ABSTRACT

AGARWAL, APOORV. Adaptive Control of a Hybrid Energy Storage System for Wave Energy Conversion Application. (Under the direction of Dr. Subhashish Bhattacharya).

A hybrid energy storage system (HESS), that comprises of a battery and a supercapacitor, is utilized to absorb the power and energy oscillations for a wave energy conversion system so as to inject a smooth power to the grid. Continuous variation in the wave profile presents a formidable challenge in terms of the power and energy allocation among the battery and supercapacitor. In this paper, an adaptive control strategy is proposed, wherein the power and energy sharing between the battery and super-capacitor is dynamically decided based on an optimization algorithm. The proposed algorithm is aimed at optimizing the total losses in the hybrid energy storage system while simultaneously maximizing the battery lifetime. Circuit simulation and experimental results from a hardware prototype are provided to validate the effectiveness of the proposed control scheme.

Moreover, the change in wave profile and improvement of control strategy poses an additional challenge for sizing of HESS due to consistent change in the power sharing between battery and supercapacitor throughout its operation. Thus, a cost-optimal sizing of HESS is presented that takes into account the capital as well as the replacement cost.

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Adaptive Control of a Hybrid Energy Storage System for Wave Energy Conversion Application

by
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Chapter 1

Introduction

1.1 Background

Energy from ocean waves presents a tremendous potential as a resource of renewable energy. Ocean wave offers a significantly higher energy density as compared to wind and solar based energy conversion. It is estimated that the global power potential represented by ocean waves is around 2 TW [1]. The Electric Power Research Institute (EPRI) in it's technical report has estimated that the total recoverable wave power energy off the U.S. coastline amounts to 1170 TWh/year [2].

Wave energy converter (WEC) devices are used to harvest energy from the ocean waves. Various energy conversion methods are employed by WECs, mainly : Point absorber such as buoys, Paddle-type, Oscillating Water Column, Attenuating-type devices, Rotating-mass based, Over-topping devices, etc [3]. Some of the WEC device are shown in Figure 1.1. [4]-[5].

(a) Pelamis WEC : Attenuating type WEC
(Pelamis Wave Power ©)

(b) Penguin WEC : Rotating Mass type WEC
(Wello ©)

Figure 1.1 Types of WEC

A grid-connected WEC system is shown in Figure 1.2. A generator is connected to the WEC with appropriate gear mechanism. The machine side converter (MSC) controls the power generation by controlling the machine current. The grid side converter (GSC) controls regulates the dc bus by controlling the power dispatched to the grid.

Figure 1.2 A WEC System with it's associated Power Conversion Systems

The ocean waves are multi-frequency signals that generally contains frequency components ranging from 0.04 to 0.25 Hz (period of 25 to 4 s) [6]. Consequently, it leads to the generation of highly oscillating power. An example of power generated from a WEC using a typical ocean wave profile cited in the technical report published by EPRI [2] is shown in Figure 1.3. It is evident from the figure that the power generated varies rapidly over short time scales. This poses a major challenge for grid integration of WEC [7] as injection of this oscillatory power directly to the grid can affect the stability of the grid.

Figure 1.3 Power generated from a WEC from a typical ocean wave profile

A solution to this problem is to integrate an energy storage system (ESS) which absorbs the oscillating power and thus, a smooth average power is delivered to the grid [8–10]. Moreover, ESS can be interfaced at the common DC link using dc-dc power converters to the existing WEC power architecture without any additional system modification. The concept behind the solution of using an ESS is shown in Figure 1.4. The Oscillating power can be segregated into it's two components - an average DC component and an oscillating component. To deliver a smooth power to the grid, the oscillating component is processed by the ESS and the DC average power is dispatched to the grid.

Figure 1.4 Concept of HESS

The average to peak power ratio from a WEC is typically around 0.1 - 0.2 [6]. Therefore, the ESS should be capable of processing a high peak power while being able to store a significant amount of energy. Batteries and supercapacitors are popularly used as energy storage devices for wave energy applications. Batteries have high energy density but low power density whereas supercapacitors can supply high peak powers but have relatively low energy density. These limiting factors reduce the economic viability for single source-based energy-storage systems – capacitor-based or battery-based. Combining battery and supercapacitor makes a hybrid energy storage system (HESS) which can deliver high peak power and at the same time, store enough energy for the required operation. This makes for a more cost-effective option than the single-source systems [11].

1.2 System Overview

In general, HESS can be categorized into three major categories: passive, semi-active and fully-active. In passive type HESS, battery and supercapacitor are coupled in parallel with the common DC link without any intermediary converter. It is the simplest HESS topology and very cost-effective [12, 13]. At the same time, it has a mmajor drawback of under-utilization of the supercapacitor because of limited voltage swing as the battery is directly coupled to it and thus, leading to poor performance. A semi-active HESS uses a DC-DC converter to integrate supercapacitor with the DC link to which the battery is directly coupled [14, 15]. It is able to utilize the supercapacitor better by permitting it to discharge to lower voltage. However, the DC link voltage control is still not possible and thus, battery needs to be sized with constraint of satisfying the DC link voltage requirements. In a fully active HESS, battery and supercapacitor are both connected to the DC link using dedicated DC-DC converters [16, 17]. Although costly, it offers a significant advantage in terms of flexibility in control of each energy storage component and thus, be able to fully exploit their inherent characteristics. It results in delivering a system capable of supplying high peak power as well as enough energy for the desired operation.

A fully active HESS has been implemented in [11] for smoothing of oscillating wave energy. Figure 1.5 depicts a grid-connected WEC system integrated with HESS. Bidirectional DC-DC power electronic converters are used to interface the battery and supercapacitor based energy storage elements to the common DC link. The HESS system regulates the DC-voltage allowing the GSC converter to supply a smoothed power to the grid. Furthermore, rating of the GSC and output cables are greatly reduced, offsetting the additional cost of the HESS to some extent.

1.3 Motivation

One of the main challenges with an HESS system is to implement a control strategy that can optimize the power sharing between the battery and the supercapacitor. This issue gets accentuated as the ocean wave profile changes at all time scales, from year to year, season to season, day to day, and even within a few hours during the same day. Variation in the ocean wave profiles is shown in [18].

Figure 1.5 A WEC System with integrated HESS [11]

(a) Average Wave Period (Seconds)

(b) Dominant Wave Period (Seconds)

Figure 1.6 Variation in Ocean wave profiles : Station 41001 - EAST HATTERAS [18]

Different control techniques for power sharing in HESS have been reported in literature. Rule-based approach for the control of the HESS has been proposed in [19]. However, the rule-based approach need not necessarily optimize performance in terms of HESS losses or battery life. In [11], a filtration based scheme is implemented which takes the full advantage of inherent characteristics of batteries and supercapacitors. However, it requires the load profile to be known in advance to select the filtration parameter for optimal performance.

Research has been carried out to implement HESS power sharing as an optimization problem solving in real-time. A multi-objective optimization approach for energy loss minimization and battery protection has been implemented in [16], but doesn't actively extend the battery life. Further, strategies such as Model Predictive Control using dynamic programming based optimization algorithm [20] may be impractical due to their large computational cost and complex calculation processes. Some of the researchers have applied tools such as dynamic programming [21], or optimization techniques such as the DIRECT algorithm[22], etc for the solution. However, these real-time controls are typically achieved at the expense of high computational and run-time overhead. Further, multi-fold complexities are introduced as it requires designing the computing hardware and a real-time optimization algorithm at the same time. This is due to the fact that designing sub-system independently can result in systems with efficiencies and performances that are unachievable [23].

Moreover, these real-time optimization strategies are not directly applicable to an HESS integrated with a WEC system considering the fact that wave spectrum of ocean waves doesn't change very rapidly. In general, the wave spectrum is assumed to be stationary for up to a duration of 3 hours [24]. In view of this, an adaptive control scheme is proposed in the present work that provides the flexibility to modify the power sharing periodically based on the variations in wave profile.

