A HYBRIDIZED SMES / BESS OPTIMAL STORAGE SYSTEM

BY

IBRAHIM M. ALOTAIBI

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This thesis, written by **IBRAHIM M.ALOTAIBI** under the direction of his thesis advisor and approved by his thesis committee, has been presented and accepted by the Dean of Graduate Studies, in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE IN ELECTRICAL ENGINEERING**.

Dr. IBRAHIM ELAMIN
(Advisor), EE DEPT

Dr. ALI A. AL-SHAIKHI
Department Chairman

Dr. MOHAMMAD A.ABIDO
(Member), EE DEPT.

Dr. SALAM A. ZUMMO
Dean of Graduate Studies

Dr. MUHAMMAD KHALID
(Member),EE DEPT

7/2/12

Date

Dedication

It is with my sincere gratitude that i dedicate this humble work to my angel that never quits praying to me (Mom). Dedication is also extended to my wife, friends whom without their valuable support, none of this work would be achievable.

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I am deeply grateful to the almighty that endued me the passion, the persistence and the determination to accomplish this humble work. In spite of the medical condition that affected my quality of life during my completion of the MS, such work wouldn't be possible without the great, invaluable support that has been provided to me from my advisor, Dr. Maan Kousa and EE chairman Dr. Ali Al-shaikhi. I am literally indebted to Dr. Ibrahim Elamin for his insightful and informative comments during accomplishing the thesis. I would love to extend my sincere acknowledgment to Dr. Samir Albiyat for his motivation that boosted up my dreams and fueled me to continue my academic journey. It is of a great chance to extend the deep gratitude to the committee members Dr.Mohammad Abido, Dr. Muhammad Khalid those who have been supportive during my graduate studies.

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LIST OF ABBREVIATIONS

RES	Renewable Energy Resources
ESS	Energy Storage Systems
BESS	Battery Energy Storage System
SMES	Superconducting Magnetic Energy Storage
PSO	Particle Swarm Optimization
DG	Distributed Generation
PV	Photovoltaic
SOC	State of Charge
KTT	Karush-Kuhn Tucker
SC	SuperCapacitor
VRB	Vanadium Redox Batteries
DOD	Depth of Discharge
IG	Intermittent Generation
WPP	Wind Power Plants
NPV	Net Present Value
MCS	Monto Carlo Simulation
CLL	Cell Lifetime Losses
AH	Battery Throughput
EB	Electric Bus
EDLC	Electric Double Layer Capacitor
HESS	Hybrid Energy Storage System
IEA	International Energy Agency
CAES	Compressed Air Energy Storage
TES	Thermal Energy Storage
PHS	Pumped Hydro Storage
LTC	Low Temperature Coils
HTS	High Temperature Coils
NaS	Sodium Sulphur Batteries
GA	Genetic Algorithm

NOMENCLATURE

P_{INT}	Intermittent Power [MW]
P_{Load}	Demand Power [MW]
P_{BESS}	Battery Charging/Discharging Power [MW]
P_{SMES}	SMES Charging/Discharging Power [MW]
E_{BESS}	Battery Storage Capacity [MWh]
E_{SMES}	SMES Storage Capacity [MWh]
P_{Sm}	Aggregated Smoothed Power [MW]
C_{BESS}	Cost of BESS per [MWh]
C_{SMES}	Cost of SMES per [MWh]
$P_{\mathrm{INT},Max}$	Intermittent Source Maximum Power [MW]
RR	Ramp Rate Limit [Mw/min]
Δt	Time Elapsed [Min]
E_{NC}	Demand Energy Not served [MWh]
$\mathrm{D}_{\mathrm{power,SMES}}$	Power Density of SMES [MW/kg]
$\mathrm{D}_{\mathrm{Energ,SMES}}$	Energy Density of SMES[MWh/kg]
$\mathrm{D}_{\mathrm{power,BESS}}$	Power Density of BESS [MW/kg]
$\mathrm{D}_{\mathrm{Energ,BESS}}$	Energy Density of BESS[MWh/kg]
$\mathrm{N}_{\mathrm{BESS}}$	Capacity of a storage [MWh]
$\mathrm{w}_{\mathrm{BESS}}$	BESS Weighting Factor
$\mathrm{w}_{\mathrm{SMES}}$	SMES Weighting Factor
$\mathrm{w}_{\mathrm{DoD,BESS}}$	BESS Depth of Discharge Weighting Factor
$\mathrm{w}_{\mathrm{DoD,SMES}}$	SMES Depth of Discharge Weighting Factor
w_{Ref}	Reference Power Weighting Factor
w_{load}	Demand Power Weighting Factor
P_{Ref}	Reference Power [MW]
$P_{Ld,trac}$	Load Tracking Power [MW]
P_T	Hybrid System Power [MW]

L	Load Power [MW]
SOC_{BESS}	BESS State of Charge %
SOC_{SMES}	SMES State of Charge %
Δx	Time Interval [Min]
L	Coil Inductance [H]
i	SMES Current [A]
P_{Prp}	Proposed Power [MW]
$P_{C,D}$	Charging / Discharging Powers [MW]
SOH	Battery State of Health %
C_{deg}	Battery effective Capacity [MWh]
γ	Li-ion Capacity Loss Coefficient %
D	Fractional Damage of BESS Lifetime %
R	Range of Cycle [0 - 100]%
A	Empirical Parameter
B	Empirical Parameter
CTF	Cycle to Failure
$T.N.Cycles$	Total Number of Cycles
N	Number of Cycles
T	Total Simulation Time [Min]
BHI	Battery Health Index %
ρ	Air Density [kg/m^3]
A	Blade Swept Area [m^2]
V	Wind Speed [m/s]

ABSTRACT

Full Name : [IBRAHIM M. ALOTAIBI]

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Renewable energy resources (RESs) are expected to spread dramatically these decades as planned in every vital vision in the region. Governments motivate the investment to replace fossil fuels with RESs. Although the RESs such as wind or solar provide an alternative and effective measure to conventional fossil fuels power plants, they inherently introduce intermittency which can be overcome by several countermeasures such as Energy Storage Systems (ESSs). Battery Energy Storage System (BESS) has widely been deployed to mitigate such implications due to their low cost and simplicity in operation. Furthermore, such applications require excessive utilization to the BESS which is inadvisable since it leads to storage deterioration. In addition, BESSs are mainly deployed in applications where high energy density capabilities are needed.

On the other hand, few researchers have considered hybridizing two storage technologies to provide a valuable approach to alleviate the shortcomings of the BESS and the implication of intermittency. In this perspective, a Superconducting Magnetic Energy Storage (SMES) characterized by high power density is hybridized along with

BESS to provide an outstanding performance to the issues commonly arise when using an intermittent source.

In this thesis, 1-minute averaged wind power is considered. Because the aggregated wind power is highly unlikely to be constant, 1-minute step change will provide the indication to ramping events behavior. A multi-stage optimization model solved by Particle Swarm Optimization (PSO) to allocate the optimal size and cost of the hybrid storage and the stand-alone storage is developed. Upon the optimal quantities that have been optimized, a weighted sum quadratic objective function is developed to efficiently operate the hybrid system taking into account various constraints imposed on the model. A comparative analysis to BESS performance in case of hybrid storage and stand-alone storage is carried out using RainFlow counting method.

The proposed work succeeded to prove that, the installation cost of the hybrid storage system to meet grid requirements is a way cheaper than the stand-alone storage to fulfill the same requirements. Furthermore, the control scheme of the hybrid storage system was successful to extend BESS lifetime as much as 4 times compared to the case where a stand-alone storage is deployed. The results are vulnerable to variations as the market trend keeps changing.

ملخص الرسالة

الاسم الكامل: إبراهيم محمد العتيبي

عنوان الرسالة: السعة المثالية لنظام التخزين الهجين المكون من البطاريات التقليدية ونظم التخزين المعتمدة على الموصلات الفائقة

التخصص: هندسة كهربائية / تخصص دقيق: قوى

تاريخ الدرجة العلمية: 7 / 5 / 1439هـ

مصادر الطاقة البديلة مرشحة للإنتشار بشكل كثيف جداً هذه العقود كما هو مخطط له في جميع خطط الدولة قصيرة وطويلة المدى . الحكومات تشجع وإستثمرت مؤخراً مئات الملايين من الدولارات لبحث سبل إستبدال الطاقة التقليدية من الوقود الأحفوري بالطاقة المتجددة والبديلة مثل الرياح والشمس وغيرهما. بالرغم من أن هذه المصادر تمثل نقلة نوعية ومصدر متجدد مهم إلا أنا تعاني من مشاكل الإنقطاع وعدم التنبؤ بسبب الطبيعة الجغرافية . بالرغم من هذه المعوقات إلا إنها يمكن التغلب عليها بإجراءات إحترازية اللتي تزيد من موثوقية الطاقة وتحسن مستوى نقل القدرة الناتجة .على أية حال , البطاريات كانت ولازالت تمثل عنصر مهم لحل مثل هذه المشاكل والتطبيقات نظرا لقلة تكاليفها وسهولة تركيبها وتشغيلها . علاوة على ذلك , هذه التطبيقات تتطلب إستخدام مفرط للبطاريات مما يقلل من جدواها الأقتصادية ويقلل عمرها الإفتراضي ويزيد التكاليف . بالإضافة إلى ذلك , البطاريات توظف في تطبيقات تتطلب كثافة عالية من الطاقة .

على الصعيد الآخر , قلة من الباحثين , فكروا في إستخدام نظام التخزين الهجين لتوفير العمل اللازم والتغلب على مشاكل البطاريات التقليدية, والتغلب على الإنقطاع المتكرر للرياح. من هذا المنطلق , سيتم دمج الموصلات فائقة التوصيل المتميزة بالقدرة العالية جداً مع البطاريات التقليدية لتجاوز العقبات المرئية مع البطاريات التقليدية والمشاكل اللتي تصاحب غالبا طاقة الرياح .

في هذا البحث سيتم إستخدام طاقة الرياح في معدل دقيقة واحدة , وبما إن طاقة الرياح لايمكن التنبؤ بإستقرارها سيتم إستخدام الدقيقة الواحدة للإشارة لـ سلوك الإضطراب اللحظي .سيتم إستخدام معادلات رياضية مكونة من مراحل متعددة ستحل بواسطة النظام الثوري لسرب الجسيمات المحسن (PSO) لتحديد السعة المثلى والتكلفة الأقل لنظام التخزين الهجين والنظام المستقل. بناءا ً على المرحلة الأولى والكميات المثلى اللتي تنتجها , سيتم إستخدام معادلات ليست خطية لإدارة وتشغيل النظام الهجين والمستقل آخذا ً في الإعتبار بعض القيود المفروض على النظام. في النهاية سيتم إجراء تحليل كمي لأداء البطارية في النظام الهجين المدمج والمستقل لتقييم العرض المقترح في هذه الرسالة .

الدراسة المقترحة في هذه الرسالة , نجحت في أن تثبت أن تكاليف النظام المدمج الهجين للوفاء بإلتزامات الشبكة إنخفضت بشكل مذهل مقارنة مع نظام التخزين المستقل المعتمد على البطاريات التقليدية . علاوة على ذلك , النظام الهجين نجح أيضا في أن يطيل عمر البطارية 4 مرات مقارنة مع النظام المستقل .مع العلم أن هذه النتائج قد تكون معرّضة للتغيّر نظراً لتغير المواصفات وتكاليف وسائل التخزين .

CHAPTER 1

INTRODUCTION

1.1 General

Growing in electrical requirements, fossil fuel depletion and ecological concerns have obliged governments and utilities to invest more in green energy. Many governments have encouraged electric power producers to diversify their resources in order to reduce the vast consumption of oil and fossil fuels. On the other hand, deregulation markets and emergence of new technologies resulted in restructuring electric utility and led to the introduction of distributed generators (DG's) where the demand requirements are met from local generators operating in the distribution system. The term DG refers to a variety of grid-connected technologies that provide power and storage at or near the end user (point of consumption). DGs often comprise of renewable energy resources such as wind and PV that offer a wide range of potential benefits. DGs may provide a low-cost and reliable power with fewer ecological consequences.

Although the DGs provide promising features, they literally suffer from a challenging behavior in terms of uncertainty and intermittency that usually encountered in wind speed and solar irradiance. However, the deployment of such resources have captured the attention lately and the penetration of renewables have been steadily growing [1]. Moreover, Due to the intermittent nature of such resources and the demand requirements that should continuously be met ,new initiatives and technologies were introduced in order to overcome the preceding points [2], [3]. In addition, the increased competition in the deregulated markets led the sustainable energy producers to figure out new technologies that might contribute to maximizing their total profits. However, the natural fluctuations in such resources can never maintain a reliable output power, Therefore, a wide range of energy storage systems are introduced to mitigate the power congestion, defer upgrading the system, and maintain reliable output power. The total power of Energy storage systems (ESSs) that has been installed in the globe jumped from a 90GW in 2008 according to [4], [5] to approximately 168.6 GW at the end of 2016 according to [6] . Moreover, Energy storage systems may increase the profits for renewable energy operators if properly selected and operated.

Energy storage systems can be classified based on the form of stored energy and the discharging period to deliver the stored energy. ESS may involve thermal technology (hot water and molten salt), mechanical technology (Flywheel, pumped hydro, compressed air energy), chemical technology (hydrogen and natural synthetic gas) and electrical technology includes (super-capacitors and superconducting magnetic energy) and electro-chemical technologies that include (lithium ion and lead-acid as well as sodium sulfur) .

Building and operating battery energy storage system (BESS) requires careful investigation due to their cost complexity. Several researchers explored the role of utilizing battery energy storage system (BESS) with wind farms to enhance the power quality, reliability and stability of the distribution system[7]–[10]. Besides, ESSs can be integrated to increase the total profits in the deregulated markets. Moreover, an effort was exerted to determine the optimal size of those BESSs as in [11].

Due to the high penetration of renewables, a sufficient capacity of storage system is required to preserve the power quality, reliability and to enhance the output power delivered. However, such demands require frequent charging and discharging of the storage system where such behavior may deteriorate some of the conventional storage devices such as electro-chemical batteries and hence resulting in a shorter lifetime. In general, the larger the installed capacity of battery energy storage, the greater is the improvements. However, the installation cost of BESS remains the main barrier of the expansion [12].

On the other hand, effective utilization of the energy storage system can possibly maximize the profits for the operators by storing the energy at low-price duration (surplus power) and deliver it back into the system during high-prices period. Back to the aforementioned drawbacks of battery energy storage system, it is essential to find out alternatives to overcome the problems associated with BESS deployment. A promising approach is to hybridize a storage system that may combine different forms of technologies in order to minimize the capital cost of installation and to overcome the shortcomings usually encountered when using single storage system.

1.2 Problem Statement

The stochastic nature of the wind /PV due to the geographical and seasonal variations introduces several challenges in terms of reliability and power quality. In addition, the uncertain patterns of renewables create a critical issue in terms of system stability and dispatchability of the generated power. The output power that could be captured from the wind is highly sensitive to any small perturbation in wind speed.

Generally, Wind power is inherently vulnerable to constant changes at different time frames depicted in Figure **1.1**. RR Indicates to the ramp rate where P_{INT} refers to the intermittent generation. Obviously Δx represents the time interval. Ramping event (rate of change) is the result of wind power differences between any two consecutive instances. It might be quantified by the instantaneous rate of change of a definite power series. However, sudden swings in the electrical power may result in acceleration or deceleration of the mechanical - electrical part and hence disrupting the network frequency according to the swing equation.

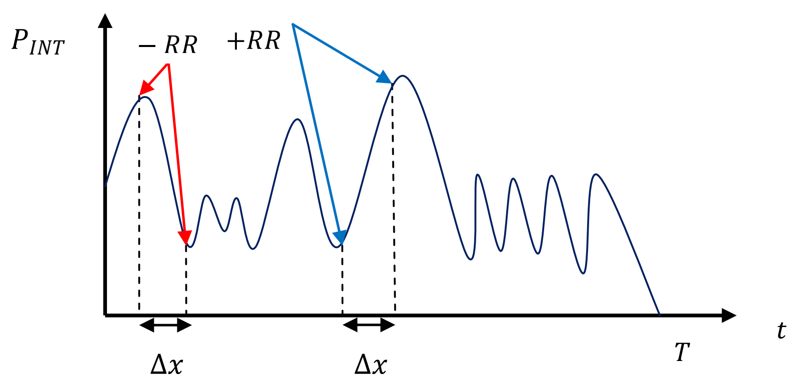

Figure 1.1: Intermittent generation ramping events

Therefore, Authorities have issued basic grid requirements in terms of voltage regulation, power factors limitations and reactive power supply and frequency changes. Accordingly, countermeasures should then be taken to regulate the power and thus maintaining a stable system frequency. As discussed in the previous sections, energy storage system has successfully been deployed to condition the volatility of wind power and to limit the ramping events to a certain extent.

Although the electro-chemical batteries have been considered as a successful measure to mitigate negative or positive ramping actions, they also introduce new challenges in terms of lifetime, depletion, deterioration due to the excessive utilization and limitation to cover up high power demands. A successful deployment to the storage system in conjunction with a volatile source should have similar pattern to P_{Prp} dictated by Figure **1.2** where the proposed new power (P_{Prp}) falls within the ramp rate regulation imposed on the system.

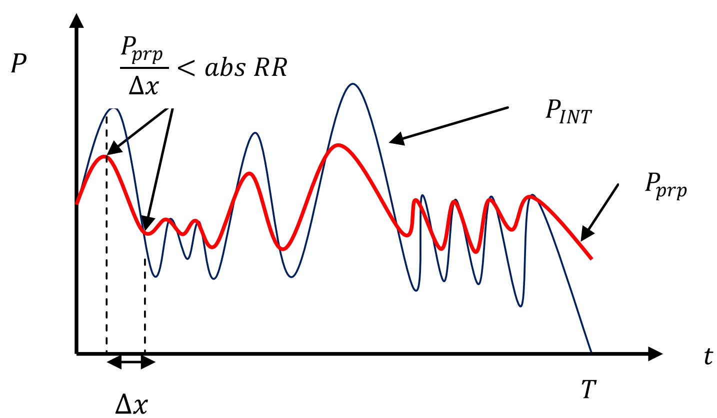

Figure 1.2: Ramped power successfully smoothed

Large power swings require high power density devices where the response time ranges from 1 second to several seconds. Such properties are highly unlikely to be found with conventional batteries. If such special batteries are commercially available, then their capital cost and deployment might be unjustified. On the other hand, few researchers have indeed thought of combining more than one storage technology in order to overcome the individual shortcomings. As in [13] the author proposed a hybrid energy system to minimize the current deviation and the state of charge (SOC) variation in the battery and SuperCapacitor respectively. Weighted sum KTT optimization model is deployed to optimize the objective function aiming to improve the energy efficiency of the overall system and to extend battery lifetime.[14] Has harnessed super-capacitor (SC) in conjunction with flow batteries to absorb high power surges of frequencies > 1 Hz by SC while the vanadium redox battery (VRB) is dedicated to absorb frequencies lower than 1 Hz. The author suggested combining both storage technologies to overcome power & energy issues if only one storage is installed. The proposed model has successfully lowered the depth of discharge (DOD) of the VRB and enhanced system efficiency. The impediment of operating battery packs only to meet the power demands of hybrid city bus has been addressed in [15]. The authors proposed a compromised battery - ultra capacitor model to increase the battery lifespan and to ensure the fulfillment of meeting high power rates. The model attempts to maintain a constant current in the battery while charges/discharges the ultra-capacitor as fast as possible in regenerative breaking/acceleration mode.

