Analysis and Control of Battery Energy Storage System to Support Ice Thermal Energy Storage System in Green Buildings

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***Abstract*—This paper investigates and analyses additional service revenues and incremental net benefit/loss in using battery energy storage system to support ice thermal energy storage system in green buildings in the context of Singapore. In addition to the main service of air cooling, the hybrid energy storage system provides additional services as in grid-scale applications and behind-the-meter applications. A real-time control strategy is proposed to perform frequency regulation, as a grid-scale application, with specific requirements in the wholesale electricity market in Singapore.**

Keywords*—*battery energy storage system, thermal energy storage system, frequency regulation, incremental net benefit

I. Introduction

Green buildings nowadays are often equipped with thermal energy storage system (TESS) to support its heat, ventilation and air cooling (HVAC) loads. In addition, due to the declining cost of energy storage, e.g. lithium-ion batteries, the increasing integration of renewable energy, e.g. solar PV and wind, and the requirement of emergency power backup, battery energy storage system (BESS) has also been installed for these buildings with proper design consideration and capacity sizing. It is obvious that synergy of TESS and BESS, which forms a hybrid energy storage system (HESS), can generate additional service revenues for operators of the green buildings. To date, the available services in the context of smart grid and smart energy world-wide mainly include contingency reserves and frequency regulation for grid-scale applications, and peak shaving, demand charge reduction, peak clipping, and power quality improvement for behind-the-meter applications [1]. Moreover, BESS can also help to enhance the dynamic stability of the system by compensation of dynamics power with fast charging and discharging power of BESS during the slow switching of TESS. Although multiple additional revenue streams can be exploited as aforementioned, the incremental net benefit of incorporating BESS still requires assessment in terms of overall profitability and economic viability throughout the lifetime of the system, e.g. as in [1, 2]. In this work, because green buildings are assumed to be already equipped with TESS, the incremental net benefit of the system as a whole is considered as the balance between (a) additional capital and operating costs introduced by BESS and (b) the increased energy savings and extra revenues gained by the new services.

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In Singapore, green buildings have been widely and supportively encouraged by Building Construction Authority (BCA) and Singapore Green Building Council (SGBC) for being more eco-friendly and more energy-efficient with smart control systems. As commercial and residential buildings account for about 25% of all emissions and about 32% of electricity consumption in Singapore, there also have been incentives from public agencies such as Energy Market Authority (EMA) and Housing Development Board (HDB) to increase the installation and adoption of low-carbon technologies, for example, solar PV energy, energy storage, combined heat/cooling power, and so on, into the buildings. These agencies regulate electricity and building-related services through market rules, industry standards and certifications, which include several important requirements, such as cost and cyber security, to be considered in this research.

Among new services that BESS offers to smart grid, frequency regulation is one of the most important services. Using individual distributed BESS with fast response for frequency regulation is studied in [3]. Although a consensus algorithm is applied for secondary frequency regulation, both local and global cost and performance of the BESSs are neither analyzed nor enhanced, and therefore, State-of-Charge (SoC) regulation can only fulfil basic safety requirement. In [4], joint optimization of TESS and BESS is developed with provision of frequency regulation service. However, real-time power dispatch and primary frequency control of BESS are not reflected. The authors in [5] estimate the cost-effectiveness of three mainstream batteries participating in frequency regulation, but the cost-performance index is not standardized. In this paper, investigation and analysis of BESS supporting ice TESS are performed with emphasis on frequency regulation as major revenue stream. A real-time control strategy for the HESS is also developed and verified with real-world requirements and electricity market rules of Singapore.

