Economic Comparison Between a Battery and Supercapacitor for Hourly Dispatching Wave Energy Converter Power

Preprint

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Economic Comparison Between a Battery and Supercapacitor for Hourly Dispatching Wave Energy Converter Power

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Abstract— **This paper demonstrates a successful dispatching scheme of slider-crank wave energy converter (WEC) production using two different kinds of energy storage systems, namely, (i) lithium-ion battery and (ii) supercapacitors (SC). The performance of two energy storage systems has been compared to develop the most economical energy storage system for a WEC hourly dispatching scheme. The cost optimization of the energy storage system considering both cycling and calendar aging expenses is made based on its usage of depth of discharge. In this study, the extensive simulation is conducted in the MATLAB/Simulink platform, and results revealed that SC is a better candidate than the lithium-ion battery in terms of economic assessment for hourly dispatching WEC power.**

***Index Terms*—hourly dispatching, wave energy converter, battery, supercapacitors, cost analysis.**

I. INTRODUCTION

Wave energy has become an attractive option for power generation, and the global penetration of wave energy in power systems has been increasing daily. As ocean waves contain tremendous energy, they have the potential to fulfill approximately half of the electricity demand in the United States. Therefore, wave energy projects are emerging as a major trend in the global transition to renewable energy. For instance, the U.S. Department of Energy supports a number of projects focused on developing technologies that will produce reliable and cost-effective electricity from U.S. water resources [1].

A wave energy converter (WEC) is a device that converts the kinetic and potential energy associated with a wave into useful electrical energy. However, because of the inherent nature of the ocean waves, a WEC generates highly variable power. As a result, the integration of WECs into a national electricity grid creates several technical and nontechnical challenges (i.e., power quality, generation dispatch control, and system reliability). Therefore, power generation using renewable energy sources is often considered as nondispatchable. Further claims suggest that the renewable source will never be able to contribute substantially toward utility-scale supply or afford base-load power [2].

The uncertainty of ocean wave energy production can be diminished by incorporating an energy storage system (ESS) in the WEC architecture. In this scheme, when a WEC is integrated into the utility grid, an ESS helps to solve some technical concerns (i.e., voltage and frequency regulation, load leveling, peak clipping-valley filling, and transient stability). Batteries and supercapacitors (SCs) are the most frequently used to solve such an issue among the several types of energy storage systems that are available. Batteries have a high energy density property (i.e., the capability of slowly charging or discharging energy at a higher energy level) but low power density property. On the other hand, SC has a high power density property (i.e., the capability of rapidly charging or discharging energy at lower energy levels) but low energy density property. Table I shows the relative properties of the battery and SC [3].

The state of charge (SOC) of ESS is defined as the capability of the ESS to hold a specific amount of charge in reference to its original capacity, and the units of SOC are percentage points. On the other hand, the lowest depletion SOC of ESS is defined as its depth of discharge (DOD). Strictly speaking, the state of charge complements the depth of discharge: as one increases, the other decreases. When ESS is overcharged or discharged beyond its DOD, the service life of ESS decreases, and the cost associated with ESS increases. Therefore, it is advisable that ESS should not be depleted beyond its recommended DOD.

As indicated before, the high penetration of highly variable renewable energy into the utility grid may introduce several challenges (i.e., mismatch between generated power and load power, voltage and frequency regulation, scheduling of generation units, and grid operation economics). For example, the utility paid an additional 28.6% of the price to the distributed generation operator for every kWh of smoothed energy delivered to the grid [4]. To overcome the aforementioned technical and economic challenges, constant

Table I. Battery and SC Performance Comparison

Properties	Battery	Supercapacitor
Specific energy density	10-100 Wh/kg	1-10 Wh/kg
Specific power density	<1000 W/kg	<10,000 W/kg
Cycle life	1000	>500,000
Charge/discharge efficiency	70-80%	85-98%
Fast charge time	1-5 h	0.3-30 s
Discharge time	0.3-3 h	0.3-0.30 s

power dispatch commitment at an acceptable interval is demanded from a renewable energy sources framework.

