Design of a Full-Time Security Protection System for Energy Storage Stations Based on Digital Twin Technology

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Abstract. Safety is a prerequisite for promoting and applying battery energy storage stations (BESS). This paper develops a Li-ion battery BESS full-time safety protection system based on digital twin technology. Firstly, from the source of safety risk of BESS, the multi-physical characteristics of "electrical-gas-sound-image" in the thermal runaway (TR) process are integrated, and a multi-level early warning protection method for BESS is proposed. It can realize real-time sensing and early warning of multi-time scale safety status from regular operation, micro-overcharge, and TR to fire. Based on the digital twin technology, the core features of the BESS digital twin are described in six aspects: the accurate mapping of virtual reality, real-time sensing, and edge processing, and the overall design framework of the digital twin BESS safety protection system is proposed. The digital twin safety protection system can fully use BESS's massive operation data, improve BESS's safety coefficient and uncover potential failure risks, providing a new idea for the digitalization and intelligence of BESS operation supervision and safety production.

Keywords: Digital twin · Battery energy storage station · Multi-level warning · Safety protection · Lithium-ion battery

1 Introduction

Electrochemical energy storage technology is widely used in power systems because of its advantages, such as flexible installation, fast response and high control accuracy [1]. However, with the increasing scale of electrochemical energy storage, the safety of battery energy storage stations (BESS) has been highlighted [2]. In July 2021, the National Development and Reform Commission pointed out in "Guidance of the National Energy Administration on Accelerating the Development of New Energy Storage (No. [2021] 1051)" that the safety of BESS should strengthen, and should enhance the online monitoring of system operation status. The level of safe operation should be improved. Safety is a prerequisite for promoting and applying BESS.

Digital twin technology was first used by NASA in the Apollo project and is now widely used in many fields such as intelligent manufacturing [3], agriculture [4], and

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aerospace [5]. The digital twin technology makes it possible to digitize and intellectualize BESS's operation supervision and safety production. Many cutting-edge scholars and experts have already taken the lead in applying digital twin technology to power equipment, grid dispatching, grid fault detection and other power fields. Weihan Li et al. of RWTH Aachen University realized online monitoring of battery status and health state assessment based on digital twin technology [6]. Shen Shen et al. of Tsinghua University, based on the CloudEPS platform, carried out integrated energy system scheme planning and design for a building-shaped park in the south, realizing intelligent planning and decision making for energy Internet [7].

However, digital twin technology is less studied in the intelligent operation and maintenance of BESS. On the one hand, the application of this technology in BESS is still in its initial stage. On the other hand, the various sensor data of BESS and the complex working conditions of multiple risk sources are difficult to represent by traditional techniques accurately as well as to simulate and deduce the abnormal conditions [8].

This paper takes BESS security protection as the application background and designs a BESS full-time domain security protection system based on digital twin technology. Firstly, we analyze the safety risk sources of BESS and propose a multi-level safety protection method for BESS with the integration of "electrical-gas-sound-image" multi-physical characteristics. Secondly, by describing the core features of the digital twin BESS at the definition level, the overall framework design of the digital twin BESS is proposed, and a BESS digital twin security protection system is built. Compared with the traditional early warning system, the digital twin safety protection system:

- Can make full use of BESS's multi-dimensional monitoring data.
- Improve BESS's safety coefficient and uncover potential failure risks.
- It provides a new idea for digital and intelligent BESS operation supervision and safety production.

2 Digital Twin Technology

2.1 Digital Twin Battery Energy Storage Stations

The digital twin BESS is a multi-physical, multi-dimensional virtual model that interacts with the real BESS in real-time through digitalization, networking and intelligence. Key data of BESS such as voltage, current, gas concentration, temperature, humidity, sound and images are connected to the network for monitoring. By centralizing data, algorithms and decisions in one, it can model and simulate and visualize all aspects of BESS production scheduling in a virtual computer environment, supporting design planning, simulation verification and analysis and evaluation of each aspect. At the same time, the digital twin BESS monitors and maps changes occurring in the physical BESS in real-time. Providing real-time data collection, optimizing production efficiency, and predicting potential risks helps O&M staff better understand failure risks and provide effective solutions.

2.2 Features of the Digital Twin BESS

Combined with the application requirements of digital twin system in other operation supervision and security protection, six core features of digital twin BESS are sorted out.

