Citation for published version:
Nie, Z, Xiao, X, Kang, Q, Aggarwal, R, Zhang, H & Yuan, W 2013, 'SMES-battery energy storage system for conditioning outputs from direct drive linear wave energy converters', IEEE Transactions on Applied Superconductivity, vol. 23, no. 3, 5000705. https://doi.org/10.1109/TASC.2013.2246852

DOI:
10.1109/TASC.2013.2246852

Publication date:
2013

Document Version
Peer reviewed version

Link to publication

SMES-Battery Energy Storage System for Conditioning Outputs from Direct Drive Linear Wave Energy Converters

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***Abstract*—The power from direct drive linear wave energy converter (DDLWEC) consists of frequent power fluctuations and long term power fluctuations due to oceanic conditions. A 60 kJ SMES is designed to work in conjunction with batteries as a hybrid energy storage system for conditioning the outputs from DDLWECs. The issues of the intrinsic power fluctuations of DDLWECs and the intermittent power generation are both addressed by the hybrid energy storage system.**

***Index Terms*—SMES magnet, hybrid energy storage, wave energy converter，renewable energy**

I. INTRODUCTION

A VARIETY of energy storage technologies have been suggested to work in conjunction with renewable energies including superconducting magnetic energy storage (SMES), super capacitor storage, batteries, etc.. These energy storage devices have their own characteristics as summarized [1, 2]. Super capacitor system and SMES could compete with each others as they have similar merits in long life cycle, high power density and fast responding abilities.

The rated voltage of a single cell of super capacitor is normally confined to the range of 2.5-3 V. Multiple capacitor units are connected in series for achieving higher voltages. The series connection reduces the total capacitance, and protection circuits are required for voltage balancing to prevent any cell from going into over-voltage. The number of series connected cells and their voltage balancing technologies define the overall rated voltage of super capacitor which is limited to a certain value. Step-up and step-down voltage conversions are generally required for regulating super capacitor's output voltage to an appropriate level before connecting to power system.

The step-up or step-down interface circuits of super capacitors could potentially cause voltage ripples in the power system as analyzed in [4]. The terminal voltage of a super capacitor is in proportional to its stored energy, which varies during charge and discharge process. Super capacitors with larger capacitance could achieve in a smaller rate of voltage/energy variations. Nevertheless, the step-up and step-down processes are relied upon the charge/discharge of an extra inductor (like the one in boost or buck converters). Once the energy stored in a super capacitor is low, its terminal voltage is low. Either a relatively larger inductor or longer charge/discharge cycles are required in the interface circuits for regulating the low terminal voltages of super capacitors to an appropriate level. Hence, the interface circuit of super capacitors could results in the following drawbacks: the extra inductor associates with extra loss, the responding speed of super capacitors could be delayed due to the step-up or step-down operations of the interface circuit; voltage ripples could be caused by inappropriate control of the interface circuit. In a contrast, the interface circuit of SMES does not incorporated with any step-up or step-down converters, its control is relatively simple and the abilities of SMES could be fully utilized in control systems.

Preliminary surveys show that marine wave power is a vast and largely untapped source of energy and has a potential to supply a significant part of our future energy needs [3]. Direct drive linear wave energy converter (DDLWEC) is one of the most promising technologies for harnessing waves for electricity generation [3]. The generated electrical power from DDLWECs represents EMF waveforms with varying frequency and amplitude; and this waveforms feature a high perk to RMS ratio due to the extracted power periodically drop to zero with a frequency twice the ocean wave frequency. The large power drop results in large fluctuations of power outputs from DDLWEC，which caused by the driving ocean waves with periods normally from seconds to ten's seconds. Moreover, the same to other renewable energy like wind and solar, the power available for extraction in wave energy converters varies dramatically with the environmental change which may varies in minutes or hours. DDLWECs output fluctuate and intermittent powers which are considered as low quality electricity sources. The output powers from DDLWECs are required to be well conditioned to a stable and continuous form of electricity before connecting to the power grid or local load.

A 60 kJ SMES was designed to handle the frequent power fluctuation caused by a particular DDLWEC in each wave period. This paper proposes a hybrid energy storage system SEMS-Battery to handle both the frequent power fluctuation and the long term power fluctuation caused by the variation of see state. The ultimate aim is to condition the output power from DDLWEC into a stable form of electricity and make this power transmittable to the grid or local load.