On the other hand, limited resources considered combining Superconducting magnetic storage system (SMES) with BESS to overcome the deficit that could not be covered using conventional batteries such as fast response, irregular cycling, and limited maximum power and relatively short lifetime. Conventional batteries however are classified among the low power density technologies whereas SMES is characterized by a fast acting time, High power density, high efficiency, and relative massive cycling lifetime. In addition, the instantaneous high power output that could be retrieved from

SMES makes it superior over other storage forms that have substantial time delay due to the energy conversion process. Generally, SMES has a low power loss due to the absence of electrical resistance during storing or releasing the energy. The research and development on High temperature SMES have been growing and encouraging results were reported to promote the deployment of SMES in electrical power applications.

Such preceding advantages make the superconducting magnetic storage system a promising technology in electrical industry. Apparently, a compromised combination of SMES/BESS provides the needful features required to meet grid code regulations.

1.3 Research Objectives

The main goal of this thesis is to develop an economical-operational planning scheme for a hybridized storage system, a stand-alone battery energy storage system, combined with an intermittent generation (IG). RainFlow counting method is implemented to estimate battery bank lifetime in both configurations. In addition, the impact of deploying a hybridized storage system on the cost and inherent characteristics of BESS is addressed. The detailed objectives of the thesis are summarized as follows:

- Develop a comprehensive survey of recent energy storage technologies with their respective applications.
- Develop a mathematical model to allocate the optimal cost and the size of the hybridized storage system considering the grid requirements and the demand energy not covered by the intermittent generation.

- Develop a mathematical model to efficiently operate the hybridized storage system while meeting the imposed constraints.
- Optimize the size and operation for a stand-alone battery system integrated with the IG source is carried out.
- Conduct a profound comparison between a single storage system and a hybrid storage system in terms of cost and operation.
- Assess the technical impact of operating the hybrid system on BESS lifetime using "RainFlow" counting method.

1.4 Thesis outline

The remaining chapters of the thesis are organized as follows: chapter two comprises a thorough literature review. In Chapter three, a recent comprehensive survey on energy storage forms, energy storage technologies and their respective characteristics is documented. A mathematical framework containing a multi-stage optimization algorithm to allocate the optimal cost and optimal size of the hybrid system as well as the single storage system is intensively investigated in chapter four. In addition, a quadratic optimization model to optimize the control signals of the hybrid system is also covered. Moreover, the battery state of health and lifetime estimation is discussed and at the end of the chapter a flowchart illustrating the sequential optimization process is delivered. Chapter five is dedicated to carry out the overall analysis that has been introduced in chapter four. Finally, a summary of the thesis, the main contributions, the prospect of future work are delivered in chapter six.

CHAPTER 2

LITERATURE REVIEW

2.1 The Application of BESS with RESs

In deregulated markets, wind power producers are obliged to several commitments due to the natural aspects of those resources. Therefore, BESS was incorporated into the system to mitigate the shortcomings that result due to the unpredictable nature of such resources. However, determining the optimal size and maximizing the profits by utilizing BESS's have intensively been researched. Nevertheless, few of those considered the lifetime losses of the BESS and their effect on the overall profits in the real time market.

Several studies have been reported in the literature to investigate the optimal size allocation of the BESS as well as increasing the wind power plants (WPPs) revenue via various optimization techniques and different approaches.

The effect of BESS's on the planning and operation of wind power plants was investigated in [16], [17]. In addition, the impact of utilizing BESS results in efficient operation of the wind power plant. The optimal power and maximum profits were determined by including the total profits of electric energy sales, total cost of BESS, transmission access fees and upgrading cost of the connected substation transformers into the objective function. It is worth to note that the life-cycle losses of the BESS weren't considered in the previous literature. The optimization problem in both literatures has been solved using nonlinear program platform. While [18] optimized the BESS by maximizing the net present value (NPV) of the total income taking into consideration the capital and maintenance cost of BESS . A non-dominated genetic algorithm was deployed to optimize this problem.

On the other hand , a BESS can be integrated with a PV system in one of power quality applications as in [19]. The intermittent nature of such resource will never maintain a reliable output power, therefore a BESS was incorporated to mitigate PV output power fluctuations. The optimal size of BESS was obtained in order to maximize the total revenue of the PV system by reducing system fluctuations. In addition , the fluctuations were taken into account for battery energy storage system sizing as in [20]–[22]. Reference [23] aims to optimize the BESS size that maximizes the total income while maintaining the output wind power constant. However, since the DC link voltage is kept steady and the capacity in [20] is determined solely based on the peak of wind generation, the size determined might not be justified and needs to be revised. Therefore, the author in [21] attempts to overcome this limitation by using stochastic optimization to accurately size the BESS.

BESSs have also been utilized in energy arbitrage and peak shaving applications as in [22]. The optimal size of a BESS integrated with a PV/battery system is determined by minimizing the net power purchased during peak hours as well as minimization of capacity degradation cost post each discharging process. Studies of a BESS blended in with a high PV/Battery penetration have been reported in [23]. BESS is optimized at each bus, based on the analysis of cost-benefits, considering voltage regulation and peak load shavings.

In a wind-diesel isolated system [24], the optimal size of BESS is carried out by minimizing the fuel and operating costs over a 20 year planning period. A two stage approach conducted to capture the wind variations and load uncertainty as different scenarios were considered corresponding to the wind profile and load. The first stage is to optimize the BESS that meets all scenarios while the next stage identifies the optimal operation based on the optimal size obtained in the first stage.

The lack of reliability and unpredictability associated with stand-alone wind power plant decreases its competitiveness against other resources [25]. Therefore, optimized BESS is introduced to subdue the gap results between the predicted and actual wind generation. BESS size is determined in order to smooth the output power fluctuations of the wind power plant within a ± 4 % of the forcasted data and for 90 % of the operational period. Integrating BESS in a system that lacks generation reserve has been investigated in [26]. The BESS is installed to provide the system with an adequate reserve. The optimal capacity and power rating are determined using temporal and non-temporal methods. Although the revenue is achieved in the aforementioned studies, the BESS accurate size might be overshadowed since the cost of BESS was not considered in [25], [26].

The optimized size and location of BESS were examined in [27] to reduce the lost wind power. The maximum spilled power and energy are being used in [27] to allocate the aggregated power and energy size of the BESS. The study is conducted from DGs owners' perspectives to maximize their income based on cost-benefit analysis.

Incorporating BESS with Hybrid systems which include both wind generating units and PVs have also been investigated in [28]. Sizing the energy storage system was investigated based on cost-benefits analysis as well as unit commitment taking into the consideration the spinning reserve. Two operational modes were separately studied, isolated and grid connected, several BESS sizes were allocated reported in [28].

From another perspective, energy storage systems can be installed as a backup to improve the reliability of a crucial system [29]. The optimal size of BESS is determined in terms of power rating and energy capacity using analytical approach to boost up the availability or alleviate the mean down time of supply to critical loads. The model was extended to an island-capable microgrid with RES where the sequential Monto Carlo Simulation (MCS) was used to study the system reliability [30]. However, expenses of the BESS were not included in the proposed model. Sizing the BESS is proposed in [31] to improve the reliability, wherein the impact of the Installment cost of the BESS on the operating cost is considered. However, the optimization technique was based on unit commitment (UC) formulation and solved using mixed integer linear programming (MILP) problem.

Due to the uncertain nature of the RESs several stochastic models were reported to optimize the BESS and DGs as in [32], [33]. In community applications, a stochastic method based on Monto Carlo Simulation (MCS) and particle swarm optimization technique is reported in [32]. The optimized size of wind generation and BESS is determined to minimize the electricity cost for a household customer taking into consideration the uncertainty in wind power, electrical prices, and demand. The author in [34] proposes an energy management scheme that enables the ESS to mitigate the stochastic nature of PV production. A quadratic programming model is used to maintain the SOC of the battery as close as possible to the middle state of charge. In[35], A model predictive control is developed to allocate the optimal size of a distributed BESS capacity by minimizing the overall cost while meeting grid integration requirements.

A wind power selling strategy based on dynamic programming is utilized to increase the revenue of the wind power plant integrated with a BESS [36]. The proposed strategy aims to take the advantage of prices variability throughout the day to generate extra income and hence increase the operational profits by carefully controlling the charging/discharging scheme of the BESS. Further constraints were imposed on the BESS operation in order to extend their lifetime and defer their replacement. However, the installation cost and lifetime losses of the BESS were not considered in the proposed model. Hence, the correct total profits achieved might be overshadowed. The aforementioned literature was extended to further deeply investigate the operational scheme of the BESS integrated with a wind farm [37]. Several constraints are added to address the detrimental effects of excessive utilization of the BESS. Battery wearing cost, lifetime losses (CLL), and throughput (AH) of the BESS are taken into consideration in the proposed model.

2.2 The Challenges of BESS Utilization

Although the BESS is widely utilized in contemporary RES's stations, utilizing the BESS has major challenges in terms of relatively low cycling times, low power density, and prolonged response as reported in [38]. Furthermore , BESS Depth of Discharge (DOD) limits the complete discharge as this may deteriorate BESS lifetime as in [39]. Several countries have still been deploying the previous generation of storage systems such as pumped hydro and flywheel where the capacity installed across the globe for the former reached 127 -129 GW as reported in [39]. Although the aforementioned technologies can supply a bulky power, they suffer from several drawbacks such as long construction time, high capital, and operating cost as well as restricted locations. Therefore, it was essential for researchers to explore new technologies that could be integrated in conjunction with RES's to overcome the challenges that accompany the previously reported tools.

Recent studies investigated the feasibility of replacing BESS with electrical energy storage systems such as Super -capacitors and Superconducting Magnetic Energy Storage (SMES). SuperCapacitors (SC) can provide fairly amount of power during the short duration interruptions, mitigate power quality issues and enhance the deliverable power to the end user as reported in [40] and [41]. Due to their structure , SC can have both characteristics of BESS and capacitors in terms of high energy density and relatively high power density [39], [40]. In addition, the most important features of SC's are high roundtrip 88-97 % and massive cycling times 100,000 compared with the BESS. However, the daily self-discharge rate is quite high and may reach 40 %. Furthermore, small to medium size SC's are commercially available while developments have been undergoing with regard to larger capacities. Thus, SC's are appropriate for short term storage applications.

On other hand, SMES has attracted researchers' attention due its excellent features over the preceding technologies. SEMS has a very fast response time (in milliseconds), high power density (4000W/Liter), very quick full discharge time (within 1 minute), and high roundtrip efficiency 95 %. In contrast to the battery energy storage system, SMES can discharge nearly the entire stored energy. In addition, their lifetime may last for approximately 30 years as reported in [39], [42], [43]. However, in spite of the distinguished features that the SMES can provide, they suffer from operational challenges in terms of cooling and commercially available size as well as high capital cost. Several attempts are now being carried out to produce large scale - SMES and high temperature coils that might bring the cost down. Furthermore, the installment of such fast response technologies to operate as a stand-alone storage is not justified yet economical wise as stated in [39], [44]. Operational wise, SMES stores the energy as a circulating current in the magnetic field and hence can release it back within milli-seconds which limits their utilization as an ultimate solution for long duration storage applications. However, Power system operators are required to weigh the outcomes against the detrimental aspects of each technology that might arise when it comes to real life applications where the perfection is unachievable.

2.3 Storage Hybridization Can Create a Value

Having stated the above, limited literature is devoted to investigate a hybridized SC, SMES with BESS to overcome the aforementioned drawbacks. Utilizing a fast response storage system with conventional batteries, this may increase the range of deployment where the former could be dedicated to act as soon as high speed fluctuations occur, while the latter is solely dedicated to supply long duration interventions or scheduled power. It is worth mentioning that an excessive utilization of battery energy storage system leads to batteries deterioration. Furthermore, the installation of hybrid energy storage system has a great impact on extending BESS lifetime if proper control scheme is carried out [45], [46] . SuperCapacitor was successfully hybridized with a BESS into an Electric Bus (EB) to maintain a constant dc voltage during generation and demand changes [45]. A power grading control algorithm was applied to achieve further improvement in battery lifetime. A quantitative analysis is then carried out to assess the utilization of the battery only and the hybrid storage system. Furthermore, the reported literature proved that operating such hybrid system complements the disadvantages of each system. A hybrid storage system consisting of SC and BESS integrated with a remote area RES is proposed in [47]. A complementary performance of the Hybrid Energy Storage System (HESS) is then examined by both theoretical analysis as well as numerical analysis using MATLAB platform .However, the conventional battery was operated as primary energy source for longer periods while the SC was dedicated to operate as an auxiliary power source to smoothen peak power. The optimal size and operation for electric double layer capacitor along with BESS are reported in [48]. The optimization is carried out using linear and quadratic programming to transmit optimal operational signals to operate BESS and Electric Double Layer Capacitor (EDLC) modules. The efficacy is then demonstrated on real wind speed data obtained in Texas,USA. It's worth mentioning that, the overall cost of the hybrid system was lower than operating the BESS only.

Another approach can be thought of is to hybridize SMES with a battery energy storage system to make use of the distinctive features of the SMES. Such approach has not been widely researched. Careful investigations need to be invested in this direction since every device has its own defects. A system of SMES - BESS was proposed in [49] to condition the fluctuated output power generated from direct drive linear wave energy converters. A SMES was designed to operate in conjunction with the batteries to smoothen the output power. Furthermore, a control topology was developed to operate the SMES and BESS during charging, discharging, and standby modes. The DC-link voltage was selected as a reference for SMES intervention due to its fast response and unlimited life span while BESS operates based on the DC power component that results from the inverter DC side.

For the sake of comparison, this paragraph sheds some light on the gaps found in the literature. For instance, the author in [50] has successfully applied a control-based algorithm of SMES - BESS to smooth out the volatility of wind power using a synergized circuitry-based real time simulation. A low pass filter is used to decouple the wind power into a high frequency component and a low frequency component. SMES is characterized by a high power density and a fast response time which qualifies it to deal with high frequency power, while the low frequency power is dealt by the BESS. Three modes (normal -warning - alarm) are suggested to efficiently operate the hybrid system.

Moreover, the proposed operational scheme succeeded to control the SOC of both devices within the desired limitation. However, the proposed energy management didn't consider the service lifetime of the BESS nor the optimal size needed. The battery bank was excessively utilized since it underwent frequent charging /discharging cycles where such behavior facilitates battery degradation. In addition, the impact of deploying SMES over the BESS performance has not been addressed. The author also didn't consider any cost investigation where the installation cost is crucial factor in such studies. In [51] The size of hybrid energy storage system is allocated so that, the capacity of BESS should sustain load demand whereas the SMES is sized to accommodate the short term fluctuations. The control strategies are simulated using the 'Simulink' in MATLAB. Like [50], the author deployed a low pass filter to decouple the high frequency component from the low frequency power . Unlike [50], a novel battery lifetime model was used to effectively estimate the bank lifespan which includes the discharging current rate. However, the proposed work lacks any cost calculations or optimality studies. Therefore, the feasibility of the proposed work is unjustified. On the other hand, the author in [48] successfully hybridized a double layer SuperCapacitor with a battery bank to sustain the ramping events . The author proposed a nonlinear model solved by a quadratic optimization technique to control the hybrid system. However, the proposed work didn't emphasize the impact of the hybridized system on battery lifetime. In addition, the work presented lacks a necessary analysis to the battery performance prior and post the hybridization.

Given the above, the aim of this thesis is to fill in the gaps overlooked in the literature reviewed above by proposing a multistage optimization models that optimize the size and the operation of a hybridized storage system comprised of a high power density device and a high energy storage system. The impact of the hybridization on battery performance will be addressed throughout the analysis. The shortcomings seen in the literature can be summarized as follows:

- **The majority of studies that is dedicated to optimize the cost:**
  - ✓ Lacks the service lifetime analysis of the BESS and the optimal coordinating signals to operate the hybrid system.
  - ✓ The impact of deploying SMES over the BESS performance has not been addressed.
- **In studies that address the impact of hybridization on BESS performance overlook:**
  - ✓ The cost investigation that justifies the selection of hybrid storage over a single storage.
  - ✓ The required economical & technical comparisons between the case of hybridization and stand – alone storage systems.

CHAPTER 3

BACKGROUND

The aim of this chapter is to document the existing energy storage technologies and their potential applications. This chapter is written for the sake of continuity and to give the reader a comprehensive overview of the recent advancements in energy storage industry. By the end of the chapter, a sufficient knowledge should have been built to help the reader recognizes the merits and demerits of a wide range of energy storage devices. Comparative tables summarizing an in-depth study of the most up-to-date characteristics and cost of installations for different ESSs are delivered at the end of this chapter.

3.1 Terms and definitions

The following terms need to be realized in order to address the distinction between various storage technologies and their respective applications. Substantial features are defined herein:

3.1.1 Power and energy

Power and energy terms are strongly linked to the applications that are used for. For instance in applications where a long duration load shifting is needed, an energy cost $/MWh becomes considerably crucial when selecting a storage technology. Similarly, an application that preserves power quality and system stability, a power cost $/MW is precisely important in storage technology selection.

3.1.2 Energy to Power ratio

The amount of installed capacity relative to the installed power is known as E to P ratio. A storage with high E to P ratio can deliver its power over a prolonged period.

3.1.3 Energy density

The ratio of the available energy to its volume and can be measured by [MWh/m^3].

3.1.4 Power density

The ratio of ESS power to its volume is known as the power density and measured by [MW/m^3].

3.1.5 State of charge

The remaining energy of the storage system relative to its rated capacity represents the SOC. A storage system of 100 % SOC is said to be fully charged ESS, while 0% SOC indicates to completely discharged ESS.

3.1.6 Response time

Response time indicates to how fast a storage technology can be brought in services and delivers its stored energy.

3.1.7 Discharging time

Refers to how long a storage technology can hold its output power over time.

3.1.8 Depth of discharge

A DOD describes how deeply a battery is discharged. Or quantifies how much energy has been delivered by the battery. For instance, a battery is said to have 0% DOD if it is 100 % fully charged or SOC is 100 %. DOD always refers to the amount of discharged capacity relative to full capacity prior storage gets recharged. Generally, the DOD can be described by:

$$DOD\,\% = \frac{Energy\ Capacity - Min\ SOC}{Energy\ Capacity} \times 100 \qquad \textbf{(3.1)}$$

3.1.9 Frequency of discharge

Indicates to how often a storage is being discharged.

3.1.10 Efficiency

Efficiency relates the input energy to the output capacity. The efficiency of storage systems is heavily affected by the ambient conditions such as the temperature.

3.1.11 Cycle life

The number of full cycles that a storage can undergo under certain conditions before it reaches 80% of its nominal capacity.

3.1.12 Self-discharge

A spontaneous internal chemical reaction with no loading action taking place in batteries is known as self-discharge. Such chemical reactions reduce the stored charge of the battery. Self-discharge decreases the shelf-life of batteries and may cause capacity degradation if the battery put in use. Ambient conditions strongly affect the self-discharge of batteries, thus, storing non-used batteries in a controlled temperature warehouses may lessen the self-discharge.

3.1.13 Round Trip Efficiency

The ratio of energy output to the energy input is known as a round trip efficiency or cycling efficiency. SMES, Li-ion batteries, Flywheels and SuperCapacitor are characterized by a high round-trip [>90] % among other storage technologies. The round efficiency of flow batteries, CAES and PHES falls in the range of [60 - 90] %.

3.1.14 Lifetime

Battery degradation is linked to various factors that adversely alter the performance and reduce the lifetime of batteries. Once a factor reaches its end limit, the battery should be replaced. The most crucial factors that degrade the lifetime of batteries are listed below:

- **Calendar lifetime:** every storage device has definite years to operate. Once those years are completed, the battery needs to be replaced even though it may not have been operated excessively.

- **Total number of cycles:** based on the storage technology, once the specified cycling number is reached, the storage capacity will no longer be available. This factor is crucial in applications that require shallow, frequent cycling times.

- **Depth of discharge:** the lifetime of most conventional storage systems is heavily affected the level of DOD.