(1) Accurate mapping of virtual reality. In building the BESS digital twin, the equipment size, performance parameters, assembly relationship and real environment in the entity, BESS should be accurately expressed in the virtual model.
(2) Real-time sensing feedback. Realize real-time sensing and monitoring of BESS operation status through sensing collection at various levels such as electrical, sound, image, and temperature signals.
(3) Edge data processing. Considering the huge amount of data generated during the operation of BESS, it will be a serious challenge to the server if the data is directly transferred to the central monitoring system, so the data needs to be initially processed, filtered and stored at a specific location before uploading to the cloud.
(4) Fault diagnosis and prediction. Based on the abnormal data monitored by multiple sensors, the digital twin system searches for the root cause of the equipment abnormality and predicts it based on the failure model. BESS takes the best measures before the abnormality turns into an accident and avoids it to the maximum extent.
(5) Autonomous model learning and optimization. The algorithms, models and decision-making mechanisms in the digital twin system should constantly be self-learning. The system will continuously optimize and update the existing models based on the analysis of massive operational data, enabling the system to adapt to different working conditions and improve the prediction accuracy.
(6) Visual interactive presentation. The digital twin system uses the 3D modeling software Blender to build an accurate 3D model and Unity, a virtual engine, to render the real-time data stream. It makes the operation and maintenance personnel intuitively feel the current state of the whole BESS.

3 Digital Twin Technology

3.1 BESS Full-Time Security Protection Method

With the massive amount of data from the operation of the BESS, systematic analysis of the risk sources of lithium-ion battery BESS is the core step to build a safety protection system. The risk sources are analyzed as shown in Fig. 1, mainly from five aspects, namely: battery failure, system failure, equipment failure, environmental factors and human factors.

According to the current available BESS safety accident investigation report, BESS safety issues are the root of the lithium-ion battery safety issues. The safety of the battery in the charging and discharging process is often the main factor causing the battery thermal runaway (TR) fire or even explosion. Overcharge will lead to the decomposition of the battery solid electrolyte interface, bulging deformation, increased heat production, lithium dendrite growth and the occurrence of TR. Especially when overcharging, the heat accumulation will eventually lead to TR [9], posing a great threat to BESS safety protection if not properly handled in time.

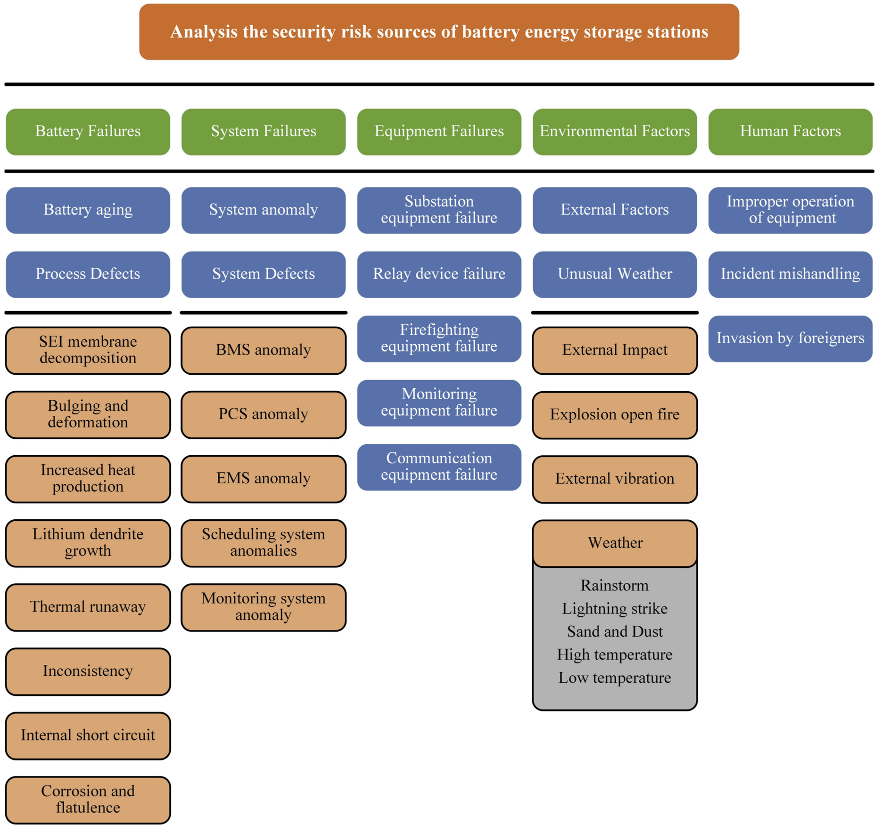

Fig. 1. BESS risk sources.

