Optimal Multi-Objective Allocation and Scheduling of Multiple-Battery Energy Storage for Energy Efficiency Improvement

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Abstract

Energy-saving issues and utilization of current power systems have recently attracted more interest due to the growing concern about climate change. There are numerous worldwide projects under study and in course of implementation to optimize the consumption of electricity. In this context, a new company has recently been established by Hydro-Québec and Sony Corporation in Québec, Esstalion Technologies, Inc., in an aim to investigate the utilization of Battery Energy Storage (BES) in bulk power systems for energy saving. This paper proposes an optimal charging and discharging algorithm for energy-saving applications of BES on the IEEE Reliability Test System 1996 (RTS96). The sensitivity of power loss to the output power of BES is defined as a new index then minimized to find the most effective times and rates for charge and discharge modes. Study results show that, with an optimized controlling schedule, BES is capable of saving energy every day of the year.

Keywords: Battery Energy Storage, Energy Saving, Optimal Allocation, Loss Reduction, IEEE Reliability Test System 1996, Sensitivity of Power Loss to Battery Energy Storage

1. Introduction

As humans near depletion of the world's limited resources of fossil fuels, using them more efficiently and more economically becomes increasingly important. Meanwhile, there has been a rising concern over pollution and global warming during past decades. The adverse effects of burning fossil fuels on the environment have been acknowledged and the move towards cleaner application of energy has made public policy imperative.

Application of Battery Energy Storage (BES) in power systems continues to evolve and is being recognized as an innovative technology which could change the way electric power exchange and usage have been known so far. Many utilities are interested in the energy-saving applications of BES units. The technology not only provides an additional chance to defer investment in network assets but also allows utilities to retire old power plants with high emissions. A power network without BES must expand and maintain an entire delivery system capable of meeting the yearly peak load at any given moment. In addition, it must operate in an instantaneous framework that is highly dependent on generating units and time-changing demands. If it comprises BES, the network is required to carry just a heavy but normal load, which results in a more efficient and more reliable utilization of the present system.

Hydro-Québec, the biggest energy producer in Canada, is conducting many projects on providing clean energy with higher efficiency and less environmental impact. Recently, Hydro-Québec and Sony signed an agreement to establish “Esstalion Technologies, Inc.”. Esstalion is a combination of Energy Storage Systems (ESS), Station, and lithium ions, what are suitable for stationary applications of lithium-ion battery technologies [1]. One objective of this new company is to reduce power losses and save energy in the Québec interconnection. Apart from increasing the supply reliability, BES fulfils other functions such as load levelling and enhancing the quality of the energy and power factor. Regarding power loss reduction with limited sources of energy, peak shaving and load-levelling scenarios are two effective and proven applications. Active power losses on the transmission and distribution networks are proportional to the square of the load current (when corona losses are ignored) [2]. The best time to provide a network with stored energy in BES is peak hours, when electricity demand spikes, and the best time to charge it is during off-peak hours. By shifting any amount of load from peak hours to off-peak hours, power loss will be decreased.

There are major challenges to be faced in the process of adopting BES. The ability of grid planners to quantify BES-related benefits and to determine BES applications, as well as evaluating propositions and allocation options, is therefore critical to a utility's adoption of BES technology. The first question that comes to mind is how to allocate and control such limited volumes of energy within the bulk systems in the real world. The allocation and control of BESs has been studied in the literature [3]-[9]. However, an effective tool for optimizing the location, design and control of a BES for energy-saving purposes which has been demonstrated on real systems is still compulsory. In this work, we use the same optimal allocation scheme described in [10] to site multiple BESs in the benchmark IEEE Reliability Test System 1996 (RTS96). Next, an optimal schedule is chosen and developed in order to offer a suitable chain of daily charges and discharges for improving energy efficiency.

The outline of the paper is as follows. Section 2 reviews the results of [10] for optimal BES allocation; Section 3 explains the proposed algorithm for charging and discharging the BES to best suit an energy-saving application; Section 4 comprises a discussion of the results and, lastly, the conclusion is given in Section 5.

2. Optimal BES allocation

In the smart-grid environment, BES is likely to play an important role in providing a wide spectrum of grid services. BES optimal sizing and siting is the first step toward maximizing the associated technical and economic values. In the presence of several objectives in a Multi-Objective Problem (MOP), a set of optimal solutions, all optimal and known as optimal pareto solutions, is mandatory rather than a single optimal solution. None of these optimal pareto solutions can be ranked better than the others in the absence of any further information.