3.2 Energy Storage

One of the substantial characteristics of electricity that it cannot be directly stored. This leaves the operators with zero tolerance when it comes to sustaining electrical demands. Continuous balancing of supply to meet the demands has an adverse impact in terms of cost and operation. The Strict following of the generation to tackle load trajectory implicates the performance of the generators by time where the tear and wear may take place and hence deteriorates the unit. Moreover, a sufficient power capacity needs to be maintained in the form of non-spinning or spinning reserves to account for any unforeseen demand or sudden loss of the operating units. Although, storing electrical energy directly in the form of electricity is unachievable, it can be however stored in other forms such as mechanical, magnetic, chemical, or thermal. Energy then could be converted to electricity if needed.

In last decades there has been a growing attention given to the energy storage industry as the penetration of renewables has been steadily increasing, a reviving needs to electrify the transportation sector making the energy storage a key enabling technology in industrial, and electricity market. Moreover, Energy storage is considered a crucial tool to effectively enable the renewables integration. Although the installment cost of ESS has been rapidly decaying, energy storage remains expensive and requires a financial support from the government in order to increase the deployment and development. Even with such obstacle, the electricity market is being reformed to allow more utilization of ESS.

The international energy agency (IEA) estimates that by 2020 the developing countries need to double their electrical capacity to sustain elevating demands [52].

However, the nations are encouraged to reduce the greenhouse-gas emissions. A substantial capacity to meet such growth will most likely be generated from wind/PV. Integrating such resources will definitely require a storage system .The retirement of fossil fuel power plants exiting today will also leave a gap in the network and hence the grid needs a considerable inertia to ascertain stability. Obviously, energy storage systems are needed to make the intermittent sources more reliable, efficient, resilient, and sustainable.

In an environment where the uncertainty of wind and solar irradiation becomes a substantial issue, the storage system becomes a sole part in electric system to smooth the output power, enhance the power delivery and to assure a reliable power. in addition, in electricity market, ensuring a relatively fixed generated power over a short period of time is distinctive feature that should be met at all time. However, grid utilities must keep an additional capacity to cover up the unforeseen demands, sudden contingencies, and losses of operating lines or plants. Electrical load is volatile in nature and behaves randomly; hence a fundamental storage technology is crucially needed to sustain such behavior.

Storage systems can be integrated to any of the five essential subsystems of the electrical grid: Generation transmission, substations , distributive substation and end users .ESS plays a vital role in generation side by storing the excess energy at times where prices are relatively low. ESS can also be utilized mitigate the congestion that may take place at the receiving end of the transmission system. in substation level, ESS can help relieving the overloaded transformer by releasing the stored energy earlier fed to the storage system .ESS also supports the capacity required from the substation . The end-user however can lower the electricity bill by storing the energy at low-cost time and retrieve back when needed.

The deployment of storage systems may provide a myriad of beneficial services such as, a time shift energy delivery to enable generation - load balancing, Deferring investments in new generated capacity, deferring upgrading the transmission system and to provide an operational support to improve system reliability.

3.3 Energy storage technologies

A wide range of technological storage approaches exit nowadays. Generally, energy storage systems are classified according to their function and storage forms as reported in [53]–[55] as depicted in Figure **3.1**. In terms of function, there are broad storage technologies that are dedicated to operate in high power applications such as flywheel, superconducting magnetic storage system (SMES), Capacitors, SuperCapacitors and specially designed batteries. While compressed air energy storage (CAES) , fuel cells, large-scale batteries, thermal energy storage (TES) and flow batteries are mainly considered for energy applications. The subsequent sections discuss in details different forms of storage technologies. However, due to the inability to store electricity directly, storing energy may take several forms as:

- **Electro-magnetic/Electro-static energy storage**: in this type energy is stored in the form of magnetic field or electric field such as SMES for the former, capacitors, and SuperCapacitors for the latter.

- **Chemical energy storage**: energy is stored in the form of chemical energy and needs to be converted in order to retrieve it back. Electrochemical energy storage includes conventional batteries such as lead-acid and flow batteries like vanadium redox. Chemical energy storage such as metal air batteries, molten carbonate, and fuel cells where the thermo-chemical energy storage consists of solar hydrogen, solar metal and solar ammonia.
- **Thermal energy storage**: Energy is hold in the form of hot or cold substance for later deployment, sensible heat systems such as steam or hot water, accumulators and graphite are concrete example for TES.
- **Mechanical energy storage**: Energy is stored in the form of kinetic energy or potential energy. An example for the former is flywheels while CAES and PHS are examples for the latter.

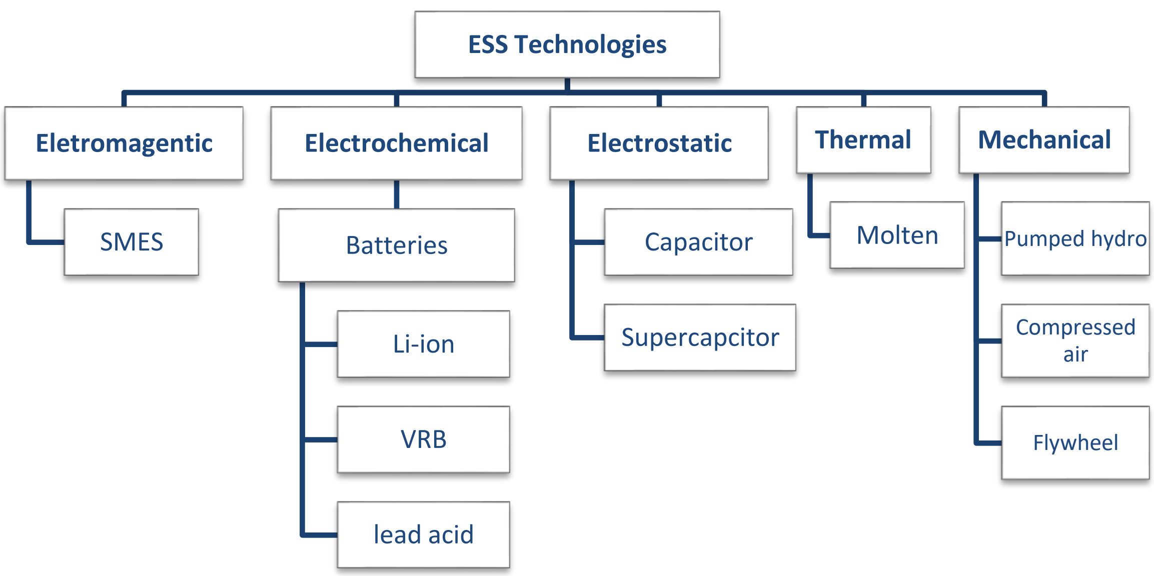

Figure 3.1: Classifications of energy storage technologies

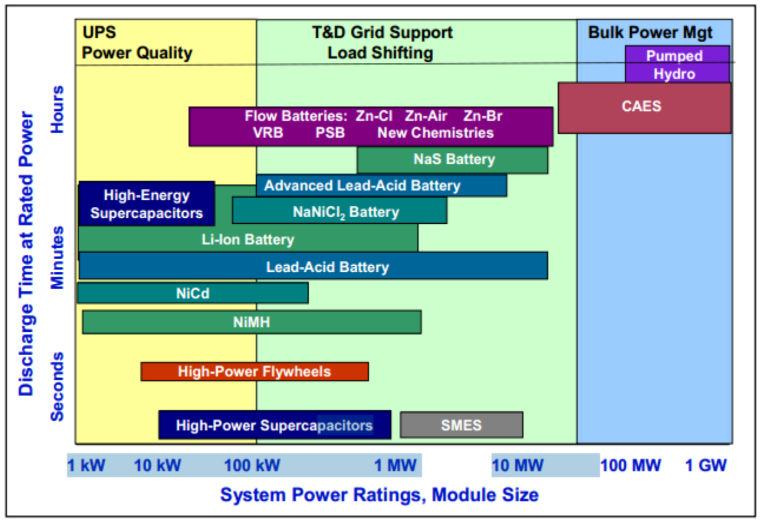

Figure 3.2: Classification of ESS based on the discharging time and power rating [53]

Storage systems are also categorized according to the power rating and the responsive time needed to discharge the stored energy [53] depicted in Figure **3.2**.

- **Short term response ESS:** energy storage of this category is capable to deliver its stored energy within few seconds to several minutes. Such technologies possess a high power density [MW/m^3]. Power quality issues are usually treated by such storage systems.
- **Medium term response ESS:** the stored energy in this category can be released within few minutes to several hours. Medium term storage is often deployed to regulate the frequency and mitigate system congestion.
- **Long term ESS:** these technologies are capable to supply energy for a long time starting from hours to days. Such technologies can sustain the unforeseen increased demands.

3.3.1 Electrical Storage Systems

3.3.1.1 Electrostatic Storage system

A capacitor which is composed of two electrodes separated by a dielectric material can be used to store energy in the form of electric field. The surface area and the distance dictate the storable energy capability. Capacitors charges substantially faster than batteries and can undergo thousands of cycles with high efficiency prior deterioration. In spite of the power applications that can be serviced by conventional capacitors, they suffer from a low power density. In applications where a large capacity is needed, the surface area must be extremely large making their utilization is unfeasible.

A SuperCapacitor uses an electrolyte solution between the electrodes instead of the conventional medium. A growing attention has been devoted to the development of SuperCapacitor especially the recent years where the penetration of the renewables has increased dramatically. SC poses a larger storage capability when compared to conventional capacitors. Generally, Capacitors suffer from a high self-discharge which limits their deployment to a power quality applications. There also a rising issue linked to their disposal since the recycling process to the obsolete devices is environmentally implicated.

SuperCapacitors combine the characteristics of conventional capacitors and electrochemical batteries. The energy is stored in the form of electrostatic charges. Newly developed SuperCapacitors are made of nanomaterials to increase the capacitance. They also have a compromised power-energy density making them a good candidate for both energy-power applications. SuperCapacitors are characterized by a relatively large cycling times and high efficiency [84% - 97%] as per [39]. However, SuperCapacitors suffer from an elevated self-discharge [5% - 40%] and their capital cost is still high around 6000 $/KWh. Therefore, their best utilization would be in short-term applications. SuperCapacitors failure is identified by a capacitive 20% reduction or elevation of the series resistance to 100 % from its reference value [56]. A SuperCapacitor schematic diagram is shown in Figure **3.3**.

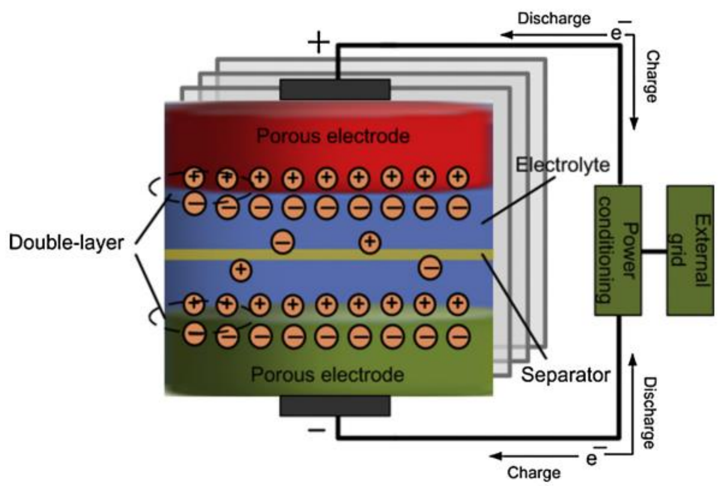

Figure 3.3: Supercapacitor schematic diagram [39]

3.3.1.2 Electromagnetic storage systems

Superconducting magnetic storage system (SMES) is basically a DC device that stores energy in the form of magnetic field [38], [39]. The DC current flowing in the superconducting wire creates the magnetic field. Furthermore, the energy is stored as a circulating current and hence it can be retrieved back almost instantaneously. SMESs are composed of a large superconducting coil at a cryogenically temperature. The temperature is maintained by several cooling mains such as using helium, liquid nitrogen. The second major component of SMES is the power conditioning subsystem and Cryogenic system that cools down the coils. Generally, when electrical current flows in a coil, electrical power is dissipated due to the resistance of the wire. However, if the coils are cryogenically cooled to their critical temperature no power dissipation is developed. One of the commonly used superconducting materials is niobium- titanium which has a superconducting critical temperature of nearly 9.2 K [39]. A typical SMES schematic diagram is shown in Figure **3.4**.

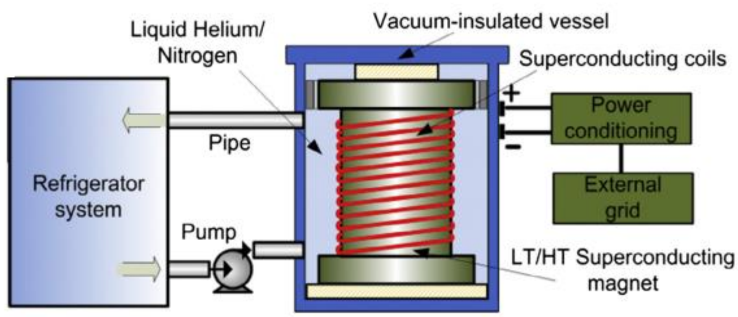

Figure 3.4: SMES schematic diagram [39]

SMES can be classified into a low temperature Superconducting coil (LTS) that operates at 5K, and a high temperature superconducting coils (HTS) working at approximately 75K. Moreover, the LTS coils are commercially available while the development of HTS is still undergoing. SMES of the size 0.1 - 10 MW has been commercially available while larger sizes in the range of 100 MWh might be available at the end of this decade.

SMES is characterized by a high power density [4000 W/Liter], a fast response time [milliseconds], can be fully discharged in less than [1 minute], and may efficiently operate for [30 years]. SMES has also a high efficiency [98%]. Unlike the conventional batteries, SMES may undergo thousands of cycling times with no to little degradation. Moreover, SMES can deliver its full stored energy with no limitation whatsoever in terms of SOC level. In Table **3.1** a list of existing projects being served by developed SMES to do the needful tasks [57]. Although SMES technology seems a promising storage system, the magnetic field produced in the surrounding area restricts their utilization.

Table 3.1: SMES existing projects [39], [57]

Location	Technical Specifications	Applications
Nosoo Power station in Jaban	10 MW rated power	System stability improvement
Upper Wisconsin by American Transmission	3 MW/0.83 kW h, the HTC cable is : each 8 MVA	Reactive power support, Power quality enhancement
Korea Electric Power Corporation, Hyundai	0.834 KWh, HTC size 750 kVA	To improve power quality

3.3.2 Electrochemical storage systems

3.3.2.1 Battery energy storage systems

The rechargeable battery is the oldest form of energy storage. The conventional battery is the most widely used technology applications where a storage is substantially required. A battery stores energy in the form of chemical energy. A battery is consisted of a positive electrode (anode), a negative electrode (cathode), one or several electrochemical cells and liquid or sold electrolyte.

Batteries can be deployed in different applications such as transportation system, energy management and power quality applications. A short time period approximately [12 months] is enough to construct a battery storage system. The installment location of batteries is flexible, they do not often require complicated measures in order to install them. However, the disposal of dumped batteries needs to be taken care of once chemical substances are used. Batteries suffer from a short range of operation since their lifetime is heavily dependent on the depth of discharge. Therefore, many batteries cannot be completely discharged due to the previous reason.

Batteries are categorized into three broad sets: flow batteries, high temperature batteries and conventional batteries. The basic structure, components, functions, and examples of each set are going to be reviewed in the following subsections.

3.2.2.1.a Lead acid batteries

The most commonly used rechargeable battery is the lead acid battery. Lead acid battery consists of lead oxide [Pbo_2] cathode and lead [Pb] anode submersed in sulfuric acid [H_2SO_4]. Lead acid batteries have low self-discharge below [0.3%], high cycling efficiency up to [90%] and a relatively low capital cost [60-400 $/KWh]. Lead acid is commonly utilized in hybrid vehicles, energy management and in applications where a backup power is required. However, the utilization of lead acid batteries is limited due to their low cycling times [<1000 cycles] and their low energy density [50 Wh/kg].

3.2.2.1.b Flow batteries (Vanadium Redox Batteries VRB)

In flow batteries, energy is stored in two dissolved redox contained in external liquid electrolyte tanks. Two reactions can be performed in the fuel cell, a considerable amount of voltage and current is generated where the size of the cell dictates the power and the size of the external tank is dedicated to energy. The bigger the tanks the more energy can be stored. An oxidation takes place during charging the battery where the electrons are drawn from the positive solution into the negative solution in a process called a reduction. When the battery turns on, the flow of the electrons reverses generating an electrical current. The power and energy in flow batteries are decoupled since the power is dependent on the cells in the stack and their size whereas the amount of electrolyte and the size of the external tanks determine the amount of energy. Unlike the conventional batteries, flow batteries can be completely discharged with no effect on their lifetime or overall performance. However, they suffer from a complicated manufacturing process that adversely affects their capital cost and operating cost.

Vanadium Redox batteries (VRB) is one of the most commonly used and mature flow batteries. The vanadium redox [V^{2+},V^{3+},V^{4+} and V^{5+}] are exploited to store energy in the external tanks. The instability of the solution reduces the energy density [~ 30 KWh/kg] which restricts their utilization in applications where a high energy storage capability is needed. In spite of the preceding drawbacks, flow batteries can operate for more than [12,000 cycles] at 100% DOD. The principle of operation for VRB is displayed in Figure **3.5**.

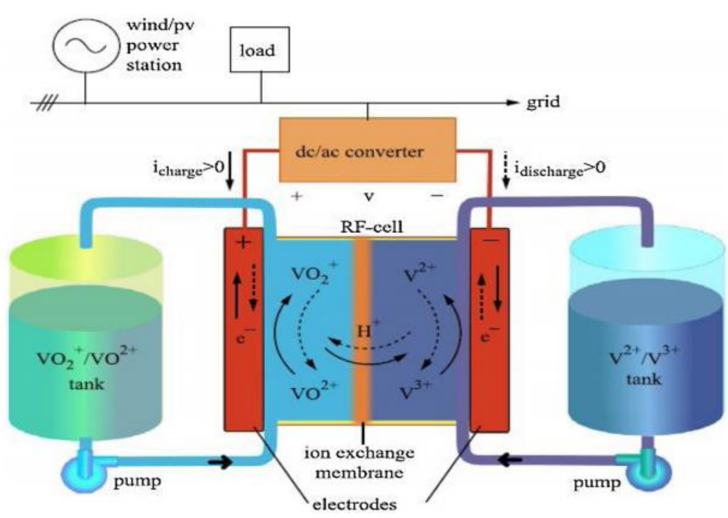

Figure 3.5: Operation principle of VRB [39]

3.2.2.1.c Lithium ion Batteries

Li-ion batteries are comprised of a lithium salt as an electrolyte, a lithium cobalt at the cathode electrode and a graphite at the anode electrode. When the battery gets charged, the lithium particles in the cathode become ions, the processes however turns over during discharging phase.

The size of lithium ion batteries can be scaled up as per the application requirements. They also pose a high power density [315 W/kg] and a high energy density [250 Wh/kg] as reported in [39] and [53]. Lithium ions batteries are perfect candidates in applications where the weight , response time substantially matters. The efficiency of Li-ion batteries is quite high [97%]. Despite the advantages stated earlier, Li-ion batteries are sensitive to the level of DOD and their lifetime degrades at higher rates of DOD. For instance, a Li-ion battery may undergo 10,000 cycles at 50% DOD while the total number of cycles may decrease to 3,000 cycles at 80% DOD. Their lifetime is also delicate to ambient conditions.

3.2.2.1.d Sodium sulphur Batteries

NaS stores energy in the form of sulphur and sodium by breaking down sodium polysulphide [53]. NaS consists of liquefied sulphur at the positive electrode and liquefied sodium at the negative electrode. Approximately 300 ℃ is needed to keep the battery at a molten stage.

NaS batteries have a relatively high power density [240 W/kg], NaS is capable to deliver a 600 % pulsated power over a 30 seconds period. It can go up 4500 cycles over 7.2 hours. This kind of battery is ecologically benign yet the disposal of the sodium requires great attention. NaS batteries require much heat resulting in battery performance deterioration.

