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Analysis on Design Failure Mode of Residential Energy Storage System

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Abstract: Residential energy storage system seizes more market share in Europe than other regions on account of terminated feed-in-tariff subsidy policy and boost in solar PV installation. This paper analyses failure mode effects of residential energy storage systems to improve product design quality. Firstly, market profile and residential energy storage system category is summarized, engineering and working principle is illustrated; then, DFMEA succession and evolution are interpreted to better understand the significance referring to engineering quality; Finally, the practical case related to DFMEA on residential energy storage system is described progressively by hierarchical tree which individually describe the structure analysis, function analysis, failure analysis, risk evaluation, optimization measurements. The research results can provide process guidance for design failure mode analysis and precautions during the research and development process of residential energy storage system.

1. Introduction

Aiming to alleviate tendency of planetary warming, restraint global ambient temperature rise within 2℃is essential, which requires greenhouse gas net-zero emissions. As claimed by IPCC, to alleviate global warming, power sector decreases utilizing of existing fossil fuel installations and postpones new installations, industry and transportation sectors contribute principally on CO2 emissions reduction [1] by using green raw material, promoting electric vehicles.

Popularizing of renewable energy, like wind and solar, their randomness and discontinuity gradually affect power supply stability. In addition, incentive polities subsidies and allowances released from regions, these uncertainties make electricity price fluctuate to a considerable degree [2]. Reliable and economic efficiency power supply lays solid foundation for universal electrification of household devices in modern life. Homeowners seeking to increase resiliency, programs change in net metering, and the financial benefits [3] stimulate the emerging and boost of residential energy storage system.

To address the phenomenon of the potential uneven design quality for manufactures in industry fields, Xin Li et al. [4] proposed DFMEA methods to analyse potential risk items in energy storage station, formulating effective design prevention countermeasures and personnel emergency measures, and the results showed that the analyzation improved the reliability of the battery. Russell Watts, et al. [5] presents a flexible alteration to typical FMEA methodology that may cut typical FMEA completion time by as much as ½ while simultaneously increasing effectiveness of the process in terms of improved final product characteristics. The key to this alteration is a focus on the Recommended Actions (RA) portion of the standard FMEA process. Sarath Jayatilleka, et al. [6] discusses SysML diagrams used across new product development processes to discover functional requirements that may be missed otherwise and feed the DFMEA to have a good start to an effective FMEAs.

Few studies have been conducted on design failure mode effect analysis in the phase of RESS development, while some take battery failure mode effect as the research goal to identify structure failure of positive and negative material, ignoring the mutuality and interactions of sub-system, such as pack model combined with battery and BMS in the energy storage system. In addition, some highlight optimization measures and ignore the construction analysis as a start to clearly understand the boundary and structure of targeted object. Therefore, this paper constructs a DFEMA workflow model to maximize system reliability by establishing constructional and functional hierarchical structure to keep all parts and functions clearly visible and to avoid being omitted, analysing the failure mode effect of ESS and putting forward countermeasures, so as to improve the of RESS.

The structure of this paper is as follows: Section 2.1 analyse Europe residential BESS market cumulative scenario; Section 2.2 constructs BESS function, category and working principal; Section 3 presents DFMEA application; Section 4 is case analysis; Section 5 is a summary.

2. Product Market Cumulative Scenario

Jonathan et al. [7] advances a flourishing development of residential BESS market in Europe from 2022 to 2026. Predicts a pessimistic 3 GWh installation capacity with 30% annual growth in the Low Scenario, whereas the 5.2 GW High Scenario resulting in a 128% growth in 2022. Anticipate High Scenario 44.4 GWh contrasting with Low Scenario 23.2 GWh and Medium Scenario 32.2 GWh in 2026 owing to the soaring growth of the residential solar rooftop market.

2.1 System Function

A residential energy storage system provides an uninterrupted power supply during blackouts. [3] It enables the integration of more renewables (especially solar PV) in the energy mix at a residential scale.

This system increases energy security by optimizing the supply and demand ratio. It also provides system stability during electricity outages by supplying energy and reducing the costs of power outages. Developing such energy storage systems decreases the need to invest in conventional power generation infrastructure, resulting in cost savings and reduced emissions. [3]

2.2 System Category

Residential BESS system product works both in grid-tied and off-grid mode, in the case of power outage, electricity power to the household apparatus will be provided from the residential BESS system product instead of the power grid.

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Words like “is”, “or”, “then”, etc. should not be capitalized unless they are the first word of the title.

3. Product principal and construction

Battery packs and integrated inverter mutually construct residential energy storage system.