In this work, we take advantage of the integer version of Speed-constrained Multi-objective Particle Swarm Optimization (SMPSO) proposed in [11]. Similarly, we will conduct our study on the RTS96 with one BES unit in each region, three units in all, as shown in Figure 1. All required data are given in [12]-[14]. The BESs are also modelled as active power generating units at unity power factor with no control on voltage. The objective functions, particle coding (Figure 2) and a possible solution for each decision variable were as follows:

$$\vec{F}(\vec{X}) = [f_1(\vec{X}) \;\; f_2(\vec{X})] \quad , \quad f_1(\vec{X}) = \sum_{n=1}^{N} C_{BES}^{n} \qquad f_2(\vec{X}) = \sum_{j=1}^{J} P_g^j - \sum_{k=1}^{K} P_d^k \tag{1}$$

where

$\vec{F}(\vec{X}) = [f_1(\vec{X}) \;\; f_2(\vec{X})]$: Vector of objective functions

$\vec{X} = (x_1, x_2, .., x_n)$: Decision variable

C_{BES}^{n} : Capacity of n^{th} installed BES (MWh)

P_g^j : Active power of j^{th} generating unit

P_d^k : Active power of k^{th} load (100% loading)

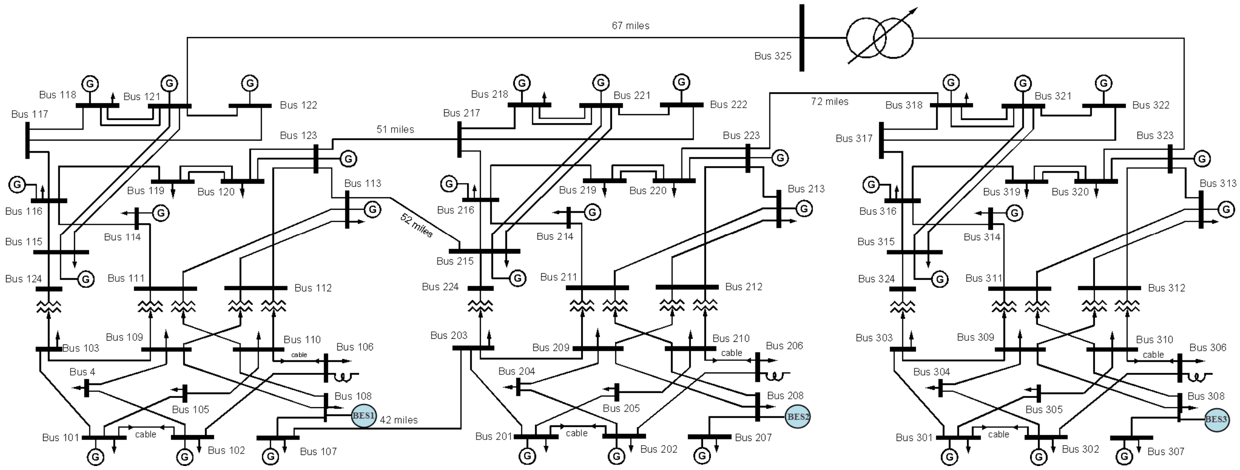

Figure 1. Simple schematic of RTS96 with three BESs

Buses nominated for the process of exploration were as follows:

Region A: [103, 104, 105, 106, 108, 109, 110, 111, 112, 117, 119, 120, 124]

Region B: [203, 204, 205, 206, 208, 209, 210, 211, 212, 217, 219, 220, 224]

Region C: [303, 304, 305, 306, 308, 309, 310, 311, 312, 317, 319, 320, 324]

Nominated capacities were: *20, 50, 100, 150 and 200* (MWh)

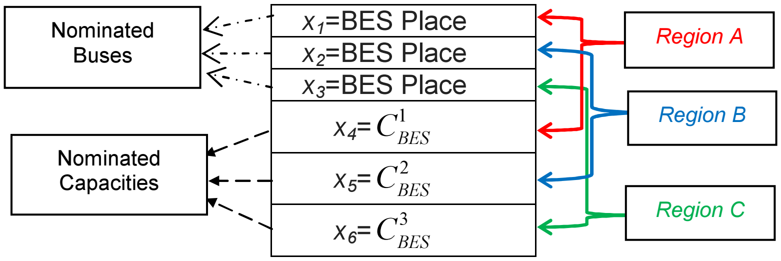

Figure 2. Particle coding including places and sizes.

$f_1(\vec{X})$ represents the total installed capacity of BESs in MWh while $f_2(\vec{X})$ is the total power loss of the benchmarked system. The objective is to minimize both thxe installed capacity and the power loss of BESs. Table 1 shows the optimal allocated BESs for the given pareto front in [10]. Solution 8 was similarly chosen for the next level of study (see Figure 1). Another interesting point is the network performance when subjected to an overloading situation. The corresponding results may encourage BES installation, since the current power system will undergo stress due to the increasing demand for electricity. The same optimization was executed with 130 and 160 percent for the loading parameter. As seen in Figure 3, any increase in the loading factor increases the power loss decrement.