II. A HYBRID ENERGY STORAGE SYSTEM FOR DDLWEC

The power conversion train of DDLWECs could be AC to

Manuscript received 08 October 2012. This research is supported by grants from the Power Electronics Science and Education Development Program of Delta Environmental & Educational Foundation, and National Natural Science Foundation (51177084，50823001).

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DC conversion then DC to AC conversion for ultimate connection to the grid, or could be AC to DC conversion then DC to DC conversion for high voltage DC transmission (HVDC). The dc link bus after the first AC/DC conversion provides a suitable location for energy storage necessary as a buffer to smooth the system power flow from a single wave energy converter (or aggregation from multiple DDLWECs).

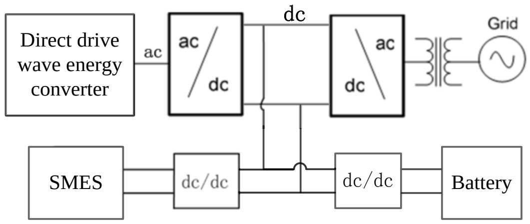

Figure 1: A micro-grid system of DDWECs and a composite energy storage

Battery is characterized with high energy density, and it can be used to smooth out the long term power fluctuations of DDLWECs up to hours. However, batteries have drawbacks in limited life cycle and relatively small power density. SMES could was chosen to assist batteries to handle the frequent power fluctuation from DDLWECs, and hence could extent the service life of battery and reduce the required capacity of battery.

A. Designing a SMES for DDLWEC

Ocean wave motion can be assumed as a sinusoidal $x(t)$ with amplitude A and period T as shown in equation (1). The maximum mechanical power of a DDLWEC can be determined by the thrust force F of the generator multiplied by the velocity of the translator of the machine as expressed in equation (2). The envelop of the power output waveforms from DDLWEC fluctuates with a frequency twice the ocean wave frequency. The SMES is controlled to absorb or release energy to handle the fluctuations as expressed by Figure 2. Hence, the energy capacity of SMES required to handle the electrical power fluctuation within a wave cycle could be evaluated by equation (3). Where a is the machine conversion efficiency between the mechanical power and electrical power. The capacity of SMES is suppose to be large than the integration of power differences between the instantaneous power and average power of DDLWEC over the period $T/4$.

$$x(t) = A\sin(\omega \cdot t) \tag{1}$$

$$\hat{P}_M = F \cdot x'(t) = F \cdot (d(x)/dt) \tag{2}$$

$$E_{SMES} = \int_0^{T/4} a \cdot \hat{P}_M \cdot \left[\cos(\omega \cdot t)\sin(\omega \cdot t + \alpha) - 1/2\right] dt \tag{3}$$

The ocean waves, having periods within 3 to 20 seconds, normally have the feasibility and potential for driving DDLWECs to generate electricity. A SMES with 60 kJ is capable of handling the power fluctuations of a 5 kW rated DDLWEC over one wave period, and allows some storage merging for the flexibility of system operations.

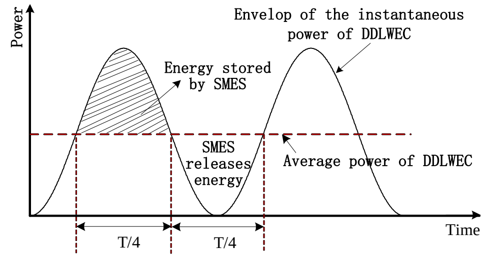

Figure 2: Energy capacity of SMES

The coil inductance of a SMES can be deduced from equation (4).

$$E_{SMES} = \frac{1}{2} L i^2 \tag{4}$$

The 2G HTS is a state-of-the-art conductor with a significantly higher irreversibility field and critical current density in an external magnetic field than 1G HTS and LTS, thus 2G HTS SMES systems will have significantly higher energy and power densities [5]. They can operate either with liquid nitrogen, gas helium, or off-the-shelf commercial cryocoolers, thereby eliminating the requirement of expensive liquid helium. Over the past decade, the 2G HTS has been significantly developed in terms of substantially increased critical current density and irreversibility field, together with a projected cost in terms of dollar per kiloamp-meter ($/kA·m) lower than 1G HTS and copper in the future. To design the magnet component of the SMES, the 2G HTS YBCO tape SC4050, produced by SuperPower, was adopted.