1.4 Scope of the Thesis

A frequency-based adaptive control strategy is developed based on the fixed filtration scheme implemented in [11] to optimize the power and energy sharing of the HESS in terms of losses and battery lifetime, which takes into consideration of the continuous variations in the wave profile.

Additionally, the operating point of the controller varies due to the oscillating power reference and change in supercapacitor voltage. This creates an additional issue of assessing the design of the controller over the entire operating range. Hence, a systematic controller design work is presented for the highly coupled control structure implemented for the operation of HESS.

Moreover, the change in wave profile and improvement of control strategy poses an additional challenge for sizing of HESS due to consistent change in the power sharing between battery and supercapacitor throughout its operation. In addition, a cost-optimal sizing of HESS must take into account the capital as well as the replacement cost.

The main contributions of this work are broadly listed as follows,

- An adaptive control strategy is proposed to optimally share the power in a HESS for varying ocean conditions, where the optimality is defined by:
 - Maximizing Battery lifetime
 - Reduction in accumulated losses in the system

Appropriate models for battery lifetime and losses have been developed and validated.

- A cost-optimal sizing procedure based on wave data that accounts for the control scheme is presented and also considers the lifetime of each energy storage system.

1.5 Thesis Organization

The thesis is organized as follows:-

- In Chapter 1, introduction to wave energy and WEC devices has been presented. The challenges to integrate WEC with grid and solutions implemented have been briefly discussed. The gaps in the reported solutions are identified for the motivation of the proposed solution.
- In chapter 2, the power sharing control strategy based on frequency based scheme is reviewed. It is followed by a systematic design of the controllers for the HESS system. Simulation results with the developed controller for different power sharing control parameters have been analysed.
- In Chapter 3, models for each performance metric developed for HESS are developed and validated. The performance is evaluated for different power sharing control parameters.
- In chapter 4, the proposed control strategy for optimally power share is presented. An overview of the optimization technique for the developed system is also briefly discussed. A simulation comparison has been presented between the proposed scheme and the conventional scheme to corroborate the superiority of the proposed strategy.
- In Chapter 5, a step-by step hardware implementation of the hybrid energy storage system is presented. Results for control of individual systems are initially obtained followed with the operation of complete system. The performance of the proposed control strategy is validated using the developed hardware test-bed.
- In Chapter 6, an Energy Storage Sizing procedure is presented with objective of minimizing the annual cost (that includes the capital as well as replacement/lifetime cost). A case study for a integrating a HESS with a single WEC is presented.

Chapter 2

Design of power sharing control for HESS

2.1 Introduction

In this chapter, the power sharing strategy based on the Frequency based Control (FBC) is described. FBC-based power allocation provides a simple and effective approach to achieve the required performance [25]. FBC has been implemented in [11, 17, 25] to separate the power demand into low-frequency and high-frequency components, with the high-frequency component supplied by the SC to keep the battery current profile smooth.

Sections 2.2-2.4 are based on the works presented in [11, 26]. Based on this work, a comprehensive design analysis and implementation for the controller is presented in Section 2.5.

2.2 Frequency based Control Theory

The fundamental idea of frequency based control strategy is that the battery supports slow frequency components, whereas supercapacitor supports the high frequency components. This helps in achieving an ESS able to provide both high energy and power capacities by taking advantage of the inherent capabilities of high power density and high energy density from supercapacitor and battery respectively.

The concept of conventional FBC for application in WEC is depicted in Figure 2.1. To deliver a smooth power to the grid, the DC component of the oscillatory generated WEC power is dispatched to the grid. The remaining fluctuating power is processed by the HESS. A Low Pass Filter (LPF) is used to separate high frequency and low frequency components of the reference power and assigned to supercapacitor and battery respectively.

Figure 2.1 Power Sharing Scheme - Conventional FBC

2.3 HESS System/Topology

Figure 2.2 shows the power architecture of a WEC system that is supported by a HESS comprising of a Battery-based Energy Storage System (BESS) and Supercapacitor-based Energy Storage System (SESS). For interfacing the super-capacitor and battery to the output dc link, a dual-active bridge (DAB) converter and a bidirectional boost converter have been implemented. The specifications for the converters are given in Table A.1.

Figure 2.2 HESS System

2.4 Control Architecture of FBC

The main objectives for design of the FBC control architecture are defined as:

- Supply a smoothed average power to the load.
- Tightly regulate the DC link voltage V_{out} .
- Regulate Supercapacitor Voltage V_{sc} within a desired band.

Figure 2.3 Control Architecture of HESS System

Figure 2.3 represents the architecture of the control scheme implemented. The operation of the control can be explained as below:

- The oscillating power generated by the WEC directly reflects into the change in the DC link voltage, V_{out} . This change is utilized to generate the oscillating current reference. Thus, by taking the input as a change in DC link voltage V_{out} , controller C_1 generates the oscillatory current reference, i_{gen}^* .
- A low pass filter, LPF_1 is used to separate out the high and low frequency components of i_{gen}^* . The high frequency current component is assigned to the supercapacitor, i_{sc}^* .
- In order to control the SC voltage V_{sc} within a certain band, a SC voltage control process is added. This is achieved by drawing a small amount of power from the battery. Controller C_3 is responsible for ensuring the V_{sc} regulation.

- A second low pass filter, LPF_2 is used to estimate the dc component from the low frequency component. This DC value of current is supplied to the load, i_{load}^* . The remaining low frequency current component is assigned to the battery, i_{bat}^*
- Controllers C_2 , C_4 and C_5 are designed to generate modulation signals for the current control of the power converters interfacing the super-capacitor, battery and grid respectively.

2.5 Design considerations for Controller

The controllers need to be appropriately designed for stable performance with sufficient bandwidth. The frequency of wave energy is generally in the range of 0.04–0.25 Hz. The power generated from a WEC is two times this frequency resulting in a spectrum containing frequency ranges from 0.08–0.5 Hz. Each energy storage system - battery or supercapacitor has an individual control based on the loop bandwidth of the controllers. The supercapacitor handles the faster dynamics compared to the battery. Therefore, the bandwidth of the controller becomes vital for a smooth and reliable operation. Moreover, the voltage loop bandwidths are kept slower than the inner current loops. The bandwidths for each of the controller is chosen as follows:

- C_1 needs to be able to generate the oscillating current which is typically in range of 0.08 to 0.5 Hz. Thus, its bandwidth is selected to be 30 Hz.
- C_3 should only output a low frequency change of voltage regulation error and thus it has a maximum bandwidth limit of 5 mHz.
- C_2 and C_4 must have at-least 10 times higher bandwidth than C_1 and C_3 respectively. Moreover, C_4 also needs to be able to track the feed-forward term LPF_1 . Thus, bandwidth of C_2 and C_4 are chosen to be 300 Hz and 10 Hz respectively.
- C_5 represents controller for grid-integration of WEC system and thus it's bandwidth is application specific. Here, it is taken as 100 Hz.

Any change in the bandwidth of the C_3 or the choice of LPF_1 cut off frequency would impact the power sharing between super-capacitor and battery. Moreover, the operating point of the controller varies due to the oscillating current reference and additional change of supercapacitor voltage. This creates an additional difficulty in guaranteeing performance and stability of the designed controllers over the entire operating range.

2.6 HESS Small Signal Model

For designing the controllers $C_1 - C_5$, suitable transfer functions need to be derived. These transfer functions can be derived from the system small signal models. The terminated small signal model for boost converter has been derived in literature work [27]. For Dual Active Bridge, a reduced order small signal model is considered [28] that ignores the high-frequency port dynamics.