Table 1. Pareto Optimal Set [10]

	x_1	x_2	x_3	x_4	x_5	x_6
Solution 1	106	208	308	20	50	20
Solution 2	108	205	306	100	100	20
Solution 3	108	204	311	150	20	20
Solution 4	108	204	304	200	100	100
Solution 5	106	204	308	50	50	20
Solution 6	108	204	308	50	50	50
Solution 7	104	204	306	20	20	20
Solution 8	108	208	308	100	100	100
Solution 9	106	208	310	100	100	150
Solution 10	108	206	306	100	100	50
Solution 11	106	208	306	100	50	50
Solution 12	108	210	306	100	150	200
Solution 13	108	206	312	200	100	200
Solution 14	111	208	311	200	150	200
Solution 15	108	209	306	200	200	200

3. BES energy-saving application

BES cannot be categorized either as a source of energy or as a consumer of energy. In discharge mode, BES may function as a generating unit with a limited volume of energy while in charge mode it may play the role of a smart load. Determination of an optimal charging and discharging schedule involves an accurate sequence of decisions to acquire the best utilization possible of BES for the desired energy-saving application.

As mentioned before, the goal is to minimize the total power loss of RTS96 when the BES is included and to improve energy efficiency. For each day, we start by identifying 8 hours with lighter loads, which are suitable for BES charging. Based on a load profile analysis, it is to identify a period of about 8 hours during which the load falls below 75% of the maximum daily value; the remaining 16 hours are earmarked for discharge mode. Thus, the proposed algorithm distinguishes suitable charge and discharge times over a day-long period. The method comprises two phases. Phase one includes a power loss calculation for each incremental step size of BESs by the algorithm illustrated in Figure 4 (charge mode). The required amounts of charge for BES are divided into a number of energy volumes. The Sensitivity of Power Loss to BES ($SPLBES$) is then defined and calculated as follows for each energy volume:

$$SPLBES(1,h_1,d,w)=\frac{P_{loss}^{BES}(1,h_1,d,w)}{\Delta P_{BES}^{n}}-\frac{P_{loss}^{normal}(h\big|_{h=H_{ch}(h_1,d,w)},d,w)}{\Delta P_{BES}^{n}}$$

(2)

$$SPLBES(j,h_1,d,w)=\frac{P_{loss}^{BES}(j,h_1,d,w)}{\Delta P_{BES}^{n}}-\frac{P_{loss}^{BES}(j-1,h_1,d,w)}{\Delta P_{BES}^{n}},\ \ j=2,3,..,ns$$