II. Requirements on Cost and Cyber Security of BESS

A. *Levelized cost of storage*

The levelized cost of storage (LCOS) metric [6, 7], which is equivalent to levelized cost of energy (LCOE), is selected for assessment of BESS cost. This international metric allows energy storage costs to be compared across different technologies, and applied to multiple application cases and also for all possible revenues from various service mechanisms. In terms of average cost per stored MWh, LCOE is calculated [7] as:

$$LCOE = \frac{CAPEX + \sum_{t=1}^{n} \frac{OPEX(t)}{(1+i)^t}}{\sum_{t=1}^{n} \frac{E(t)}{(1+i)^t}} \quad (1)$$

where CAPEX is total capital investment cost; OPEX(t) is annual total cost in year (t), including operational cost, maintenance manpower cost and equipment cost; E(t) is total discharged energy in year (t); n is technical lifetime (years); t is year of technical lifetime (1, .., n); i is discount rate (%) referring to weighted average cost of capital (WACC). The cycle aging cost inside OPEX is further explored in [8]. Note that BESS end-of-life scrap value, decommissioning cost and disposal cost are excluded in the calculation. Besides LCOS, levelized cost of capacity (LCOC) is also considered in order to assist in capacity planning for the power network.

In this study, lithium-ion battery is chosen as the most suitable technology because of its proven economic value with high benefit-cost ratio (BCR) and internal rate of return (IRR) in PJM market [9, 10] and Korea [11]. TABLE 1 presents the most recent costs of lithium-ion battery.

TABLE 1. ESTIMATES (2018) OF UNSUBSIDIZED LEVELIZED COST OF STORAGE AND CAPITAL COST OF LITHIUM-ION BATTERY *[1]*

	Distribution	Micro-grid	Commercial	Residential
LCOE ($/MWh)	261	346	853	950
LCOC ($/kW-year)	548	968	426	475
Capital cost ($/kWh)	283	435	576	749
Capital cost ($/kW)	2,266	1,739	1,279	1,497

Based on the cost of BESS using lithium-ion and the revenue from HESS operations under market rules of Singapore, the total net benefit should be positive with reasonable subsidy from the government so as to promote clean energy and green buildings.

B. *Internet connectivity and cyber security*

Within a green building, local area network (LAN) provides communication backbone for multiple subsystems and components, e.g. over TCP/IP and building automation protocols. Supervisory control and data acquisition (SCADA) is then the control layer above this communication layer. However, due to stringent cyber security requirement, external communication, i.e. Internet connectivity, may be discouraged, or even prohibited in extreme cases. Under these circumstances, price signal, such as universal Singapore energy price (USEP), can be updated manually in months with human in the loop for accountability. Currently, USEP is published by Energy Market Company (EMC) on their website, and accessible with public API with updates every 30 minutes and one-day ahead forecast. Data analytics and prediction modules are then required to analyze the patterns of the price signal and recommend the control actions accordingly. In addition, for fast real-time and highly variable signal such as automatic generation control (AGC), which is refreshed every 4 seconds, a special requirement must be submitted to EMA. EMA will check and provide the AGC signal to the valid subscribers. Due to this strict legal process, operators of green buildings may search for other alternatives in order to be able to provide frequency regulation service without using AGC signal. For example, an offline optimal control policy that imposes SoC thresholds, as described in [12], can be utilized.

III. REAL-TIME CONTROL STRATEGY OF HESS

In literature, there have been multiple research efforts to develop real-time control strategies for BESS to participate in frequency regulation and increase the revenues by coordinated operations with TESS. However, these strategies are either over-complex with many parameters required [4], or over-simplified with several operational constraints neglected [13]. Therefore, a real-time control strategy for HESS is proposed herein in order to fulfil the following real-world operation requirements:

- *Power dynamics:* The HESS should be able to quickly regulate dynamic power for frequency regulation, e.g. response time of less than 1s.
- *Energy capacity:* The HESS should be able to dispatch energy such that BESS is not over-charged and not over-discharged while providing the fast dynamic power with extended effective capacity, e.g. the HESS with 400kWh BESS is able to continuously release 400kW power for more than 1 hour by using TESS to support.
- *Operation of TESS:* Number of switching on/off of TESS within a time period, e.g. 24 hours, is strictly limited, and may require human in the loop, which introduces variable response time. This requirement is normally raised because of the safe operating procedures of TESS considering thermal and mechanical constraints, and cyber security concerns.
- *Regulation by EMC/EMA:* The HESS must ensure continuity of frequency regulation service with features such as output range setting, basepoint setting, multiple types of regulation signals and dead-band [14].

