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APPLICATION OF LITHIUM-ION BATTERIES IN ENERGY STORAGE SYSTEMS

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Yi-Kuan Ke and Ting-Hong Wu

Key words: Power system, renewable power, peak load, energy storage system (ESS).

ABSTRACT

Energy storage systems (ESSs) have features that can help solve various problems in the power system, such as renewable power shortage because of utility peak load. Energy storage technology and markets are gradually developing in the Taiwan power grid. In contrast to the conventional power grid model, energy storage employs a new technology in the power system. Although energy storage has several advantages in the power system, there are also challenges in its application.

In this study, we investigated battery applications in ESSs and set up a simulation model to determine its benefits on power load. We implemented an ESS model to demonstrate that energy storage helps stabilize power load in various power events to prevent power load interruption.

I. INTRODUCTION

Because of vigorous implementation of non-nuclear homes and use of green energy, such as renewable energy without pollution, by the government, nuclear power plants may shut down operations. The new renewable energy units have not been established everywhere in Taiwan, and although the old thermal and gas power units are fully loaded with power, it is not sufficient to meet the increasing demand of power load. Energy storage systems (ESSs) have become a crucial power resource for a grid when the reserve capacity rate of a power grid is less than 6% (Taiwan Power Company, 2018). An ESS can supply power to a grid to maintain the reserve capacity rate of the power grid at a minimum of 6%, especially in case of heavy power load demand at peak times in the summer season. Reliability and safety are the most essential features of the battery models or types of batteries used to maintain power stability. In this paper, we compared several commonly available batteries in the market and decided to use lithium-ion batteries in the ESS model. We simulated a power system to analyze the voltage and current changes in case of accidental trips and to predict and prevent loss of power load. Most importantly, the ESS model provides power quickly to maintain the power load.

The main purpose of this research was to investigate whether the ESS model can maintain the power load in case of sudden power events or grid power insufficiency. Battery discharging and charging relations are the key characteristics to realize in an ESS.

Load voltage and current are affected by the phenomenon of power change because of trip events that affect continuous operation. An ESS has an independent function to provide required power to maintain grid stability and to avoid power disconnection in North, Central, and South zones.

II. ENERGY STORAGE

The most common large-scale energy storage models can be divided into three types, namely mechanical, electromagnetic, and chemical (Zarębski, 2018).

The mechanical energy storage model includes pumping water, compressed air, and flywheel energy storage. The electromagnetic model includes a super capacitor and superconducting magnetic energy storage. The chemical energy storage model includes a lithium-ion battery, metal-air battery, metal-ion battery, and a novel flow battery.

Different energy storage methods are applicable for different scales, for example, power storage systems with capacity less than 1 MW use flywheel energy-storage, batteries, capacitors, and super capacitors. Power storage systems with a capacity of 10-100 MW use a vanadium redox flow battery, shallow compressed air energy-storage power generation system, sodium-sulfur battery, and a fuel cell. Power storage systems with a capacity greater than 100 MW use hydroelectric systems, deep compressed air ESS, and new technologies with greater energy storage capacity, such as superconducting magnetic energy storage and hydrogen energy storage (Hsieh, 2014). For use at home or in small communities, lithium-ion batteries are the most widely used type of energy storage, such as those with a 6-kW capacity power (Eaton, 2018).

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The energy storage battery platform mainly uses energy storage technologies such as lithium-ion batteries, sodium-sulfur batteries, and lead storage batteries. These three battery production technologies are most commonly used in ESS; in particular, lithium-ion batteries occupy over 50% in ESS of battery type. The ESS software can always monitor ESS status and ESS software can control ESS power in the specific period of time for adjustment of utility power. It can also record events, power flow, battery charging and discharging percentages, and remotely monitor and control functionality.

This paper establishes a home-based ESS simulation model with critical and non-critical loads and distinguishes between the two to assess their performance and to determine the profit incurred when critical load uses ESS. In the simulation, in case of power trips, the ESS can maintain the power supply in the home-base model at critical loads. Therefore, home-based electricity will not affect critical load loops, such as the refrigerator, lighting, and other machines, during utility power shutdown.