3.3.3 Chemical Energy storage systems (fuel cells)

Unlike the conventional batteries, a fuel cell doesn't store energy; instead they produce electricity as long as the hydrogen and the oxygen are supplied into the system Figure **3.6** . Like the conventional batteries, a fuel cell has an electrolyte and electrodes to perform the reaction needed. Hydrogen is fed into the anode, upon contact, hydrogen ions travel to the cathode crossing the electrolyte where they recombine with free electrons and oxygen forming electricity. Heat and water are released as bi-products. Fuel cells stacks are comprised of individual cells which are repeated until the required power is reached.

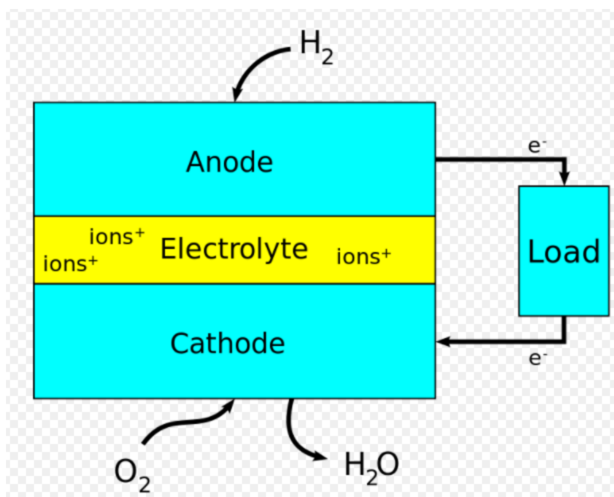

Figure 3.6: Hydrogen fuel Cell [39]

3.3.4 Mechanical storage systems

3.3.4.1 Pumped hydroelectric storage (PHS)

A typical PHS is a mechanical energy storage that is comprised of two water reservoirs. The energy is being stored in the form of gravitational potential energy. In charging phase, the water is pumped into higher altitude reservoir during off-peak demands. While in peak demands period, the water is released from the upper reservoir to the lower reservoir. The flow of the released water drives the turbine which in turn drives the generator to produce electricity. A schematic diagram of a typical PHS is depicted in Figure **3.7**.

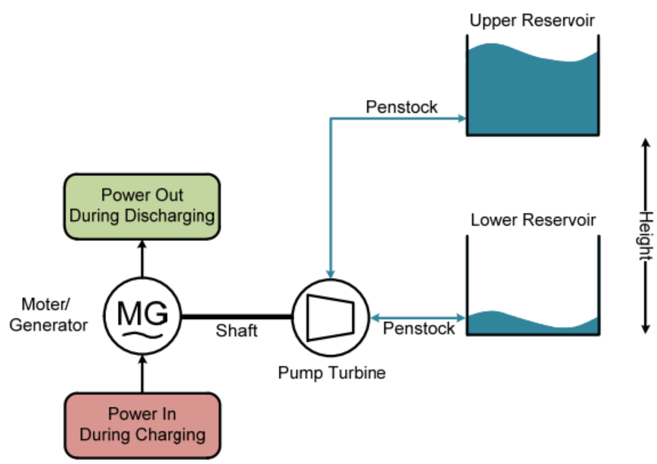

Figure 3.7: Schematic diagram of PHS [39]

The amount of energy stored is dictated by the height between both reservoirs and the volume of stored water. PHS seems to be a mature storage system that contributing by 3% to the overall global generation. Among other storage technologies, PHS installed capacity reached 129 GW in 2012 [58]. Expensive backup power plants could be avoided if PHS is deployed. PHS poses high power, energy capabilities making the technology is extremely useful in applications where a bulk capacity is required. Moreover, the anticipated lifetime of PHS may sustain more than [40 years] reported in [53]. However, environmental regulations may restrict large-scale PHS deployment since the location of installation needs to be carefully selected. They also suffer from a long construction time and a relatively high capital cost.

Various PHSs have already been built and still operating with a rating starting from [1 MW] up to [3 GW] reported in [39], [59]. Due to the site limitation, alternatives have been investigated, underground formation to the lower reservoir has been considered but such measures have yet to be commercialized.

3.3.4.2 Compressed air storage systems (CAES)

CAES stored energy in the form of high pressurized air. During off-peak periods, the excessive energy feeds a bi-directional motor/generator that drives a chain of compressors that inject air into aboveground pipes or underground caverns. The pressurized air can be extracted and released upon demand. Once the demand falls below the generation, the compressed air is pushed back and gets heated and combusted. The turbines then capture some of the energy in the compressed air. CAES is actively involved in large scale applications such as load shifting, peak shaving, wind fluctuations suppression, and frequency control. CAES of the size [10 MW] - [100 MW] is already deployed. However, a geographical location may represent a substantial barrier to install and operate such technology. Therefore, a careful feasibility study needs to be conducted when considering such energy storage system. a schematic diagram showing CAES components and the operational scheme is portrayed in Figure **3.8**.

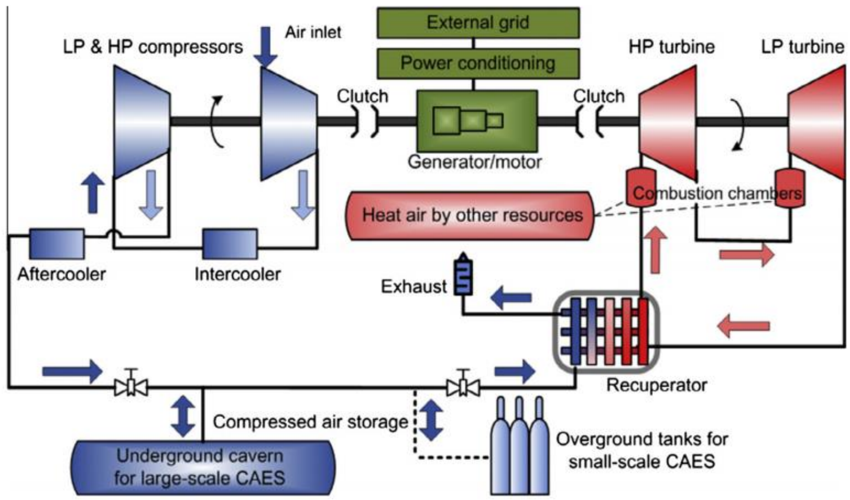

Figure 3.8: Operational scheme of CAES [39]

3.3.4.3 Flywheel storage system (FSS)

A typical flywheel is comprised of a flywheel, bearings, a bi-directional motor / generator, a vacuum chamber and an electronic compartment. In flywheels, a kinetic energy is being stored in the form of rotational mass. Electricity is utilized to accelerate or to decelerate the flywheels. In charging phase (off-peak), flywheels act as a motor and as a generator otherwise. The amount of energy that can be stored is dependent on the rotational speed of the flywheel and its inertia [39]. The components of a typical FSS are shown in Figure **3.9**.

Flywheels require little maintenance, may provide a large number of cycling times[>100,000] published in [53]. The level of DOD doesn't affect the lifetime of FSS.

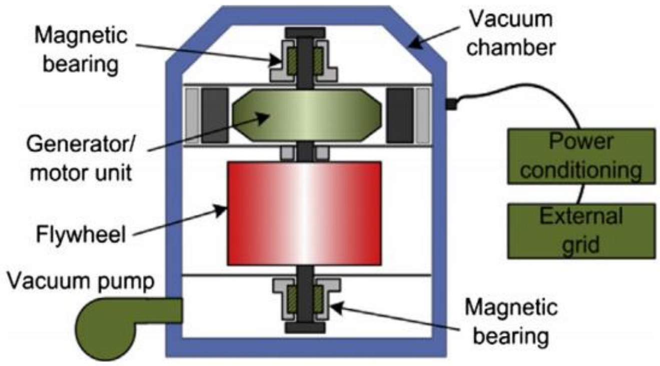

Figure 3.9: A simple design to an FSS [39]

3.4 Summary of Energy Storage Technologies

The subsequent tables sum up the most recent important characteristics of various storage technologies. Several thesis parameters utilized in the analysis of the upcoming chapters are referred to the following tables.

Table 3.2: ESS technologies characteristics [53]

Energy S. Technology	Energy Density	Power Density	Discharge Time	Life Time	Capital Cost		Technological Maturity
	Wh/kg	W/kg		(Year)	$/KW	$/KWh	
Mechanical Energy Storage							
PHES	0.5–1.5	–	1–24 h +	40–60	600–2000	5–100	Matured
CAES	30–60	(0.5–2.0)	1–24 h +	20–40	400–800	2–50	Developed
Flywheel	10–30	400–1500	Millisecs–15 min	15	250–300	500–1000	Commercial
Electrochemical Energy Storage							
Lead Acid Battery	30–50	75–300	Secs–hrs	5–15	200–300	120–150	Commercial
NiCd Battery	50–75	150–300	Secs–hrs	10–20	500–1500	800–1500	Commercial
Sodium Sulfur (NaS)Battery	150–240	150–230	Secs–hrs	10–15	1000–3000	300–500	Commercial
Lithium Battery (Li-ion)	75–250	150–315	Mins–hrs	5–15	1200–4000	300–1300	Demonstration
VRFB	10–30	—	Secs–10 h	5–10	600–1500	150–1000	Demonstration
Electrical Energy Storage							
SuperCapacitor	2.5–15	500–1300	Millisecs–60 Min	20+	100–300	300–10,000	Developed
SMES	0.5–5	500–2000	Millisecs–secs	20+	200–300	1000–10000	Demonstration
Chemical Energy Storage							
Hydrogen Fuel Cells	800–10,000	500+	Secs–24 h+	5–15	–	6000–20000	Developing
SNG	10,000	(0.2–2)	1–24 h +	10–30	–	–	Developing
Thermal Energy Storage							
CSP	-43.05	–	Mins–hrs	30	–	3500–7000	Developing

Table 3.3: ESS technological characteristic comparison [53]

ES Technology	Power rating	Storage duration	Self-discharge per day	Cycle Life(cycles)	Round trip Efficiency (%)	Response time	Class
Mechanical Energy Storage							
PHES	100–5000 MW	Hrs–Mons	Very small	–	65–87%	1–2 min	long term
CAES	5–300 MW	Hrs-Mons	Small	–	50–89%	1–2 min	long term
Flywheel	0–250 kW	Sec–Mins	100%	–	85–95%	1–2 min	Short term
Electrochemical Energy Storage							
Lead Acid Battery	0–20 MW	Mins–days	0.1–0.3%	500–1000	75–80%	Seconds	Long term
NiCd Battery	0–40 MW	Mins–days	0.2–0.6%	2000–2500	85–90%	Seconds	Long term
Sodium Sulfur (NaS) battery	50 kW–8 MW	Sec-Hrs	20%	2500	80–90%	Seconds	Short term
Lithium Battery(Li-ion)	0–100 kW	Mins–days	0.1–0.3%	1000–10000+	85–90%	Seconds	Long term
VRFB	30 kW–3 MW	Hrs–months	Small	12000+	85–90%	Seconds	long **term**
Electrical Energy Storage Systems							
Double Layer Capacitor/ super Capacitor	0–300 kW	Sec–hrs	20–40%	100,000+	90–95%	Milliseconds	Short term
SMES	100 kW–10 MW	Sec–hrs	10–15%	100,000+	95–98%	Milliseconds	Short term
Chemical Energy Storage Systems							
Hydrogen Fuel cell	0–50 MW	Hrs–months	nearly 0	100+	20–50%	Sec–Mins	Long term
SNG	–	–	–	1000–10000	30–38%	Mins	Long term
Thermal Energy Storage Systems							
CSP	10 kW–200 MW	–	1%	–	<60%	10 min	Long term

3.5 Applications of Storage systems

Storage systems can be deployed to conduct several tasks. An important factor to effectively operate a storage technology is determining the main objective of the application for which storage is being deployed. A myriad of potential applications with different technical requirements exist today and might be met with certain storage technologies based on the function needed. Some applications require long duration storage systems while others needs fast response ESSs.

3.5.1 Time-Shift of Energy delivery

Time- delaying energy allows grid operators to charge storage systems with the excessive capacity during low-cost periods and supply it back during high-price periods. The generator lifetime is implicated if frequent adjustments take place to follow load variations. Such operational scheme does vividly shorten units' life expectancy and increases cost, technical insufficiencies.

3.5.2 Credit Capacity

Credit capacity characterizes the ability of storage system to supply electricity in locations where upgrading the exiting capacity is deferred. For instance, if the exiting generation capacity fails to meet the peak demands, storage may provide the needful energy to shave the peak demand until the new expansion is economically, technically justified. Moreover, storage system could also be deployed at the receiving end to relieve transmission capacity congestion dictated by the thermal limits of the lines.

3.5.3 Grid Support (ancillary services)

Storage system can be harnessed to provide the so called "grid ancillary services". As reported in the literature, Ancillary services refer to the services that could be provided by the storage system to the transmission and distribution system to enhance the power quality and to maintain a stable grid performance. An ESS can furnish the following services:

- ✓ **Frequency control**: A frequency is altered if the generation exceeds or falls below demands whatsoever, hence by a proper operational scheme to the ESS, a frequency can be kept within a tight bound.
- ✓ **Voltage Control:** Storage system can be used to avoid voltage limits violations and may play a vital role in deferring grid reinforcement.
- ✓ **Spinning reserves**: a generator is often operated below its rated capacity to account for any sudden capacity loss from other units or demands surges. A storage system is capable to deliver the capacity needed to offset such overall capacity deficit.
- ✓ **Black start recovery**: if a system failure takes place, some of the generator units collapses and encounters impediment to retain synchronism, therefore a storage system might be beneficial to help restoring synchronization by providing a reference frequency to the units put off during the failure.

3.5.4 Power quality

Broad applications such as military centers, telecommunication centers, and information stations require highly efficient power as the disrupted power may cause a substantial security threats to the operators. Such interruption is intolerable; therefore a fast acting storage system may be utilized to offset any unplanned loss of power that may suddenly occur.

3.5.5 Intermittent renewables integration

Storage systems have been strongly linked to the integration of intermittent resources. Such resources cannot be tied to the grid without proper measures to ensure reliable, deliverable output power. The behavior of those resources is highly unforeseen due to seasonal and geographical variations. Therefore, Authorities have issued special regulations to organize the integration of the intermittent generation in terms of voltage, frequency. In order to keep the frequency within a tight bound, a ramp rate limitation has been imposed on the output power to prevent the sudden swings that might alter system frequency.

3.6 Operational duration requirements

Given the chart below, applications requirements vary according to the objective for which a storage is being utilized. Figure **3.10** and Table **3.4** describe various applications with respect to their required characteristics.

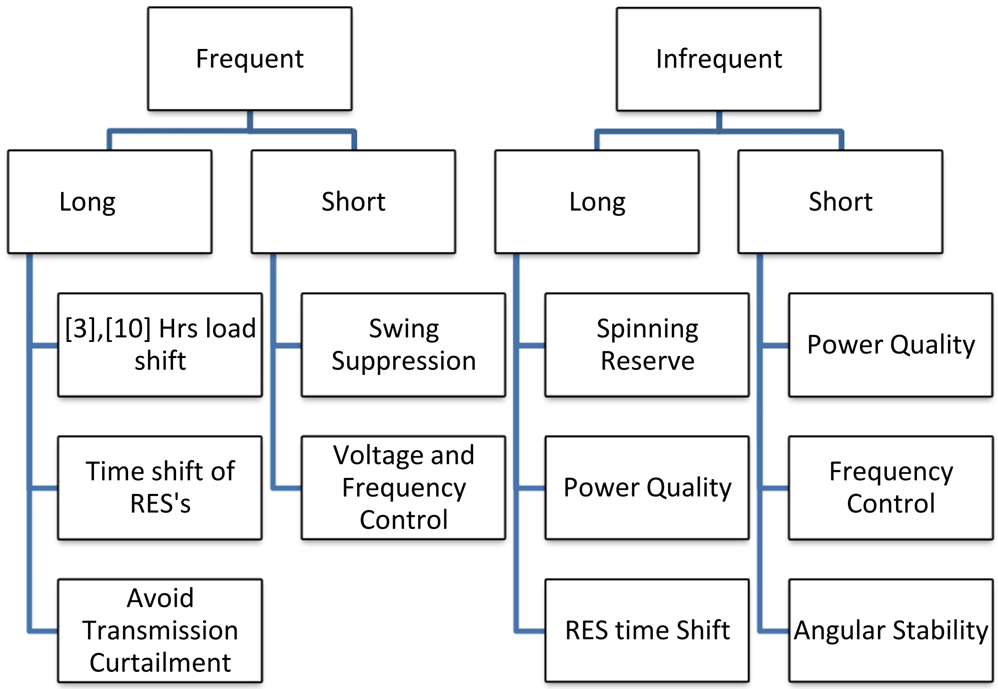

Figure 3.10: ESS applications vs type of cycling and characterized duration

Table 3.4: Application requirements

Requirements Applications	Discharge duration	Discharge depth	Response time	Lifetime, Cycles	Energy efficiency
Long Discharge Freq. Use	Hours	Deep DOD	Minutes	< 10000	Crucial
Short Discharge Freq. Use	Minutes	Shallow DOD	Seconds	>10000	Crucial
Long Discharge Infreq. Use	Hours	Deep DOD	Minutes	<1000	Not Important
Short Discharge Infreq. Use	Seconds	Shallow DOD	Seconds	<1000	Not Important

3.6.1 Long Duration Applications

A Long duration application requires a high energy storage system that is capable to cover up a prolonged discharging cycles ranging from 1 hour to couple of hours. The following applications can be seen as prolonged duration applications:

- Load shifting.
- Mitigating transmission congestion
- Enhancement of RES forecast hedging
- Intermittent resources time shift
- Spinning Reserves
- Reliability

3.6.2 Short duration Applications

In contrast to the long duration applications, a short duration application requires a fast response storage system to accommodate the quick charging/ discharging processes seen in power applications. The following can be thought of as short applications:

- Swings suppression
- Power quality issues
- Regulation control
- Grid stability

3.6.3 Frequent discharge

There are a variety of applications that need the storage system to be continuously cycled in order to charge/ discharge to perform the task needed. The following applications can require frequent cycling:

- Regulation control
- Power system reliability
- Fluctuation smoothness

- Load and time shifting
- Transmission curtailment

3.6.4 Infrequent discharge

A storage system that may undergo less than 20 cycles yearly to perform the needful services falls into the category of infrequent discharging applications.

3.7 Summary of CHAPTER 3

Given the survey carried out in the previous sub-sections ,weighing the pros and cons of every storage technology covered throughout chapter 3 and by comparing the characteristics summarized in Table **3.2** and Table **3.3** , Li-ion battery and SMES have been selected to form the hybrid storage system in this thesis.

CHAPTER 4

MATHEMATICAL MODELING

4.1 Grid Regulations

Active power control normally includes requirements that should be satisfied regarding ramping up and/or ramping down events where the instability of the system becomes a great concern [60]. However, several countries impose ramping regulations in order to preserve system stability and reliability. Grid Code requirements are listed in Table **4.1** as an example. Having stating that, the ramp rate will be taken into consideration in this thesis to effectively satisfy the capacity of frequency regulation [46], [48] and [61], [62] as well as [63].

Table 4.1: Grid Code Requirements [60]

Installed Capacity	Germany	Ireland	England	China
1- Min ramp rate [MW]	5% -10 % of rated output/Min	1 - 30 [MW]/Min	No limits below 300 [MW]	- 10 [MW]/ Min for Capacity <30 MW. - 20%/ Min for 30 < Capacity <150 [MW] - 30 [MW]/ Min for Capacity >150 [MW]
10 - Min ramp rate [MW]	10% of rated output/Min	1-30 [MW]/10 - Min	50 [MW]/ Min for 300 < Capacity < 1000 [MW]	- 2 [MW] /Min for Capacity < 30 [MW] - 6.67 %/ Min for 30 < Capacity <150 [MW] -10 [MW]/ Min for Capacity >150 [MW]

However, In order to sufficiently integrate an intermittent source into the grid, the following requirements must be faithfully discerned:

- Ramp rate.
- Power droop with frequency.
- Power curtailment.