The modelling approach and real-time control strategy of HESS to meet the above requirements are described as follows.

A. *Modelling of TESS*

In real-world, there are a wide variety of TESSs, for instance, HVAC systems, combined heat-power (CHP) systems, district cooling or heating systems etc. In this study, to focus on the widely used parameter of TESSs, which is the start-up/shut-down time, the first order system is used. The normalized transfer function of the studied TESS is then:

$$G_T = \frac{1}{1+\tau_T s} \quad (2)$$

where τ_T is time constant of TESS. The settling time of TESS, which is equivalent to start-up/shut-down time, is calculated as:

$$T_T = 4\tau_T \quad (3)$$

For instance, a district cooling system with start-up time of 10 minutes as illustrated in *Fig. 1*, has the time constant of 150 seconds.

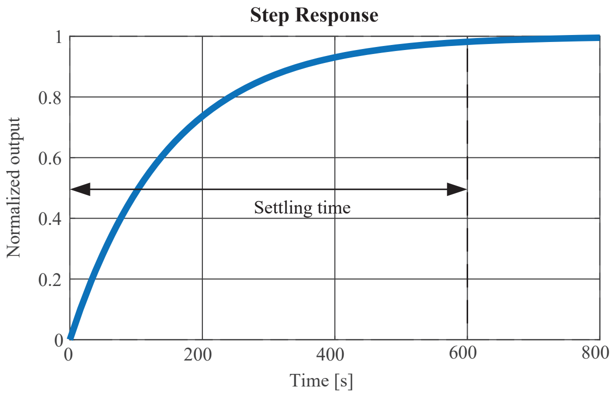

Fig. 1. Control response of TESS

In addition to the above dynamic response time of the physical TESS, when human in the loop is considered, another variable time delay, denoted as T_{HIL}, is introduced in the control system for TESS. This extra time delay is typically for the personnel in charge to verify, report and then activate the TESS. Therefore, the overall variable response time of TESS is $(T_T + T_{HIL})$.

B. Modelling of BESS

Similar to TESS, BESS with its fast dynamic response can also be modelled as a first-order system with small time constant τ_B, typically in the range of hundreds of *ms*. The response time of BESS is normally fixed because BESS is controlled automatically, and time delays due to communications are negligible.

C. Real-time controller of HESS

The diagram of HESS control system is shown in *Fig.* 2. As can be seen, due to human in the loop, operation mode δ_T of TESS requires verification by the personnel before forwarded to the TESS.

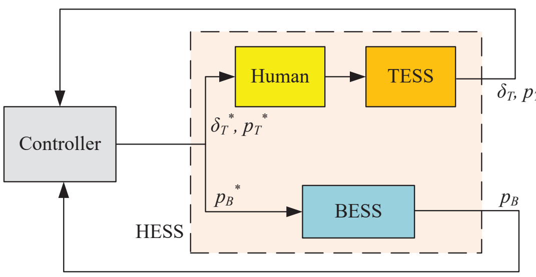

Fig. 2. Diagram of HESS with real-time controller

If TESS operation mode δ_T denotes the number of TESS modules in operation, the instantaneous power of HESS can be calculated as:

$$p_{HESS} = p_B + p_T(\delta_T) \qquad (4)$$

When TESS and BESS are operated separately, due to slow dynamics of TESS with response time in minutes, TESS cannot participate in frequency regulation which requires response time of 4 seconds stated by EMA and EMC [14]. The effective range of power for frequency regulation is therefore limited by power rating of BESS, which is from p_B^{min} to p_B^{max}. However, when TESS and BESS are operated joinly in real-time with the proposed real-time controller, the effective range of power for frequency regulation will be extended further, with minimum value of $p_B^{min} + p_T^{min}$, and maximum value of $p_B^{max} + p_T^{max}$. For instance, HESS consisting of a 400kW rated BESS and a (0, -400kW, -800kW) three-mode TESS has the full power range from -1200kW to 400kW. Using equilibrium operating point of -400kW, this HESS will have the effective 800kW power, both ramp-up (+) and ramp-down (-), to participate in frequency regulation, compared with only 400kW power if using BESS separately. *Fig.* 3 illustrates this capability in extending power range of HESS.