The main purpose of this work is to encourage the complete integration of ocean wave energy to the utility grid. This integration ensures a desired dispatching of WEC output power at 1-hour increments for a specific duration, (12 hours is considered in this study). The authors used the 1-hour dispatching interval because most of the supply-side adjustment to the utility grid occurs on an hour-to-hour basis. In this work, ESS comprises either a lithium-ion (Li-ion) battery or a SC that is integrated into the WEC framework, which is capable of absorbing or supplying the necessary levels of power to keep the system's output power constant at a specified confidence level.

The authors used a dispatching scheme to supply the WEC output power to the utility grid rather than the traditional smoothing technique. A dispatching scheme enables the WEC to be a reliable source of power for the power grid, as it can be controlled like any other conventional generator, such as a thermal or a hydro power plant. Moreover, WEC output power supplied to the power grid using a dispatching scheme provides a lot of flexibility to the utility grid especially in the scheduling of generation units, grid ancillary services, and grid operation economics.

The cost associated with the battery or SC energy storage system primarily depends on two aspects: (i) lifetime of the ESS, and (ii) minimum capacity required of the ESS. The service life of the ESS mainly depends on the usage of DOD and the rate of charging-discharging power changes. Generally, the energy storage manufacturers specify energy storage cycle life as a function of DOD, and the deeper discharge of energy storage decreases the lifetime and correspondingly increases its cost substantially. Therefore, the state of charge of the ESS has always been regulated to prevent the depletion of the ESS beyond its recommended DOD, which helps to increase its lifespan. However, this kind of SOC regulation also limits the full utilization of the ESS, which is one factor that can increase the required energy storage size. Thus, based on the usage of SOC, there is a trade-off between the service life and the minimum capacity required of the ESS. In this study, we investigated the optimum value of DOD that exhibits the best competitive ESS cost for hourly dispatching WEC power to the utility grid.

In this paper we also present an economic comparison of two different types of energy storage systems—a Li-ion battery and (ii) SC—to find the most economical ESS for dispatching WEC output power to the grid. Both cycling and calendar aging costs associated with ESS are considered during this economic assessment.

The rest of the paper is organized as follows: a literature review on the same topic is presented in Section II. The methodology and control methods used for hourly dispatching of WEC power are described in Section III. Section IV verifies the effectiveness of the proposed methodology and control methods through simulations. Finally, conclusions of this research are summarized in Section V.

II. STATE-OF-THE-ART REVIEW

A previous study [5] presents the sizing of SC energy storage for smoothing the direct-drive wave energy converter power generation. The authors used the SC as an energy storage system because of its high cycling capability and better alignment with the WEC constraints. The sea state was considered to always be the same (i.e., wave height 3 m, wave period 8 s), and the SC state of charge was regulated within a SOC range while exploiting the SC sizing for smoothing the WEC power generation. In addition, the output set point power that means the grid reference power is always assumed constant for the entire duration (i.e., 2 hours are considered). Because the absolute difference between the instantaneous WEC production and the grid reference power determines the required energy storage size, this kind of hypothesis might lead to increase the required energy storage size for this application.

In [6], a control strategy was introduced to mitigate the inherent natural power fluctuations of wave generation systems using SC as an energy storage system. The purpose of using SC is to smooth WEC power fluctuations to regulate the injected grid power. We used the sizing methodology for SC to ensure that the grid- injected power remained constant during the observation interval (i.e., a 30-minute observation interval was considered). The resulting SC size might not be compatible with the weight and dimension constraints of the embedded floating buoy generation system. As a result, an acceptable trade-off between the system performances, which is measured in terms of power fluctuation reduction, and its physical feasibility needs to be considered.

T. Kovaltchouk et al. utilized an aging model for SC that considers both cycling aging and calendar aging in SC life cycle cost analysis [7]. The authors implemented this aging model in the SC sizing for smoothing the WEC output power to satisfy the grid flicker constraint. Using this technique to filter WEC power while ensuring a limited voltage range might result in the total number of cycles required for SC being very high. Consequently, this phenomenon might affect total SC cost.

In [8], an aging-aware life cycle cost comparison between the battery and SC to smooth WEC power was investigated. The authors compare the performance of two energy storage technologies to determine which energy storage system exhibits the lowest life cycle cost for smoothing the WEC power with a flicker constraint. The authors found that the life cycle cost of SC is less expensive than Li-ion batteries for this application. However, the authors did not attempt to find the optimum DOD for the battery and SC. Because the life cycle cost of ESS depends on the usage of its DOD, this factor needs to be considered during an energy storage cost comparison investigation. It is important to note that none of the previously mentioned studies investigated the capability of dispatching with WEC power.