III. BATTERY

Many types of batteries are available in the market. The following batteries are most commonly used.

1. Lead-Acid Battery

In lead storage batteries, commonly known as lead-acid batteries, the electrodes are made of lead and the electrolyte is a sulfuric acid solution. They are further divided into two types, namely open and valve control. The open type requires regular electrolyte maintenance, and the valve control type does not require maintenance (Brasil and Melo, 2017). The lead-acid battery was first developed as a mature low-cost technology. However, its large size and resulting pollution are disadvantageous. Lead-acid batteries are mostly used in an uninterrupted power system (UPS). When the UPS has a greater capacity, a higher capacity lead-acid battery is required to meet the power load demand. Therefore, size and environment protection in lead-acid battery recycling remain a challenge.

2. Nickel-Cadmium Battery

Nickel-cadmium batteries use nickel hydroxide (NiOH) and metallic cadmium (Cd) as chemical energy sources for electricity production. When the nickel-cadmium battery is discharged, the discharge voltage changes with small variations. Heat is absorbed during charging and the internal resistance is less, which causes the battery to overcharge slightly. The pollution caused by heavy metal cadmium is an environmental protection problem.

3. Nickel-Metal Hydride Battery

A nickel-metal hydride (NiMH) battery is a modified version of the nickel-cadmium battery. Instead of heavy metal cadmium, it uses metals to absorb hydrogen. Compared with a nickel-cadmium battery, it has a higher capacity, less memory effect, less environmental pollution, and higher recy cling efficiency. It is an environmentally friendly battery. NiMH batteries are used with more power-consuming products because such products produce larger output current by using NiMH batteries.

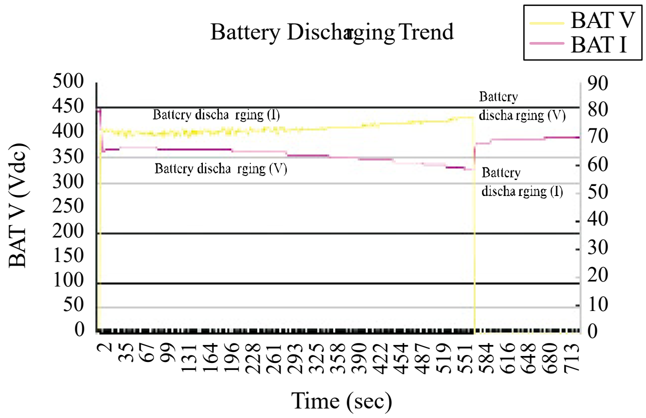

Fig. 1. Lithium-ion battery discharging and charging.

4. Lithium-Ion Battery

Lithium-ion batteries mainly rely on the movement of lithium ions between the positive and negative electrodes to achieve the function as a battery model. A lithium-ion battery uses a lithium compound as the electrode material, and it is usually the positive electrode. Lithium-ion battery materials have lithium cobalt oxide ($LiCoO_2$), lithium manganate ($LiMn_2O_4$), lithium nickelate ($LiNiO_2$), and lithium iron acid ($LiFePO_4$). Lithium manganate is a good cathode material because it has high safety and low cost (Li and Zhang, 2018). Lithium nickelate and lithium manganate share the characteristics of low cost, high safety, and high temperature protection.

As the most commonly used rechargeable batteries in portable electronic products, this battery has high energy density, no memory effect, and low self-release rate. It has better life time with stable charging and discharging curves than other battery types have.

A lithium-ion battery has a better cycle life, requires no maintenance, and is equipped with a built-in battery management system to monitor changes in battery status, temperature, current, and discharge. Fig. 1 presents monitored battery voltage and current curves during discharging and charging, and it is evident that battery discharging is stable with better characteristics in case of lithium-ion batteries.

As shown in Fig. 2, lithium-ion battery deep discharge exhibits a consistent decrease, which shows that lithium-ion batteries remain stable during deep discharge to supply power load.

IV. COMPARISON OF BATTERY FUNCTIONS

The different types of batteries in the market are presented in Table 1.

Table 1. Comparison of battery characteristics.

