time $T_{discharge} = T_{discharge\ start} - T_{discharge\ end}$ (h)

System capacity $Q_{measured} = T_{discharge} \times I_{discharge}$ (Ah)

System capacity in %, $Q_{measured} = \frac{Q_{measured}}{Q_{rated}} \times 100$

Make the calculation average for 5 cycles.

5.7 Energy Efficiency Test

The energy efficiency test measures the ratio of the net energy delivered by the MBS during the discharge period to the energy consumed by the system for charging. Efficiency is typically expressed as a percentage. This test is conducted at state of charge (SOC) levels of 100%, 75%, 50%, and 25%, with each SOC level requiring 5 cycles. This test considers all system losses during each cycle, including factors such as power converter losses, power consumption for auxiliary systems, heating/cooling power, and other relevant losses.

Procedure

1. Measure the voltage of the MBS.
2. Charge the MBS applying CV mode charging to maximum operating voltage to 850Vdc (100% SOC) for test 1. Measure the voltage and charging current of the MBS during charging.
3. Keep the MBS at rest in an active standby state for a certain period of time recommended by the manufacturer.
4. Discharge the MBS applying CC mode discharging to minimum operating voltage to reach 600 Vdc (0% SOC). Measure the voltage and discharge current of the MBS during charging.
5. The MBS needs to be left at rest for same period of time like step 3 at an active standby state.

6. Repeat steps from 2 to 5 for 4 times to complete a total of 5 cycles.
7. Keep a record of all measurements.
8. Maintain the temperature at 25°C.
9. In the case of test 2, 3 and 4 in step 2 the system should be charged to 75%, 50% and 25% SOC level respectively.

Result calculation

Accepted charge energy= Q_{charge}

released discharge energy = $Q_{discharge}$

Energy consumed by auxiliary system during charge= Q_{AC}

Energy consumed by auxiliary system during discharge= Q_{AD}

Energy efficiency $\eta = \frac{\sum Q_{discharge}}{\sum Q_{charge}} \times 100 = \frac{\sum(Q_{charge} - Q_{AC} - Q_{AD})}{\sum Q_{charge}} \times 100$

Calculate energy efficiency for every test and find an average.

5.8 Duty Cycle Test

The objective of duty cycle testing is to evaluate the capability of the MBS to function effectively within specific applications. In grid level applications, the test is performed for round trip efficiency for frequency regulation, peak shaving, PV smoothing and many more. The test applies different discharge power rates (C-rate) under normal atmospheric conditions(25°C).

Procedure

1. Charge the MBS applying CV mode charging to maximum operating voltage to 850Vdc (100% SOC). Measure the voltage and charging current of the MBS.
2. Keep the MBS at rest in an active standby state for a certain period of time recommended by the manufacturer.
3. Integrate the MBS with the gird system for specific applications.
4. Apply discharge power (C-rate) to discharge the MBS in 6 hours to minimum operating voltage to reach 600 Vdc (0% SOC). Measure the voltage and discharge current of the MBS.
5. The MBS needs to be left at rest for same period of time like step 3 at an active standby state.
6. Repeat steps from 1 to 5. In step 4, discharge the MBS in 4 hours.
7. repeat steps from 1 to 5. Now discharge the MBS in 2 hours.
8. Keep a record of all measurements.
9. Maintain the temperature at 25°C.

Result calculation

Calculate efficiency for every cycle like Energy Efficiency Test.

Compare among them.

5.9 Self-discharge Test

The purpose of this test is to determine the capacity loss due to keeping the MBS standing for a certain period of time at ambient temperatures(25°C.).

Procedure

1. Measure the voltage of the MBS.
2. Charge the mobile battery system applying CV mode charging to maximum operating voltage to 850Vdc (100% SOC).
3. Remove all the measuring devices connections to allow the MBS to stand in an open-circuit mood.
4. Keep the MBS at rest in an active standby state for 7days.
5. Reconnect all the measuring devices and measure voltage.
6. Discharge the battery applying CV mode discharging to minimum operating voltage (600Vdc)
7. Repeat the steps from 2 to 6 and complete10 cycles.