3.1 Principal

Residential BESS system works both in grid-tied and off-grid mode, in the case of power outage, residential BESS provide electricity power to the household apparatus substituting for the power gird.

3.1.1 Power transmission

In order to realize electric power transmission between battery and PCS, an electrical path is constructed to achieve electricity flowing from plate lugs on each battery module, through BMS ports and fast-plug connectors in sequence, eventually into power converter systems.

3.1.2 Communication mode

Aiming to be capable of fulfilling electric power demand in various specific scenarios, BMS is designed to realize the communication between battery packs and PCS, by monitoring and controlling cells status and equalizing electricity among cells.

3.2 Construction

The energy storage system consists of a power control module and a battery expansion module, which can store and release electric energy according to the requirements of the inverter management system. Electrical power is transmitted bi-directionally between the residential energy storage system and power converter system in conformity with specific requirement in varied scenarios.Fig.1 shows the pack system in residential energy storage system.

Figure 1: Outline of residential energy storage system

4. DFMEA development and application

AIAG, VDA, and SAE are among the most influential organizations in the world that apply FMEAS. AIAG and VDA jointly published the AIAG VDA FMEA Manual in June 2019. This manual replaces the fourth version of the FMEA manual published by AIAG in 2008 and the FMEA standard for VDA products and manufacturing published in June 2012.[8]

DFMEA tool is used to connect the product designer with the end user, so as to form a closed loop of product design and use. At the beginning of the design, the failure that may occur in use is identified, root cause analysis is carried out, preventive measures are proposed, risk prioritization is further conducted, and improvement measures are proposed to reduce the risk of failure.

Fig.2 DFMEA workflow diagram illustrates five major steps during DFMEA implementation process, starting with DFMEA preparation, being followed by product analysis and risk analysis, furthermore optimization and ending at DFMEA documents.

DFMEA team is established and target object is determined in the first step of DFMEA preparation. Firstly, different team member roles and their functions are confirmed before DFMEA being executed, followed by defining target objects which is system, subsystem or component level, and confirming with analysis borderline such as outer customers, service and manufacturer.

Secondly, system analysis, including of constructure analysis, function analysis and failure mode analysis, is conducted. In order to acquire the specified hypotaxis, constructure analysis needs to be started from the step of decomposing the integrate system into subsystems and components. Aiming to define interaction between single part, energy transfer pathway, information transfer pathway and physical contact are well defined to assure nothing is missed in deconstruction process. Boundary-diagram and construction tree-diagram are normally applied in product analysis process as ancillary analysis tools to benefit for structural thinking in product analysis process. Following with function analysis, in order to identify roles of various parts, function analysis is conducted by defining required effects and their corresponding executive subjects. Ending with failure mode analysis, which is implemented to identify potential failure modes, causes, and failure effects quantified as severity, preparing for specific countermeasures to be conducted to dilute failure effect.

Thirdly, risk analysis is executed after product analysis. Aiming to define controlling approaches to weaken failure effects, risk analysis is performed by recognizing current precaution control characterized as frequency of occurrence, and correspondent prevented detection control defined as detectability. In order to assure resources being assigned with critical issues, action priority is evaluated via the product of severity, frequency of occurrence and detectability, the higher the number, the higher the action priority and the greater the failure effect.

Fourthly, improvement measures are tendered based on above analysis data. Improving measures stage, mainly concludes precaution measures, detective measures, improvement measures description, person in charge of improvement measures and timeline and status of improvement actions. After series of improvement actions, product of severity, frequency of occurrence and detectability is revaluated to assure these countermeasures are effectual.

Lastly, DFMEA data is documented as knowledge accumulation for subsequent application.

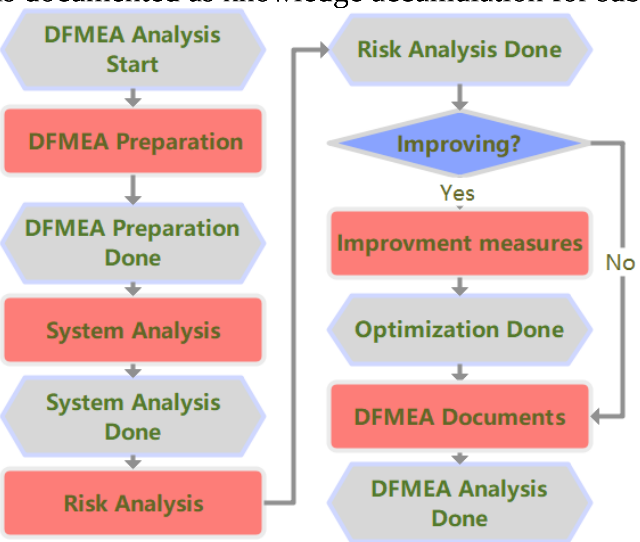

Figure 2: DFEMA workflow diagram[8]

5. Case Study

5.1 DFEMA Preparation

5.1.1 The object of residential energy storage system DFMEA

Residential energy storage system is the whole system, wherein pack system is the most critical subsystem, according to functional category, furthermore, cells and BMS are of primary importance in the pack system. So, the cells and the BMS in the pack system are defined as DFMEA target objects.