3.2 TR Early Warning Method Based on Multi-feature Parameter BESS

Batteries present many state parameters at the beginning of an accident, including external and internal signals, and are in a constant state of evolution. It is crucial to select and identify their effective signals as safety warning feature parameters. Based on the team's years of research, this paper proposes a TR early warning method based on multiple feature parameters from four dimensions: internal temperature monitoring (electrical signal), gas detection (gas signal), sound recognition (sound signal) and image recognition (image signal).

3.3 Full-Time Multi-level Security Protection System Design

Using the characteristics of the early TR of Li-ion battery BESS, a full time-domain multi-level safety protection system for Li-ion battery BESS is established from four perspectives of "electrical-gas-sound-image" signals. The system will collect multi-dimensional parameters to evaluate the safety status of BESS in real-time. Different types of warning signals will be issued for different abnormal conditions, and different protective measures will be linked.

A collaborative cloud-side approach is adopted to diagnose and predict faults more quickly. The "sound signal-characteristic sound" and "image signal-characteristic image" are processed at the side in compartment units, and only the processed data are sent back to the central monitoring system of the BESS. The "electrical signal-characteristic impedance" and "gas signal-characteristic gas" are uploaded directly to the central monitoring system of the BESS and compared with the fault model in real-time. A warning signal is immediately issued when a fault signal is detected, and a linkage strategy is adopted.

It is sensitive to identifying minor faults (e.g., the high internal temperature of individual cells) and eliminates potential hazards by changing the operation strategy. When "gas signal and characteristic gas" and "sound signal and characteristic sound" are detected, a warning signal is issued, and the faulty battery is withdrawn from operation to avoid the spread of the accident so that it can avoid the occurrence of TR and other accidents more than 10 min in advance. In addition to issuing a warning signal, the "image signal-characteristic image" links with relevant fire-fighting measures to avoid fire and explosion accidents. Through the strategy of multi-level safety protection in the whole time domain, the identification and treatment of multi-level faults of a single unit, module and system are realized.

4 Design of BESS Security Protection System Based on Digital Twin

4.1 Framework Design

The digital twin BESS is based on digital models, big data analysis and artificial intelligence. Driven by massive key data and intelligent algorithms, it realizes two-way interaction and real-time information interoperability between digital virtual BESS and real BESS using digital twin technology. Its digital twin BESS framework design is shown in Fig. 2.

Combining the current development status and functional requirements of BESS technology in China, the digital twin system is divided into a physical layer, perception layer, communication layer and twin application layer.

(1) Physical layer. The physical layer is the cornerstone for building the digital twin system, which creates virtual digital models for physical entities through digital twin technology and provides accurate mapping, behavior simulation and state prediction for the real BESS.
(2) Perception layer. The perception layer is the "sensory system" of the digital twin, which obtains key data from the BESS in real-time through various sensors and measurement devices. It is used to drive the operation of the digital twin system.
(3) Communication layer. The communication layer is transmitted to the twin application layer via a wired network, LAN, Bluetooth, Beidou communication, WIFI, 5G or 4G, etc., to provide data support for the operation of the twin application layer.
(4) Twin application layer. The twin application layer encapsulates models, algorithms, simulations, predictions and specific functions in the digital twin system. It presents them in a visual form to the user side.