	Lead acid	Nickel cadmium	Nickel hydrogen	Lithium cobalt	Lithium manganese	Lithium iron
Operating Voltage (V)/cell (By type)	2V	1.2V	1.2V	3.7V	3.8V	3.3V
Volume energy density (Wh/L) (Average)	100	150	250	400	400	400
Weight energy density (Wh/Kg) (Average)	30	57	70	133	90	120
Power (W/Kg) (Average)	300	190	200	430	420	430
Cycle life	400	500	500	> 500	500~1000	> 2000
Instant discharge (C)	Medium	HIGH	HIGH	HIGH	Very HIGH	Very HIGH
Continuous discharge (C)	Low	Medium	HIGH	Low	HIGH	Very HIGH
Charging (C)	Low	Low	Medium	Low	Medium	HIGH
Energy efficiency (%)	Around 45%~65%	75%	70%	90%	90%	95%
Self-release rate	Medium	Medium	Medium	Low	Low	Low
safety	Safety	Unsafe	Safety	Unsafe	Safety	Safety
Temperature characteristics	Not Good	Medium	Medium	Medium	Medium	Good

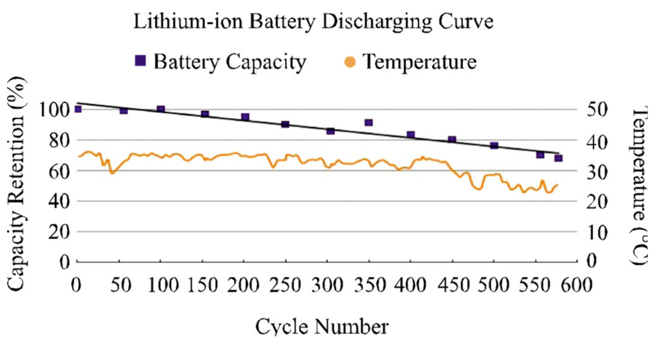

Fig. 2. Lithium-ion battery deep discharge.

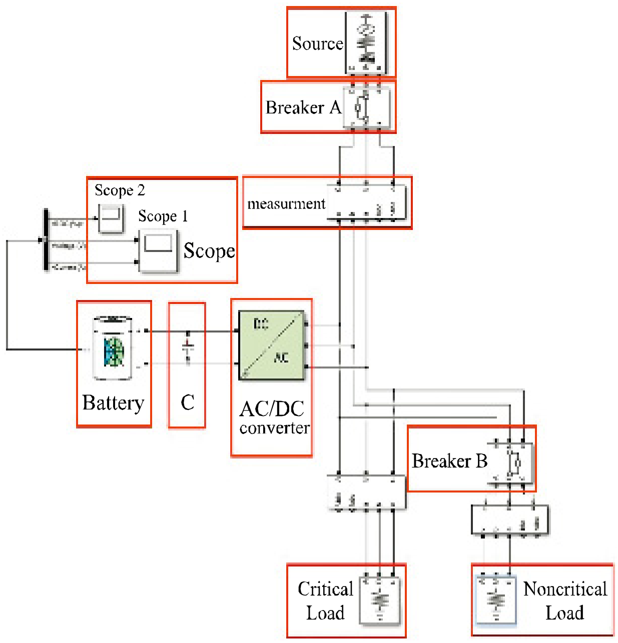

Fig. 3. ESS simulation architecture.

Table 1 lists the characteristics of various types of batteries. In this list, for the most suitable batteries for ESSs, characteristics such as safety, power consumption, efficiency, cycle life, and dimension, are considered. It is evident from Table 1 that lithium-ion battery has better characteristics applicable to an ESS. (Yuchen et al., 2018).

V. SIMULATION

This paper uses the Simulink power system toolbox in Matlab math software Simulink function to design the architecture of the ESS model. The power system architecture contains the mains power, lithium-ion battery, critical load, non-critical load, AC/DC converters, capacitors, circuit breakers, and oscilloscopes. Power to the critical loads and non-critical loads are supplied from the utility. The power connection is connected to the AC/DC converter at this point and the converter is connected to the lithium-ion battery to maintain the voltage and current power load stability. The section between the lithium-ion battery and AC/DC converter, which is parallel to the capacitor, maintains a stable voltage and current, as shown in Fig. 3. (Garmabdari et al., 2017; Jinga et al., 2017).