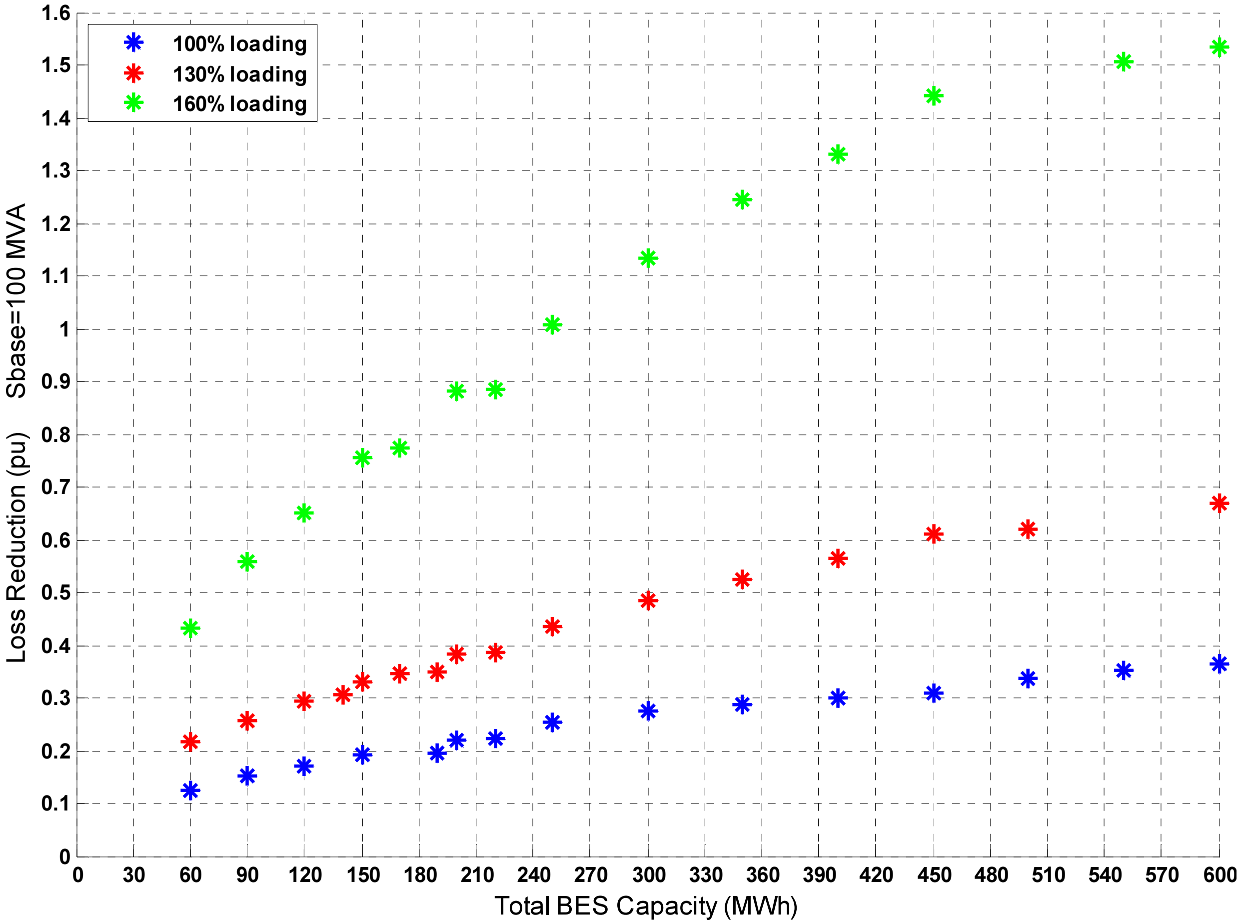

Figure 3. Power loss reduction for optimal pareto front sets under different loading parameters

In equation (2), the parameters are defined as follows:

$P_{loss}^{normal}(h,d,w)$: Power loss of the system for hth hour, dth day and wth week without BES (pu)

h_1: index vector of charging hours

$H_{ch}(h_1,d,w)$: Charging hours for dth day and wth week

$P_{loss}^{BES}(j,h_1,d,w)$: The power loss when system includes jth incremental step of energy volume of BES for hth hour ($h = H_{ch}(h_1,d,w)$) (pu)

$SPLBES(j,h_1,d,w)$: The $SPLBES$ for jth incremental step, dth day, and wth week

$\Delta P_{BES}^{n} = {C_{BES}^{n}}/{ns}$: Size of BES energy volumes charged in one hour (pu)

ns: Total number of BES energy volumes for each unit

At each hour, if applicable, generating units equipped with Automatic Generation Control (AGC) have to be re-dispatched based on a method already proposed in [10].

By the end of phase 1, we have computed the $SPLBES$ for the energy volumes. Phase 2 specifies those energy volumes to the hours with more benefits on the power loss. For each day of the year, the following steps are performed for charge mode:

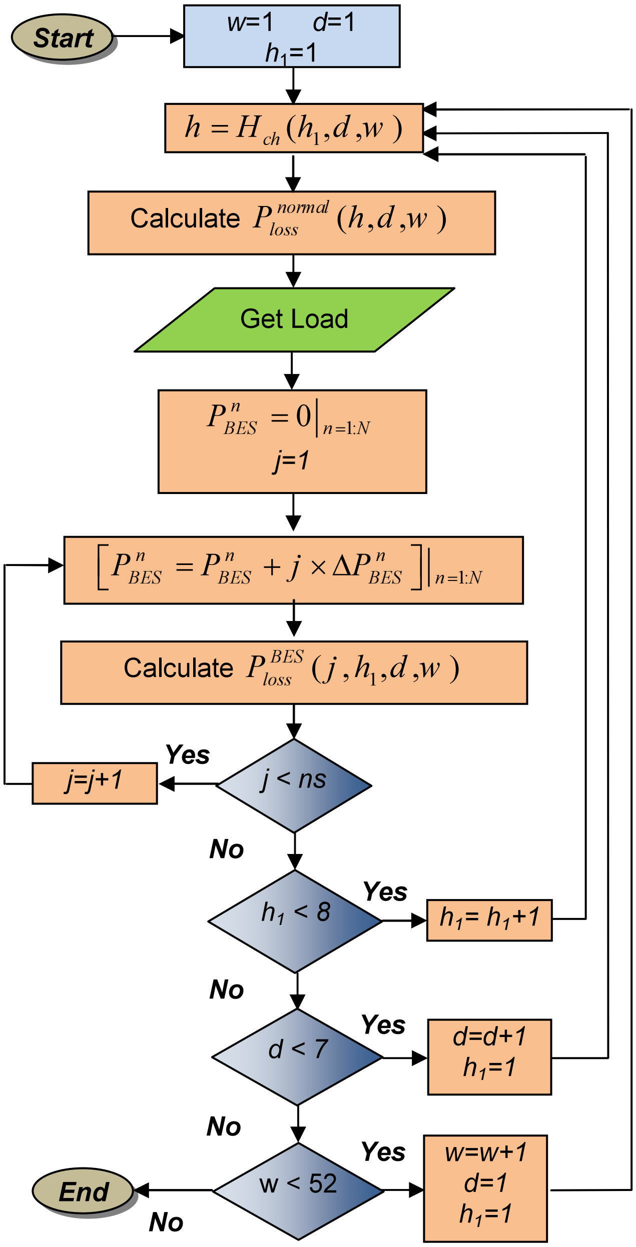

Figure 4. Power loss calculation for each incremental step of BES size

Step1:

Find the minimum value of $SPLBES$ and, for corresponding hour, **calculate**:

$$BES_{ch}^{R}(h_1, d, w)_n = \Delta P_{BES}^{n}\Big|_{n=1:N} \tag{3}$$

Step2:

If j is equal to ns, **go** to the next day.