However, due to the control architecture implemented being highly coupled as shown in Figure 2.3, the small signal model for each converter cannot be considered mutually exclusive to each other. The small signal model for the whole system is shown in Figure 2.4.

A simple phase shift modulation technique has been adopted for the operation of a DAB converter. By controlling the phase shift ϕ across the leakage inductor L_{lk} , the amount of active power transfer can be controlled. In the model shown, D is equivalent to $\frac{\phi}{\pi}$. For the Boost converter, D_b represents the duty cycle of the boost converter having inductance, L_{bat} .

Figure 2.4 Small Signal Model for Boost Converter

2.7 Transfer-functions derivations

The different transfer functions required for the controllers design can be inferred by modelling each of the controller's closed loop model from the control architecture shown in Figure 2.3. The closed loop models for controllers $C_1 - C_4$ are shown in Figure 2.5, Figure 2.7, Figure 2.9 and Figure 2.8 respectively.

As stated in section 2.5, the voltage loop controller C_1, C_3 bandwidths are kept much slower than the inner current control loops and thus eliminating the current control dynamics for design of controller C_1, C_3 . In Figure 2.5, if the input current controller are designed for at-least 10 times the bandwidth of C_1 , then it can be simplified to Figure 2.6.

Figure 2.5 Controller C_1

Figure 2.6 Controller C_1 simplified

Figure 2.7 Controller C_2

Figure 2.8 Controller C_4

Figure 2.9 Controller C_3

From the HESS small signal model in Section 2.6, different cases can be derived based on which of the small signal variation does not effect the intended transfer function and thus, can be considered zero.

2.7.1 Case 1 : $\hat{d}_b = 0, \hat{v}_{bat} = 0$

Closed loop model transfer functions for design of controller C_2 can be determined by assuming $\hat{d}_b = 0, \hat{v}_{bat} = 0$. The updated small signal model for this case is shown in Figure 2.10. The relevant transfer function determined is given by Equation (2.1).

$$\frac{\hat{i}_{sc}}{\hat{d}} = \frac{(1-2D)V_{out}T_s}{2nL_{lk}} \quad (2.1)$$

Figure 2.10 HESS Small Signal Model - Case 1: $\hat{d}_b = 0, \hat{v}_{bat} = 0$

2.7.2 Case 2 : $\hat{d}_b = 0, \hat{d} = 0, \hat{v}_{bat} = 0$

The updated small signal model for case : $\hat{d}_b = 0, \hat{d} = 0, \hat{v}_{bat} = 0$ is shown in Figure 2.11. From this, closed loop model transfer functions for design of controller C_1 and C_3 can be determined. The relevant transfer function for C_1 is given by Equation (2.2). Similarly, the transfer function for C_3 is given by Equation (2.3).

Figure 2.11 HESS Small Signal Model - Case 2 : $\hat{d}_b = 0, \hat{d} = 0, \hat{v}_{bat} = 0$

$$\frac{\hat{v}_{out}}{\hat{i}_{gen}} = \left(\frac{1}{C_{out}s} \parallel \frac{Ls}{(1-D_b)^2} \parallel R_{load} \right) \quad (2.2)$$

$$\frac{\hat{v}_{sc}}{\hat{i}_{bat}} = \frac{2nL_{lk}(1-D_b)}{D(1-D)T_s} \frac{1}{C_{sc} * C_{out}s^2 + 1} \quad (2.3)$$

2.7.3 Case 3 : $\hat{d} = 0, \hat{v}_{bat} = 0$

Closed loop model transfer functions for design of controller C_4 can be determined by assuming $\hat{d} = 0, \hat{v}_{bat} = 0$. The updated small signal model for this case is shown in Figure 2.12. The relevant transfer function determined is given by Equation (2.4).

$$\frac{\hat{i}_{bat}}{\hat{d}_b} = \frac{V_{batt}}{Z_{fict}(1-D_b)^3} \frac{Z_{fict}C_{out}s + 2}{\frac{LC_{out}}{(1-D_b)^2}s^2 + \frac{L}{Z_{fict}(1-D_b)^2}s + 1} \quad (2.4)$$

Figure 2.12 HESS Small Signal Model - Case 3 : $\hat{d} = 0, \hat{v}_{bat} = 0$

2.8 Controller Designs

Each controller designed is a PI type controller represented by Equation (2.5). For each controller, applicable bode plots and closed loop system step responses have been provided to show the performance and stability of the design. The controller parameters obtained are given in Table 2.1.

$$C_1 = \frac{k_p s + k_i}{s} \quad (2.5)$$

Table 2.1 Controller Parameters

Controller	Parameter	Value
C₁	K_p	0.5
	K_i	$2 \times \pi \times 0.1$
C₂	K_p	0.05
	K_i	$2 \times \pi \times 5$
C₃	K_p	0.01
	K_i	$2 \times \pi \times 0.01$
C₄	K_p	0.1
	K_i	$2 \times \pi \times 100$

(a) Bode Plot **(b)** Unit Step Response**Figure 2.13** Controller C_1 plot

Figure 2.14 Controller C_2 plot

Figure 2.15 Controller C_3 plot

Figure 2.16 Controller C_4 plot

2.8.1 Feed-forward terms - LPF_1 and LPF_2 Design

The feed-forward terms LPF_1 and LPF_2 are given by Equation (2.6) and Equation (2.7). LPF_1 represents the filter that is responsible for separation of low frequency and high frequency components, and thus is the main parameter to decide the power sharing in a HESS. LPF_2 is the low pass filter to separate out the DC or the average power that is to be supplied to the grid. As such, its cut off frequency is very low in the order of 10^{-3} Hz.

$$G_{LPF_1} = \frac{\omega_c}{s + \omega_c} \quad (2.6)$$

$$G_{LPF_2} = \frac{\omega_c'^2}{s^2 + 2\zeta\omega_c' s + \omega_c'^2} \quad (2.7)$$

2.9 Simulation of Frequency based Control

In [26], WEC system has been emulated using a practical wave data taken from the survey report [2]. The WEC generated power data from [26] has been used as for simulation of the generated oscillating power.

Steady state operation of the WEC system with HESS connected at the dc link is shown in Figure 2.17 and Figure 2.18. The generated power is shown for 90 seconds. The DC link voltage, V_{out} is regulated at 300 V. The super-capacitor reference voltage is set at 20V. The super-capacitor voltage varies in accordance with the low frequency change of the WEC power averaged over the wave cycle. As can be seen, the supercapacitor handles the faster dynamics aka the high frequency components and battery handles the slow dynamics aka the low frequency components. Figure 2.17 and Figure 2.18 represents two scenarios with cut-off frequencies of 0.02 Hz and 0.04 Hz respectively. The results for these different cut-off frequencies are tabulated in Table 2.2.

	Cut-off frequency (Hz)	Battery		Supercapacitor	
		Peak Power (kW)	Peak Energy (kWh)	Peak Power (kW)	Peak Energy (kWh)
Wave	0.04				
Profile 1	0.2				

Table 2.2 Simulation Results - Comparison with different cut-off frequencies

From the table, it can be observed that the peak power and energy rating of battery and supercapacitor are dependent on the cut-off frequency.

Figure 2.17 Simulation Results: Cut-off frequency = 0.02

Figure 2.18 Simulation Results: Cut-off frequency = 0.04

2.10 Limitation of the Conventional Frequency-based control scheme

From the simulation results tabulated in Table 2.2, it is shown that the change in the choice of the cut off frequency changes the peak power and energy rating and thus, influences the power sharing in a HESS. In the previous works [11, 26], selection of an optimal operating cut-off frequency has not been pondered upon. Moreover, due to the seasonal variations in ocean waves a fixed cut-off frequency based LPF operation can lead to under-utilization and over-utilization of the HESS. Also, this change in wave profile poses a challenge for sizing of HESS as the power sharing between battery and supercapacitor can vary a lot throughout its operation. Hence, we propose in this paper, a cost-optimal sizing procedure of HESS and an adaptive filter-based operation of HESS that account for the variability in the ocean wave profiles.