In the mains power supply, system parameters for normal conditions are set as follows: voltage is 220 V, 60 Hz, critical load is 500 W, non-critical load is 1500 W, battery capacity is 20 Ah, initial lithium-ion battery power is 90%, output of the three-phase AC/DC converter is 220 V, and conversion efficiency is 97%.

(1) Situation 1: Normal work.

The simulation time is 0-5 s. When the power is normal, the operating voltage of the mains supply is 127 V and the operating current is 27.5 A, as shown in Fig. 4.

Normally, for the critical load, the operating voltage is 127 V and operating current is 1.3 A, as shown in Fig. 5.

Normally, for the non-critical load, the operating voltage is

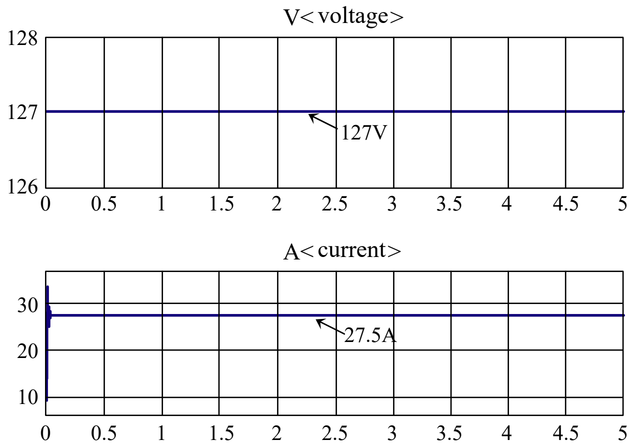

Fig. 4. Utility electricity condition.

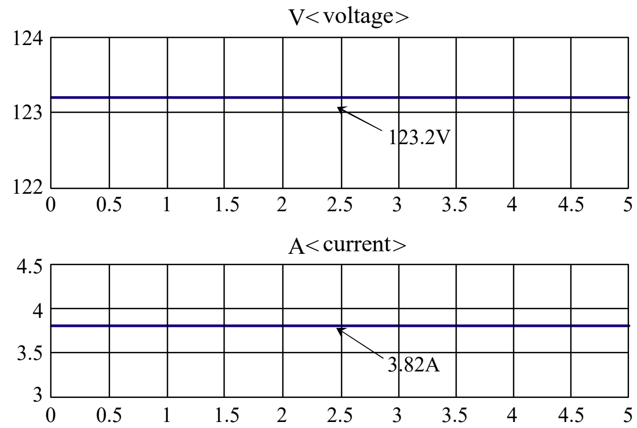

Fig. 6. Non-critical load in normal condition.

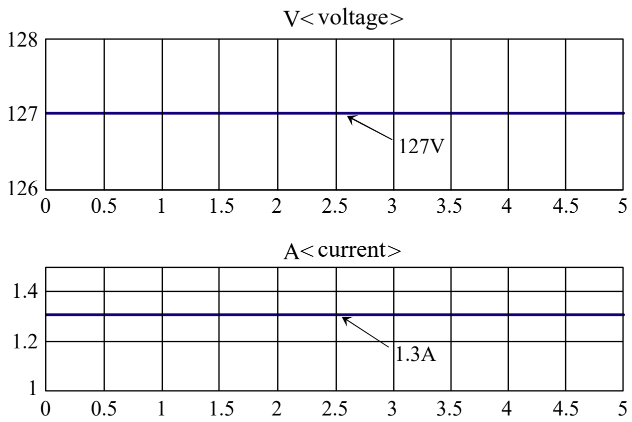

Fig. 5. Critical load in normal condition.