III. PROPOSED METHODOLOGY

A. System Topology

The topology of the wave energy converter system (WECS) with ESS is shown in Fig. 1. The WEC system comprises a slider-crank wave energy converter, AC synchronous generator rated at 149.2 kW, a gearbox, and an AC/DC rectifier. Because the frequency of real ocean waves is usually low (i.e., between 1/6 Hz and 1/10 Hz), a gearbox is needed between the slider crank and the generator to operate the generator around its nominal speed range.

The ESS in consideration, which is either Li-ion battery or SC, is connected in parallel with the WECS, and a bidirectional DC/DC converter is associated with the energy storage bank. The WECS and ESS are connected in parallel to the DC-link capacitor that serves as the DC bus, and the inverter is used to control the voltage level at the DC link. In this scheme, the WECS and ESS are connected to the DC bus as a current source, and the inverter controls the DC bus voltage. Therefore, controllable power flow is feasible by controlling the current flow through the DC/DC converters [9].

B. Determination of Dispatch Power Reference

In this study, we adopted a novel slider-crank power-take-off system for converting ocean wave energy into electrical energy presented in [10]. In this framework, the heave motion of ocean waves is converted into rotational motion via a slider-crank mechanism. Normally, an irregular wave comprises several regular sinusoidal waves with different amplitudes, angular velocities, and phases. In this research, the excitation force is calculated from irregular waves generated through the Joint North Sea Wave Project (JONSWAP) spectrum. The actual significant wave heights and the peak periods of irregular waves recorded at the National Oceanic and Atmospheric Administration (NOAA) on March 30, 2020, [11] are used to calculate the wave excitation force by the method proposed in [12]. After this, wave excitation force is utilized to determine the WECS electrical power production that is used to predict the dispatched power level on an hourly basis for a specific duration (12 hours is assumed). The predicted dispatched power on an hourly basis is referred to as the grid reference power ($P_{Grid,ref}$), which is calculated by estimating the average electrical power that the WECS is capable of providing over each dispatching period, and acts as a target power level for the entire system. Therefore, the WECS and ESS are responsible for supplying this target power to the utility grid for the entire duration for each hourly dispatching period.

C. Control of ESS

In this study, we implemented the ESS control framework shown in Fig. 2. In this scheme, the ESS is responsible for maintaining the system's power injected into the utility grid and the grid-side inverter is responsible for keeping up a stable DC bus voltage. The reference power for the ESS ($P_{ESS,ref}$) is the difference between the grid reference power and WECS output power, which is expressed as:

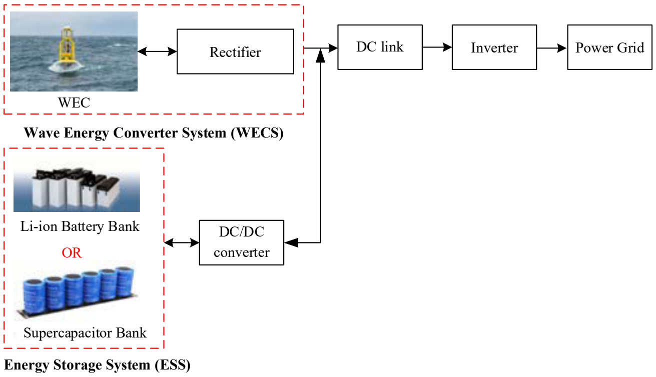

Figure 1. Structure of the wave energy converter system with ESS.

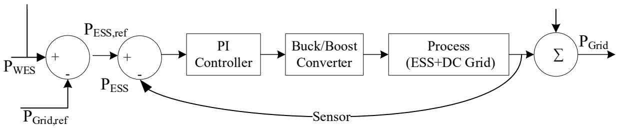

Figure 2. ESS power control framework.

$$P_{ESS,ref} = P_{Grid,ref} - P_{WECS} \qquad (1)$$

The reference signal for the ESS is compared with its instantaneous value (P_{ESS}) to determine the duty ratio for the associated power converter. In this study, we employed a proportional integral (PI) controller to decide whether to increase or decrease the duty ratio, and to mitigate the proportional error and integral error of the system.