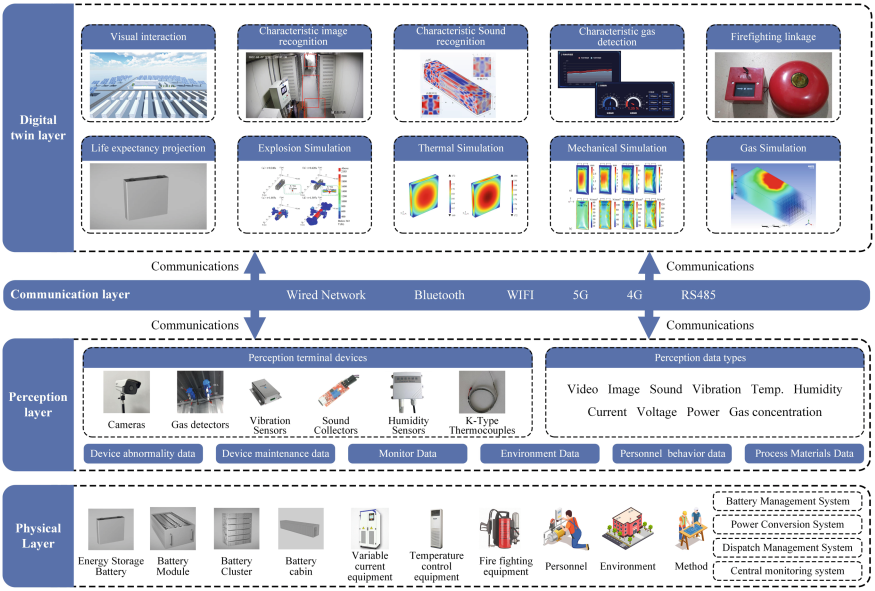

Fig. 2. Digital Twin BESS Security Protection System Framework.

4.2 Digital Twin Security Protection System Implementation Solution

The BESS digital twin security protection system is divided into five parts: interactive system, data processing, simulation analysis, edge processing and communication security implementation. The development languages involved are VUE, JavaScript, C#, Egg.js and Python, and the system uses various encryption methods to encrypt the data stream to ensure the system communication security. The main technologies used in each module of the twin system are shown in Table 1.

Table 1. Main technologies used in each module of the twin system.

Function Modules	Technology			
Interaction System	HTML	CSS	Unity	Blender
	VUE	Egg.js	JavaScript	C#
Data Processing	Redis	C#	SciPy	Numpy
	Python	Pandas	Scikit-learn	MySQL
Simulation Prediction	FLACS	ANSYS	COMSOL Multiphysics	
Edge processing	TSN	NeSTiNg	FPGAs/SoCs	OMNeT++
Communication Security	Crypto	jwt	sha256	HTTPS

(1) In terms of an interactive system. Use Blender to model the devices in the physical world accurately. The model is rendered using Unity, a virtual engine, and the Unity project package is packaged into Webgl.js and imported to the website for display rendering. The website is mainly written in HTML, CSS, VUE and JavaScript, and Egg.js is chosen as the programming language for the server side.
(2) In terms of data processing. Firstly, the sensor acquisition data is processed by the method of the downscaling transformation matrix. After obtaining the characteristic pattern of a certain type of event (disturbance, accident, etc.), it is constantly calibrated with the real collected data to improve the sensing signal's accuracy.
(3) In terms of simulation prediction. COMSOL Multiphysics software is used for battery TR simulation and mechanical simulation. This simulation software is well adapted to the battery TR involving multi-factor coupling, which can solve the problem of TR research requiring a large number of partial differential equations and has strong applicability [10]. The gas simulation uses ANSYS software to optimize the gas detector location by performing a diffusion simulation of the characteristic gas and then studying the propagation velocity and path. Explosion simulation uses FLACS explosion simulation software to give blocking explosion spread protection strategy and fire linkage measures by studying the impact of gas explosion in energy storage compartment triggered by battery TR.
(4) In edge processing. For the problem of packet loss or non-deterministic time delay transmission of key information in grid-level energy storage communication systems, a "cloud-edge-end" cooperative processing scheme is adopted. The "end", i.e., the BESS individual battery, module and cluster side, adopts the sensing information priority classification technology and improves the robustness of the communication system in case of wired network failure based on the wired-wireless redundant master-slave network architecture. The "edge", i.e., at the TSN gateway, forms an edge computing node to effectively share the load pressure of the BMS in the cloud. The "cloud" is the energy storage battery management system, the unified management of intelligent battery analysis and decision-making.
(5) In terms of communication security. Crypto, jwt, sha256 and HTTPS are chosen to encrypt data streams. The Crypto module provides encryption functions, including hashing, HMAC, encryption, decryption, signature and verification functions of OpenSSL, which guarantees the security of information transmission while transmitting information efficiently.

Based on the above implementation scheme, our team has built a visual digital twin BESS security protection system, as shown in Fig. 3.