Frequency regulation is one of the ancillary services that could be mitigated by a storage system. However, the regulation is utilized to reconcile "offset" the power differences resulted from the intermittent source. It is more convenient to damp the ramping events by a storage system that possess a fast ramp rate (e.g. SMES , SuperCapacitor and flywheels) instead of using a conventional generator where the wear and tear become an issue if utilized.

4.2 Wind Data

Given the wind speed profile, wind power (Watts) can be computed using equations **(4.1)** reported in [64] . Where C_p refers to the utilization factor and ρ represents the air density. A and V indicate to the swept area and wind speed respectively.

$$P = \frac{1}{2} C_p \rho A V^3 \qquad \textbf{(4.1)}$$

4.3 Load Data

The load profile has been slightly modified, extracted from [65].

4.4 Hybrid system Configuration

Difficulties may arise if active power requirements only met by the intermittent generation. Accordingly, we intend to develop a basic hybrid system combining a BESS, SMES and the intermittent source as depicted in Figure **4.1.**

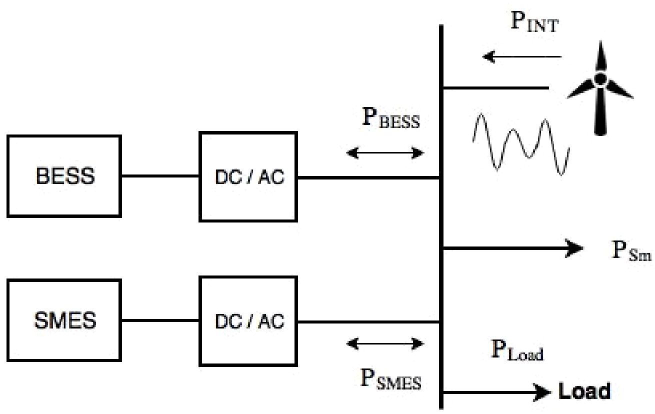

Figure 4.1: Proposed hybrid system

As noted in Figure **4.1** P_{INT} in [MW] is the generated power by the intermittent source, P_{BESS} in [MW] represents the output power of the BESS system, P_{SMES} is the generated power by SMES system. P_{Sm} is the smoothed total output power of the proposed system. The hybrid system exploits the BESS to tackle the ramp rate constraint and the SMES to sufficiently offset the sudden fluctuations in the output power of the intermittent generation considering the lifetime of the BESS.

4.5 Optimized Capacity and Cost Minimization

The mathematical model is developed to minimize the installation cost and to optimize the capacity of BESS and SMES while meeting the grid integration requirements and the surplus load energy not sustained by the intermittent generation. The references listed herein [34], [48], [52], [65], [66] are precisely used henceforth to develop the mathematical models.

4.5.1 Objective Function

The objective function of the proposed hybrid system becomes:

$$Min\ [C_{BESS}E_{BESS} + C_{SMES}E_{SMES}] \quad \textbf{(4.2)}$$

Where ,C_{BESS} and C_{SMES} are the cost per MWh of BESS and SMES respectively . E_{BESS} and E_{SMES} are the energy capacity of BESS and SMES, respectively.

4.5.2 Constraints

Figure **4.2** depicts output power and energy capacity of the system when the intermittent generation fails to sustain the ramp rate constraint. $P_{INT,MAX}$ presents the maximum generated power by the intermittent source while *RR* indicates the ramp rate constraint imposed on the system in [MW/Min]. The horizontal axis is defined as the time elapsed since the generated power of the intermittent source falls at a rate of *RR* [MW/Min]. The shaded area depicted in Figure **4.3** represents the unserved load energy that couldn't be met with the intermittent source, and needs to be fulfilled by the storage system. E_{NC} can be found by subtracting the common area of daily load from the integration of the area underneath the intermittent generation, or can easily be found using (trapz) built-in function in MATLAB.

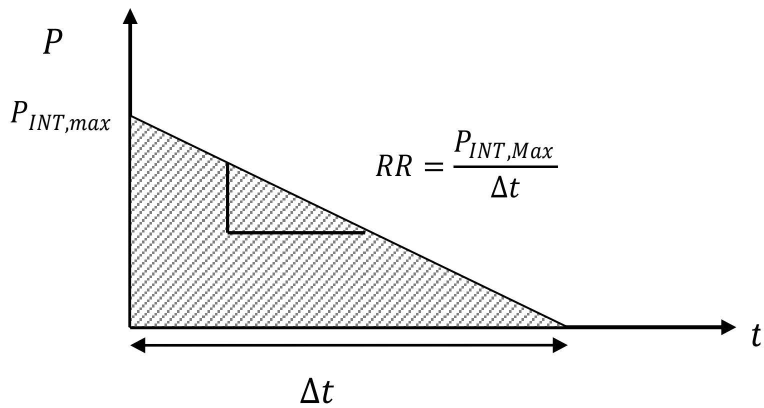

Figure 4.2: Energy capacity of hybrid ESS

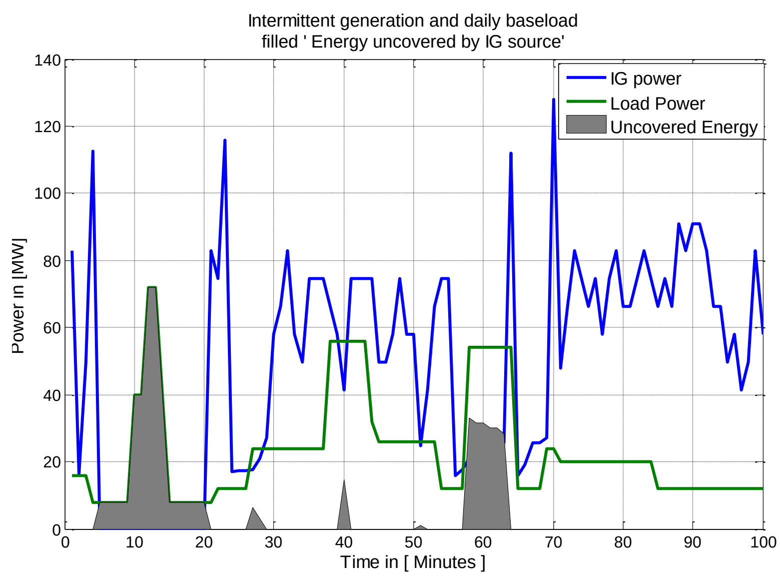

Figure 4.3: IG power and load profile vs energy unserved

$$P_{BESS} + P_{SMES} \geq P_{INT,max} \quad \textbf{(4.3)}$$

$$E_{BESS} + E_{SMES} \geq \frac{1}{2} P_{INT,Max} \frac{P_{INT,Max}}{60 \times RR} + E_{NC} \quad \textbf{(4.4)}$$

Storage rated power: Constraint **(4.3)** restricts the system to meet the ramp rate constraint with only the BESS and/or the output of the SMES when the generated power of intermittent generation unexpectedly falls to zero.

Energy Capacity of ESS: Constraint **(4.4)** implies that the energy capacity of BESS and SMES need to fulfill the ramp rate constraint and to the total load energy not served by the intermittent generation when the aggregated power of the system falls to zero at a rate of $60 \times RR$ [MW/h].

Operation at middle state of charge: With regard to batteries' operation, it is advisable to operate them below the cut-off depth of discharge which is kept 50 % to extend batteries' lifetime. However, we will assume the operation of the storage system at the middle SOC (50%) therefore **(4.4)** becomes as follows:

$$E_{BESS} + E_{SMES} \geq P_{INT,Max} \frac{P_{INT,Max}}{60 \times RR} + E_{NC} \qquad \textbf{(4.5)}$$

Energy and power densities: it is quite essential to relate the maximum power of the storage system to the energy capacity. The aforementioned quantities could be obtained by the so-called power density and energy density of the storage system which are mathematically described as:

$$P_{SMESmax} = D_{Power,SMES} \times \frac{E_{SMES}}{D_{Energ,SMES}} \qquad \textbf{(4.6)}$$

$$P_{BESSmax} = D_{Power,BESS} \times \frac{E_{BESS}}{D_{Energ,BESS}} \qquad \textbf{(4.7)}$$

Where $D_{Power,SMES}$ [MW/kg] and $D_{Energ,SMES}$ [MW/kg] are the power density and the energy density of the superconducting magnetic storage system (SMES) while $D_{Power,BESS}$ [MW/kg] and $D_{Energ,SMES}$ [MW/kg] are referred to the battery energy storage system .

Obviously, in order to achieve a minimum cost of installation for both BESS and SMES, a linear programming given by **(4.2)** is going to be implemented along with the equality constraints in **(4.6)** , **(4.7)** and inequality constraints in **(4.3)** and **(4.5)**.

4.5.3 Summary of Section 4.5

The consecutive mathematical models presented in the previous sub-sections can be summarized as follows:

The **objective function** is given by:

$$Min \quad [C_{BESS}E_{BESS} + C_{SMES}E_{SMES}] \tag{4.8}$$

The **inequality constraints** are:

1. $$P_{BESS} \ + \ P_{SMES} \ \geq P_{INT,max} \tag{4.9}$$
2. $$E_{BESS} + E_{SMES} \geq P_{INT,Max} \frac{P_{INT,Max}}{60 \times RR} + \ E_{NC} \tag{4.10}$$

Where the **equality constraints** are given by:

1. $$P_{SMESmax} = D_{Power,SMES} \times \frac{E_{SMES}}{D_{Energ,SMES}} \tag{4.11}$$
2. $$P_{BESSmax} = D_{Power,BESS} \times \frac{E_{BESS}}{D_{Energ,BESS}} \tag{4.12}$$

4.6 Optimized Operation

Due to the various advantages of lithium ion batteries that have been discussed in section **3.2.2.1.c,** a Li-ion battery is adopted to proceed in the analysis of the remaining thesis. However, Battery aging analysis hasn't been assessed intensively. Few reports pointed out that gradual degradation is linked to several factors such as state of charge, temperature, internal resistance, and discharging rates. It is reported that high discharging current deteriorates the battery very rapidly and may lead to system failure if not observed carefully. It is therefore essential to operate the battery at the middle state of charge where the internal resistance becomes infinitesimal as depicted in Figure **4.4** reported in [66].

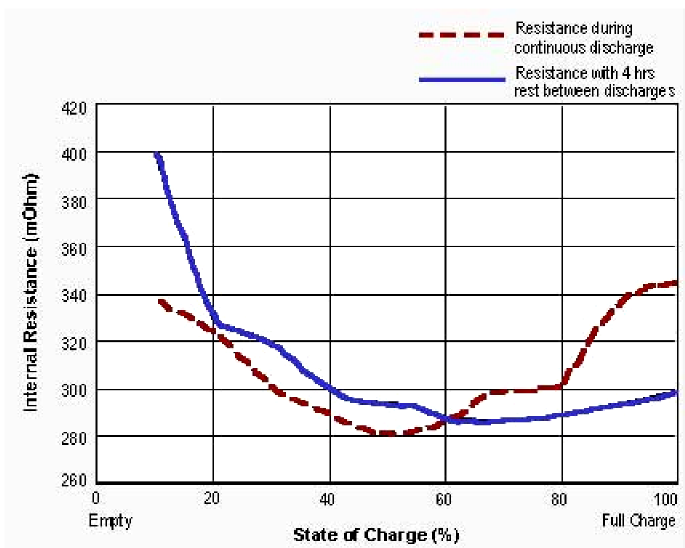

Figure 4.4: SOC vs Internal Resistance of Li-ion [66]

Qualitatively, every charging/discharging process contributes to a cumulative battery's degradation no matter what the depth is. Although the micro-cycles of Depth of Discharge (DOD) degrades the battery performance over time, However, maintaining a lower level of DOD would immensely extends the battery lifetime as later sections would prove this claim. For instance, Figure **4.6** brought from [67] portrays a typical total number of cycles as a function of DOD range for a given battery dictated by the manufacture datasheet. It is obvious that the cycle-life prolongs as the DOD decreases. Due to the importance of tackling the DOD throughout this thesis, henceforth, both SOC and DOD are used interchangeably.

4.6.1 Objective Function

For low current ratings, it is required to minimize the current deviation. If the busbar voltage of the hybrid system is kept constant, then it is evident that the current deviation is proportional to real power deviation according to $N_{BESS} = V \times Ah\,;\,Wh$. Therefore, the proposed mathematical model is composed of a weighted sum of two competing objectives [68], where the former part aims to minimize the residual power difference and the latter is to maintain the operation at the middle SOC to assure having a relatively low internal resistance [34]. Proper weighting factors have been added and utilized in the objective function in order to achieve a better performance of the hybrid system and maintaining the SOC at 50 %. Hence, the objective function of the proposed model will be as follows:

$$\begin{gathered} Min\, PP = \sum_{\Delta t=1}^{T}[w_{BESS}\left(P_{BESS}(t)\right)^2 + \\ w_{load}(P_{ld.trac}(t))^2 + w_{SMES}\left(P_{SMES}(t)\right)^2 + \\ w_{DoD,BESS}\left(DoD_{BESS}(t) - DoD_{BESS,Ref}\right)^2 + \\ w_{DoD,SMES}\left(DoD_{SMES}(t) - DOD_{SMES,Ref}\right)^2 + \\ w_{Ref}\left(P_{Ref}(t)\right)^2] \end{gathered} \tag{4.13}$$

PP is the function that needs to be optimized. Where $P_{BESS}(t)$ and $P_{SMES}(t)$ represents the output powers of BESS and SMES respectively. The proposed system has daily base load that needs to be sustained. Therefore,$P_{ld.trac}$ is the power difference between the proposed hybrid power and the load demand which helps tackling the load behavior. Obviously, $DoD_{BESS}(t)$ and $DoD_{SMES}(t)$ are referred to the instantaneous depth of discharge for both systems. DoD_{Ref} is kept 50% of the nominal capacity for both storage devices. The last term P_{Ref} helps stabilizing the system by minimizing the residual of the total output power of the hybrid and the previous intermittent power. w_{BESS} and w_{SMES} are the weighting factors of real power deviations of BESS and SMES respectively. Clearly, $w_{DoD,BESS}$ and $w_{DoD,SMES}$ are the weighting factors to operate both systems at approximately 50 % of SOC. The weighting factors are properly selected after several attempts, trials and based upon the experience to avoid excessive utilization of the BESS. Setting appropriate weights in the model helps prolonging the battery life by maintaining the operation at middle state of charge (SOC).

The minimal power deviation can be found by **(4.14)** and **(4.15)**, while the load trajectory can be computed by **(4.16):**

$$P_{BESS}(i) = P_{BESS}(t) - P_{BESS}(t-1) \quad \textbf{(4.14)}$$

$$P_{SMES}(i) = P_{SMES}(t) - P_{BESS}(t-1) \quad \textbf{(4.15)}$$

$$P_{Ldtrck}(i) = P_T(t) - L(t) \quad \textbf{(4.16)}$$

If the charging and discharging efficiencies are assumed to be unitary then ,as reported in [69], [70], the instantaneous state of charge SOC and the DOD for both systems are computationally found by :

$$DoD_{BESS}(i) = 100 - SOC_{BESS}(t) \tag{4.17}$$

$$DoD_{SMES}(i) = 100 - SOC_{SMES}(t) \tag{4.18}$$

Estimation of the **SOC** has widely been researched. However, Columb counting algorithm is implemented to tackle the instantaneous state of charge covered in [71]. The instantaneous energy can be approximated using right Riemann sum described in Figure **4.5** and formulated by **(4.19)** reported in [72]:

$$Area = \int_a^b f(x)dx = \lim_{T\to\infty} \sum_{i=1}^{T} f(x_{i-1}) \times \Delta x \tag{4.19}$$

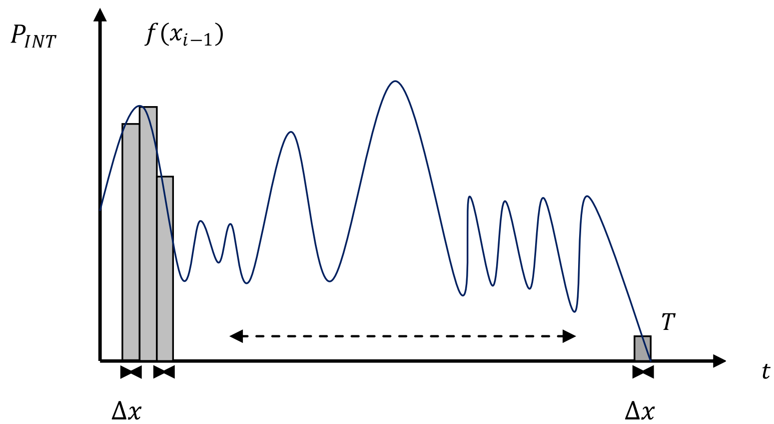

Figure 4.5: Estimation of definite integrals using right Riemann

$$SOC_{BESS}(t) = SOC_{BESS}(t-1) + \frac{\int_t^{t+\Delta t} P_{BESS}(t)dt}{E_{BESS}} \times 100 \tag{4.20}$$

$$SOC_{SMES}(t) = SOC_{SMES}(t-1) + \frac{L \times i^2}{2 \times E_{SMES} \times 3600} \times 100 \tag{4.21}$$

$$SOC_{SMES}(t) = SOC_{SMES}(t-1) + \frac{\int_t^{t+\Delta t} P_{SMES}(t)dt}{E_{SMES}} \times 100 \tag{4.22}$$

In equation **(4.23)**, P_{Ref} relates the total output of the hybrid system to the previous intermittent generated power which provides the reference to help maintaining stabilization of the system. P_{Ref} is evaluated as follows:

$$P_{Ref}(i) = P_{Prp}(t) - P_{INT}(t-1) \quad \textbf{(4.23)}$$

$P_{Prp}(t)$ refers to the aggregated output power of the hybrid system and can be found by:

$$P_{Prp} = P_{SMES} + P_{BESS} + P_{INT} \quad \textbf{(4.24)}$$

4.6.2 Constraints

For the sake of achieving better performance of the storage system, the objective function **(4.13)** and the sequential equations **(4.14) - (4.24)** are subjected to several constraints as described in the following paragraphs.

Energy capacity limits: The total energy supplied by both BESS and SMES should not exceed their respective nominal capacity as described by **(4.25)** and **(4.26)**.

$$\sum_{\Delta t=1}^{T} P_{BESS} \times \Delta t \leq E_{BESS} \quad \textbf{(4.25)}$$

$$\sum_{\Delta t=1}^{T} P_{SMES} \times \Delta t \leq E_{SMES} \quad \textbf{(4.26)}$$

Storage rated power: the charging /discharging powers of hybridized systems are restricted to the rated power of their individual ratings.

$$|P_{C,D}| \leq P_{BESS} \quad \textbf{(4.27)}$$

$$\left|P_{C,D}\right| \leq P_{SMES} \tag{4.28}$$

SOC levels physical limits: The instantaneous state of charge of the storage system is not permitted to fall below a minimum SOC or to exceed a maximum SOC. Hence, physical constraints are imposed as follows:

$$SOC_{SMES,Min} \leq SOC_{SMES}(t) \leq SOC_{SMES,Max} \tag{4.29}$$

$$SOC_{BESS,Min} \leq SOC_{BESS}(t) \leq SOC_{BESS,Max} \tag{4.30}$$

Demand-supply balance: given the daily load consumption, the proposed generated power of the hybrid system is restricted to meet the load demand over the entire period of the simulation.

$$P_{Prp}(t) \geq L(t) \tag{4.31}$$

Ramp rate limits : Eventually , the difference between the current aggregated power of the hybrid system and the previous control period should be managed as derived in **(4.32)** validated by [61], [73]. RR refers to the ramp rate power [MW/min]. Obviously, the absolute value of the aggregated power of the hybrid system is restricted to fall below or equal RR , chosen to be 6 % /min of the rated power for ramping up/ down events as per [56].

$$\frac{\left|P_{Prp}(t) - P_{Prp}(t-1)\right|}{\Delta t} \leq RR \tag{4.32}$$

Apparently, the proposed operational scheme of the hybrid system is formulated as the quadratic function of **(4.13)** with sequential equations in **(4.14) - (4.24)** and linear inequality constraints **(4.25) - (4.32)**.