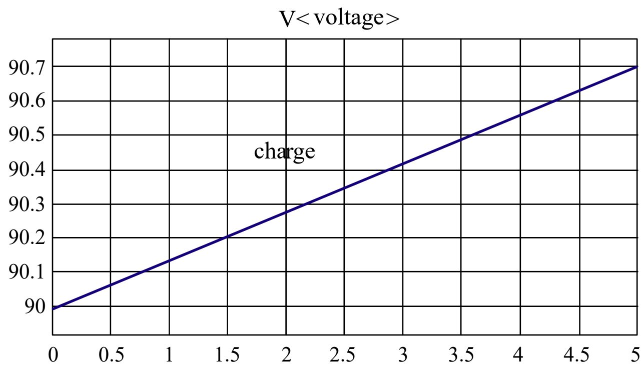

Fig. 7. Lithium-ion battery charging status.

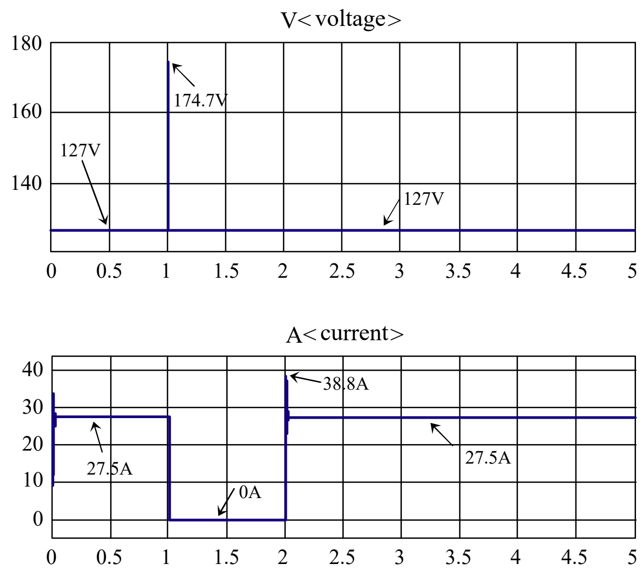

Fig. 8. Power trip situation.

123.2 V, operating current is 3.82 A, and power consumption is 500 W, as shown in Fig. 6.

When utility power is normal, the lithium-ion batteries charge until they are fully charged. In Fig. 7, at the beginning of the charging operation, when utility power is connected to power load using the ESS, battery capacity is at 90%.

Figs. 4-6 show that utility power is normal and that critical and non-critical loads are stable.

(2) Situation 2: Power trip.

In the second situation, the circuit breaker A trips and the mains supply is disconnected at the first second of simulation. After 1 s, the original normal state is restored in a second of simulation time, and the circuit breaker B trips the non-critical load when the mains supply trips. To avoid insufficient supply to the critical load, in this moment, the ESS supplies power to the critical load to ensure that it has power. From 0-1 s before utility power is disconnected, the operating voltage of the mains supply is 127 V and the operating current is 27.5 A. In the 1 s when circuit breaker A trips because of a utility power event, there will be a short-duration transient phenomenon, as shown in Fig. 8. The voltage surge because of the transient phenomenon causes the voltage to increase quickly by 47 V, however, because it is a transient phenomenon, its duration

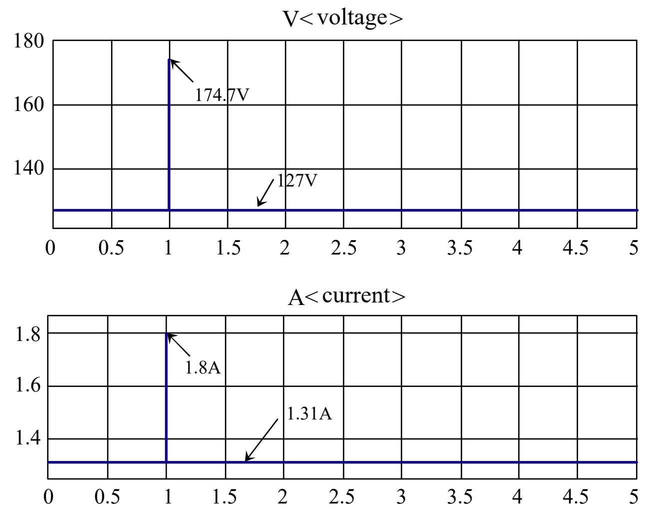

Fig. 9. Critical load conditions in power trips.