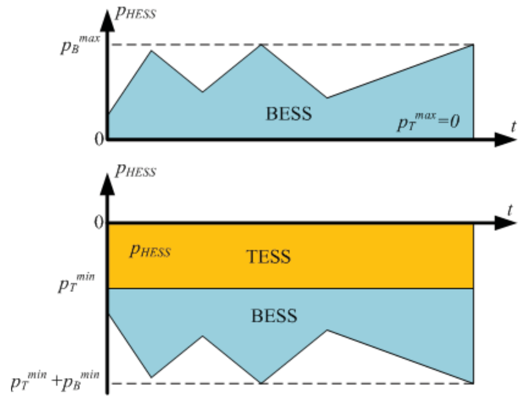

Fig. 3. Extending power range of HESS by coordinated operation

Coordination of HESS operation, however, has several difficulties. First, human in the loop causes uncertainty with variable response time. Second, TESS has slow dynamics and requires some amount of time to reach the control set-point. Finally, TESS may have discontinuous power output depending on its operation mode. The real-time controller, therefore, has to overcome these problems in order to ensure smooth operation of HESS.

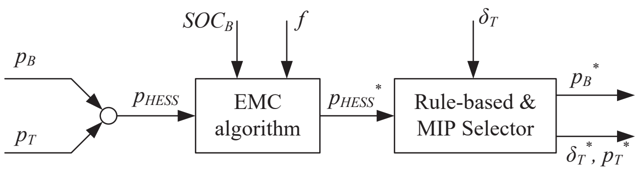

Fig. 4. Structure of real-time controller

The structure of the real-time controller in order to fulfil the aforementioned requirements is depicted in *Fig. 4*. As can be seen, to satisfy the requirements of output range setting, basepoint setting, multiple types of regulation signals and dead-band, EMC algorithm [14], as illustrated in *Fig. 5*, is applied to regulate the total power of HESS. Next, a rule-based selector equipped with Mixed Integer Programming (MIP) or fuzzy logic is utilized to analyze and compute the desired power outputs of BESS (p_B^*) and TESS (p_T^*), and also the associated operation mode of TESS (δ_T^*). This selector ensures constraints of TESS are complied with, for example, number of switching on/off per day, ramp rates etc. Moreover, via mode selection, the selector can also help to balance the SoC of BESS to avoid over-charge and over-discharge by using TESS to offset. Note that instead of full range from 0% to 100%, BESS is set to operate within a safe SoC range of 5% to 95%, in the case illustrated in *Fig. 5* below.

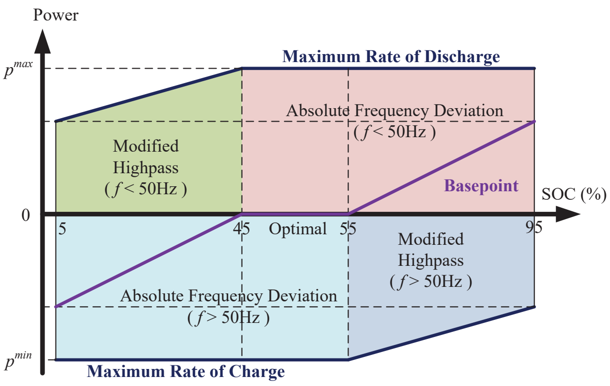

Fig. 5. EMC algorithm for provision of frequency regulation by batteries

IV. Simulation Results

To verify the proposed real-time control strategy as aforementioned, numerical simulations are conducted on Python. The energy manager, as developed in [4], for time frames larger than 30 minutes is reused. The specifications of the HESS are listed in *Table 2*.