5.2 DFEMA Analysis

5.2.1 Residential energy storage system structure analysis

Structure analysis is used to reveal the fundamental constitute elements of the residential energy storage system, depict transfer process of energy and information within this whole system and reveal physical contacts among the major components. Fig.3 and Fig.4 illustrate there are 4 major subsystems in the whole residential energy storage system including of wiring box, connections, pack system and base. Take the highlighted PACK System as example, which consists of cells, BMS and structure sheet metal, wherein, energy and information are transferred between BMS and cells, structure sheet metal is physically supporting BMS and Cells.

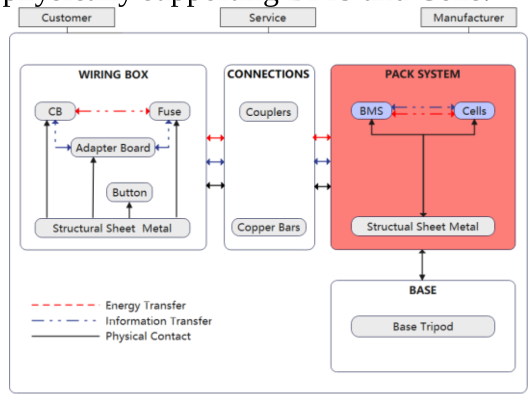

Figure 3: Residential energy storage system boundary diagram

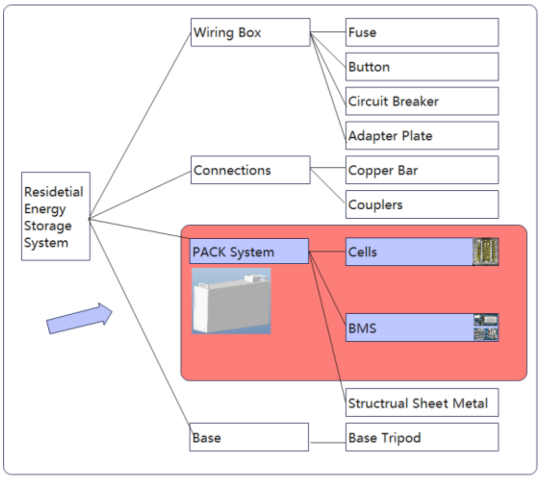

Figure 4: Residential energy storage system structure analysis hierarchical tree

5.2.2 Residential energy storage system function

Function analysis identifies key features of each main components. Fig.5 presents functional decomposition of residential energy storage system. Wiring box is designed to connect RESS with power converter system. Connections is acted as the transferring pathway for electrical energy and communication signal between two adjacent subsystems. Pack system is used to reserve and release electrical energy according to requirement. Base is equipped as physical support of Pack system. Within the highlighted pack system in Fig.5, cells are used for electric storage and release, BMS is used for Li-ion battery management, such as cell overvoltage and undervoltage control, SOC and SOH statistic analysis etc.

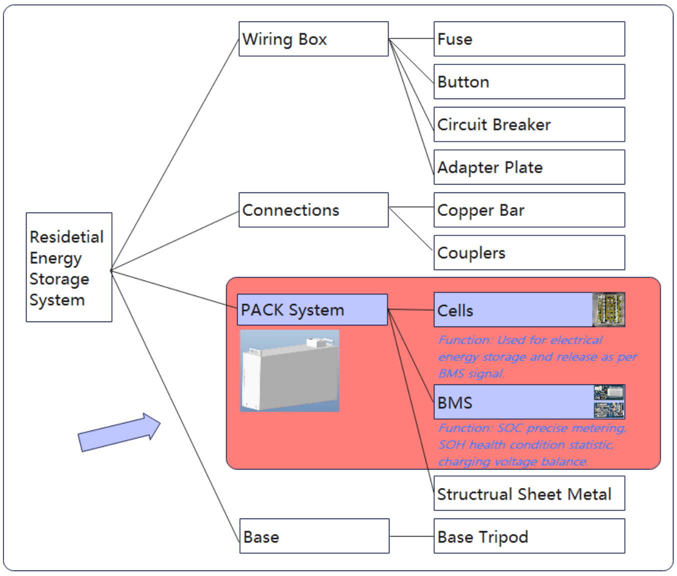

Figure 5: Residential energy storage system function analysis function hierarchical tree