Otherwise:

Increment the value of j, **find** the next minimum value of $SPLBES$ and, for the corresponding hour, **calculate**:

$$BES_{ch}^{R}(h_1, d, w)_n = BES_{ch}^{R}(h_1, d, w)_n + \Delta P_{BES}^{n}\Big|_{n=1:N} \tag{4}$$

In Equations (3) and (4), $BES_{ch}^{R}(h_1, d, w)_n$ is the charge rate of the nth BES unit. Note that the same phases with a slight modification are applicable for discharge mode.

4. Discussion and results

In this work, 100% for depth of discharge and 95% for charge/discharge efficiencies have been set, based on private discussions with some of the most advanced LiFePO4-based BES developers. The BES is also cycled during 24 hours and ns is equal to ten. Simulation results with the optimal solution (solution 8 in Table 1) can be summarized as follows:

- The energy-saving application of BES with the proposed algorithm for charge and discharge is capable of saving energy every day of the year. The amount of energy saved is higher during week (i.e., Mon-Fri) (Figures 5 and 6).

- Figure 7 shows the power loss and loss reduction without/with BESs over the course of the peak day of the year. It is seen that the power loss increases during charging hours and decreases during discharging hours. In general, a 5.45 MWh reduction in daily energy losses is feasible.

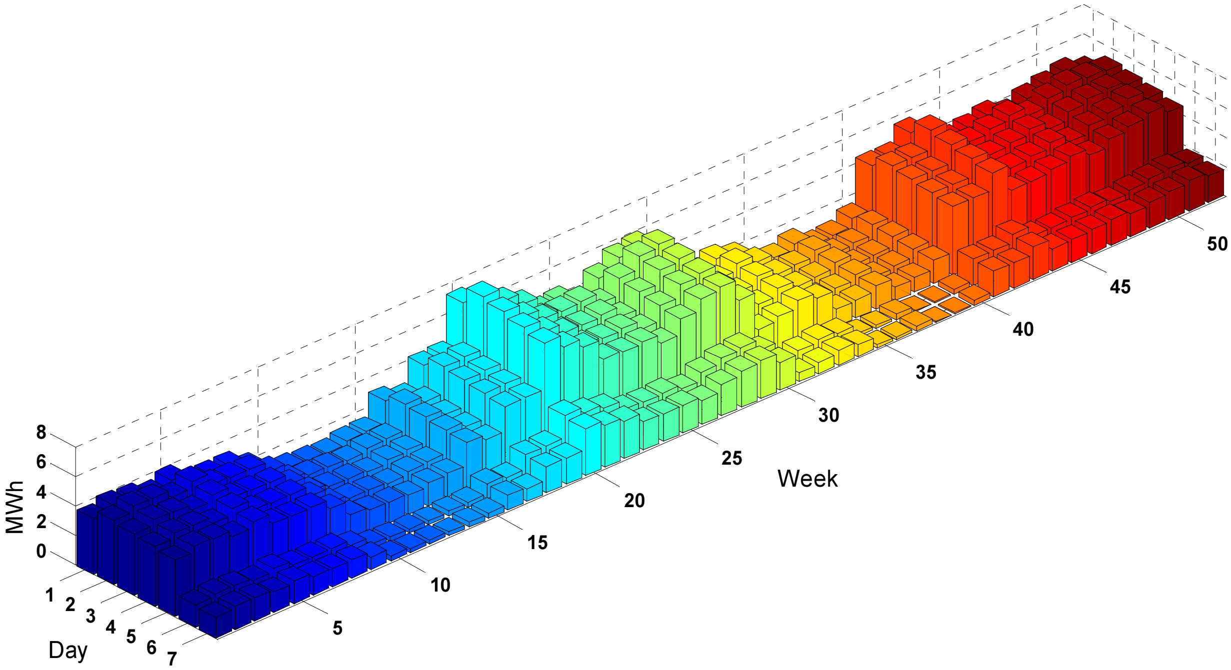

Figure 5. Energy saved (in MWh) with BES, day by day and over a year.

- In an energy-saving application, the BESs charges and discharges during more hours than in a marginal loss reduction application. For example, the charge/discharge hours were 4 h/3 h in marginal loss reduction applications [10] whereas in an energy-saving application, the charge/discharge hours are 7 h/12 h (Figure 7). In other words, the rate of charge and discharge with the energy-saving application is less than the peak-shaving application. Note that there are five hours during which the BES is in idle mode.