Table 2. Specifications of HESS in simulation

Parameter	Value
Battery energy storage system	
Power rating	-400kW to 400kW
Energy capacity	400kWh
Time constant (τ_B)	50ms
Thermal energy storage system	
Operation modes	0 (OFF), 1 (ON, P_{T1}), and 2 (ON, P_{T2})
Rated power of mode 1 (P_{T1})	-400kW (charge)
Rated power of mode 2 (P_{T2})	-800kW (charge)
Time constant (τ_T)	75s

First, it is important to validate if TESS can assist to extend the limited capacity of BESS. As each price period in Singapore's electricity market has the length of 30 minutes, the dynamic allocation of capacity within this time interval is illustrated in *Fig. 6*. As can be seen, SoC of BESS can be either increased or decreased by selecting the suitable operation mode of TESS, whereas the power output of HESS remains constant. This capability is useful for the energy manager to rebalance the SoC of BESS when this SoC is close to its upper limit or lower limit.

Second, the maximum ramp rate of HESS under the control scheme is investigated and simulated. *Fig. 7* shows the ramp-up event of HESS from its minimum power of -1200kW (charge) to its maximum power of 400kW (discharge). In this case, a constant ramp-rate of 2.666kW/s is applied whereas the TESS changes its operation modes step-by-step, i.e. from mode 2 back to mode 1, and then back to mode 0. As shown, activation of TESS to change from mode 2 to mode 1 is delayed by 30 seconds. This is to help HESS to avoid exceeding the desired ramp rate because initial response of TESS is not under regulation and more than the desired constant ramp rate while BESS is already discharging at its minimum power and unable to compensate. Nevertheless, activation of TESS change from mode 1 back to mode 0 is still triggered after 300 seconds, and the overall time required for the ramping event is 600 seconds, which is equivalent to the settling time of TESS for two-step mode switch (i.e., $2T_T$ or $8\tau_T$). Note that under this operation, BESS requires at least 9.1% capacity margin to operate, and constant ramp rate of HESS is achieved throughout the whole operation range.