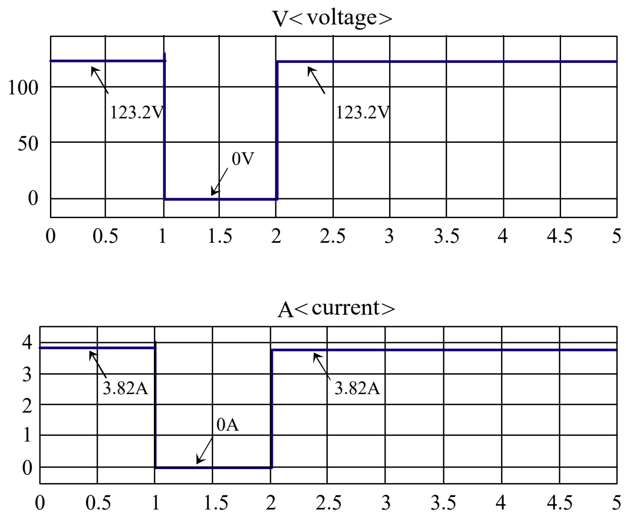

Fig. 10. Non-critical load condition in case of power trips.

will be short and it will not affect the power load. After 2 s, the power recovers and circuit breakers A and B are closed to supply power to the power load.

Normally, the critical load is 127 V and the operating current is 1.31 A. At the first second of simulation time, the voltage experiences a surge of about 47 V because of the cutoff of circuit breakers A and B, and power is supplied by the lithium-ion battery. The current part also generates an increasing surge of approximately 0.5 A, but it is still in a range that the load can withstand because of its small amplitude. After utility power is restored, circuit breakers A and B are closed and power is restored, and this power has no effect on voltage and current, as shown in Fig. 9.

Normally, the non-critical load is 123.2 V and the operating current is 3.82 A. At the first second of simulation time, the voltage and current drop to 0 V and 0 A, respectively, because the breakers A and B are cut off. Current and voltage dropping to zero affects the non-critical load; however, to maintain critical load, it is necessary to cut off the non-critical load because energy storage power has limited capacity and cannot meet the power demand of critical and non-critical loads. In this simulation, the total load capacity is greater than the energy storage capacity. Therefore, the simulation system is divided into critical and non-critical loads. The ESS can keep the critical load operational in case of utility power loss events. After power supply is restored, the circuit breakers close, and voltage and current levels become normal, as shown in Fig. 10.

As shown in Fig. 11, the lithium-ion battery has a charging voltage of 30.62 V and charging current of −100.6 A. The negative sign implies that the current flow is toward the battery and not toward the load. At the first second of simulation time, circuit breakers A and B are cut off and the lithium-ion battery is in discharge mode with a discharge voltage of 25.6 V and discharge current of 20 A. It supplies power to the critical load. In the second simulation when utility power is restored, the

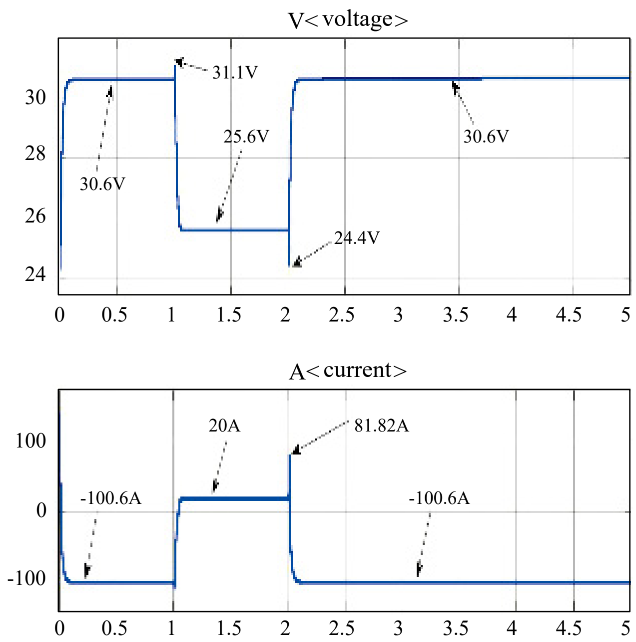

Fig. 11. Battery voltage and current status during power trips.

circuit breakers close. When the breakers close, there is a surge of 81.8 A in the current and a small reduction of 24.4 V in the voltage. The voltage sag does not affect the system because it is a transient situation. For different lithium-ion battery modes, 2-5 s is the charging mode and 1-2 s is the discharging mode, as shown in Fig. 12.