It is important to seek the proper value of proportional gain constant (K_P) and integral gain constant (K_i) for the ESS converter where the system exhibits minimum overshoot and a quick settling time. Two different kinds of energy storage systems are considered in this study: battery energy storage system (BESS), and supercapacitors energy storage system (SESS). Through manual tuning and observing the response of the converter, the optimum performance is found for the BESS PI controller when K_P is equal to 1×10^{-6}, and K_i is equal to 6×10^{-4}. Likewise, the optimum performance is found for the SESS PI controller when K_P is equal to 1×10^{-6}, and K_i is equal to 1×10^{-4}.

D. Sizing of ESS

In order to ensure that the ESS can accommodate the amount of energy that it has to be charged or discharged, we must evaluate the minimum capacity required for the ESS. The minimum capacity required for the battery and SC is determined through integrating the power profile of the battery and SC over each dispatching period. First, the absolute maximum amount of energy used by the battery is calculated by integrating the battery power curve over each dispatching period and then comparing it to the other dispatching period's maximum energy needed for the battery. Next, (2) is used to calculate the minimum capacity required for the battery to successfully dispatch the WECS power to the utility grid at 1-hour increments for the entire duration.

$$C_{BESS} = \frac{E_{sj}}{DOD_{max}} \qquad (2)$$

where, E_{sj} is the total energy discharged or charged (whichever is greater) over the simulation period, and DOD_{max} is the maximum depth of discharge used by the energy storage system.

In a similar mechanism, the maximum energy utilized by the SC is calculated. Then, (3) is used to calculate the required SC size.

$$E = \frac{1}{2} CV^2 \tag{3}$$

where E is the energy measured in Joules, C is the super capacitor's capacitance measured in Farads, and V is the supercapacitor's voltage measured in volts.

E. Cost Optimization for ESS

As indicated earlier, the service life of an ESS mainly depends on the usage of DOD and the rate of change of the charging-discharging power. The relationship between the cycle life and the usage of DOD is approximately exponential [13] and for the Li-ion battery it can be fitted as:

$$C_i = 28270\, e^{(-2.401 DOD_i)} + 2.214\, e^{(5.901 DOD_i)} \tag{4}$$

where Ci is the number of cycles when the depth of discharge is DOD_i. The relationship between DOD and cycle life calculated using (4) is shown in Fig. 3.

As mentioned earlier, the cost associated with an ESS primarily depends on two aspects: lifetime and minimum capacity required. Equation (2) shows that the minimum required capacity for a BESS is inversely proportional to the usage of its DOD. On the other hand, the deeper discharge of a BESS reduces its service life, as shown in Fig. 3. Therefore, in this study, to find the proper value of DOD that exhibits the least cost (\$/kWh) BESS for dispatching the power of the WECS, we ran the simulations in way that considers every possible value of BESS DOD. In a similar mechanism, we investigated the optimum value of DOD for SC. Unlike the Li-ion battery, SC can be charged and discharged an unlimited number of times. Thus, the total of charging-discharging cycles for the SC is assumed constant (i.e., 500,000) in this study [14].

F. Cost Optimization for ESS

1) ESS Cycling Cost: Because of the highly variable nature of WEC output power, the charging-discharging cycles of energy storage are irregular in this case. Therefore, the service life of the energy storage is estimated using the charging-discharging characteristics of ESS over a period. The equivalent service cycle life ($C_{B,T}$) of the battery over the period, T_S, is calculated using (5).

$$C_{B,T} = \sum_{j \in T_s} \frac{E_{sj}}{E_{sr}} \tag{5}$$

where E_{sj} is the total energy discharged or charged (whichever is greater) over the simulation period, T_s, and E_{sr} is the battery's rated energy capacity multiplied by the DOD and a correction factor to derate the manufacturer's data (a correction factor of 0.8 is assumed in this study) [15].

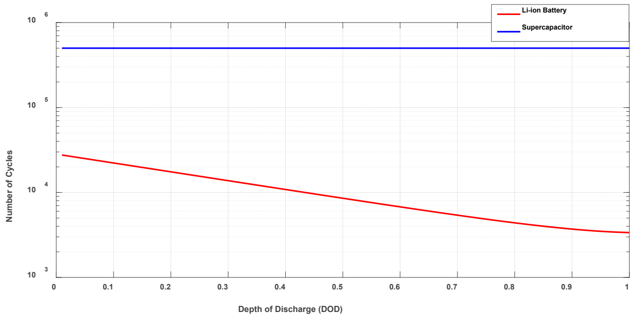

Fig. 3. The relationship between DOD and cycle life.