Result calculation

The initial storage energy = $Q_{measured}$

Discharge energy at step 6 = $Q_{discharge}$

Self-discharge rate = $\frac{Q_{measured}-Q_{discharge}}{Q_{measured}\times 7} \times 100$

Calculate the average self-discharge rate for 10 cycles.

5.10Reference Signal Tracking Test

The reference signal tracking test evaluates the capability of the MBS to follow a duty cycle when integrated with a grid service. The test is complex and requires precision technical set up. Test set-up depends on the configuration of the grid. Therefore, the test parameters must be synchronized according to the grid parameters. The grid parameters are determined by the applications of the test, for example frequency regulation, Reactive Power Support and many more.

parameters

Grid parameters	Depending on application
Initial voltage	850Vdc
End test voltage	600Vdc
Initial SOC	100%
SOC at signal change	50%

Applied charging and discharging current	C/2 rate
Temperature	25°C

Procedure

1. Charge the MBS applying CV mode charging to maximum operating voltage to 850Vdc (100% SOC). Measure the voltage and charging current of the MBS during charging.
2. Keep the MBS at rest in an active standby state for a certain period of time recommended by the manufacturer.
3. Discharge the MBS applying CC mode discharging to reach 50% SOC level. Measure the voltage and discharge current of the MBS at 5ms interval during discharge.
4. Apply a command for changing set point of power output for duty cycle.
5. Discharge the MBS to 0% SOC at C/2 rate applying CC mode discharging.
6. The MBS needs to be left at rest for same period of time like step 2 at an active standby state.
7. Repeat steps from 1 to 6 for more 4 times to complete a total of 5 cycles.
8. Keep a record of all measurements.
9. Maintain the temperature at 25°C.

Result calculation

Set point of power output = $P_{set\ point}$

Instantaneous output power by MBS = P_{MBS}

Rated power of the MBS = P_{rated}

Number of measurements = N

Signal tracking error RMS = $\sqrt{\frac{\Sigma(P_{set\ point} - P_{MBS})^2}{N}}$

Signal tracking error RMS % = $\frac{\sqrt{\frac{\Sigma(P_{set\ point} - P_{MBS})^2}{N}}}{P_{rated}} \times 100$

5.11 Response Time and Ramp Rate Test

Like signal tracking test, the response time and ramp rate test are also complex and requires precise test set up and measurement. The test is performed to estimate how long it takes for the MBS to go from no charge to full charge rate(C-rate) and from no discharge to full discharge rate (C-rate) at system rated power. The test results will validate the energy delivery capability of the MBS. The response time and ramp rate are calculated for both charge and discharge processes.

Parameters

Reference Signal Tracking Test

Procedure

1. Charge the MBS applying CV mode charging (C/2 rate) to 50% SOC level. Measure the voltage and charging current of the MBS at 5ms interval during charging.
2. Keep the MBS at rest in an active standby state for a certain period of time recommended by the manufacturer.
3. Set configuration to record the time stamp from starting the next step to 0% SOC level.
4. Discharge the MBS applying CC mode discharging (C/2) rate to reach 0% SOC level. Measure the voltage and discharge current of the MBS at 5ms interval during discharge.
5. The MBS needs to be left at rest for same period of time like step 2 at an active standby state.
6. Set configuration to record the time stamp from starting the next step to 50% SOC level.
7. Repeat steps from 1 to 6 for more 2 times to complete a total of 3 cycles.
8. Keep a record of all measurements.
9. Maintain the temperature at 25°C.

Result calculations

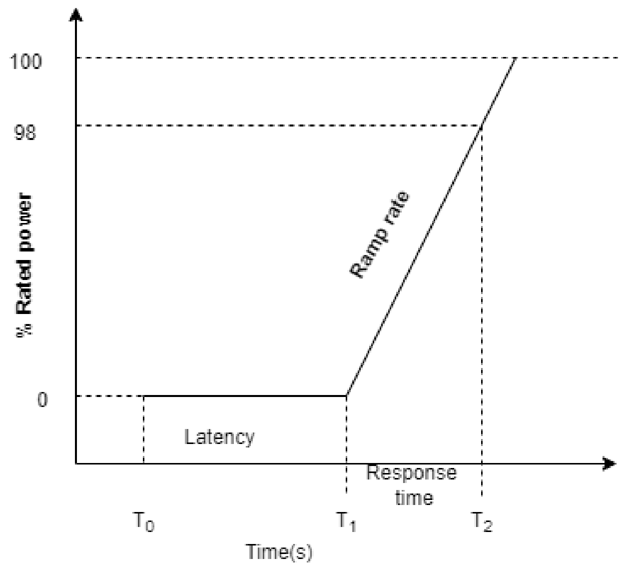

Figure 5.8: Graph of signal of charge and discharge processes.