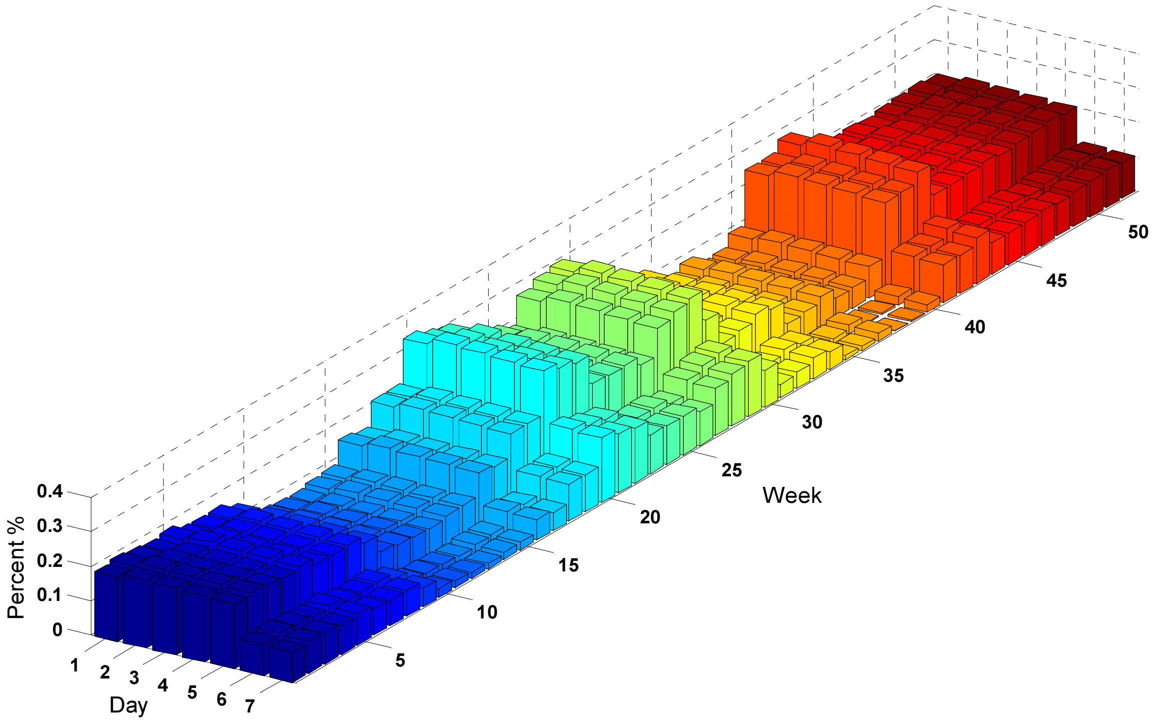

Figure 6. Saved energy (in percent) with BES, day by day and over a year

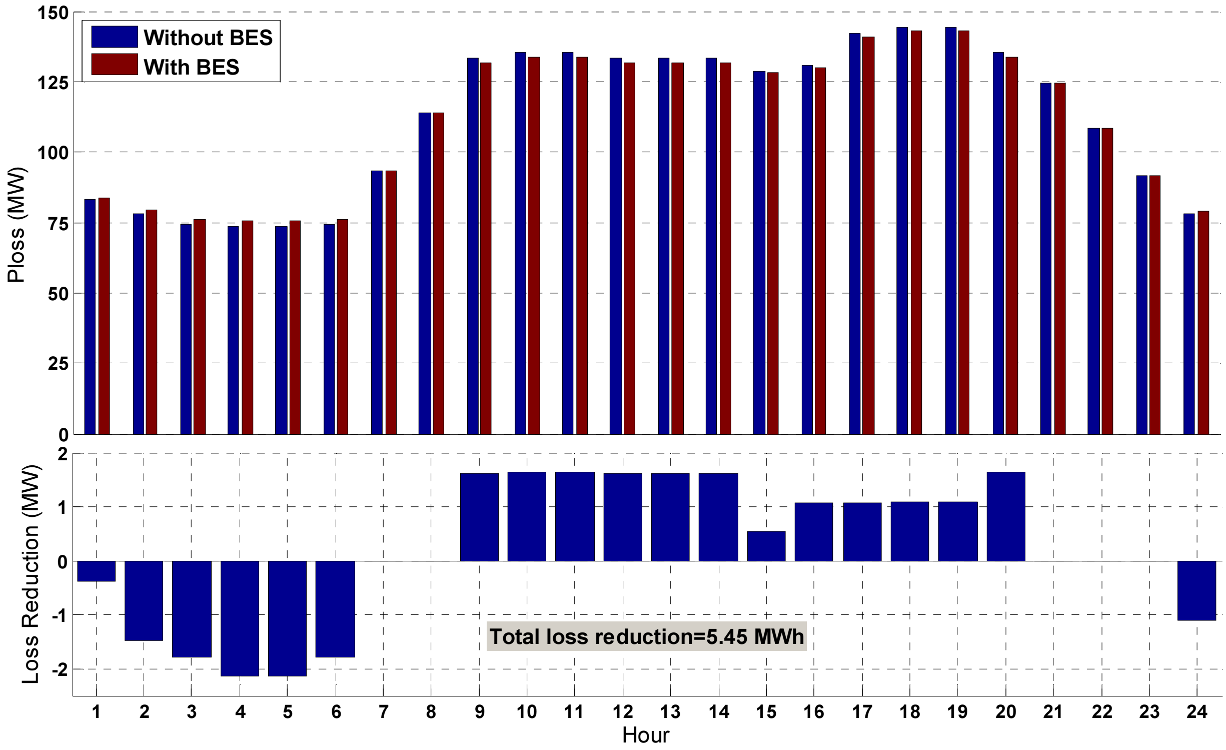

Figure 7. Energy-saving results for the peak day of the year (Week=51, Day=2).