Figure 3 shows the main interface of the system. Among them, Fig. 3a shows the main interface of the digital twin safety and security system, Fig. 3b shows the 3D visualization demonstration interface of the digital twin safety and security system, Fig. 3c shows the interface for viewing the operating status of the energy storage compartment, and Fig. 3d shows the interface for monitoring the battery pack inside the energy storage compartment. Among the main pages, from left to right and from top to bottom, are the general overview of on-grid devices, currently selected BESS, historical alarm time statistics, internal and external battery temperature, on-grid power plant selection

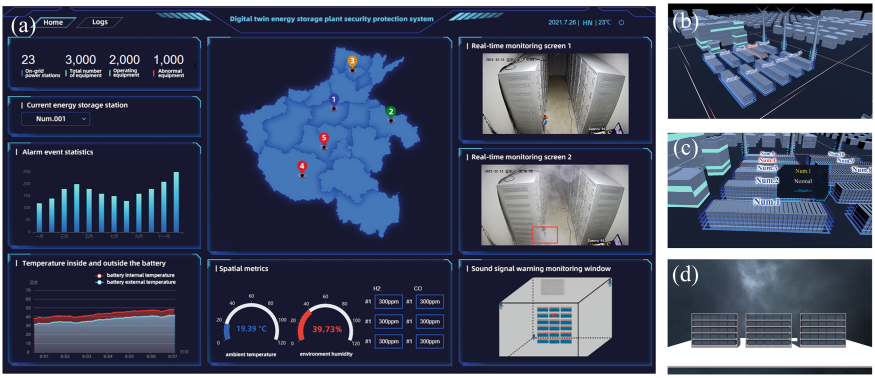

Fig. 3. Digital Twin Security Protection System.

window, space indicator window, energy storage compartment real-time monitoring window 1, energy storage compartment real-time monitoring window 2 and sound warning monitoring window.

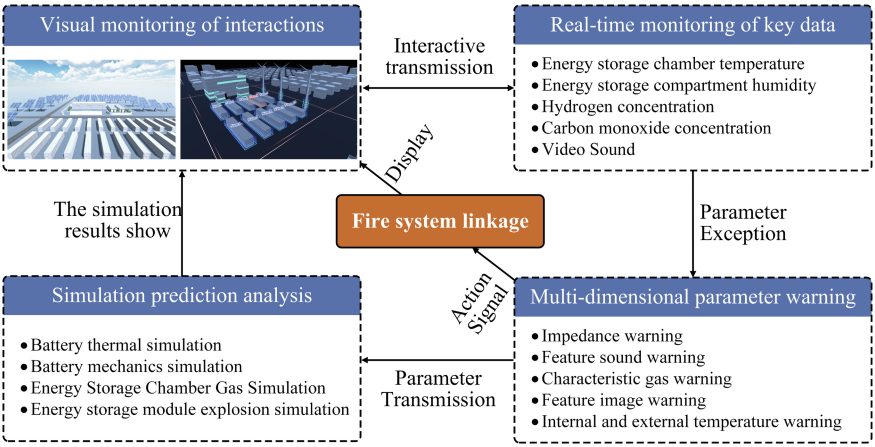

Fig. 4. Digital twin security protection system operation mechanism.

The operation mechanism of the digital twin security protection platform is shown in Fig. 4. The system monitors the temperature, humidity, video, sound, hydrogen concentration and carbon monoxide parameters of the storage compartment through various sensors to estimate the state of the storage compartment comprehensively. It visually presents the results of the system. When the system detects abnormal data, it will send an abnormal signal alarm in different forms. It will link with the fire fighting system for necessary failures, thus reducing the chance of accidents. While the alarm occurs in the system, according to the abnormal parameters, the multi-dimensional simulation will also run simultaneously in different sub-systems. The final simulation results will be displayed in the system in virtual rendering.

5 Conclusion

In this paper, we propose to integrate digital twin technology with BESS and give the connotation and core features of digital twin BESS and the framework. Based on this, a lithium-ion battery BESS digital twin safety protection system is constructed, which realizes real-time sensing and mapping of BESS full-time domain multi-level safety protection and status. It also provides comprehensive evaluation for different types of abnormal signals and fire linkage for necessary faults, effectively improving BESS's safety operation reliability. However, the construction of the overall digital twin system of BESS is a huge project involving extensive technology and difficult integration, and its theoretical system support cannot be achieved overnight. This paper is expected to provide inspiration and reference for the research on the application of digital twin technology in BESS.

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