Global optimization algorithm is incorporated into COMSOL Multiphysics package and Matlab [6]. When the total length, inner radius and the number of pancakes are set, one configuration of magnet is achieved. Applying current density to the section area, the electromagnetic field is calculated. Incorporate the $Ic(B)$ dependence of magnetic flux density in parallel and perpendicular direction, achieve the max current. Then a table of stored energies with different configurations is produced. Thus, optimal configuration is finally selected with the least length of YBCO tape, which is shown in Figure 3 and Table 1.

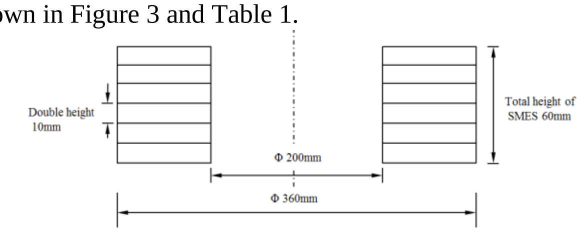

Figure 3: Schematic double pancake coil

Since the current running through HTS is considerable large, Lorentz force should be analyzed to assure the stability of the SMES device. The mechanical force field is checked in COMSOL which is powerful to solve multi physical fields. In our design, we need to solve the coupled electromagnetic field and mechanical field.

The 60 kJ SMES was designed with 24.5 H inductance and allowing 70 A maximum currents. The SMES is based on double-pancake structure and it was optimized to the smallest size. The design steps of this SMES are described in detail in a collaborating paper.

Table 1: Design specification of HTS magnet for 60 kJ SMES

Parameter	Quantity
Conductor length	8200m
Number of double pancake	6
Total Height	60mm
Total Turns	7800
Inductance	24.5H
Operation current	70A

B. Control Topologies to the Hybrid Energy Storage System

SMES is a superconducting coil that stores energy in the magnetic field generated by DC current flowing through it. Thus it is essentially an inductance. SMES is capable of absorbing or releasing power from power system with fast responding time.

The interface circuit controls the energy exchange between SMES and the Shared DC link as shown in Figure 4(a). This interface circuit requires 2 IGBTs, 2 fast diodes and an output capacitor C. The interface circuit can be operated in three different modes: charge mode, discharge mode and standby mode as shown respectively from Figure 4(b)-4(d). In the charge mode of SMES, Z1 and Z2 are turned on; SMES is controlled to charge up and absorbing redundant power from the power system. In the discharge mode, Z1 and Z2 are off and D1 and D2 are forward biased; the SMES is controlled to release power for meeting the system's power demand. Figure 4(d) shows the current path of SMES in the standby mode, Z2 is turned on and D2 is forward biased in this mode.

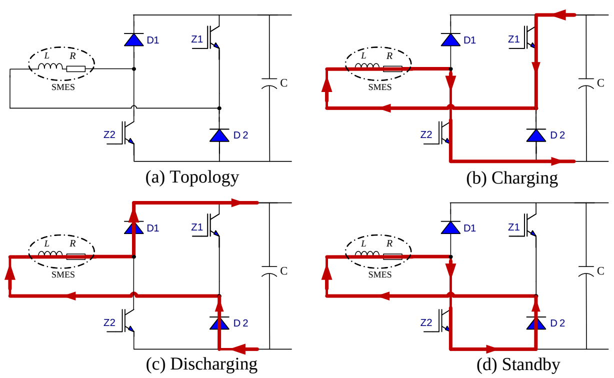

Figure 4: The interface circuit topology of SMES and its current paths in different states

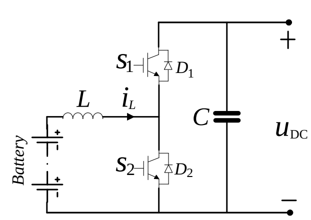

Figure 5: Interface circuit for battery

A DC/DC topology shown in Figure 2 has been widely used as the interface circuit for connecting batteries to power systems. When the battery is in discharging mode, L, S_2 and D_1 are operated as a boost converter. When the battery is in charging mode, L、S_1 and D_2 are operated as a buck converter. Apart from semiconductor devices, an extra inductor is required for both boost and buck operations.