Signal sending time =T_0

Signal stamp time =T_1

Time at 100% rated power =T_2

Communication latency $T_{latency}$= $T_1 - T_0$

Rise time $T_{rise} = T_2 - T_1$

Response Time $T_{response} = T_{latency} + T_{rise}$

$$Ramp\ rate\ = \frac{P_{rated}}{T_{response}}$$

Calculate all value for both charge and discharge.

5.12 HPPC Test

HPPC test is a multipurpose and multifunctional test intended to evaluate the dynamic response of the MBS. Findings of the test include various aspects, for example available power over the operational range of SOC, internal resistance of battery, peak power of the MBS. Analyzing this information provides an understanding of SOC in relation to open circuit voltage (V_{ocv}) and the state of health (SOH) of the battery system. The test is conducted in various temperature conditions (-10°, 0°, 10°, 25 °C) both for charging and discharging. power charging pulse is applied to increase SOC and discharge pulse is applied to reduce SOC level.

Procedure

The test can commence at a temperature of -10°C initially, followed by subsequent test cycles conducted at increasing temperatures of 0°C, 10°C, and 25°C sequentially.

1. Charge the MBS applying CV mode charging to maximum operating voltage to 850Vdc (100% SOC). Measure the voltage and charging current of the MBS during charging.
2. Keep the MBS at rest in an active standby state for a certain period of time recommended by the manufacturer.
3. Apply discharge current pulse to discharge the MBS.
4. SOC must be discharged during every pulse. Thus, the discharge current must be high enough to discharge battery in a specific time.
5. Keep the MBS at rest for 1 minute after every discharge pulse.
6. Apply the same discharge pulse to reduce more capacity.
7. Repeat steps 5 and 6 until the SOC level reduces to 0%.
8. Follow 1hour rest phase to evaluate the static equilibrium status.
9. Measure the voltage and discharge current of the MBS at 5ms interval during every discharge pulse.
10. Keep a record of all measurements.
11. Repeat the test at 0°C, 10°C and 25°C.
12. In the case of charge pulse test, apply charge pulse to increase SOC following same steps of discharge pulse test.

Result calculation

As mentioned earlier, the test results provide various aspects of the MBS, providing in general calculations is challenging. The calculations depend on what parameters need to be estimated and the calculation method. For example, using the 2nd Order Thevenin Model [84], internal resistance, polarization resistance, discharge resistance, polarization capacitance, discharge capacitance can be calculated from the voltage response of the test as shown in Figure 5.10

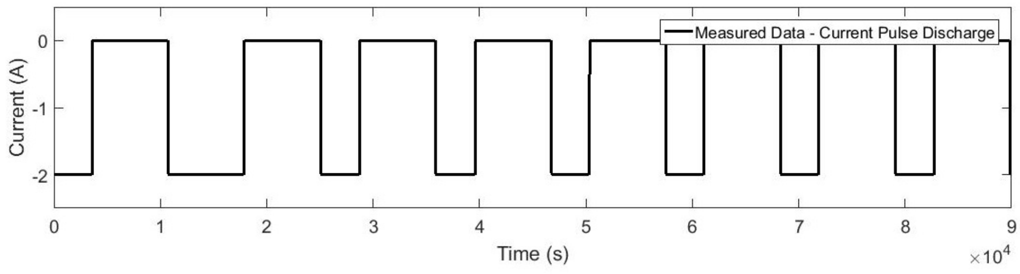

Figure 5.9 : Discharge current pulses [85].