Chapter 3

Basis for the Proposed Adaptive Control Strategy

3.1 Introduction

Section 2.10 demonstrated that the power sharing in a HESS can be changed by changing the cut-off frequency. This indicates that optimal power sharing in a HESS can be obtained by careful selection of the cut-off frequency.

However, what is considered optimal must be defined before anything else. Hence, a set of performance metrics are defined to specify the optimality. These metrics are then evaluated against different cut-off frequencies to get an intuition for selection of the optimal cut-off frequency. Section 3.2 gives an overview of the metrics implemented. Models developed and the effect of change of f_c for each metric has been observed in sections 3.3-3.4.

3.2 Performance Metrics

To optimize the power sharing between the two energy storage components, performance metrics such as the battery lifetime and overall losses in the HESS system have been utilized:

- **Losses in HESS:** The average power supplied to the grid can be shown by Equation (3.1), where $\langle . \rangle$ represents average value. Thus, the average power generated by WEC, $\langle P_{WEC-gen} \rangle$ supplies both the average power supplied to the grid, $\langle P_{grid} \rangle$ and the average power loss in HESS, $\langle P_{HESS-loss} \rangle$.

$$\langle P_{grid} \rangle = \langle P_{WEC-gen} \rangle - \langle P_{HESS-loss} \rangle \quad (3.1)$$

Thus, power losses in the HESS integrated with the WEC should be minimized to decrease the cost of power generation ergo the power supplied to the grid.

- **Battery Lifetime:** In an HESS, the batteries take a dominant share of the annual cost. Moreover, they have a limited lifetime as compared to supercapacitor. Hence, increasing their lifetime is pivotal for cost justification of the energy storage systems. The lifetime of the battery depends primarily on two parameters - the magnitude of peak currents and number of charge/discharge cycles.

The stark contrast of a supercapacitor to its counterpart is its ability to operate for a significantly large number of cycles before failure. Moreover, the number of cycles are independent of its Depth of Discharge. Thus, the supercapacitor lifetime has been excluded in the optimization process.

Sections 3.3-3.4 presents the models developed for HESS losses and battery lifetime respectively. Further, the cut-off frequency f_c of the low pass filter is varied to observe the trend for each metric against f_c .

3.3 HESS Losses

3.3.1 HESS Loss Model

Instantaneous losses for HESS system can be taken as sum of losses in each individual unit and is shown by Equation (3.2). $P_{Batt-loss}$, $P_{SC-loss}$, $P_{Conv1-loss}$, and $P_{Conv2-loss}$ represent the instantaneous losses in Battery, Supercapacitor, DC-DC converter 1 and 2 respectively.

$$P_{HESS-loss} = P_{Batt-loss} + P_{SC-loss} + P_{Conv1-loss} + P_{Conv2-loss} \quad (3.2)$$

3.3.1.1 Battery Model

The equivalent circuit model for a battery is represented in Fig. 3.1 [29]. It includes a dependent DC voltage source representing open-circuit voltage V_{bo} of the battery, internal resistance R_s and two RC networks - $R_{t,s}$ - $C_{t,s}$ and $R_{t,m}$ - $C_{t,m}$ to model the transient response/performance of the battery in seconds and minutes respectively. From the model, the instantaneous power loss for the battery can be calculated and is given in Equation 3.3. As R_s is much greater than $R_{t,s}$ or $R_{t,m}$, the loss in the battery can be approximated to be only due to R_s [15].

$$P_{Batt-loss}(t) = I_b^2(t)R_s + \frac{V_{t,s}^2(t)}{R_{t,s}} + \frac{V_{t,m}^2(t)}{R_{t,m}} \approx I_b^2(t)R_s \quad (3.3)$$

Figure 3.1 Battery Circuit Model

3.3.1.2 Supercapacitor Model

The first order circuit model for a supercapacitor (SC) is represented in Fig. 3.2 [30]. It is modelled by a variable capacitance C_{sc} decided by the SC voltage, internal resistance R_{sc} and leakage resistance R_{pc} . An inductance can be modelled in the circuit but has been ignored as the application intended is for low frequency operation [30]. As R_{pc} is usually large, the loss in the SC can be approximately given by Equation 3.4.

$$P_{SC-loss}(t) = I_{sc}^2(t)R_{sc} + \frac{V_{osc}^2(t)}{R_{pc}} \approx I_{sc}^2(t)R_{sc} \quad (3.4)$$

Figure 3.2 Supercapacitor Circuit Model

3.3.1.3 Power Converter (DAB) Loss Model

An approximate loss model for simple phase shift modulation for a DAB converter is presented in [31]. The total DAB loss is given by Equation (3.5).

$$P_{DAB-loss} = P_{Tx-DAB} + P_{L-DAB} + P_{Cap-DAB} + P_{Sw-DAB} \quad (3.5)$$

where, P_{Tx-DAB} - Transformer Losses, P_{L-DAB} - Inductor Losses, $P_{Cap-DAB}$ - Capacitor Losses and P_{Sw-DAB} - Power Switch Losses for a DAB converter.

Figure 3.3 DAB

3.3.1.4 Power Converter Boost Loss Model

In [27], a loss model for boost converter has been presented. It is presented by Equation (3.6).

$$P_{Boost-loss} = P_{L-Boost} + P_{Cap-Boost} + P_{Sw-Boost} \quad (3.6)$$

where, $P_{L-Boost}$ - Inductor Losses, $P_{Cap-Boost}$ - Capacitor Losses and $P_{Sw-Boost}$ - Power Switch Losses for a Boost Converter.

Figure 3.4 Boost

3.3.2 Accumulated HESS Losses

Accumulated losses in HESS can be calculated from Equation (3.7), where N is the number of samples taken over a time-slice of T_s duration, where T_s is defined in hours.

$$E_{HESS-loss} = \sum_{n=1}^N P_{HESS-loss}(n) \times \frac{T_s}{3600} \quad (3.7)$$

3.3.3 Effect of cut-off frequency on accumulated HESS Losses

A wave pattern in [2] has been analysed here for the given HESS loss model. Figure 3.5 depicts the variation in accumulated HESS losses with f_c over different 100s time-slices. The trend-line shows that an increase in f_c can help minimize losses.

Figure 3.5 Accumulated losses vs cut-off frequency for different 100s time slices.

Moreover, it has to be noted that this behavior is for a particular wave pattern analyzed and thus, the particular trend might not be true in all conditions.

3.4 Battery Lifetime

Lifetime of the battery can be primarily maximized by decreasing [32]:

- magnitude of peak currents
- number of charge -discharge cycles at high current levels

3.4.1 Battery Lifetime Model

A battery lifetime model developed in ?? has been implemented. The model is based on rain-flow counting algorithm that uses the battery manufacturer's data of number of cycles to failure vs Depth-of-Discharge (DoD). It has been explained in detail in Chapter 6, Section 6.5. The algorithm stores a continuous time series data and then process the data in blocks. This approach is problematic for its online-implementation, as the algorithm must process all of the stored data at the same time, taking significant computational resources.

Thus, for quantifying the battery lifetime without incorporating complex calculations, a standard deviation function has been implemented. Standard deviation (denoted by σ) is a measure that is used to quantify the amount of variation or dispersion of a set of values. Ergo, the damage due to magnitude/variation in battery current can be quantified by its standard deviation for a time period T_s . This is represented by Equation (3.8).

$$SD_{bat} = \sigma(I_{bat}) = \sqrt{\frac{\sum_{n=1}^N (I_{bat}(n) - \bar{I}_{bat})^2}{N - 1}} \quad (3.8)$$

To further validate the Equation (3.8) implication on battery lifetime, analysis of two battery current waveform with different σ is presented. Assumption initial DoD of 70 % and battery is taken to be . The waveforms as shown in Figure 3.6 have same mean value with different σ of 0.96 and 1.23 respectively. Using the rainflow-counting based battery lifetime model, lifetime of battery is estimated to be 2.8 times higher for Figure 3.6a as compared to Figure 3.6b. This shows us that the higher standard deviation maps to lower battery lifetime.