Then, the expected lifetime of the battery, $E|L_B|$, is calculated by using:

$$E|L_B| = \frac{C_{B,n}}{C_{B,T}} \times T_s \tag{6}$$

where $C_{B,n}$ is the life cycle of the battery provided by the manufacturers.

Thus, the cycling cost of the battery ($C_{Bat,cycle}$) can be expressed by:

$$C_{Bat,cycle} = \frac{E_B \times C_B}{E|L_B|} \tag{7}$$

where E_B is the battery capacity (kWh) and C_B is the battery cost (\$/kWh).

In a similar way, we calculate the expected lifetime ($E|L_S|$) and the cycling cost ($C_{SC,cycle}$) of the SC.

2) ESS Calendar Aging Cost: In order to consider the calendar aging cost for battery usage, we adopted a degradation model [16] of the battery in this study. The calendar aging cost of the battery ($C_{Bat,calendar}$) considering its DOD usage and the initial cost is calculated as:

$$C_{Bat,calendar} = \frac{C_B}{C_{B,n} \times 2 \times DOD \times E_B \times m^2} \tag{8}$$

where m is the efficiency of the battery that was assumed to be 92% for a Li-ion battery.

We incorporated the SC aging model proposed in [7] to calculate the SC calendar aging cost. The expected lifetime of the SC $E|L_S|$ decreases because of its degradation properties over the period, which can be expressed as:

$$\frac{1}{T_{life}} = \frac{1}{E|L_S|} \times \left(e^{\left(\ln(2) \frac{\theta_c - \theta_c^{ref}}{\theta_0} \right)} \right) \times \left[\left(e^{\left(\ln(2) \frac{V - V^{ref}}{V_0} \right)} \right) + K \right] \tag{9}$$

where θ_0, θ_c^{ref}, V_0, V^{ref}, and K are aging parameters described in [7].

Thus, the calendar aging cost of the SC ($C_{SC,calendar}$) considering the initial capacity and the initial cost of SC is calculated as:

$$C_{SC,calendar} = \frac{E_S \times C_S}{T_{life}} \tag{10}$$

where E_S is the SC capacity (kWh), C_S is the SC cost (\$/kWh), and T_{life} is the SC service life degradation caused by aging.

After calculating the cycling and the calendar aging cost of the ESS, the total cost associated with the battery and SC can be expressed as:

$$C_{Bat,total} = C_{Bat,cycle} + C_{Bat,calendar} \quad (11)$$

$$C_{SC,total} = C_{SC,cycle} + C_{SC,calendar} \quad (12)$$

Therefore, the normalized battery and SC cost (\$/kWh) can be calculated using (13) and (14), respectively. After obtaining the battery and SC cost per kWh, the associated cost with the ESS is also increased by 10% to account for operation and maintenance as well as power converter costs.

$$Bat_{cost,norm}\left(\frac{\$}{kWh}\right) = \frac{C_{Bat,total}}{P_{WEC} \times WEC_{CF} \times T} \quad (13)$$

$$SC_{cost,norm}\left(\frac{\$}{kWh}\right) = \frac{C_{SC,total}}{P_{WEC} \times WEC_{CF} \times T} \quad (14)$$

where P_{WEC} is the wave energy converter capacity (kW), WEC_{CF} is the WEC capacity factor (30% is assumed in this study), and T is the number of hours in a year. The unit price of the Li-ion battery and SC are 271 \$/kWh and 2500 \$/kWh, respectively, to calculate the price of the energy storage system.

IV. SIMULATION RESULTS

In this research, we conducted simulations in the MATLAB/Simulink environment. Wave excitation force is calculated with MATLAB and imported into the Simulink model. In order to evaluate the performance and economic assessment of the ESS framework, we derived two cases of excitation force data from randomly generated irregular waves through the JONSWAP spectrum. The significant wave heights and peak periods of irregular waves recorded at NOAA on March 30, 2020 (i.e., average values of wave heights in meters [1.3, 1.1, 1.1, 1, 1, 1.1, 1, 1, 1, 1, 1, 1] and average values of wave peak periods in seconds [6, 6, 6, 7, 7, 6, 7, 7, 6, 6, 7, 7]) on an hourly basis from 12 a.m. to 12 p.m. were used to calculate the excitation force data. Therefore, WEC electrical power production can vary at different points of time even though the same wave height and peak period of irregular waves are used to generate the wave excitation force data.