4.6.3 Summary of Section 4.6

The mathematical models derived above to optimize the operation can be summarized as follows:

The **objective function** is given by:

$$Min\ PP = \sum_{\Delta t=1}^{T} \Big[w_{BESS}\big(P_{BESS}(t)\big)^2 + w_{load}\big(P_{ld.trac}(t)\big)^2 + w_{SMES}\big(P_{SMES}(t)\big)^2 + w_{DoD,BESS}\big(DoD_{BESS}(t) - DoD_{BESS,Ref}\big)^2 + w_{DoD,SMES}\big(DoD_{SMES}(t) - DOD_{SMES,Ref}\big)^2 + w_{Ref}\left(P_{Ref}(t)\right)^2 \Big] \quad \textbf{(4.33)}$$

The **Equality constraints** are:

1. $$P_{BESS}(i) = P_{BESS}(t) - P_{BESS}(t-1) \quad \textbf{(4.34)}$$
2. $$P_{SMES}(i) = P_{SMES}(t) - P_{BESS}(t-1) \quad \textbf{(4.35)}$$
3. $$P_{Ldtrck}(i) = P_T(t) - L(t) \quad \textbf{(4.36)}$$
4. $$DoD_{BESS}(i) = 100 - SOC_{BESS}(t) \quad \textbf{(4.37)}$$
5. $$DoD_{SMES}(i) = 100 - SOC_{SMES}(t) \quad \textbf{(4.38)}$$
6. $$SOC_{BESS}(t) = SOC_{BESS}(t-1) + \frac{\int_t^{t+\Delta t} P_{BESS}(t)dt}{E_{BESS}} \times 100 \quad \textbf{(4.39)}$$

7. $$SOC_{SMES}(t) = SOC_{SMES}(t-1) + \frac{L \times i^2}{2 \times E_{SMES} \times 3600} \times 100 \quad \textbf{(4.40)}$$

8. $$SOC_{SMES}(t) = SOC_{SMES}(t-1) + \frac{\int_t^{t+\Delta t} P_{SMES}(t)dt}{E_{SMES}} \times 100 \quad \textbf{(4.41)}$$

9. $$P_{Ref}(i) = P_{Prp}(t) - P_{INT}(t-1) \quad \textbf{(4.42)}$$

10. $$P_{Prp} = P_{SMES} + P_{BESS} + P_{INT} \quad \textbf{(4.43)}$$

The **inequality constraints** are:

1. $$\sum_{\Delta t=1}^{T} P_{BESS} \times \Delta t \leq E_{BESS} \quad \textbf{(4.44)}$$

2. $$\sum_{\Delta t=1}^{T} P_{BESS} \times \Delta t \leq E_{BESS} \quad \textbf{(4.45)}$$

3. $$\left|P_{C,D}\right| \leq P_{BESS} \quad \textbf{(4.46)}$$

4. $$\left|P_{C,D}\right| \leq P_{SMES} \quad \textbf{(4.47)}$$

5. $$SOC_{SMES,Min} \leq SOC_{SMES}(t) \leq SOC_{SMES,Max} \quad \textbf{(4.48)}$$

6. $$SOC_{BESS,Min} \leq SOC_{BESS}(t) \leq SOC_{BESS,Max} \quad \textbf{(4.49)}$$

7. $$P_{Prp}(t) \geq L(t) \quad \textbf{(4.50)}$$

8. $$\frac{\left|P_{Prp}(t) - P_{Prp}(t-1)\right|}{\Delta t} \leq RR \quad \textbf{(4.51)}$$

4.7 Battery Bank State of Health and Lifetime Assessment

Once the multi-stage optimization algorithm is carried out, the resulted DODs and the discharging powers are utilized to assess the BESS performance in both configurations. The following subsections are intended to address the behavior of BESS lifetime and state of health.

4.7.1 Battery aging model

Aging assessment of the batteries is reported in [74]–[76]. In order to investigate the impact of the proposed optimization model on the battery's lifetime, it is necessary to tackle the instantaneous state of health of the battery as described by **(4.52)** and **(4.53)**. Among the objectives maintaining the SOC of the batteries at approximately 50 % where the cycling time becomes maximal as reported in [48], [66].

$$SOH(t) = \frac{C_{deg}(t)}{E_{BESS}} \tag{4.52}$$

$$C_{deg}(t) = C_{deg}(t-1) - E_{BESS} \times \gamma \times [SOC(t-1) - SOC(t)] \tag{4.53}$$

The procedure utilized above is dictated by [76]. The instantaneous nominal capacity which degrades over every discharging process was taken into account. Doing so provides a precise assessment of the battery's SOH. γ refers to the capacity loss coefficient and kept 0.3 % for Li-ion batteries as reported in [75], [51], [77].

4.7.2 RainFlow Counting Method

As discussed in the preceding paragraphs, the system is inherently vulnerable to irregular cycling (partial charging/discharging) due to the variable nature of the RES's which contributes to the degradation of the conventional batteries. Therefore, it is quite essential to develop a model that tackles those micro-cycles and investigate their contribution to the capacity loss. A cycle is said to be completed if the charging/discharging process runs and returns to the point where it started. RainFlow counting algorithm has successfully been deployed in [51], [75] to decompose the irregular cycling incurred during the operation. In addition, RainFlow counting [78] extracts the range and micro-cycles details from an irregular DoD profile . It has the ability to identify the frequency and the range of cycles that a BESS has gone through during a given DOD time history [79]. Moreover, degradation of cycle-life can then be obtained by summing up all the incurred cycles as in **(4.54)**:

$$D = \sum_{i=1}^{n} \frac{(cycle_i \ \times R_{i,DoD})}{A \times R_{i,DoD}^{B}} \times 100 \qquad \textbf{(4.54)}$$

Where D refers to the degradation of cycle-life, R indicates to the range of the ith Micro-cycle in the DOD time horizon, n is however the total number of cycles. A and B are empirical parameters to determine the rated cycle-life at a given DOD range. Battery manufacturers usually provide an experimental datasheet that relates the cycle-life to a corresponding DOD. Figure **4.6** depicts a typical cycle to failure CTF versus DOD resulted from a curve fitting at a given discharge rate (1 Crate).

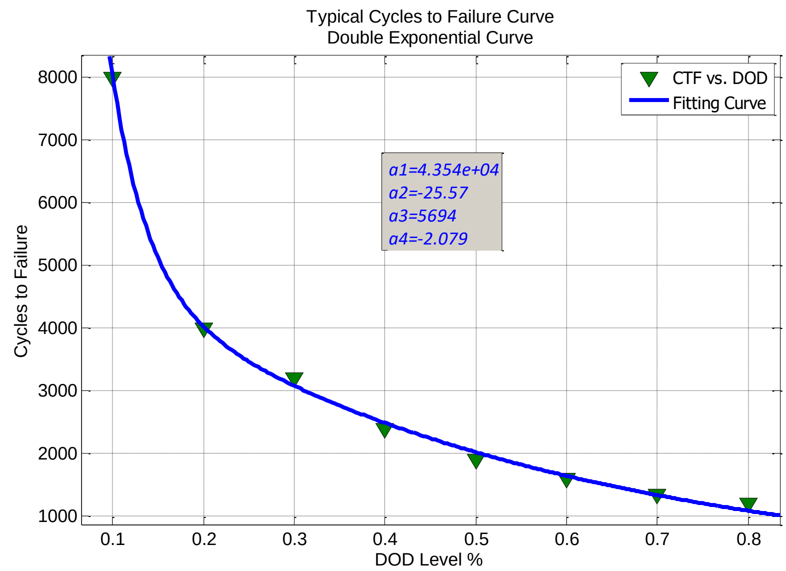

Figure 4.6: Typical CTF vs DoDs

Battery cycle to failure **CTF** is defined as the total number of cycles that the battery can charge/discharge before the nominal capacity degrades to 80 % of its initial capacity. For instance, the battery in Figure **4.6** would undergo over 1600 cycles at 60% DOD before it reaches the end of life. However, the author in [51] utilized a logarithmic polynomial given by **(4.55)** to describe the relationship between CTF and DOD, While author in [80] uses a double exponential curve given by **(4.56)** to relate the CTF to different DODs.

$$CTF = a_0 + a_1\, DoD^{-1} + a_2 DoD^{-2} + a_3 DoD^{-3} \qquad \textbf{(4.55)}$$

$$CTF = a_2 e^{a_3 R} + a_4 e^{a_5 R} \qquad \textbf{(4.56)}$$

$1/CTF_i$ is defined as the fractional of life consumed up at different stress levels during cycle i.Post several cycles,if the fractions multiplied by the number of cycles sum to 1, then the battery is said to be disposed and needs to be replaced with a new one as this definition is analogous to Miner's rule reported in [80]–[82] . For instance, if one-half year is considered for simulation, assume that there are N_i cycles to 10 fractional depth of discharges ranging from 10% to 60%, and for each single DOD there corresponds a CTF_i, at the end of simulation the overall fractional damage, D, would be given by:

$$D = \sum_{i=1}^{10} N_i \frac{1}{CFT_i} \quad \textbf{(4.57)}$$

If for example, D equals 0.5 at the end of the specified duration, then half of the life has been used up and the battery bank needs to be replaced every 12 months, in other words, if D reaches 1 battery bank collapses and failure occurs. Having determined the battery's life faction consumed given by **(4.57)**, the expected battery lifetime can then be estimated as:

$$Life_{Years} = \frac{T.N.Cycles}{D} \quad \textbf{(4.58)}$$

4.7.3 Battery Health Index (BHI)

In addition to the previous analysis that has been carried out to assess the battery health, further investigations could be extended to include the battery health index (BHI) derived in **(4.59)**. BHI as reported in [83] which measures the deviation of the SOC from the reference, typically kept 50%. A minimal deviation provides a good indication to an effective utilization of the BESS [58]. High values of BHI indicates excessive utilization of BESS.

$$BHI = \sqrt{\frac{1}{T}\sum_{t=1}^{T}(SOC(t) - 50)^2} \quad \textbf{(4.59)}$$

4.8 Solution methodology

Once the mathematical optimization model is classified, the optimization algorithm is selected and coded using MATLAB. However, the following sub-sections briefly discuss the optimization approach and the optimization algorithm utilized in the thesis.

4.8.1 Classical Method for Multi - Objective Optimization

One of the most common and simplest approaches to tackle a multi-objective optimization problem is the **weighted sum technique**. In this method, the set of objectives gets scalarized by user-defined weights and converted to a single objective optimization problem. The weights are carefully selected based on the relative importance of each objective.

4.8.2 Optimization Algorithm

Particle Swarm Optimization is a stochastic optimization technique developed by Dr. Eberhart and Dr. Kennedy in 1995 , inspired by the flocking and the social behavior of the birds .In PSO , the potential optimal solutions (particles) fly through the problem space tackling the current optimum particles. A set of variables have their values modified closer to the particle whose value is approaching to the target at any time. However, PSO comprises a population of candidate solutions called swarm. Every particle in the swarm is a potential solution in the set. The principle of operation of PSO is discussed in details in [84], [85].

Due to its simplicity and ability to solve various types of multi-objective optimization problems, PSO is selected as a solution method in this thesis. Clearly, PSO resembles any evolutionary computation technique like genetic algorithm. However, unlike GA, particle swarm optimization has no evolving operators such as mutation or crossover. PSO is characterized by few parameters that should be adjusted makes it superior among other evolutionary algorithm. The parameters assigned to PSO in this thesis are listed in Table **4.2.**

Table 4.2: PSO parameters

Swarm size	50
No. of decision variables	100 For Stand alone and 200 for hybrid S.
Max No. of iterations	5000
Damping ratio of Inertia Coefficient	0.99
Inertia weight	1
Personal learning Co.	1.5
Global learning Co.	2.05

4.8.3 Solution Framework

Figure **4.7** describes the solution algorithm followed in this thesis where the sequential steps listed below are implemented and delivered in CHAPTER 5.

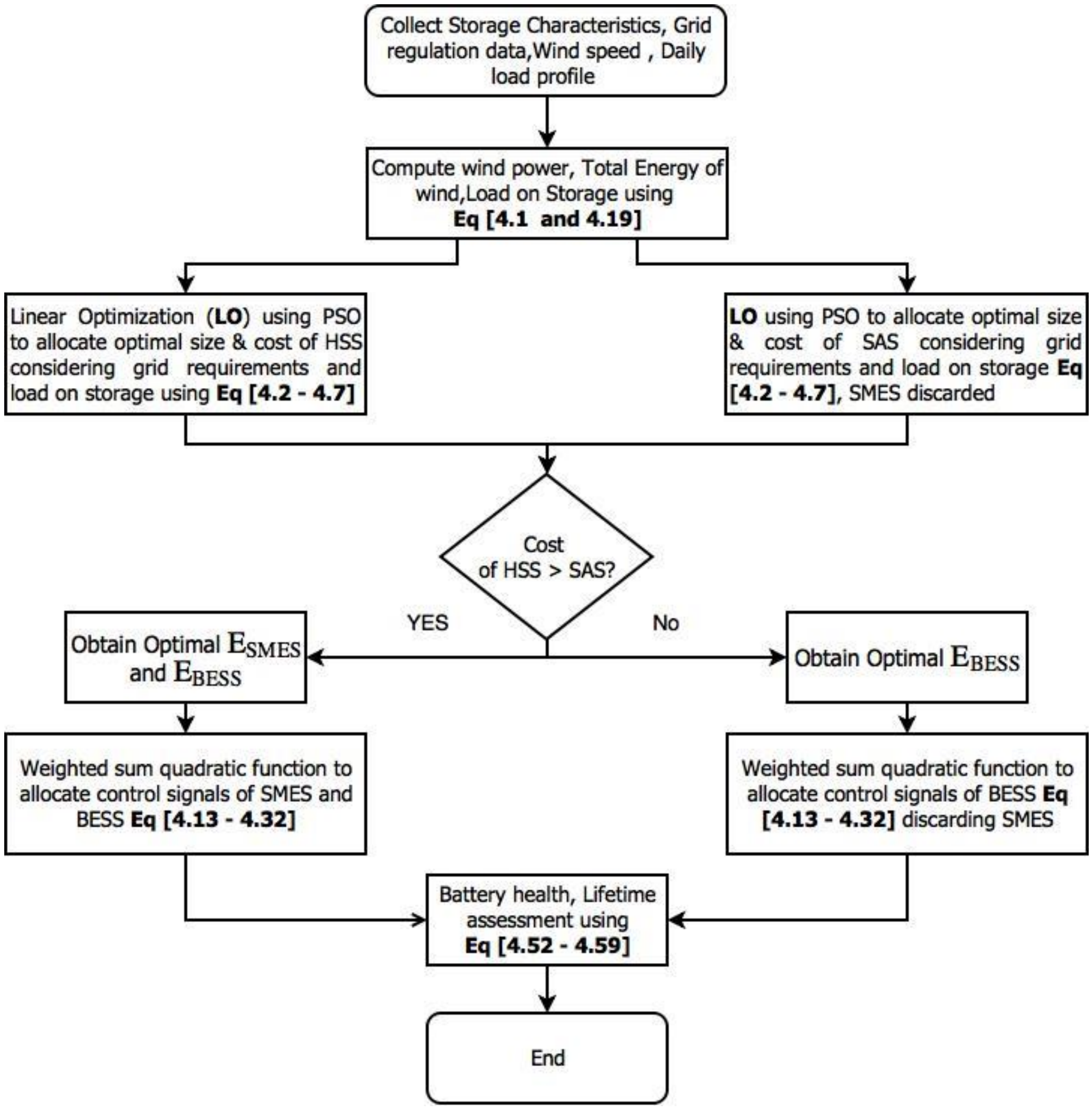

Figure 4.7: Solution algorithm

CHAPTER 5

RESULTS AND ANALYSIS

5.1 Results and Discussions

Having defined in details the previous sub-sections, it is now the proper time to intensively discuss the results sequentially as the investigation proceeds along this chapter.

5.1.1 Proposed Hybrid Energy Storage

In this sub-section , in order to derive a minimal cost to install the hybrid storage system, the proposed linear programming model formulated by **(4.2)** will be implemented in MATLAB using Particle Swarm Optimization [86] along with the linear inequality constraints **(4.3)** and **(4.5)** and the equality constraints given by **(4.6)** and **(4.7)**.

5.1.1.1 Case Study

the specifications of SMES and BESS are listed in Table **5.1** referenced to [87]. However, few quantities have been modified based upon a short survey on the internet.

Table 5.1: SMES and BESS specifications

Characteristic	SMES	BESS
Lifetime(Cycle)	10^6	4000
Energy density(Wh/kg)	5	250
Power Density(W/kg)	2000	315
Cost($/KWh)	10000	1300

5.1.1.2 Cost and Size Optimization of the Hybrid ESS

The maximum intermittent generation $P_{IG,Max}$ is supposed to be 200 [MW]. The results of the proposed optimization model are summarized in Table **5.2**. The results might be overshadowed due to the relatively high capital cost of the SMES, However, the hybrid system would require less budget to cover up 200 [MW] of rated power. The installment cost of the BESS only is approximately 206,304,206 [dollars], while the hybrid system costs 72,564,575 [dollars]. For the sake of justification, due to the low power density of the BESS, nearly 158 [MWh] is required to sustain a 200 [MW] of rated power.

Table 5.2 : Optimized installation results

Characteristics	battery energy storage system only	Hybrid System	
		SMES	BESS
Installment Cost $	206,304,206	72,564,575	
Optimal Capacity [MWh]	158	0.334	53
Rated Power [MW]	200	133.6	66.78

5.1.1.3 Operational Scheme Optimization of the Hybrid ESS

A wind speed profile for 1440 minutes of DESMONIC, IOWA state in USA is embraced to develop the output power of a wind farm whose characteristics are listed in Table **5.3**. Equation **(4.1)** is deployed to develop the wind power trajectory.

Table 5.3: Wind farm parameters

Characteristics	Blade Radius [m]	Air Density [kg/m^3]
Quantity	85	1.22

The developed intermittent power is utilized to conduct the proposed model given by **(4.13)** subjected to the equality constrains **(4.14) - (4.24)** and the inequality constraints **(4.25) - (4.32)**. However, due to the limited capacity of the processor and the memory of the computer, only portion of the data will be analyzed and the rest of the profile will be investigated whenever possible. Figure **5.1** depicts portion of the wind trajectory history where the power swings are apparently violating the allowable ramp rate limits dictated by [60]. Figure **5.2** is the truncated plot of the preceding plot where the power swings are extremely sharp. Since such profile precisely resembles the intermittent generation behavior, obviously, this portion will be exposed to the proposed model.