C. Control Methods to the Hybrid Energy Storage System

The blocks shown in Figure 6 represent the control method for an interface circuit that connects the SMES with the DC Link. The outer control loop maintains the DC link voltage to a desired value u_{ref}. The inner control loop improves the ability of current response of the system. The DC link voltage u_{DC} is taken as the feedback signal u_{fd} and subtracted from the desired DC link voltage u_{ref}. This results an error signal which is then adjusted by a proportional and integral controller (PI). A reference signal i_{ref} is therefore obtained from the outer loop, and used to generate PWM signals for controlling the SMES current i_{SMES}. The energy stored in SMES is proportional to the continuous current carried by SMES. The current flow as well as power flow of SMES is controlled to maintain the DC link voltage at a stable value. When the DC link voltage is higher than the desired reference value u_{ref}, the SMES turns to charge mode and instantly absorbs the excessive power, stopping the increment of DC link voltage. When the DC link voltage is lower than the desired reference value u_{ref}, the SMES turns to discharge mode and instantly supplies power to maintain the DC link voltage.

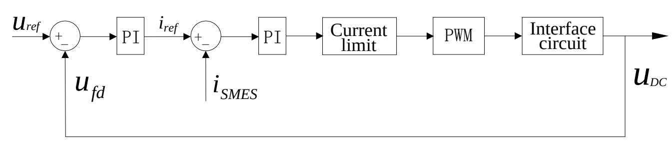

Figure 6: Controls to the interface circuit of SMES

The interface circuit of battery shown in Figure 5 can be operated in two different modes: charge mode and discharge mode. In the discharge mode, L, S_2 and D_1 are operated as a boost converter, inductor L stores energy when S_2 is turned on, both the energy storage device and L release energy to the DC link via D_1 when S_2 is off. In the charge mode, L、S_1 and D_2 are operated as a buck converter, and the energy storage device is controlled to store the redundant power from the DC link.

The DC link voltage in the system shown in Figure 1 can be analysis into AC and DC components. Since the power density of battery is relatively low, the SMES system can be used to handle the instant fluctuation part of the power generated by DDLWECs or the AC components of the DC link voltage. The system shown in Figure 1 is supposed to output a stable and continuous power P_G to the grid or local load in a time scope of hours.

The available wave power, that is ready for extraction from the ocean, can be predicted from the weathercast over a certain time. Hence, the output power generated from a DDLWEC can be evaluated for some particular waves. The high frequency components of power output from DDLWECs can be removed by low pass filter or running average filters, and this remains the DC or average power components $P_w(t)$ with slow variations.

Referring to equation (5), the difference between $P_W(t)$ and the P_G is handled by the battery. When $P_E(t)$ is positive, the battery turns to charge mode and absorbs the redundant power generated by DDLWECs via controlling the Dc/Dc converter shown in Figure 5. When $P_E(t)$ is negative, the battery turns to discharge mode and injects power to the DC link for maintaining a stable DC voltage and constant output power P_G. The control block of the interface circuit for battery is shown in Figure 6.

$$P_E(t) = P_W(t) - P_G \tag{5}$$

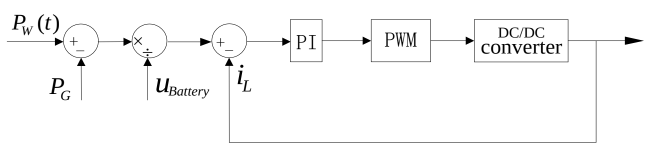

Figure 6: Controls to the interface circuit of battery

The energy capacity of battery is selected to handle P_E, the difference between P_G and $P_W(t)$, at a specific location over a certain time. Taking the integration P_E over time *t* gives the maximum energy E_{batt} that needs to be stored by the battery. Actual wave data of a specific location over a certain time are required to calculate the actual required capacity of batteries in the system. In this paper, a Li-ion battery module with 15 AH ($\text{Amps}\cdot\text{Hour}$) and 51.2 V terminal voltage was selected in the simulation for handling the power fluctuations of the 5 kW rated DDLWEC driven by multiple waves with various power potentials.