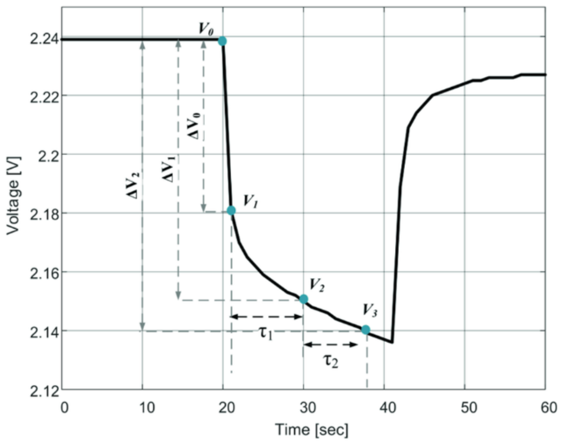

Figure 5.10: Voltage response from HPPC test [86].

5.13 Thermal Performance Test

The thermal performance test aims to demonstrate the ability of the MBS to provide targeted output power at various temperatures. The effect of temperature change on device performance is also measured by conducting the test within the operating temperature range (-20°C to 55°C). Generally, the test is conducted at the beginning of battery life (BOL) and the end of battery life (EOL). At the middle of battery life, the highest and lowest operational temperature are selected for this test [73].

Procedure

1. Charge the MBS applying CV mode charging to maximum operating voltage to 850Vdc (100% SOC) at 25°C.
2. Raise or decrease the ambient temperature of the system to the targeted temperature.
3. Keep the MBS at rest in an active standby state for a certain period of time recommended by the manufacturer.
4. Conduct an energy storage test and HPPC discharge pulse test.

Result Calculation

Calculate the parameters from the test results following the calculation of HPPC test. And compare the results with the results of energy storage test and HPPC test conducted at 25°C.

5.14Cycle Life Test

The test assesses cycle life and performance to ensure the MBS can meet a specified target over its service life. The test involves repeating the performance of a test profile until the released reach a specific amount. The battery cycle life is a function of cycle depth or DOD. The total number of ampere-hours that a battery is able to deliver is relatively constant. A decrease in the daily cycle depth correlates with a reduction in the battery's lifespan. From the test, it is possible to track the factors like the number of complete cycles, DOD, especially cumulative Ah released by the battery. Analyzing these factors can help to assess the SOH and predict the remaining cycle life of the battery system [87].

Procedure

1. Charge the MBS applying CV mode charging to maximum operating voltage to 850Vdc (100% SOC). Measure the voltage and charging current of the MBS during charging.
2. Keep the MBS at rest in an active standby state for a certain period of time recommended by the manufacturer.
3. Discharge the MBS applying CC mode discharging to minimum operating voltage to reach 600 Vdc (0% SOC). Measure the voltage and discharge current of the MBS during discharge.
4. Measure the released power.
5. The MBS needs to be left at rest for same period of time like step 2 at an active standby state. Need to keep the battery OCV mood during the rest period.
6. Repeat steps from 1 to 5 complete the required number of cycles.
7. Keep a record of all measurements.
8. Maintain the temperature at 25°C.
9. Repeat the test after 28 days.

Result Calculation

- Calculate the released power.
- Compare the result with rated power.

6 Conclusion and Future Work

6.1 Conclusion

A theoretical study on the fundamentals of battery was conducted to gather knowledge of working principles of battery, different battery chemistries, SOC and SOH. Afterword, the study investigated battery aging and degradation mechanisms to enhance understanding of battery performance characteristics. This theoretical investigation elucidates that temperature, internal resistance, operating voltage, and SOC are the factors that contribute to the aging and degradation of batteries, consequently leading to a decline in SOC and battery performance.

A literature review was conducted on the mobile battery systems (MBS), followed by a comparative study between MBS and other battery systems, including those for stationary applications and EVs. Exploring the research history indicates that technically MBS have greater similarity to stationary battery systems than to EV battery systems in terms of applications, system properties, and size. However, similar to EVs the MBS face various robust environmental conditions. Other challenges confronting MBS include transportation limitations and relatively higher per unit energy prices.

The analysis of existing testing practices and different battery test standards in both stationary battery systems and EVs provides valuable insights into battery testing systems considering test conditions, test equipment and challenges.