- We can take advantage of hour 24 some days and charge the BES for a day ahead of usage. Load demand decreases gradually after peak hours, providing a chance to charge the BES. If this is done, the State Of Charge (SOC) during a day, by typical definition, will be negative (Figure 8. SOC%(b)) while for a working 24 hours, starting one hour earlier, it is positive (Figure 8. SOC%(a)).

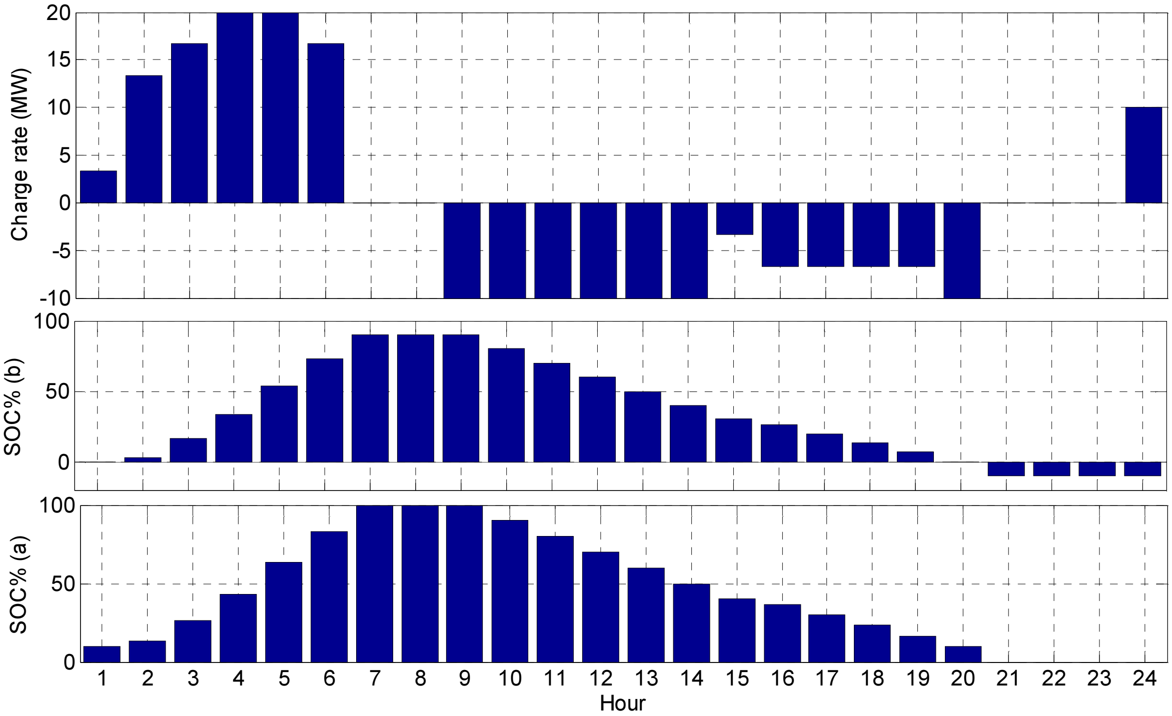

Figure 8. Ch/Dch rates; SOC%(a): SOC of BESs charged a little from the day before; SOC%(b): SOC of BESs over a day (Week=51, Day=2)