Figure 3.6 Battery Current Waveform

3.4.2 Effect of cut-off frequency on Battery Lifetime

The effect of variation of the low-pass filter cut-off frequency, f_c , using the same wave pattern is studied. Figure 3.7 represents the battery and supercapacitor current for two different f_c values. It can be observed that an increase in f_c leads to an increase in the battery current ripple as well as the peak value of the battery current. The σ value are found to be 0.1 and 0.2 for f_c of 0.04 Hz and 0.14 Hz respectively. This shows that a decrease in f_c can help maximize battery lifetime.

Figure 3.7 Battery/supercapacitor currents for two cut-off frequencies over a 100s time slice.

3.5 Summary - Effect of varying cut-off frequency

It can be discerned from Figure 3.5-Figure 3.7 that the low pass filter cut-off frequency, f_c , has a significant effect of the performance metrics. Sections 3.3.3 and 3.4.2 shows in order to decrease losses, a higher f_c is preferred whereas to maximize battery lifetime, lower f_c is required. Thus, improving both the performance metrics simultaneously is a conflicting objective. Hence, optimization methods can be utilized to achieve a balance between the two. Further details about the optimization methodology used are explained in Chapter 4.

Chapter 4

Proposed Control Strategy

4.1 Introduction

The optimal operation of HESS is usually achieved by considering the problem of HESS power sharing as an optimization problem. This optimization problem is solved in real time using tools such as neural networks, dynamic programming, model predictive control and other optimization methods. The real-time control is typically achieved at the expense of high computational power. However, these strategies may not be directly applicable to an HESS integrated with a WEC system considering the fact that wave spectrum of ocean waves doesn't change very rapidly. In general, the wave spectrum is assumed to be stationary for up to a duration of 3 hours [24]. With this in view, a frequency-based adaptive control scheme is proposed that provides the flexibility to modify the power sharing periodically based on the variations in wave profile as shown in Fig. 4.1.

4.2 Adaptive FBC

The distribution of power between the two energy storage devices is formulated as an optimization problem. An appropriate aggregate objective function is developed from the performance metrics. The optimization objectives are:

1. Minimize accumulated losses in HESS represented by Equation (3.7).
2. Maximize Battery Life : The damage due to magnitude/variation in battery current is quantified by its standard deviation over the period T_s as shown in Equation (3.8).

A single objective function is formulated as a weighted-sum of normalized objectives as given in (4.1). The trade-off factors - γ_1, γ_2 affect the trade-off between the objectives included in the objective function and can be chosen according to the designer needs to have more focus on losses

or battery lifetime. Moreover, each objective has a different scale and hence, are normalized by using base values to makes optimization less sensitive to their scale.

$$F(f_c) = \gamma_1 \times \frac{E_{HESS-loss}}{E_{HESS-loss}^{base}} + \gamma_2 \times \frac{SD_{bat}}{SD_{bat}^{base}} \quad (4.1)$$

The optimization problem with constraints is given by:

$$\begin{aligned} &\text{Minimize: } F(f_c) \\ &\text{Such that: } f_c^{min} \leq f_c \leq f_c^{max} \\ &\max\left(\sum_{n=1}^N I_{bat}(n)\right) \leq I_{bat}^{max} \\ &\max\left(\sum_{i=1}^N I_{sc}(n)\right) \leq I_{sc}^{max} \end{aligned} \quad (4.2)$$

The first constraint restricts the design space of the design variable f_c , which can be determined by analyzing the frequency content of the wave spectrum. The second and third constraints are to limit the maximum currents handled by the battery and supercapacitor respectively.

Figure 4.1 Proposed Control Scheme

The objective function is non-convex and hence, an optimization technique based on genetic algorithm is adopted. Moreover, the trends are uncertain for all wave conditions making the objective of minimizing the total losses and maximizing lifetime an uncertain optimization problem for which meta-heuristic techniques such as genetic algorithm based optimization are still able to solve for the global minimum.

A block diagram representing the overall implementation of the proposed scheme with an adaptive filter is shown in Figure 4.1. Supercapacitor voltage, V_{sc} , battery voltage, V_{bat} , DC link voltage, V_{out} and generated power, P_{gen} are measured and stored over a time-slice, T_s (chosen to be 100s). The optimization algorithm is implemented and is used to determine the optimal value of the cut-off frequency, f_c^* , of the adaptive filter. The process is repeated over every time-slice.

4.3 Instant of change of cut-off frequency

The instance when the cut-off frequency is changed to its optimal value, results in sudden variations in Battery Power reference. It has been illustrated in Figure 4.2. The momentary fluctuation highlighted in red box conflicts with our objective of increasing the battery lifetime. Therefore, the proposed control strategy is further improved by incorporating a rate-limiter. The updated control strategy is shown in Figure 4.3. The low-frequency component is passed through a rate limiter to control charge/discharge rates of the battery. The high frequency component is formed by the difference between the Hess power reference and the updated low frequency component.

Figure 4.2 Effect of change

Figure 4.3 Proposed Control Strategy with Rate Limiter

4.4 Genetic Algorithm based Optimization technique

The objective function is non-convex and hence, an optimization technique based on genetic algorithm is adopted. The significant features of the developed optimization algorithm are stated as follows:

- A real encoded strategy is implemented for the problem.
- Arithmetic Crossover type with crossover rate of 90 % has been implemented. Two children are generated from two parents using Equation (4.3) with $\beta = 0.3$.

$$\begin{cases} Child_1 = \beta \times Parent_1 + (1 - \beta) \times Parent_2 \\ Child_2 = \beta \times Parent_2 + (1 - \beta) \times Parent_1 \end{cases} \quad (4.3)$$

- For mutation, the Equation (4.4) is implemented. It changes the values of a random design variable by adding/subtracting it by a value in range of $\{-0.1, +0.1\}$. Here, n is selected randomly to be integer value of 1 or 2. A mutation rate of 10 % has been implemented.

$$Child^{new} = Child^{Original} + (-1)^n \times 0.01 \times rand(); \quad (4.4)$$

- For constraint handling in Genetic Algorithm, the method proposed in [33] is implemented. The unique thing about this method is that penalty parameters are not needed. Instead, only feasible solutions are evaluated. It states "If the solution is infeasible (that is, at least one constraint is violated), the designer will never bother to compute its objective function value (such as the cost of the design). It does not make sense to compute the objective function value

of an infeasible solution, because the solution simply cannot be implemented in practice. It proposes to use a tournament selection operator, where two solutions are compared at a time, and the following criteria are always enforced:

1. Any feasible solution is preferred to any infeasible solution.
2. Among two feasible solutions, the one having better objective function value is preferred.
3. Among two infeasible solutions, the one having smaller constraint violation is preferred.

Based on this method, a tournament size of 4 is taken to converge on the fitter solution quicker. In the code, condition 1 given above is implemented as it is. If there are more than 1 feasible solution, the design with minimum objective value is selected. For all the designs being infeasible, the design with smallest constraint violation of the maximum (of all the constraints) is selected.

- **Convergence criteria used**

Following two convergence criteria are implemented simultaneously :

1. The maximum constraint violation is less than 10^{-6} .
2. The objective function value does not decrease for more than 50 generations.