These previous theoretical investigations indicate a scarcity of standards testing method designed specifically for evaluating the performance of the MBS. Thus, a test proposal for MBS was formulated, taking into account factors such as the characteristics of basic battery technology, MBS specifications, and existing testing standards. The proposal includes nine performance tests: energy storage capacity test, energy efficiency test, duty cycle test, self-discharge test, reference signal tracking test, response time and ramp rate test, HPPC test, thermal performance test, and cycle life test. To illustrate potential performance test scenarios, an MBS was chosen, and the necessary testing equipment was studied. It reveals two potential configurations for test setups. One option comprises utilizing a programmable bidirectional power supply alongside a battery tester and a data logger. The second option involves employing a single compact battery cycler. Afterword, a common test picture for all the proposed performance tests was presented, along with detailed descriptions and procedures for each individual test.

Limitation

Initially it was planned that one of the proposed tests would be conducted in the laboratory, depending on time permits. However, no test could be conducted due to limitations in available time and testing equipment. Instead of conducting any experiment, the focus has been given to the theoretical presentation of the proposed tests for the MBS.

6.2 Future work

The following list outlines possible directions for future study, based on this thesis output.

1. Try to execute each proposed test within the laboratory setting in order to assess the efficacy and performance of the MBS.
2. Conduct field-level performance testing on the MBS with high storage capacity.
3. Implement the test setup according to the two proposed combinations while searching for other configurations.
4. This thesis primarily focuses on performance testing for MBS. Conduct similar research to investigate mechanical, abuse, and safety testing for the MBS.
5. Further research can be done on software solutions suitable for the proposed tests.

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Appendices

Appendix A: Research Proposal for Master's Thesis.

University of South-Eastern Norway

Faculty of Technology, Natural Sciences and Maritime Sciences, Campus Porsgrunn

Research Proposal for Master's Thesis

Title: Calibration and testing methodology of mobile battery systems.

USN supervisor: Mohammad Khalili Katoulaei (main supervisor), co-supervisors: Sambeet Mishra, Thomas Øyvang, and Mohammed Yassin.

External partner: Skagerak Energi (Jørgen Nyhus, Håvard Hadland)

Taskn background:

High-power battery systems [1] for charging industrial installations and machines have no well-established performance testing methodologies, i.e. Such as in IEC62660 for Electrical Vehicles (EVs). There is a need to conduct research on the area for developing high-power battery industries to make relevant comparisons of power density, capacity, charge and discharge efficiencies, and life cycles. Hence, some testing techniques and methodologies are needed for the industry to measure performance parameters, frequencies, limit values, etc.

Task description:

1. Review of State-of-the-Art Mobile Battery Systems:
- Conduct an in-depth review of state-of-the-art mobile battery systems utilized in charging installations, industrial machinery, and relevant applications.
- Review battery technology types for energy storage systems
- Review the testing and testbeds used for characterization of mobile battery storage systems.
- Identify specific challenges and requirements associated with these systems, considering variations in voltage, capacity, and charging methods.
- Review the degradation mechanism in the battery storage systems.

2. Standardized Test Procedure Proposal:
- Propose relevant test procedures for the evaluation of mobile battery storage systems, encompassing parameters, test frequency, and test conditions.

3. Battery Performance Testing:
- Design an experimental setup to conduct performance testing of mobile battery systems.
    - If time allows measure and analyze the behavior of the batteries under various loads and charging conditions (focusing on key parameters such as capacity, cycle life, charge/discharge efficiency, voltage, and current characteristics).

4. Documentation and Reporting:
- Document the experimental setup, procedures, and detailed findings.
- Provide a comprehensive report on the performance testing outcomes, highlight key observations and insights.

Student category: EPE

Is the task suitable for online students (not present at the campus)? No

Practical arrangements:
Skagerak Energy will provide equipment to develop the laboratory setup.

Supervision:
As a general rule, the student is entitled to 15-20 hours of supervision. This includes necessary time for the supervisor to prepare for supervision meetings (reading material to be discussed, etc).