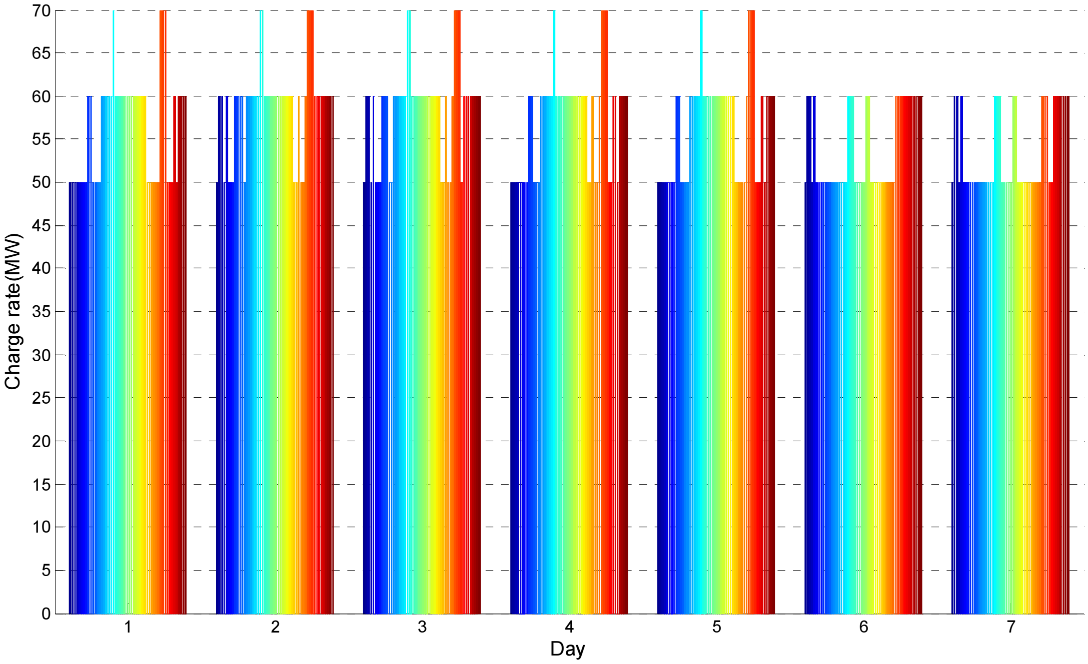

Figure 9. Charging rate of BESs for each day of week

- If BES operates in the energy-saving application, 1138.7 MWh can be saved over one year, i.e. about 0.1613% on average, while this value was about 422 MWh, 0.0598% on average, in the marginal loss reduction application (more than 2.7 times bigger). Note that the BES size is 3.5% of the total load of the RTS96 (8500 MW vs. 300 MWh).

- Generally, BES operates more smoothly in the energy-saving application compared to results of the peak-shaving application [10]. In addition, BES charges at higher rates and discharges at lower rates on weekdays compared to weekends (Figures 9 and 10).

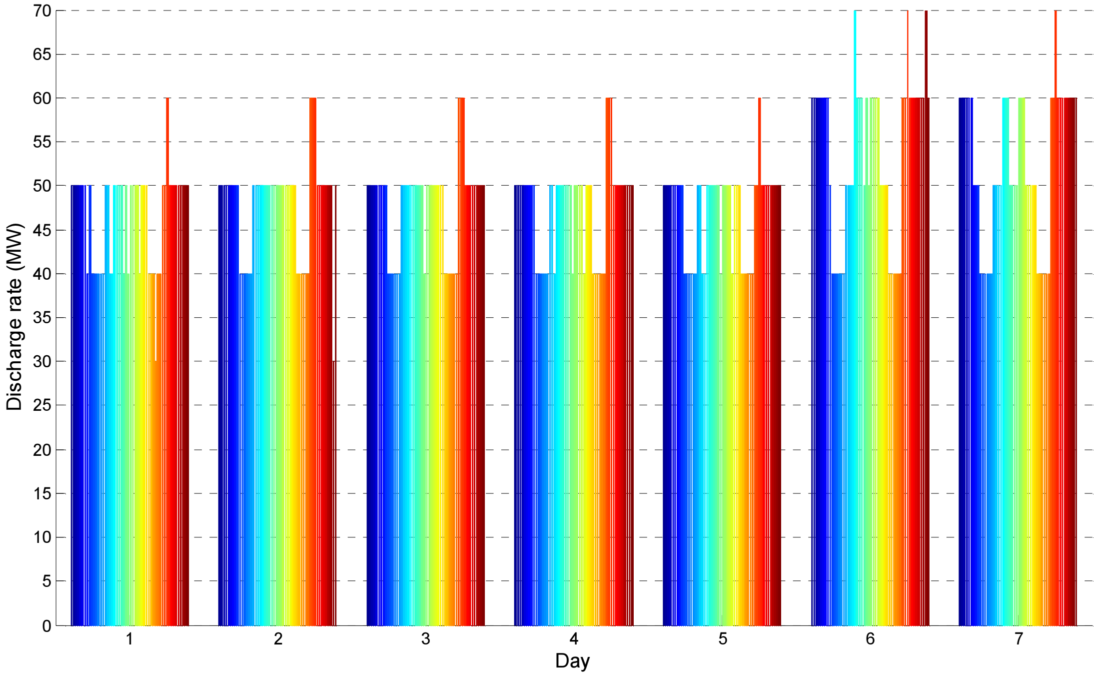

Figure 10. BES discharging rate for each day of the week

5. Conclusion

As a new solution to the climate change and global-warming dilemma, this paper offers an optimal charging and discharging algorithm for battery energy storage for energy-saving applications. The IEEE reliability test system was chosen to study and develop this Idea. As a new index, the sensitivity of power loss to battery energy storage is defined then minimized to find the most effective charge/discharge hours and rates. Study results show that battery energy storage with an optimized controlling schedule is capable of saving energy every day of the year.

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