5.2.3 Residential energy storage system failure Analysis

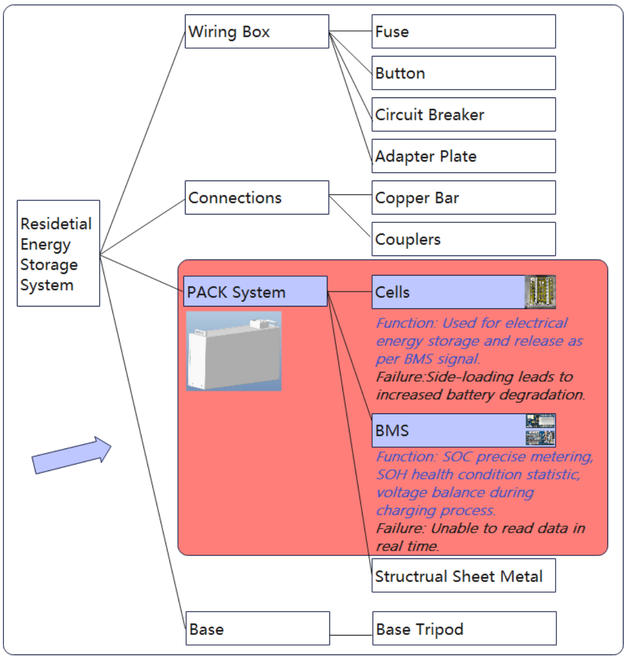

Figure 6: Residential energy storage system failure analysis hierarchical tree

In order to identify potential failure mode of key components and bring out countermeasures to reduce damage to RESS, risk analysis is carried out. As shown in Figure 6, in the highlighted pack system, one of cells failure modes is when cells are laid on their sides, electrical energy in cells is degraded because stress of lugs is increased to a certain extent. Switching to BMS, one failure is communication not in real time, cells data can only be read 2 seconds later because MODBUS communication can only be polled; another failure is PCS does not wake up cells after batteries are completely empty because voltage is not automatically outputted to charge the battery and activate it after PCS recovers power supply.

Table 1 converts the structure and functional analysis results from above hierarchical trees into the form.

Table 1: Structure analysis and functional analysis form of residential energy storage system

Structural Analysis			**Functional Analysis**		
Product, element or process system structure			Function profile of product or process		
System (Project)	System/ Relative interface	Part element (Project/Interface)	Function, requirement and expected output of system	Function, requirement and expected output of elements	Function, requirement and expected output and property of parts
Residential Energy Storage System (RESS)	PACK System	Cells	Electricity energy storage or release according to photovoltaic power capacity and customers' electricity load condition.	Electric energy reserved and released by cells when required.	Electric energy store or release according to BMS instruction.
		BMS			SOC precise metering, SOH health condition statistic, charging voltage balance during electric charging process.

Table 2 reveals failure chains of cells and BMS. Failure chain is a causal relationship loop for components, failure mode is failure form or phenomenon, failure cause is related reasons that provoke failure mode, failure effect is influence to customers in case of failure mode. It also quantitatively represent severity of each failure mode, which is used, combined with numbers of frequency of occurrence and detectability, to reckon the action priority in next risk evaluation step.

Table 2: Failure analysis form of residential energy storage system

	Failure analysis			
	Failure chain establishment (each product or process or function, analyse potential failure effect, failure mode, failure cause)			
	Failure effect	Severity	Failure mode	Failure cause
Cells	Side-loading aggravates battery's attenuation and reduce the defined life cycles under required SOH.	6	Cells are loaded in a special way.	Stress of lugs of the cells is increased to a certain extent.
BMS	Battery communication data is delayed by 2 secs instead of in real time, which makes the battery status data can't be read in real time.	5	Can't read cells status data in real time.	Communication delay occurs when parameters are written, because the communication mode of Modbus can only be polled.
	Battery goes into hibernation. Battery charging and discharging cycles cannot operate normally.	5	PCS can't wake up cells after energy in the batteries is completely empty.	After PCS's power supply is recovered, the voltage is not automatically outputted to charge the battery and activate the battery.

5.2.4 Residential energy storage system risk analysis

After previous product analysis, RESS DFMEA is drifted onto step of risk analysis. Table 3 Risk Evaluation identifies controlling method against failure cause and failure mode, defines numbers for quantitative assessments on two parameters of occurrence frequency and detectability, after multiplying with severity of failure effect in risk analysis form, action priority is arranged in sequence, when the calculated AP is H or M, improvement measures need to be performed.