As indicated earlier, we examined two cases of excitation force data to validate the ESS performance for hourly dispatching the WEC system's power to the grid. The power profiles of the WEC system, BESS, P_{Grid}, and $P_{Grid,ref}$ for case 1 are shown in Fig. 4. Here, the actual dispatched grid power (P_{Grid}) is the combination of the power of the WECS and BESS, and an inverter injects this power into the utility grid. The grid reference power ($P_{Grid,ref}$) is used as a target power level for the WECS and BESS to provide to the utility grid. As shown in Fig. 4, the power injected into the grid (P_{Grid}) remains constant in each dispatching period and successfully follows the grid reference power ($P_{Grid,ref}$). Therefore, it can be concluded that the ESS successfully absorbs or supplies the necessary power to provide constant power to the utility at a 1-hour dispatching period for an entire duration from the highly variable WECS framework. Fig. 5 shows the simulation results for case 2 and reveals that P_{Grid} remains constant in each dispatching period and successfully follows $P_{Grid,ref}$ as well. Moreover, when the SC is incorporated instead of the BESS as an energy storage system in the ESS framework, it exhibits a similar phenomenon to provide constant power on an hourly basis to the utility grid for both cases considered in this study.

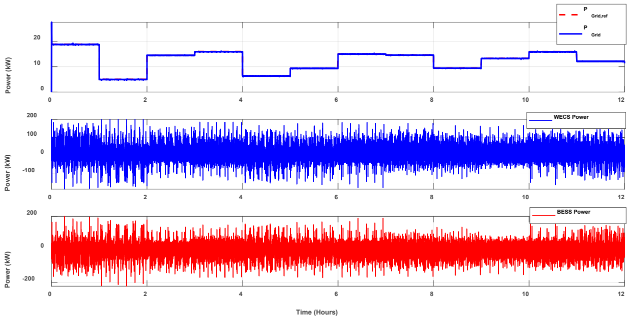

Fig. 4. Case 1: Simulation results for 1-hour dispatching.

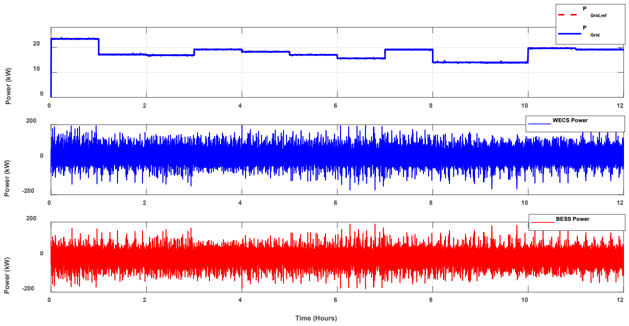

Fig. 5. Case 2: Simulation results for 1-hour dispatching.

In order to seek the optimum value of DOD that exhibits the least cost (\$/kWh) of BESS for hourly dispatching the power of the WECS, we ran the simulations considering every possible value of the BESS DOD. The BESS cost per kWh as a function of its usage of DOD is shown in Fig. 6. From Fig. 6, the optimum value of the BESS DOD that exhibits the minimum cost is found at 42% DOD for both cases. At 42% DOD, the minimum cost of BESS is found to be nearly the same (i.e., 3.17 cents/kWh for case 1, and 3.32 cents/kWh for case 2).

The SESS cost per kWh as a function of its usage of DOD is shown in Fig. 7. We observed that the full utilization of the SC exhibits the least cost for both cases. The cost associated with the ESS is directly proportional to the ESS capacity and is inversely proportional to the service life of the ESS. As shown in Fig. 3, the total number of charging-discharging cycles of the SC as a function of its DOD usage remained constant because the SC can be charged and discharged a virtually unlimited number of times. Also, the capacity required for the SC becomes minimum when it is fully utilized. Consequently, at a 100% DOD, the SC shows the least cost for both cases. Further, the minimum cost of the SESS is also found to be nearly the same (i.e., 1.21 cents/kWh for case 1 and 1.27 cents/kWh for case 2). Specifically, the energy storage cost as a function of its DOD usage in the range between 10% to 100% is shown in Fig. 6 and Fig. 7.