III. Simulation Results and Discussions

DDLWECs generate AC power with varied frequency and amplitude. The EMF waveforms shown in Figure 7 are simulated for a particular DDLWEC driven with waves of 5 seconds period and 0.8 meter amplitude followed by waves with 1.2 meter amplitude. The 0.8 meter and 1.2 meter waves could drive the DDLWEC outputting average powers of 230 W and 760 W respectively. The DC link voltage is maintained at a stable value of 425 V as shown in Figure 7. In other words, a constant power of 500 W was delivered to the grid or local load nevertheless the power of DDLWEC is fluctuating.

The SMES-battery system is controlled to absorb or release power to the DC link. The positive values in Figure 8 and Figure 9 show that the SMES and battery devices are releasing power to the DC link for meeting the load demand, when the DDLWEC is generating power less than the load demand in this time interval. The negative values in the pictures show that the SMES and battery devices are absorbing power, as the DDLWEC is generating excessive power. The battery handles the slow varying power fluctuations of DDLWECs caused by different ocean waves. The battery charges and discharges slowly, and does not frequently change charge and discharge states as can be seen in Figure 9. This could significantly extend the service life of battery.

As shown in Figure 10, the SMES frequently changes its states between charge and discharge for handling any instantaneous power or voltage fluctuations in the DC link and ensuring a constant DC link voltage. The responding speed of SMES is fast and only depends upon the switches' speed in the interface circuit. The carrying current of SMES decreases as the SMES is releasing energy; and the SMES current increases as it is absorbing energy as shown in Figure 11.

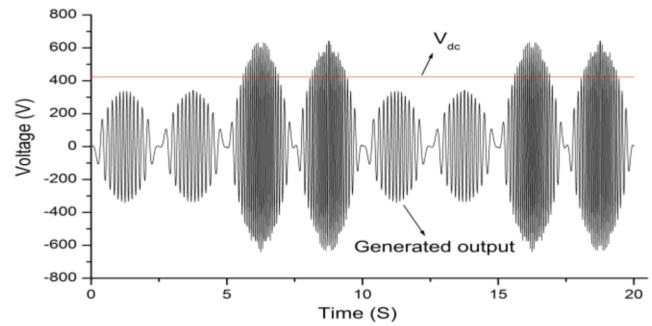

Figure 7: Generated EMFs of DDLWEC and the maintained DC link voltage by SMES-battery system

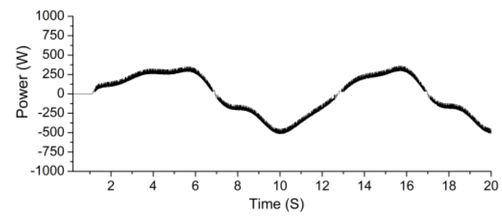

Figure 8: The battery releases or absorbs power

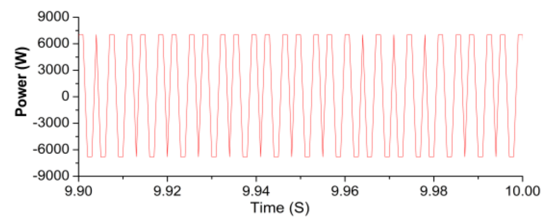

Figure 9: The SMES releases or absorbs power

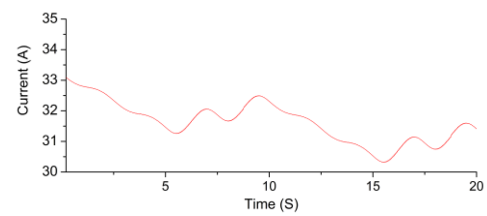

Figure 10: The carrying current of SMES

IV. Conclusions

A 60 kJ SMES is designed to work in conjunction with batteries as a hybrid energy storage system for conditioning the outputs from direct drive linear wave energy converters (DDLWEC). Simulation results have shown that the proposed hybrid energy storage SMES-battery system can successfully addressing the both the frequent and slow varying power fluctuations from DDLWECs and maintaining stable and dispatch-able electrical power to the grid or local load. The hybrid system combines the benefits of SMES and battery, and controls the two various energy storage types to cover the drawbacks of each others.

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