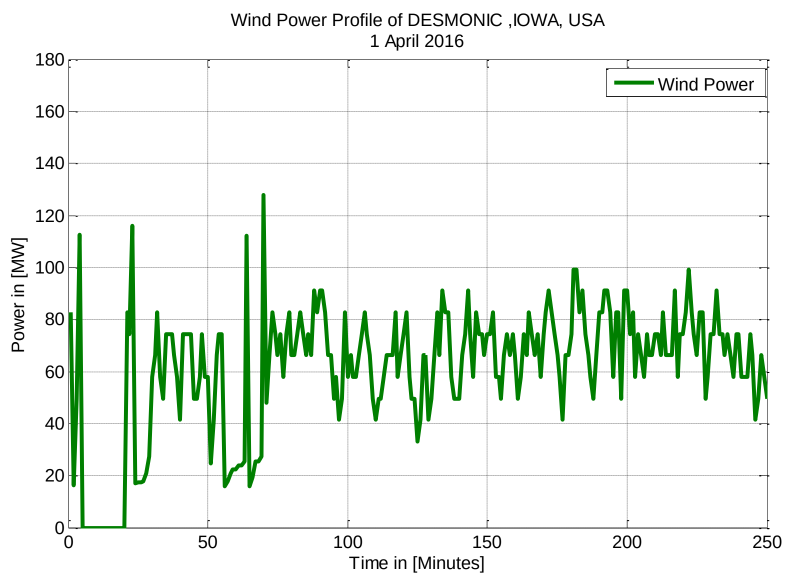

Figure 5.1: Generated Wind Power

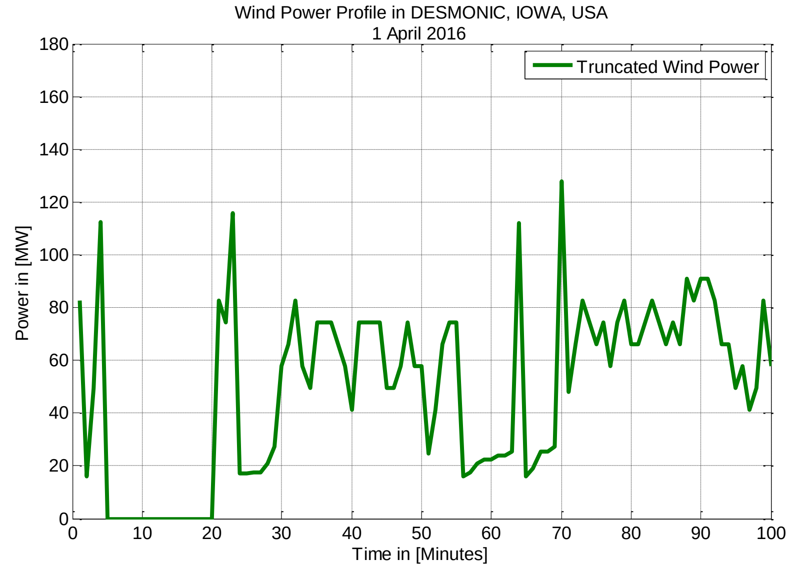

Figure 5.2: Truncated Version of the previous trend

The weighting factors $w_{BESS}, w_{SMES}, w_{DoD,BESS}, w_{DoD,SMES,}$ and $w_{Ref}, w_{Ld,track}$ are carefully selected not only to prioritize the operation and hence extending battery lifetime but also to preserve the stability of the overall system. They were approximated as indicated in **(5.1)**.

$$\begin{gathered} w_{BESS} \gg w_{SMES}, w_{DOD,BESS} \gg w_{DOD,SMES} \\ w_{DOD,BESS} \gg w_{BESS} \text{ and } w_{BESS} < w_{REF} < w_{DOD,BESS} \end{gathered} \qquad \textbf{(5.1)}$$

Based on trials, the selection of the combination listed in Table **5.4** is superior among others published in [48], [68], [88], [89].

Table 5.4: Selected weighting factors

Characterized Weighting Factor	w_{BESS}	w_{SMES}	$w_{ld,track}$	$w_{DOD,BESS}$	$w_{DOD,BESS}$	w_{REF}
Value	100	1	1	10000	100	1000

The proposed operational scheme sends the control signals to BESS and SMES as portrayed in Figure **5.3** and Figure **5.4** respectively. Apparently, Compliance of the BESS and the SMES to the transmitted signals would virtually improve the BESS **SOC** as depicted in Figure **5.5**.

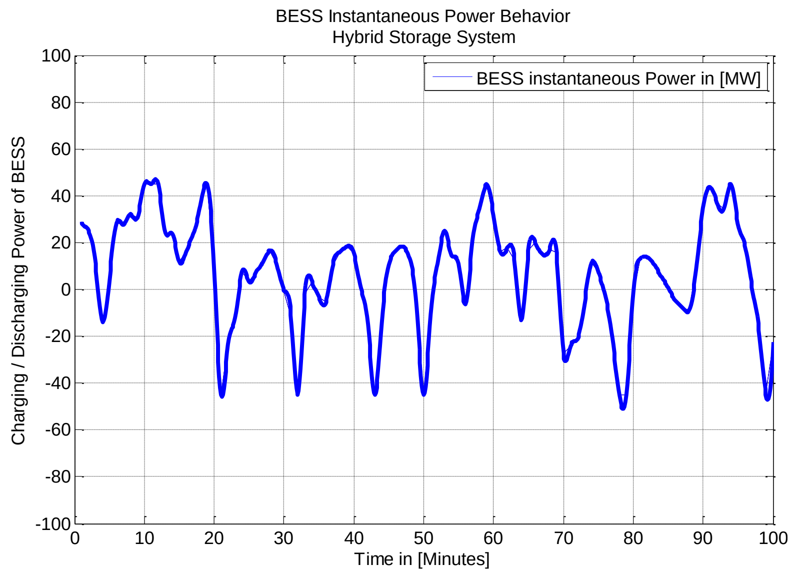

Figure 5.3: BESS Output Power following the scheme

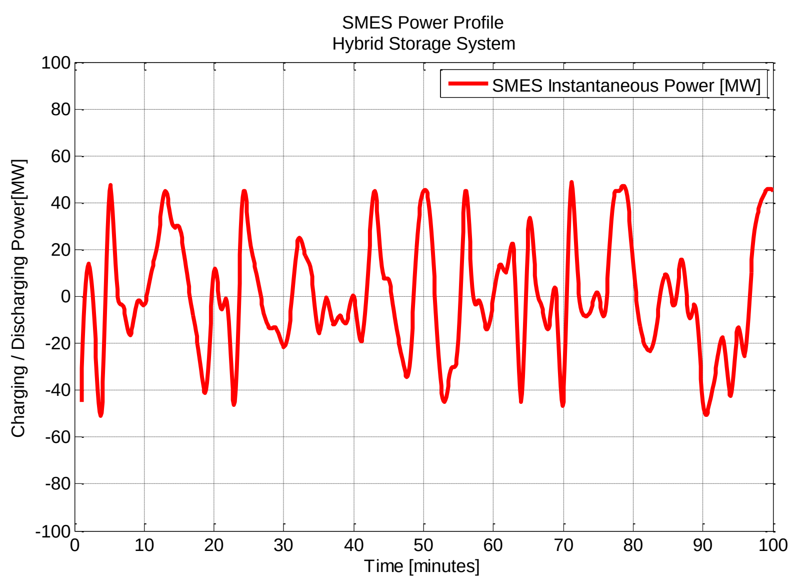

Figure 5.4: SMES Output Power

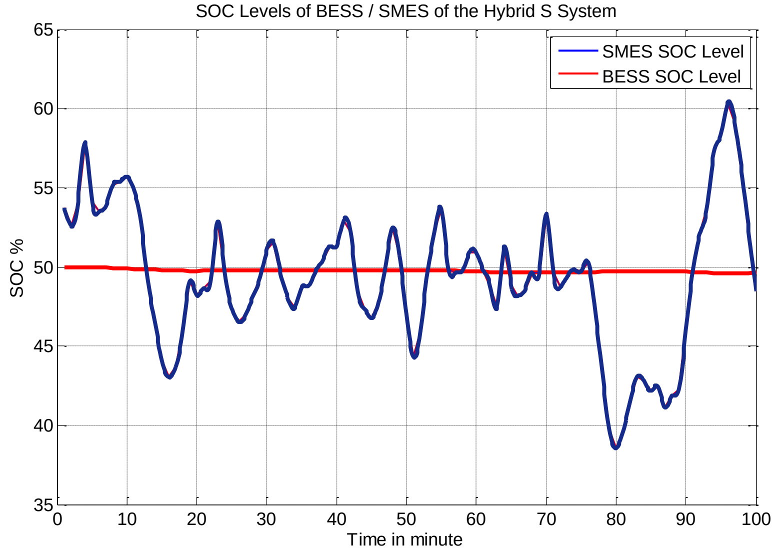

Figure 5.5: SOC for both BESS and SMES

Evidently, battery degradation is strictly linked to lower levels of **SOC**. Such impact is being avoided by operating the BESS and SMES near 50% along the entire period. Moreover, batteries are prone to experience an overall failure if exposed to unplanned and large loading where the bank SOC behavior remains low for the majority of the time. Accordingly, the proposed scheme overrides such operation and successfully kept the SOC in the vicinity of 50% as plotted in Figure **5.5**.

Having determined the **SOC** profiles for both systems, the total output of the proposed hybrid system is plotted in Figure **5.6** along with the wind power trajectory. The ramp rate limit has successfully been met by the proposed model. The wind power (blue dotted line) at [13 Min] to [14 Min] has swung very sharply, suddenly changed by [111.22 MW/Min]. Such behavior violates grid requirements and alters system frequency, while the proposed output considers the ramp rate limit in case of ramping up or down as dictated by equation **(4.32)**. The proposed power (bold red line) for the same period changed only by [12.57MW/Min], which falls within the allowable range depicted in Figure **5.6**.

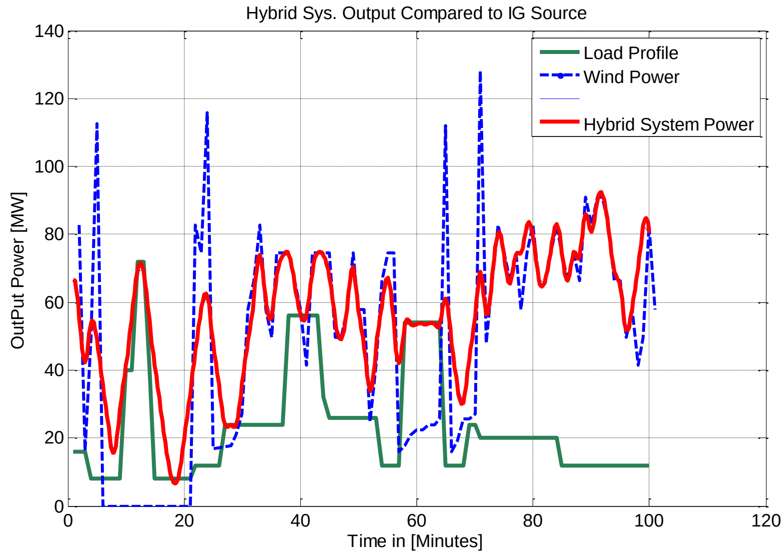

Figure 5.6: Proposed power compared to the IG source

A massive violation to the ramp rate limits of the IG source (blue dotted line) is depicted in Figure **5.7**, where the positive and the negative ramps reach [∓100 MW/Min]. Such violation will alter system stability and reliability. Accordingly, the proposed operational scheme considers such behavior where the sudden swings were maintained within the desired limitations as observed in the same plot.

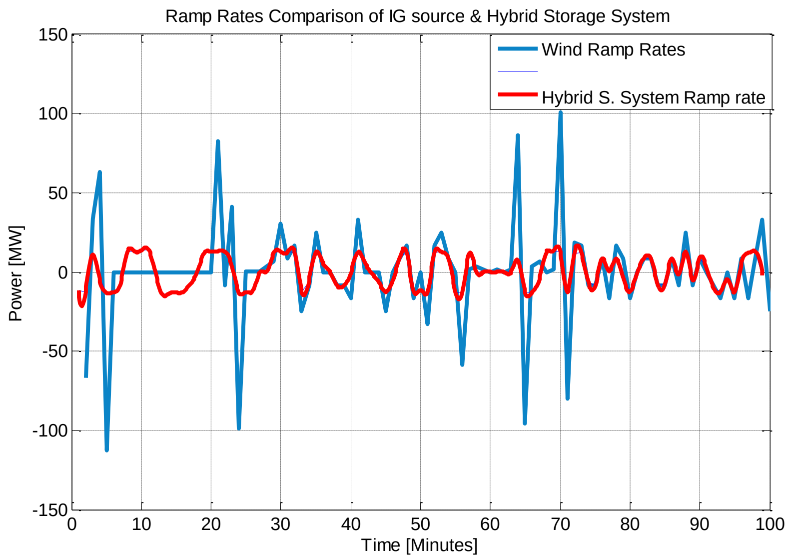

Figure 5.7 : Ramp events of the proposed power to the IG ramps

5.1.2 Stand-Alone BESS

Referring to Case Study reported in section **5.1.1.1** investigated in the previous section, **SMES** will be discarded from all models derived in **(4.2) to (4.32)**.

5.1.2.1 BESS Optimal Size and Cost

PSO is used to analyze the influence of installing BESS only on the overall cost. PSO is converged post 150 iterations where the results are listed in Table **5.2** for the sake of comparison and Table **5.5**. BESS requires a relatively large capacity of storage [158 MWh] to cover up a large rating of power [200 MW] and consequently a higher cost is spent to BESS only installation. On contrast, the proposed model evidently showed that hybridizing both systems (SMES and BESS) would fulfill the power rating with much lesser cost.

Table 5.5: Summarized Results of deploying battery energy storage system only.

Characteristic	BESS
Rated Power [MW]	200
Energy Storage[MWh]	158
Cost [$]	206,349,206

5.1.2.2 Stand-alone BESS Optimized Operational Scheme

Technically, BESS is enforced to sustain the ramp rate constraint imposed on the system, however, if the BESS solely responds to such sudden swings, battery bank will experience irregular and frequent charging/discharging cycles. Consequently, the behavior of the bank **SOC** cannot be kept near 50% as this was possible in case of the hybrid system depicted in Figure **1.1**. For instance, in Figure **5.8** the intermittent generation had gone through sudden swings as precisely seen in minute [21-22], the generated power ramped up from [0 MW] to [82.76] in which the ramp constrains is violated .Such behavior is mitigated by the proposed operational scheme which brought the total power difference below the RR. The rate of change for the same period is on [12.52 MW/Min]. In addition, the pattern of the load profile violates the RR as observed in the duration of [13 - 14]. The negative rate of change is [32 MW/Min] which is above the allowable RR.The rate of change of the proposed power is restricted to be [12.5 MW/Min] for the same period. The smoothed power fell from [70.07 MW] to [57.5 MW] for the duration of [13 -14] minutes.

The proposed output is portrayed compared to the intermittent generation in Figure **5.8**, where the SOC behavior herein is plotted in Figure **5.9**. However, such rapid fluctuations may accelerate BESS deterioration and immensely lessen its lifetime.

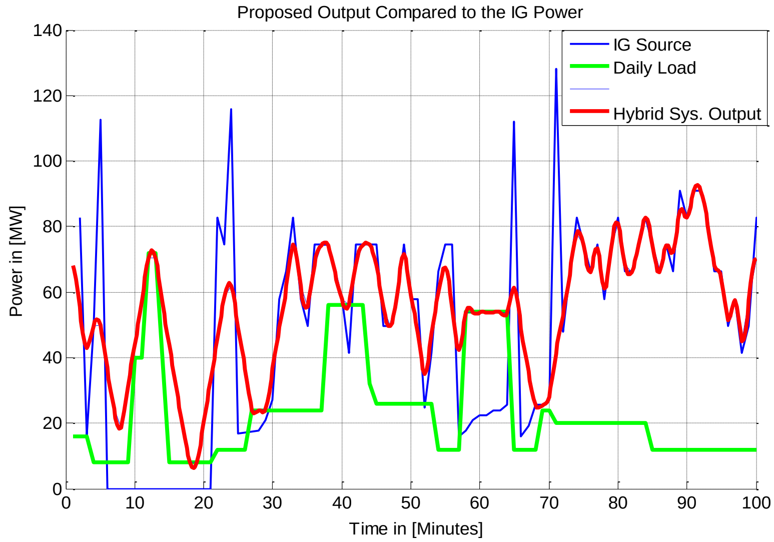

Figure 5.8: Proposed output with BESS only.

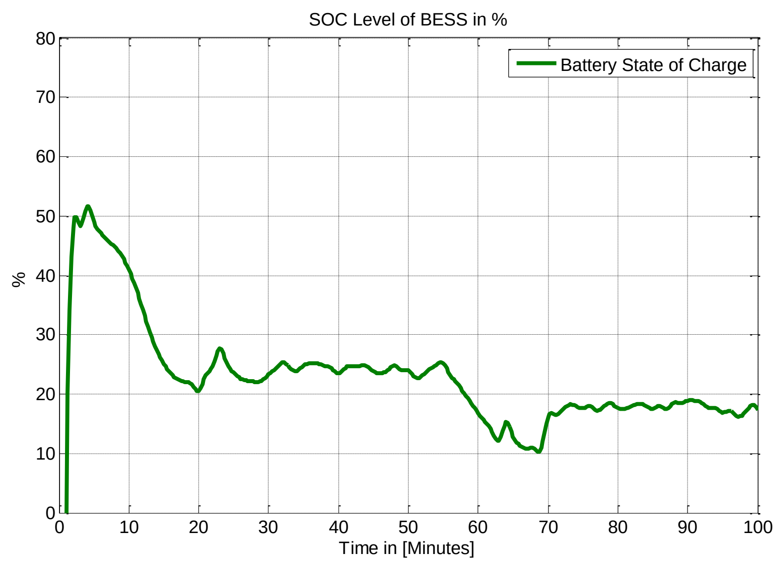

Figure 5.9: SOC of the BESS

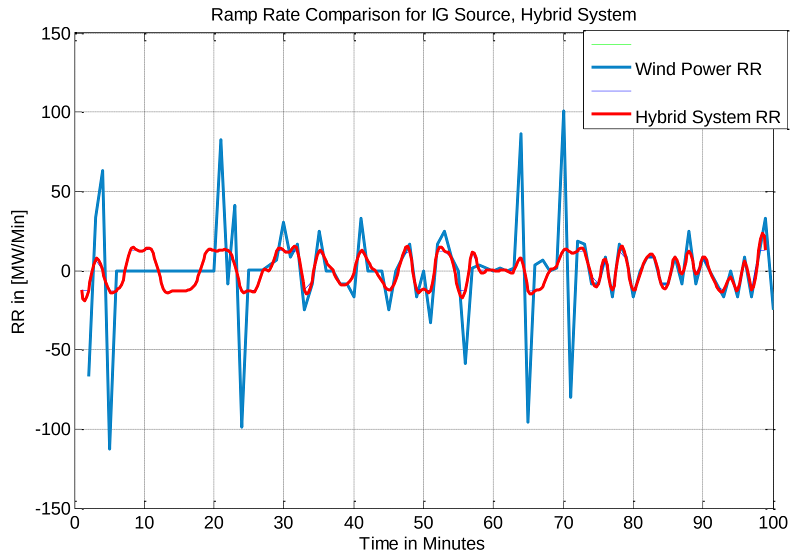

Figure 5.10: IG ramps to the proposed scheme with only BESS

As seen in Figure **5.10**, although the unwanted behavior has successfully been contained by efficient operation to the BESS, the expenditure to sustain such ramps by a stand-alone battery is unacceptable. The charging / discharging power of the battery bank is portrayed in Figure **5.11**.