4.5 Simulation Results

A simulation analysis is carried out by simulating a wave profile from [2]. The different parameters selected for the simulation study are given in Table 4.1. The trade-off parameters γ_1, γ_2 are chosen as 0.5 to give equal weight-age to both objectives.

Table 4.1 Proposed Scheme - Parameters

Parameter	Unit
Time Slice Period	100 seconds
γ_1, γ_2	0.5
$E_{HESS-loss}^{base}$	800 Wh
SD_{bat}^{base}	0.2
f_c^{min}	0.002 Hz
f_c^{max}	0.3 Hz
I_{bat}^{max}	0.25 A
I_{sc}^{max}	0.85 A

The adaptive frequency based control scheme is run with data for time-slice of 100 seconds. This has been selected to demonstrate the scheme and can be itself optimized by processing the local data of the ocean wave profiles for the location where the WEC device is being installed to. Figure 4.4 shows the optimal f_c^* solved by the algorithm for different time-slices based on the previous data for a period of 400 seconds. The cut-off frequency in the Figure 4.1 is updated with f_c^* every time-slice.

Figure 4.4 Optimum f_c^* for different time-slices

Figure 4.5 compares the proposed adaptive filter based scheme with a traditional frequency based control strategy with a low pass filter that has a fixed cut off frequency. The value of the objective function is consistently lower with the proposed optimal approach and this can lead to energy savings as the accumulated losses are considerably reduced.

From Figure 4.5, it is challenging to ascertain the worth of the improvement provided by the proposed scheme. Thus, simulation results in terms of their separate objective function is analysed. The results of each objective for both schemes is tabulated in Table 5.2. The results show:

- decrease in accumulated losses by 5 kWh units
- the reduction in sum of Standard deviation suggesting improvement in battery lifetime. When the battery current profile data for both schemes are fed to the battery lifetime model, improvement in Battery Lifetime by 1.05 times is estimated.

Figure 4.5 Proposed adaptive f_c scheme vs a fixed f_c scheme

Table 4.2 Simulation Results - Comparison between proposed adaptive scheme vs conventional scheme for a period of 24 hours

Scheme	Summation of SD_{bat}	Accumulated Losses (kWh)
Conventional FBC	7.1936	36.865
Proposed Adaptive FBC	4.6904	31.998

4.6 Conclusion

The simulation results show the dominance of the proposed adaptive scheme over the conventional scheme. It shows minimization of losses by 5 units and maximization of battery lifetime by 5% for simulation over a period of 24 hours. Although these numbers may seem small, but when considered over a period of year or more they lead to a significant improvement in cost effectiveness for the HESS system.

Chapter 5

Hardware Results

5.1 Introduction

In earlier chapter, an adaptive control scheme has been proposed to achieve better performance than the convention scheme in terms of losses and battery lifetime. Simulation results have been provided to reflect the superior performance. A scaled down hardware test-bed has been developed in the laboratory to experimentally validate the effectiveness of the proposed approach. A hybrid energy storage system consisting of a lead acid battery and supercapacitor module with their respective power converters are tested with an oscillating power profile generated by a typical WEC.

5.2 Hardware System Topology Overview

The schematic overview of the whole hardware system is shown in Figure 5.1. The components of the system are as follows:

- For interfacing the super-capacitor to the output dc bus, a dual-active bridge (DAB) converter has been implemented. A simple phase shift modulation scheme has been applied for its control. Additionally, DC blocking capacitors have been used in the high frequency port.
- For connecting battery with output DC bus, a bi-directional boost converter is used with duty cycle control.
- A DC programmable supply is used as a current source for emulating WEC attributes.
- A resistive load is implemented to emulate the power delivered to grid. It's chosen such as to provide average WEC power.
- Additionally, pre-charge resistors, circuit breakers and protection schemes have been include for safety of circuits and personal.

Figure 5.1 Schematic Overview of Hardware Setup

5.3 Demonstration of Individual Systems

Initially, demonstration of individual systems has been presented. Closed loop control of DC-DC converters - DAB and boost is shown followed by emulation of WEC by a DC programmable supply. These experimental results shows the hardware functionality of the individual systems.

(a) Dual Active Bridge (DAB) Converter

(b) Bi-directional boost converter

Figure 5.2 Prototype Converters

5.3.1 Closed loop control of Individual Power Electronic Converters

- Closed loop DC current control has been implemented for the boost converter and the DAB converter. A 1hz Sine wave is taken as reference to show the current control of the converters. The input current control of DAB is shown in Figure 5.3a and the steady state operation is shown in Figure 5.3b. The closed loop implementation of the boost converter is shown in Figure 5.3c. The inductor current is able to track the desired reference.
- Additionally, a double closed loop control of DAB converter has been implemented. It consists of an outer voltage loop followed by inner current loop. A 1hz Sine wave is taken as reference. Output voltage and input current waveforms are shown in Figure 5.3d.

(a) DAB reference tracking performance - Input current

(b) DAB steady state waveforms - AC port

(c) Boost reference tracking performance

(d) Double loop control of DAB

Figure 5.3 Experimental Results - Individual Power Electronic Converters

5.3.2 WEC Emulation by a DC programmable supply

In order to validate the proposed control scheme, generated power profile needs to be identical as would be from a real WEC in the ocean. Thus, to emulate this oscillating generated power, a programmable DC power supply is controlled as a current source with the wave pattern input. Figure 5.4 shows the generated current profile.

Figure 5.4 Experimental Results - Emulation of WEC by DC programmable supply

5.4 System Setup

The experimental set-up including power supply to emulate WEC, power conversion circuit and energy storage elements - battery and supercapacitor is shown in Figure 5.5. The control architecture shown in Figure 2.3 has been implemented for the control scheme updated with the proposed adaptive control shown in Figure 4.1. Here, the positive direction of power flow is taken as the power flowing out of the unit.

Figure 5.5 Experimental Setup of HESS

(a) Battery

(b) Supercapacitor

Figure 5.6 Hardware - Energy Storage Systems (Specifications in Table 5.1)

Table 5.1 Hybrid Energy Storage System Maximum Rating

Parameter (Unit)	Value
Battery	
Voltage Rating (V)	48
Amp-hour Capacity (Ah)	18
Maximum Current (A)	5
Supercapacitor	
Voltage Rating (V)	48
Capacitance (F)	165
Maximum Current (A)	20

5.5 Startup of the System

The system is started in a logical sequence. At the start, the super-capacitor can be completely discharged. Therefore, at the start, the super-capacitor is charged by the power from the DC source (grid). Simulation results for understanding the start-up sequence has been shown in Figure 5.8.

1. At time t_0 , the battery to the output dc link through a current-limiting resistor.

2. At time t1, the resistor is shorted leading to a very small inrush of battery power.
3. At time t2, the DC link starts ramping to 190V through a DC source (equivalent to grid side converter taking power from grid.)
4. At time t3, the charging of super-capacitor is started. A time break is provided as the supercapacitor takes a lot of time to charge.
5. The charging is completed at time t4 and the charging sequence is switched off. The super-capacitor is charged up to slightly higher voltage (41 V) than the steady-state reference voltage of 40 V.
6. At time t5, the output DC link voltage is regulated to 200V by the super-capacitor interfaced by a DAB.
7. At time t6, the boost converter is started with the controller objective of regulating the super-capacitor voltage. Also, power generation by WEC emulator using power supply is started and load is connected.

Figure 5.7 System Startip - State Machine

Figure 5.8 Simulation Results- Start Up

Similar results are also obtained in the hardware demonstration. Figure 5.9 shows the start-up sequence in hardware. It shows a zoomed in image of the waveform to signify the start-up procedure. A cut-off frequency of 0.02 Hz is taken during the start-up.