Submitted by: MD NAZRUL ISLAM, ID: 259050, M.Sc. in EPE

Date and signature: Nazrul 01.02.2024

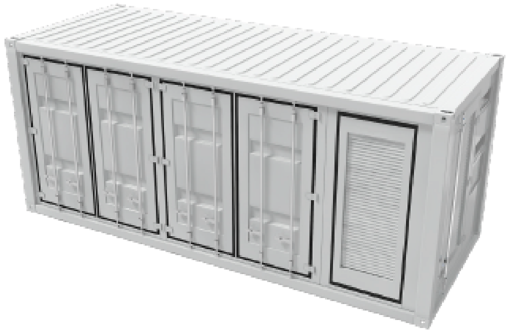
Supervisors:

Name	Date and signature
Mohammad Khalili Katoulaei (main supervisor)	
Sambeet Mishra (co-supervisors)	
Thomas Øyvang (co-supervisors)	
Mohammed Yassin (co-supervisors)	Mohammed Yassin

[1] Skagerak Energi AS - Kverneland Energi

Appendix B: EVESCO Battery energy storage system.

evesco
ELECTRIC VEHICLE ENERGY STORAGE COMPANY



ES-10001000NA

Power: 1000kW
Energy: 1106kWh

Containerized Battery Energy Storage System
LiFePO4 Battery Technology

FEATURES

- 20' containerized design complete with battery, PCS, HVAC, fire suppression, lighting and local controller
- Maximum safety utilizing the safest type of lithium battery chemistry (LiFePO4) combined with an intelligent 3-level Battery Management System
- Outstanding performance and long lifespan with over 5000 cycles at 1C
- Bi-directional PCS with multiple modes for flexible charging and discharging of batteries
- Prefabricated containerized design makes for quick and easily onsite assembly
- Optimized for both on-grid and off-grid applications
- Integrated local controller for operation status control, DC grid-connection control, protection and data exchange

APPROVALS

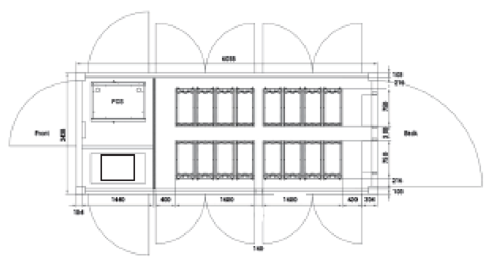
- UL 9540A thermal runaway tested
- UN 38.3 certified
- IEC62619/62477 certified
- UL 1741 PCS, UL 1642 Cells , UL 1973 Modules

The graphics shown may differ from the actual structure.

SYSTEM SPECIFICATIONS

Nominal Energy	1106 kWh
Usable Energy (@95% DoD)	1028 kWh
Rated AC Power (via PCS)	1000 kW
Nominal Capacity	1440 Ah
Nominal DC Voltage	768 Volts
DC Voltage Range	672 ~ 852 Volts
Max. Continuous Charge	1440A @ 1C
Max. Continuous Discharge	1440A @ 1C
Grid-tied AC Connection	AC Bus 480 Vac (423 ~ 528 Vac settable)
Operating Temperature Range Charge Discharge	 32°F (0°C) to 113°F (45°C) -4°F (-20°C) to 131°F (55°C)
Cell Chemistry	Lithium Iron Phosphate (LiFePO4)
Dimensions (L x W x H)	6058 x 2438 x 2591 mm mm
Weight (Approx.)	TBC
Enclosure	20' GP container IP54
Containerized System Includes	Battery, PCS, HVAC, FSS, Local Controller, Lighting & DC Power Meter

SYSTEM LAYOUT



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Rev3: 0521

Appendix C: Chroma 17040E Regenerative Battery Pack Test System.

REGENERATIVE BATTERY PACK TEST SYSTEM MODEL 17040E

Chroma 17040E Regenerative Battery Pack Test System is a high-precision system specifically designed for secondary battery module and pack tests. The energy regenerative function greatly reduces power consumption during discharge, and ensures a stable power grid without generating harmonic pollution on other devices - even under dynamic charge and discharge conditions. Where traditional equipment discharges waste energy in the form of heat, Chroma 17040E can recycle the electric energy discharged by the battery module back to the grid, thus reducing waste energy and alleviating HVAC requirements.