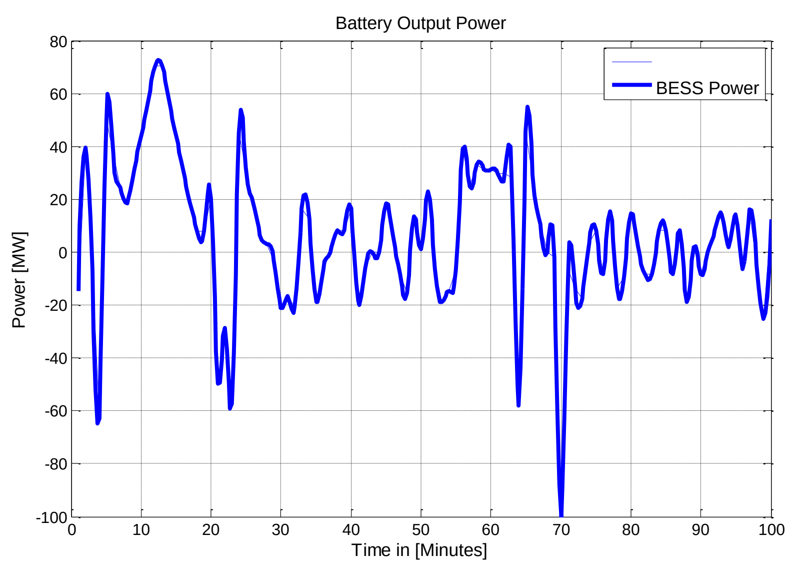

Figure 5.11: Battery System Instantaneous Power

5.2 Battery Bank Characteristics Investigation

5.2.1 Battery State of Health

The model described in **(4.52)** and **(4.53)** is deployed to assess the battery state of health in both configurations. Consecutive values of the SOH should emphasize the impact of hybridizing BESS along with the SMES. As seen in Figure **5.12** and Figure **5.13**, the state of health of the battery bank in the hybrid system has significantly improved as compared to BESS only. Generally, degradation occurs over every charging/discharging protocol. However, the BESS would fail if its capacity drops below 80% of its initial (Nominal) Capacity. Qualitatively, in case of BESS only, the storage bank would fail approximately at the end of simulation where the capacity dropped to 78%, while in hybrid system, the battery is still healthy and maintained more than 90% of its nominal capacity.

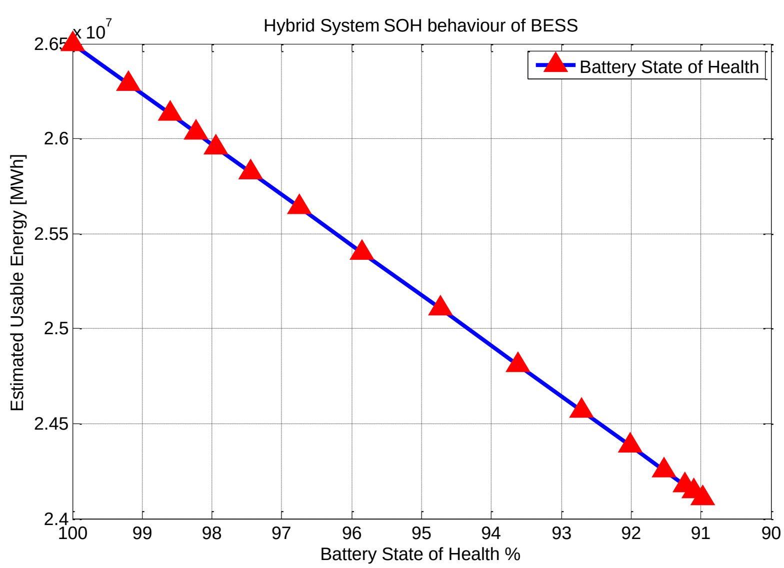

Figure 5.12: Hybrid System SOH of the battery

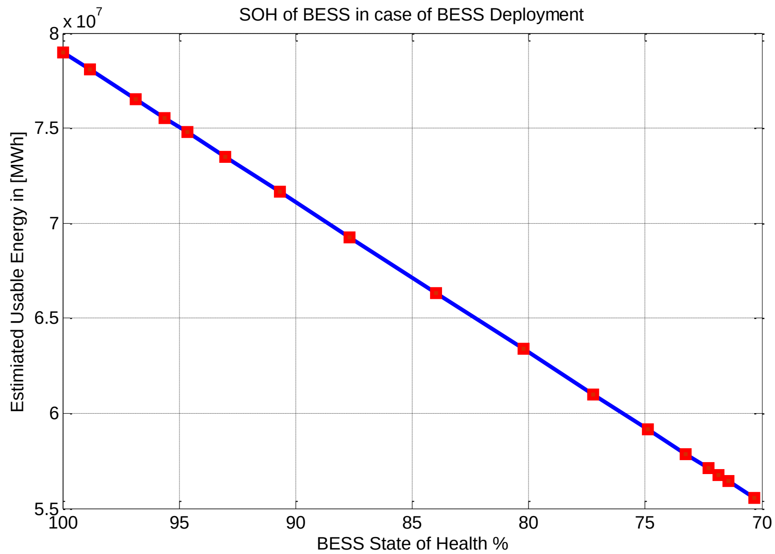

Figure 5.13: Battery SOH % if BESS only is operated

5.2.2 Battery health index

Battery health index (BHI) authored in [83], is an alternative way to examine and tackle the battery behavior during the operation. BHI measures how the SOC deviates from the reference value which is kept 50%. Results of both systems are listed in Table **3.1** and summarized along with different battery characteristics in Table **5.7** for the sake of Comparison.

Table 5.6: BESS BHI

Characteristic	BESS Only	Hybrid System
BHI	30.9 %	0.267 %

5.2.3 Battery degradation Model

Degradation is typically observed as a reduced storage capacity where charging/ discharging protocols yield fewer Ampere-Hours in or out the battery or an increased internal resistance. However, All batteries have a definite lifetime which is influenced by surrounding environment and the way the bank is deployed electrically. Qualitatively, every charging/discharging process contributes to the bank deterioration. Likewise, Storage degradation has been linked not only to the number of cycles but the amplitude of the cycle which has a detrimental impact on battery lifetime. However, all batteries have a calendar life provided by the manufacturer datasheets. Having said so, Figure **5.14** is an example plot of a cycle to failure for a specific battery as a function of micro-cycles of different DODs.

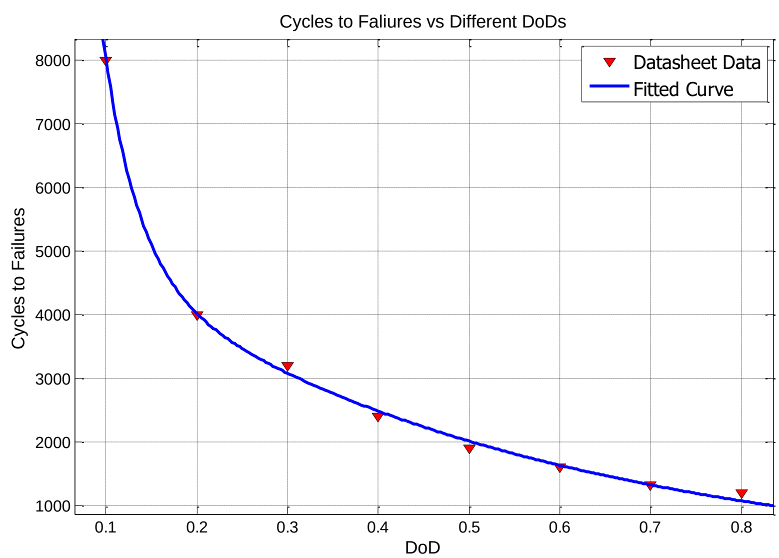

Figure 5.14: Cycles to Failure scheme

Literally, the battery would undergo over 2000 Cycles at 50% DOD before a collateral damage to the bank takes place. However, RainFlow Counting algorithm authored in [78] is utilized herein to extract the DOD sub-cycles to help estimating the Energy storage degradation. Equations **(4.54)** to **(4.58)** Covered in section **4.7** reported in [51], [75] in details will be applied to effectively trace battery degradation aspects. For instance, the histogram depicted in Figure **5.15** presents the extracted number of individual cycles versus the range of DODs in the case of deploying battery energy storage system only.

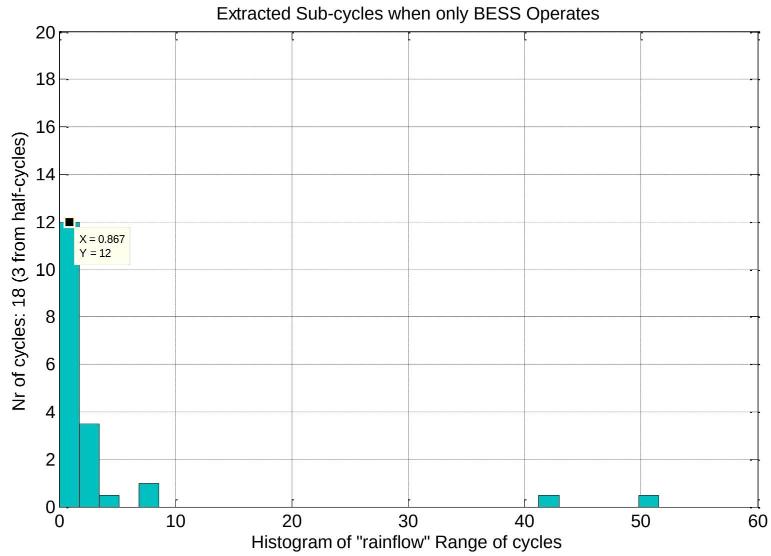

Figure 5.15: Number of extracted cycles vs Range of Cycles

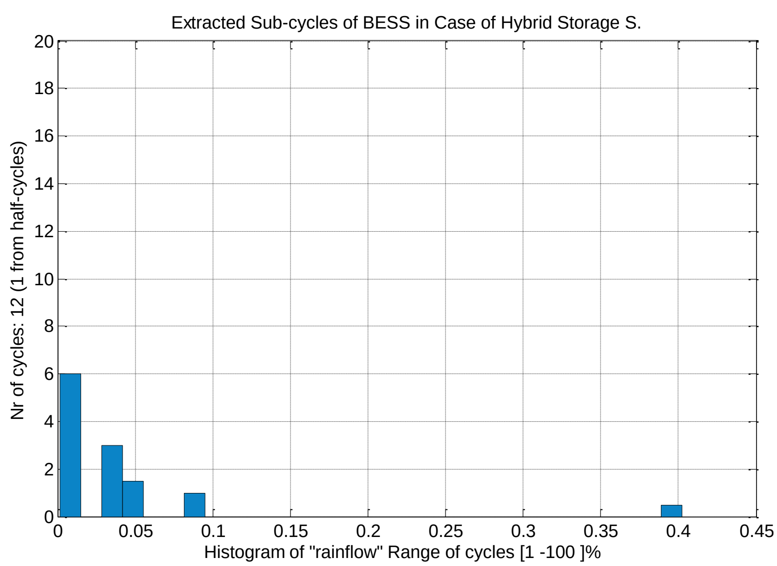

Figure 5.16: Extracted Cycles Vs Different DoDs for hybrid System

Obviously, in a system that uses only a single storage system, the DODs amplitudes and the total number of cycles are larger as compared to the case of hybrid storage system as depicted in Figure **5.16**. The former behavior will absolutely degrade the battery more rapidly. Such impact is investigated using previously indicated equations whereas the results are summarized in Table **5.7**.

Table 5.7: Batteries' Characterizing Results

Characteristic	Degradation	Cycles/Year	Lifetime/ Years	BHI
BESS only	12.319	544.57	7.35	30.9 %
Hybrid System	0.006	141.36	28.29	0.267 %

RainFlow counting algorithm has been reported as a successful tool to determine the fatigue cycles presented in a given profile. Storage systems are prone to act irregularly and hence with enough repeated cycling protocol, a part or overall banks will weaken and eventually deteriorate and fail. Even though tackling the fatigue damage for a system exposed to cyclic amplitude seems an easy task by using Miner's Rule, this is however, unachievable in real world loading histories where the cycling pattern is not uniform. In addition, RainFlow technique not only beneficial to trace the fatigue damage of a given profile, but also reduces the profile to a minimal history required to preserve the damage data. Apparently, the range of cycle divided by 2 yields the amplitude as authored in [90].

RainFlow has successfully been applied herein to extract the sub-cycles of different DODs with their corresponding number of cycles for both systems. Moreover, the extracted data utilized in equations **(4.55) - (4.59)** to determine battery characteristic listed in Table **5.7**. Likewise, the DODs extracted from the RainFlow have been imposed on the CTF fitting curves as depicted in Figure **5.17** and Figure **5.18** for both configurations.

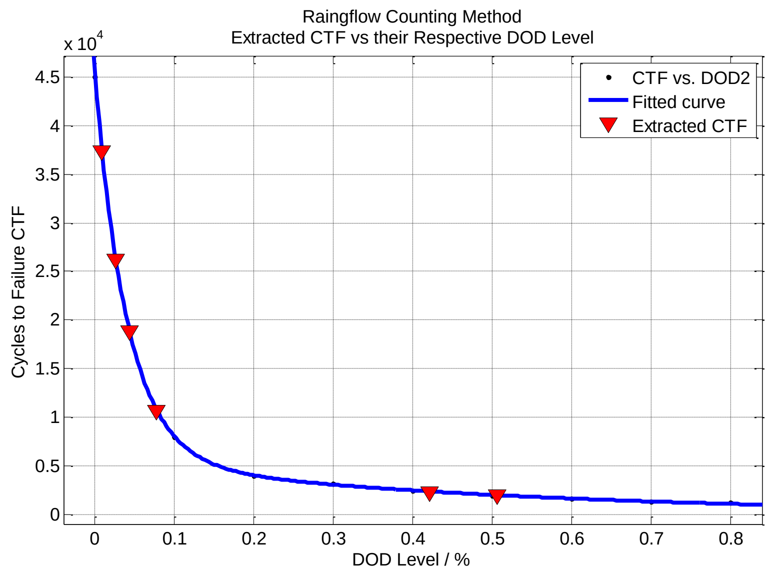

Figure 5.17: Number of CTF vs extracted DODs for BESS Only

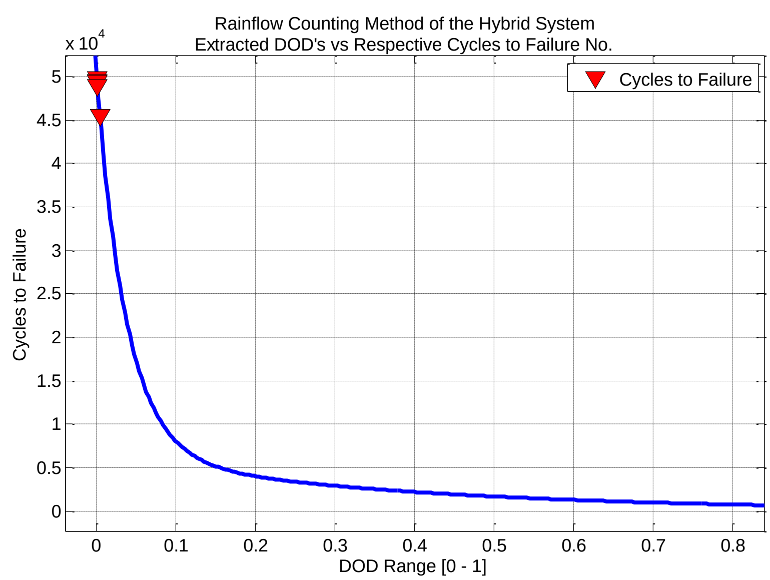

Figure 5.18: Extracted DODs with their Corresponding CTF

5.3 The Prospect of Storage Cost Variations

Since the cost of storage technologies is falling down, a comparative analysis in terms of cost and technical features has been performed to assess the feasibility of the current study presented in this thesis. The results are summarized in Table **3.1**.

Table 5.8: Summary of overall cost analysis

Procedure	BESS	SMES	Hybrid System Cost $	SMES Only or BESS Only $	
Base case	-	-	72,564,575	BESS	SMES
				206,304,206	533,338,955
Prices decreased by	30 %	Same	51,561,245	BESS only 144,444,444	
Prices decreased by	30%	30%	50,562,103	-	
Prices decreased by	Same	30 %	71,232,433	SMES ONLY 373,337,268	

As seen in Table **5.8**, since the capital cost of SMES is quite high compared with the conventional batteries, the hybridization remains economically and technically justified even if the prices continue to fall at the same rate. Furthermore, the installation cost of stand-alone SMES or stand-alone BESS is larger than the hybrid storage system in the base case and after cost reduction. This reveals that, the hybrid storage system to meet load energy needs and grid regulation requirements is always superior to stand-alone systems to do the same tasks.

5.4 Comparison with a Published Work

For the sake of comparison and to assess the feasibility of the thesis, reference [51] has been selected to address the contribution of the accomplished work. The authors have successfully applied a control based algorithm of SMES - BESS hybrid system to smooth out volatility of wind power using a synergized circuitry-based real time simulation. A low pass filter is used to decouple the wind power into a high frequency component and a low frequency component. SMES is characterized by a high power density and a fast response time which qualifies it to deal with high frequency power, while the low frequency power is dealt by the BESS. Three modes (normal -warning - alarm) are suggested to efficiently operate the hybrid system. Moreover, the proposed operational scheme succeeded to control the SOC of both devices within the desired limitation. However, the proposed energy management didn't consider the service lifetime of the BESS nor the optimal size needed. The battery bank was excessively utilized since it underwent frequent charging /discharging cycles where such behavior facilitates battery degradation. In addition, the impact of operating the hybrid storage system over the BESS performance has not been addressed. Furthermore, no cost analysis has been carried out to accurately evaluate the feasibility of installing the hybrid storage system.

Given the shortcomings discussed above, the work presented in this thesis attempted to fill in the gaps overlooked by the authors in [51] and other publications in the same field.

CHAPTER 6

CONCLUSIONS

6.1 Conclusions

The mathematical model developed in this thesis has successfully been applied to optimize the minimum cost and the operation for both configurations (hybrid system) and (Conventional BESS). Operational wise, the ramp rate constraint imposed on the system was satisfied in both configurations. Moreover, the proposed operational scheme provided a reliable and smooth output power trajectory. However, in terms of cost and operation, the advantages of installing hybrid system over the BESS only have been addressed throughout the consecutive analysis conducted in CHAPTER 5. Apparently, the proposed model is successfully able to prove that the cost of hybridizing both systems might be overshadowed due to their individual capital costs. In addition, the cost of installation of the hybrid system didn't exceed 34% of the cost in case of operating BESS only. Such results sound promising in nowadays market where the RESs have become the bone of electricity network. RainFlow Counting Algorithm has been utilized to determine the consecutive fatigue damage calculations that usually take place whenever a storage system is exposed to real-world loading (irregular cycling). The application of RainFlow counting in the case of SMES is pointless, since the main goal of selecting such technology is its ability to sustain endless quantities of regular and irregular cycling patterns.

6.2 Contributions

The foremost contribution of the thesis is trying to fill in the gaps uncovered in the literature introduced in CHAPTER 2. The main thesis contributions can be summarized as follows:

- An optimization model to allocate the optimal size and the optimal cost of the hybrid storage system considering demand energy and grid integration requirements is developed.
- A modified optimization model that consists of competing objectives to efficiently operate the hybridized storage system taking into consideration demand energy, maintaining BESS SOC at the middle state of charge and ramping events encountered in the input source is carried out.
- Developing a detailed economical, technical comparison between a hybridized storage system and a single storage system containing BESS only.
- The feasibility of the proposed work is proved.
- A detailed battery lifetime analysis for both cases is implemented.
- A Comprehensive recent survey in the industry of storage technologies is carried out.

6.3 Future Work

- The proposed model can be modified to include battery parameters and efficiency points for both energy storage technologies.
- A real-time simulation is a potential extension to this thesis.
- Battery lifetime estimation may be modified to include several variables.
- Kalman filter based-technique might be utilized to accurately estimate BESS and SMES state of charges.

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VITAE

Name	:Ibrahim M. Alotaibi
Nationality	:Saudi
Date of Birth	:9/10/1985
Email	:Alotaibi.ib@gmail.com
Address	:Gassim - Unaizah
Academic Background	MS. Electrical Engineering - Energy Systems
	Expected graduation in DECEMBER 2017
	King Fahd University of Petroleum and Minerals
	Bachelor's of Electrical Engineering in FEB 2011
	Alqassim University