Figure 5.9 Hardware Results- Start Up

5.6 Comparison of Proposed Optimal Control vs Convention Control

Figure 5.10, Figure 5.11 and Figure 5.12 and shows the steady state-waveforms for different cut-off frequencies of 0.02 Hz, 0.08 Hz and 0.15 Hz over a period of 500 seconds. Figure 5.13 shows the experimental results for proposed adaptive scheme. The cut-off frequency is updated after every time-slice of 100 seconds.

On doing analysis using the models developed on the data obtained, the improvements are determined to be:

- Minimum improvement in Battery Lifetime by 1.015 times (Using Battery Lifetime Model).
- Decrease in accumulated losses by at least 1 Wh units

Table 5.2 Simulation Results - Comparison between proposed adaptive scheme vs conventional scheme extrapolated for 24 hours

Scheme	Summation of SD_{bat}	Accumulated Losses (Wh)
$f_c = 0.02\text{Hz}$	6.7152	479.4336
$f_c = 0.08\text{Hz}$	15.158	486.5702
Proposed Adaptive FBC	5.7804	478.5523

Figure 5.10 Hardware Results- Steady State Cutoff frequency 0.02 Hz

Figure 5.11 Hardware Results- Steady State Cutoff frequency 0.08 Hz

Figure 5.12 Hardware Results- Steady State Cutoff frequency 0.15 Hz

Figure 5.13 Hardware Results- Steady State Cutoff frequency - Adaptive

Chapter 6

HESS Sizing

6.1 Introduction

In this chapter, a scheme for sizing of the Hybrid Energy Storage System is developed. The sizing of storage elements depend majorly upon the control scheme implemented for power sharing. In frequency-based control scheme, the high frequency power spectrum is assigned to the supercapacitor and low frequency power spectrum to the battery. Thus, the sizing of the storage components is highly dependent on the filtration parameter. Section 6.2 defines the required capacity of any Energy Storage System (ESS). Sections 6.3-6.4 defines the sizing of battery and supercapacitor based ESS. A lifetime model for battery is implemented in 6.5 to account for degradation of battery. It is followed up by a flowchart for sizing HESS based on the cost model developed for HESS. A case study for a particular wave profile is presented to show the validity of the scheme developed.

6.2 Energy Storage Sizing

An Energy Storage System (ESS) can be characterized by its rated power and energy capacity. The required capacity of ESS can be calculated as follows:

Power Capacity: The power capacity of ESS should be able to meet the absolute maximum required power.

$$P_{ESS_0} = \max|P_{ESS}(t)| \quad (6.1)$$

where P_{ESS_0} is the required power capacity of ESS.

Energy Capacity: To avoid the physical damage of ESS due to deep discharge, the state of charge (SOC) should be limited to reasonable bounds. ADD another REASON.

$$\text{SOC Limits : } SOC_{min} \leq SOC \leq SOC_{max} \quad (6.2)$$

where SOC_{max} is the upper limit of SOC and SOC_{min} is the lower limit of SOC.

According to the power profile of ESS, the accumulative energy relative to the original energy status of ESS can be calculated from (6.3).

$$E_{ESS}(t) = \int_0^t (P_{ESS}(t) \times T_s) / 3600 \quad (6.3)$$

where $E_{ESS}(t)$ is the energy requirement at time t .

The energy capacity of ESS should be able to meet the difference between the maximum energy and the minimum energy. Considering the SOC limits, the energy capacity of ESS can be determined from (6.4).

$$E_{ESS_0} = \frac{\max(E_{ESS}) - \min(E_{ESS})}{SOC_{max} - SOC_{min}} \quad (6.4)$$

where E_{ESS_0} is the energy capacity of ESS in kWh.

From these Power and Energy ratings of the energy storage units, number of cells commercially available required to obtain the rating required are determined [34].

6.3 Battery Sizing

The Rint model, i.e a voltage source connected by an internal resistance, is used here to represent the battery dynamics owing to its simplicity and acceptable accuracy.

For achieving the required voltage, power rating and energy rating, a battery pack composed of $n_{b,p}$ parallel string of $n_{b,s}$ series connected cells is used. The main parameters of the battery pack can be calculated from the battery cell parameters using (6.5).

$$\left. \begin{aligned} V_{batt} &= n_{b,s} \times V_{batt}^{cell} \\ R_{batt} &= \frac{n_{b,s}}{n_{b,p}} \times R_{batt}^{cell} \\ E_{batt} &= n_{b,s} \times n_{b,p} \times V_{batt}^{cell} \times Q_{batt}^{cell} \\ P_{batt} &= n_{b,s} \times n_{b,p} \times V_{batt}^{cell} \times I_{batt}^{cell,max} \end{aligned} \right\} \quad (6.5)$$

where V_{batt}^{cell} , Q_{batt}^{cell} , R_{batt}^{cell} and $I_{batt}^{cell,MAX}$ denote the terminal voltage, capacity, internal resistance and the maximum charge/discharge current of the battery cell. V_{batt} , R_{batt} , E_{batt} and P_{batt}^{max} represent the terminal voltage, internal resistance, Energy capacity and the maximum power rating

of the battery bank.

From equation 6.5, it can be observed that power and energy rating of the battery pack depends essentially on the total number of batteries $N_{batt} = n_{b,s} \times n_{b,p}$. Thus, N_{batt} can be determined according to the battery cell power P_{batt}^{cell} and the battery cell energy E_{batt}^{cell} using (6.6).

$$N_{batt} = \max\left(\frac{E_{bat}^{max} - E_{bat}^{min}}{DOD_{bat} \cdot E_{bat}^{cell}}, \frac{\max|P_{bat}(t)|}{P_{bat}^{cell}}\right) \quad (6.6)$$

where DOD bat is the depth of discharge of the battery and $E_{max\ bat}$ and $E_{min\ bat}$ are the maximum and the minimum levels of the energy in the battery mission respectively. The main specifications of the battery cell are shown in Table .

$$DOD_{batt} = DOD_{batt,0} - \frac{\int_0^t (I_{batt} \times V_{batt}) dt}{E_{batt} \times 3600} \quad (6.7)$$

6.4 Supercapacitor Sizing

Owing to the low energy density characteristic of SCs, SC cells are threaded to form SC bank with the purpose of storing more energy and increasing the terminal voltage. The main parameters of the SC pack are given by:

$$\left. \begin{aligned} C_{sc} &= \frac{n_{sc,p}}{n_{sc,s}} \times C_{sc}^{cell} \\ R_{sc} &= \frac{n_{sc,s}}{n_{sc,p}} \times R_{sc}^{cell} \\ V_{sc} &= n_{sc,s} \times V_{sc}^{cell} \end{aligned} \right\} \quad (6.8)$$

where C_{sc} and V_{sc} denote the capacitance and the terminal voltage of the SC bank, $n_{sc,s}$ denotes the number of series connected SC cells, $n_{sc,p}$ denotes the number of parallel connected battery cell stings, R_{sc}^{cell} is the SC cell resistance, C_{sc}^{cell} is the SC cell capacitance and V_{sc}^{cell} is the SC cell voltage.

$$DOD_{sc} = DOD_{sc,0} - \frac{\int_0^t (I_{sc} \times V_{sc}) dt}{E_{sc} \times 3600} \quad (6.9)$$

The terminal power of SC bank is calculated using (6.10).

$$P_{sc} = n_{sc,s} \times n_{sc,p} \times V_{sc}^{cell} \times I_{sc}^{max} \quad (6.10)$$

Due to the linear relationship between the terminal voltage and the state-of-charge (SOC) of the SC, the SC pack energy can be derived from (6.11).

$$E_{sc} = \frac{1}{2} \times n_{sc,s} \times n_{sc,p} \times CUCcellV2UnSOC2U \quad (6.11)$$

The working SC SOC window is from 20% to 90% in order to fully capitalize on the stored energy while avoiding the detrimental effects of overcharging/discharging.