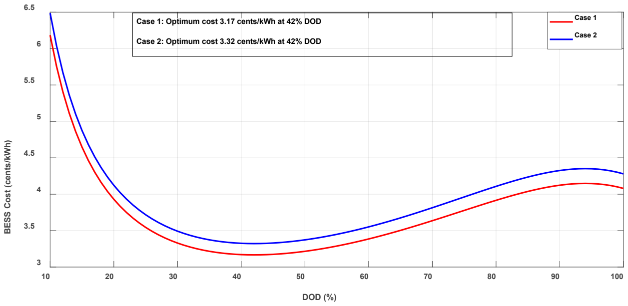

Fig. 6. BESS cost (¢/kWh) at different DOD levels.

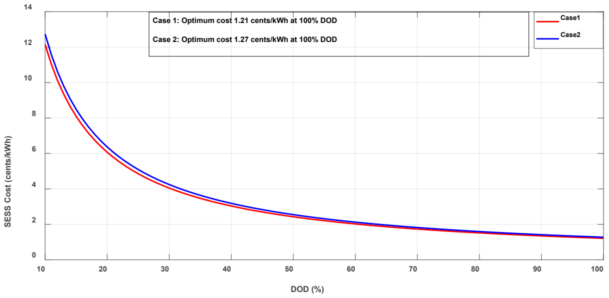

Fig. 7. SESS cost (¢/kWh) at different DOD levels.

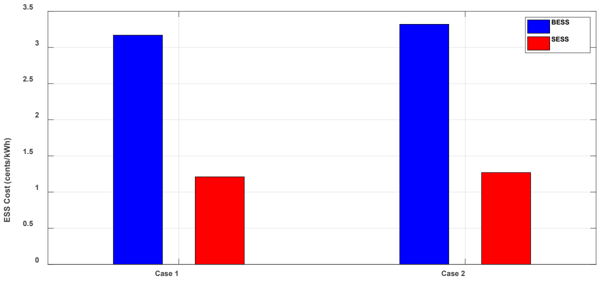

Fig. 8. ESS cost comparison (¢/kWh) at optimum DOD.

In order to seek the most economical ESS for hourly dispatching the power of the WECS, economic comparison of using two different types of energy storage systems is presented in Fig. 8. The SESS unit cost for cents/kWh is clearly smaller than the BESS for hourly dispatching the WECS's power to the utility grid. It is also noticeable that the energy storage system cost can be reduced by approximately 61% by using the SC instead of the Li-ion battery for this application. Fig. 8 validates this fact.

The percentage of error between the actual dispatched grid power (P_{Grid}) and the grid reference power ($P_{Grid,ref}$) is calculated to quantify the power quality criteria. The histogram of this percentage of error is shown in Fig. 9. Because P_{Grid} successfully tracks the desired grid reference power ($P_{Grid,ref}$) closely in each dispatching period, the undesired deviation is found to be extremely low for both cases. It also indicates the effectiveness of dispatchability provided by the WECS and ESS framework.

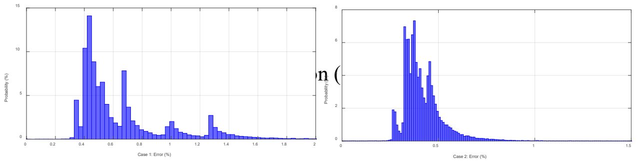

Fig. 9. Histogram of hourly dispatching error results.

V. CONCLUDING REMARKS

In this study, we demonstrated that WEC power can be successfully dispatched on an hourly basis at an error of less than 1% most of the time. Therefore, by using the ESS control method presented in this research, wave energy converters can be used as a reliable source of power to afford the base load demand in the utility.

The cost optimization of the ESS is one of the catalysts for the fast growth of renewable energy generation in the world. In this paper, the energy storage life cycle cost is optimized as a function of its DOD usage. Moreover, we investigated an economic comparison between an Li-ion battery and SC to develop the most cost-effective energy storage system for hourly dispatching WEC power. We found the SC to be less costly than the Li-ion battery for this application. In future studies, more in-depth analysis with SC characteristics will be considered. Also, longer wave duration data will be utilized for more comprehensive analysis.

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