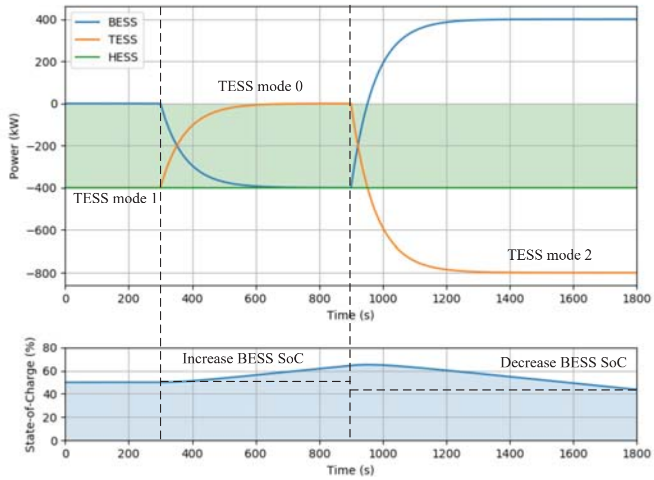

Fig. 6. Constant power output of HESS while re-balancing SoC of BESS

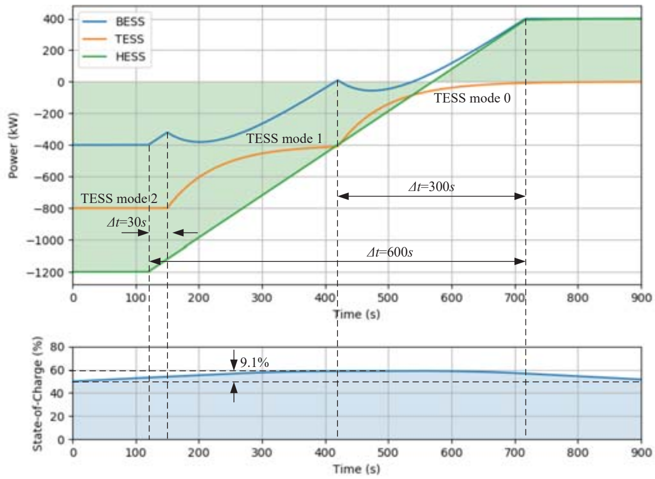

Fig. 7. Ramp-up of HESS with constant ramp rate and TESS two-step mode switch

Finally, ultra-fast ramp rate of HESS is studied and illustrated in *Fig. 8*. This mode of operation is in favour when the real-time controller detects a large power gap between the current operating point and the next one. The controller then can decide to change operation mode of TESS in a single step, i.e. from mode 2 directly back to mode 0, or *vice versa*. Similar to the previous case, due to the unregulated power output of TESS during mode switching and the saturated operating point of BESS, time delay of 30 seconds is still required for activation of TESS mode change. It can be seen that for the first duration of 300 seconds of the ramping event, the HESS obtains the constant ramp rate of 5.333kW/s. However, when BESS reaches its maximum discharge rate, another duration of 60 seconds is required for the TESS and also HESS to reach their full discharge rates. Under this operation, BESS requires capacity reserve of 7.2%, which is less than the reserve of 9.1% as in the previous operation scheme.

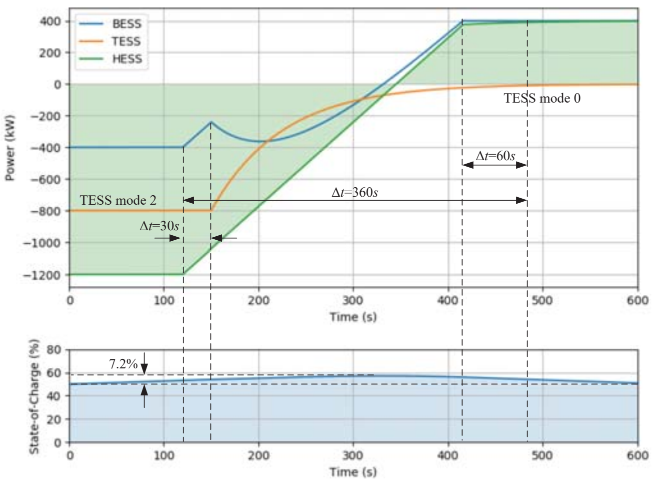

Fig. 8. Ramp-up of HESS with constant ramp rate and TESS one-step mode switch

The above constraints of ramp rates, time delays, and capacity reserves are then programmed into the rule-based selector as well as the energy manager. Based on the ramp rate desired, the real-time controller will also have to incorporate the time delays caused by human in the loop. If this variable time delay T_{HIL} is less than 30 seconds, its impact to dynamics performance of HESS is negligible.

With the same dataset and operation scheme as presented in [4], the 400kW and 400kWh BESS can help to generate about US$58,000 revenue from regulation service over 6 months under ideal case of simulation using MATLAB, with perfect forecast and success of all regulation bids. Besides, using KERMIT for frequency regulation study shows that in average, this BESS has to operate 873 full cycles over the period of one year, considering real-world data of electrical frequency in Singapore. With the LCOE under micro-grid application as listed in TABLE *1*, this can be translated into US$60,400 of BESS cost over 6 months. The incremental net loss, therefore, is US$2,400 over 6 months, or US$4,800 per year. Based on this amount of incremental net loss, with considerations that cost of lithium-ion will further decrease in near future and BESS provides multiple benefits to the power grid, such as capacity firming, it is worth for Singapore government to develop subsidy schemes in order to promote use of BESS in green buildings.

V. CONCLUSION

In this paper, a hybrid energy storage system that combines battery energy storage system with thermal energy storage system is analyzed for its revenue-generating operations in green buildings and in the context of Singapore. A real-time control strategy that incorporates several real-world requirements in the electricity market of Singapore is developed. Based on simulations with real-world data, it is found that the net incremental loss of deploying BESS is small. Promotion of using BESS, especially together with TESS to form HESS for green buildings in Singapore, therefore, should be encouraged. With complex dynamics requirements and market regulations as presented, the control and management framework to operate such HESS still requires further enhancement, for example, to be equipped with artificial intelligence. The future work, hence, will be development of a full controller of HESS with artificial intelligence embedded in both local-level rule-based/MIP selector and online system-level energy manager.

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