Similarly to the battery sizing procedure, the number of the supercapacitor cells N_{sc} ($= n_{sc,s} \times n_{sc,p}$) should satisfy the power and energy constraints.

$$N_{sc} = \max\left(\frac{E_{sc}^{max} - E_{sc}^{min}}{DOD_{sc} \cdot E_{sc}^{cell}}, \frac{\max|P_{sc}(t)|}{P_{sc}^{cell}}\right) \quad (6.12)$$

where DOD_{sc} is the depth of discharge of the supercapacitors, E_{sc}^{max} , E_{sc}^{min} , E_{sc}^{cell} and P_{sc}^{cell} are the maximum and the minimum energy of the SC energy profile, the maximal SC cell energy and the maximal SC cell power, respectively.

The SC degradation has been ignored since the cycle-life of SCs can reach the magnitude of millions of recharges without notable performance deterioration.

6.5 Battery Lifetime

The lifetime of the battery depends on several parameters, i.e., temperature, charge and discharge cycles, depth of discharge etc. [32]. To simplify, only the numbers of the charge and discharge cycles are taken into account.

A battery lifetime model based on rain flow counting method and Pmalger Milner rule has been implemented [35, 36].

The cycle to failure for a given depth of discharge of a typical battery can be seen in Figure 6.1. The curve shows the maximum number of cycles the battery can handle for one specific depth of discharge. However, during the operation of the battery, it will not be discharged to a specific depth-of- discharge level all the time but to various levels. The damage done to batteries with each charge/discharge cycle is modeled as follows: Moreover using curve fitting on Figure 6.1, a seventh-order polynomial is generated given by:

$$C_{Failure}(x) = p1 * x^7 + p2 * x^6 + p3 * x^5 + p4 * x^4 + p5 * x^3 + p6 * x^2 + p7 * x + p8; \quad (6.13)$$

where C_F is the number of cycles to failure, indicating the damage to the batteries; $a_1 - a_5$ are fitting constants; and DOD is the depth of discharge in a cycle.

The rain-flow-counting method is applied to calculate the number of cycles that the battery has experienced for each depth- of-discharge level. This method simply counts all the cycles that had occurred for each depth-of-discharge level of the battery.

Figure 6.1 No. of Cycles vs DoD for a typical battery

According to the Palmgren-Miner rule (Johannesson and Thomas, 2001), the damage fraction at any stress level S is linearly proportional to the ratio of number of cycles of operation to the total number of cycles that produces failure at that stress level S . Using the rule, battery damage can be estimated as:

$$D_{batt} = \sum_{DoD_{ESS}=0.1}^{DoD_{ESS}=0.9} \frac{N_{cyc}(DoD_{ESS})}{N_{CF}(DoD_{ESS})} \quad (6.14)$$

where N_{cyc} is the number of full cycles with depth-of-discharge amplitude DoD_{Bat} . Event of failure is defined if total damage exceeds unity, i.e. when D is greater than 1.0.

The lifetime of the battery is defined by

$$L_{batt}[\text{years}] = \frac{T_{sample}[\text{years}]}{D_{batt}} \quad (6.15)$$

where, T_{sample} is the period for which the sample is analysed.

6.6 Cost Model

The cost model for a HESS is given by Equation 6.16. It also takes into account the lifetime of each energy storage element which is significant in the case of a battery.

$$\text{Annual Cost } C_{HESS} = \frac{Cost_{batt}^{cell} \times N_{batt}}{TL_{batt}} + \frac{Cost_{sc}^{cell} \times N_{sc}}{TL_{sc}} \quad (6.16)$$

6.7 Flowchart for sizing

In this FBC scheme as mentioned earlier, the high frequency power spectrum is assigned to the supercapacitor and low frequency power spectrum to the battery. This is achieved by feeding the power to be processed by the storage system (PESS) through a low pass filter to extract the low frequency power components (PLF). The high frequency power components (PHF) is determined by subtracting the low frequency components, PLF from PESS.

Figure 6.2 gives the procedure for sizing a HESS based on an input of wave profile. The Battery Cell and supercapacitor cell specifications are defined from the Table 6.1. Using FBC scheme, the power profile is segregated into Battery (low-frequency) and Supercapacitor (high-frequency) power profiles. Equations 6.2- 6.3 the power and energy ratings are calculated. Number of cells of battery and supercapacitor are then calculated using equations 6.6- 6.12. Using the DoD profiles, the lifetime of energy storage components is estimated. If the annual cost determined using equation 6.16 is less than the previous cost, the parameter cut-off frequency is incremented. This process is repeated over a large data of wave-profiles to obtain the least-cost sizing of HESS.

Figure 6.2 Flowchart - HESS Sizing for integration with WEC

6.8 Case Study

A typical ocean wave pattern reported in the EPRI report [2], is used for analyzing the costs associated with sizing of HESS. The power generated from this wave pattern is shown in Figure 6.3. Using the flowchart 6.2, a sizing analysis is investigated. Specifications of battery and supercapacitor used for analysis are given in Table 6.1.

Figure 6.3 Power generated from WEC

Table 6.1 Energy Storage Component Specifications [37, 38]

Parameter (Unit)	Value
Battery	
Cell Power Rating (W)	256
Cell Energy Rating (Wh)	256
Cell Cost (\$)	20
Supercapacitor	
Cell Power Rating (W)	3400
Cell Energy Rating (Wh)	0.66
Cell Cost (\$)	30

The results are given in Table 6.2. They show that a HESS is more economical than a single energy storage system- battery-based or supercapacitor-based, even after considering the extra cost of power electronic converters required. The resulting parameters for the optimal sizing of HESS are given in Table 6.3.

Table 6.2 Sizing Results - Comparison

Energy Storage System	Cost (k\$)
Battery-based ESS	138.7
Supercapacitor-based ESS	62.58
Hybrid Energy Storage System	43.51

Table 6.3 Parameters for Optimal Sizing of HESS

Parameter (Unit)	Value
Cut-off frequency (Hz)	0.015
Number of Battery Cells	71
Number of Supercapacitor Cells	1600

Chapter 7

Conclusion and Future Work

7.1 Summary

An adaptive filter based optimal control approach, has been proposed for optimized power sharing in a HESS comprising of a battery and a supercapacitor for a WEC application, that takes into account the variability of the ocean waves. A case study for sizing HESS based on its annual cost has been presented.

7.2 Scope of Future Work

- As the operating point are time-varying, it leads to a LTV (Linear time Variant) System for which the classical control methods may provide too overcompensated controllers. Thus, the controller design can be extended to include a LTV plant study for designing of optimal controllers.
- **HESS Sizing for Multiple WEC :** Generally, multiple WEC systems are usually installed in a site to for return on investment. As the systems are spatially scattered, optimal array arrangement can provide natural power smoothing and increase the average power generated. This helps reduce the rating of HESS required and thus lead to lower cost of large scale WEC farms. Using existing models for wave-interaction, the impact of array arrangement on HESS sizing can be studied.

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APPENDIX

Appendix A

Converter Specifications

Table A.1 Converter Parameters

Parameter	Value (Unit)
Dual Active Bridge	
Input Voltage, V_{sc}	$4.5\text{V} \pm 0.5\text{V}$
Output Voltage, V_{out}	50 V
Turns Ratio, n	1:10
Switching frequency, f_s	10 kHz
Leakage Inductance, L_{lk}	10 μH
Magnetizing Inductance, L_m	0.253 mH
Operating Power, P_{dab}	20 W
Input dc bus capacitor, C_{sc}	165 F
Boost	
Input Voltage, V_{batt}	12 V
Output Voltage, V_{out}	50 V
Switching frequency, f_s	5 kHz
Inductance, L	25 mH
Operating Power, P_{batt}	12 W
Input dc bus capacitor, C_{batt}	460 μF
Output dc link capacitor, C_{out}	1000 μF