The 17040E has built-in parallel channels and dynamic profile simulation functions. The parallel capability maximizes the charge and discharge current and power, thus increasing the efficiency and flexibility of equipment utilization. The dynamic profile simulation allows users to load a battery waveform of a given drive profile in either current or power mode to meet the NEDC/FUDS requirements.

Its bidirectional architecture assures uninterrupted current during the charge and discharge transient state so that the driving conditions can be accurately simulated in line with the ISO, IEC, UL, and GB/T international test standards.

Equipped with Chroma's powerful Battery Pro software, the test system offers flexible test editing functions to perform independent channel tests, and conforms to various requirements for testing secondary battery packs with high safety and stability.

Chroma 17040E ensures protected charge/discharge testing through multiple safety features including Over Voltage Protection, Over Current Protection, Over Temperature Protection, and external parameter detection. The recovery functions prevent that test data is interrupted or lost in the case of power failure.

Ethernet CE

MODEL 17040E

KEY FEATURES

- Meets international standards for battery testing: IEC, ISO, UL, and GB/T, etc.
- Regenerative battery energy discharge (Eff. >90%, PF >0.95, I_THD <5%)
- Auto-ranges with multiple voltage and current ranges for optimal resolution
- High accuracy current/voltage measurement
  ±0.02% r.d.g. + 0.02% r.n.g.
  ±(0.05% of r.n.g.)
- Current slew rate (10%~90%)
  1ms (100kW~600kW)
  10ms (800kW~1.2MW)
- Dynamic (current/power) driving profile simulation tests for NEDC, FUDS, HPPC
- Test channel parallel function
- Test data analysis function
- Data recovery protection (after power failure)
- Automatic protection for abnormalities
- Battery simulator (option)
- High power test equipment
  Voltage range: 100~1700V
  Current range: 0~4800A
  Power range: 0~1.2MW
- Customized integration functions
  - Integrated temperature chamber
  - BMS data analysis
  - Multi-channel voltage/temp. recording

FIELDS OF APPLICATION

- Power battery module
- Energy storage system
- Motor driver
- Power control system

Chroma

Appendix D: ITECH ITS5300 battery pack test system.

ITS5300 Battery cell/ Battery module /Battery Pack BOL Test System

ITS5300 battery charging discharging test system provides turnkey testing solution from Milliampere-grade single cell to Megawatt battery pack. During charging-discharging life cycle test (BOL Test), it can simulate the real working condition, such as driving cycle, current pulse and self-defined waveform, to realize the comprehensive evaluation of battery life time, energy, and endurance mileage. The system is applicable to new products development, quality analysis/incoming inspection, production test and so on. Modular design provides great flexibility and independence for the test system configuration.

To meet the demand of production line testing in large quantities, ITS5300 can simultaneously test the performance of hundreds of independent battery modules/cells, greatly improving the testing efficiency and production of production line.ITS5300 also provides regenerative test solution, and the regenerative efficiency up to 95%, it solves the problem of high electricity cost caused by high power storage battery or large quantity battery module/cell test.

ITS5300 provides comprehensive protection function, not merely hardware itself has over-voltage, over-current, over-temperature, anti-islanding protections, but also the system has optional functions such as emergency stop module, power-off memory function, anti-sparkling and reverse connection protection, under voltage protection etc, so as to effectively ensure the reliability of long-time operation of the system.

The ITS5300 battery test system offers a wealth of test steps and powerful statistical analysis capabilities. The channels can be operated synchronously/independently without affecting each other, and support third-party device control (temperature box or water-cooling system). Without any language programming background, users can quickly master the test program editing and running. Powerful statistical analysis function, to assist testers to quickly filter data, efficient completion of battery performance parameters analysis.

FEATURE

- Modular design, Maximum voltage and power up to 2250V/1152kW
- Power regenerative efficiency up to 95%
- Full protection
- High precision measurement, up to 0.02%+0.02%FS
- AC/DC internal resistance test
- Strong scalability, easy to integrate other equipment
- High sampling rate, up to 1ms
- Rich charging and discharging test steps
- Seamless current switching, road conditions simulation
- Data query and statistical analysis functions

01 ITS5300 Battery Cell/ Battery Module/Battery Pack BOL Test System