The ESS model designed in this paper can support and help in case of a utility power event. Energy storage can also adjust utility power and house load flexibility. An ESS can save house power expenses because it injects power from lithium-ion battery to house power load to reduce utility offering demand to reach grid regulation, as shown in Fig. 13.

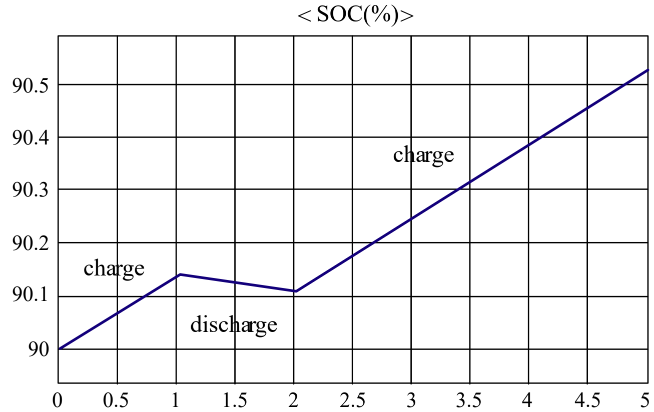

Fig. 12. Battery power status during power trips.

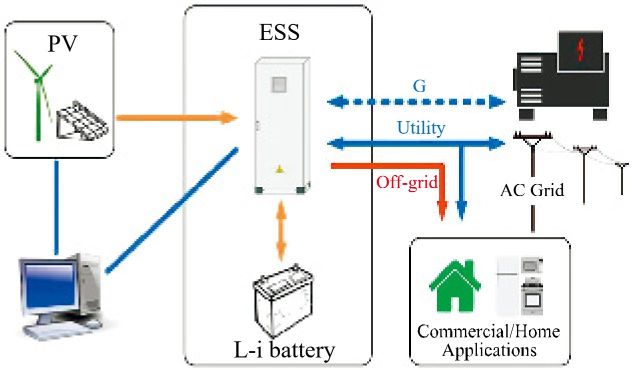

Fig. 13. ESS modes in power system application.

VI. CONCLUSION

For the lithium-ion battery in a chemical ESS, it is necessary to consider the safety, power consumption, efficiency, cycle life, space, and maintenance period. The lithium-ion battery charging and discharging curves demonstrate favorable characteristics.

Fig. 7 shows the lithium-ion battery charging curve in normal condition of grid power. Fig. 12 shows the lithium-ion battery discharging and charging curves during grid power loss and recovery. The curves show that the lithium-ion battery has safe and stable charging and discharging abilities.

Fig. 12 shows the simulation of lithium-ion battery charging process. Under stable conditions, when grid power is restored, after discharging in case of power loss, the charging curve is proportional to the capacity of the lithium-ion battery and to the charging time. Therefore, using lithium-ion batteries in an ESS model for energy storage applications is an acceptable choice.

An analysis of the results of this paper indicates that the use of lithium-ion batteries as the battery type in an ESS model is an acceptable choice.

An ESS is different from a UPS because a UPS is only used in case of normal power loss, voltage drops, and frequency changes beyond a limit. It quickly switches the power supply to battery mode to provide power, to maintain output, and to avoid loss. If an internal fault occurs in the UPS, it switches to bypass mode to maintain output and avoid loss. An ESS has similar functions as a UPS, however, it can also meet changes in power demand to save electricity expenses and to reduce utility power demand. The main benefit of ESS is when the power shortage happens at peak times because it can save grid power to meet power demand to maintain a minimum grid reserve capacity rate of 6% for grid safety dispatch and operation, along with stability and reliability.

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