Table 3: Failure analysis form of residential energy storage system

	Risk Evaluation				
	Identify controlling method regarding failure cause and failure mode				
Cells	Current preventive control	Frequency of occurrence	Current detective control	Detectability	AP (Action priority)
BMS	1. increase stress of the end plate; 2. Preserve gap between cells to provide expansion space.	4	Current detective control	5	M
	Polling interval is reduced to 1 sec per pack and total interval is 4 seconds.	3	Visual inspection	4	M
	Manually activate the battery.	3	Visual inspection	4	M

5.2.5 Residential energy storage system improvement measures

Necessary measures are confirmed in Improvement measures step to reduce risks in last step.

Table 4 Detailed countermeasures are brought forward to address failure modes with action priority assessed as H or M in risk evaluation step.

In the pack system, preventive measures such as increasing end plate strength and preserving gap between cells are adopted to reduce battery degradation. Turning to the BMS, one improvement measure to fasten polling speed, such as reduce polling interval into 1 second per pack to reduce communication time interval, another improvement measure is at the moment PCS detects output voltage and charges battery, after power supply from city is recovered.

Table 4: Residential energy storage system improvement measures form

	Improvement Measures						
	Confirm necessary measures to reduce risks						
	Preventive measures	Detective measures	Improvement measures description	S	F	D	AP
Cells	l. Lay flat or upright. If lay side is necessary then equivalent stress of end plate is less than that of 10mm Aluminium fixture; 2. Recommend 0.5mm-0.7mm strip gap between cells, and not interfering with lugs.	Visual inspection	Feedback as meeting with the warranty requirements of 1350 kWh in l0 years.	2	2	5	L
BMS	Fasten polling speed, Done or Error of previous command trigger next one.	Visual inspection	Feedback as meeting with the requirement.	1	2	6	L
	Automatic activation of charging. Does not shut down after undervoltage protection, at the setting interval, the output voltage is detected by the inverter; can charge the battery after electric power from the city is recovered.	Visual inspection	Feedback as meeting with the requirement.	1	2	5	L

5.3 DFEMA Improvement verification

8.2.2	TABLE: Overcharge control of voltage (battery system)				P
Sample No.	OCV at start of test for Cell/Cell Blocks, (V dc)	Maximum Charging Current, (A)	Max. Charging Voltage, (V dc)	Max. Voltage of Cell/Cell Blocks, (V dc)	Results
CPS ESSR-05KL1	2.89 to 2.94	50	57.55	3.611	A

8.2.3	TABLE: Overcharge control of current (battery system)			P
Sample No.	OCV at start of test, (V dc)	Max. Charging Current, (A)	Max. Charging Voltage, (V dc)	Results
CPS ESSR-20KL1	50.1	240	51.8	A

8.2.4	TABLE: Overheating control (battery system)		P
Model No.	OCV at start(SOC 50%) of test, V dc	Maximum Charging Current, A	Measured Maximum Charging Voltage, V dc
CPS ESSR-05KL1	52.6	50	54.6
Maximum Specified Temperature of Battery System, °C		Maximum Measured Cell Case Temperature, °C	Results
50		49.8	A

Figure 7: IEC 62619 battery system overcharge control test result

When performing overcharge control tests according to IEC 62619, the exceeded voltage can be applied on the cell(s) in the battery system, Fig.7 test result showed that no fire or explosion occurred on the battery system after overcharge control of voltage/current and overheating control, the prototypes successfully passed the certificate tests. This test sufficiently proved the performance and function safety of residential battery system.

6. Conclusion

Based on the fifth DFMEA workflow, this paper analyzes the residential energy storage system design failure mode effect analysis to reduce development quality cost shorten product launching period and simultaneously improve product development success ratio.

Pack system is critical subsystem in resident energy storage system, furthermore, cells and BMS are top priority in pack system. Cells electrical power capacity will affect whole endurance life and commercial warranty, while cells layout will significantly affect cells capacity. Through implementing design failure mode effect analysis in early design stage, supplemented with simulation analysis, recommended measures are adopted to preventively eliminate potential failure effect, potential quality cost increasement resulting from design failure is avoided.

BMS is another key component, as the cells status management element, it is designed to prove cells work in the maximum efficiency, assure the whole residential energy storage system operated as per customer requirement, through reporting cells status in real time. In time communication with PCS and cells activation and hibernation as per specified triggering signal will directly affect customers using experience.

Generally, some limitations in this study deserve further study. Firstly, the research object is relatively limited, and it is necessary to further expand relevant elements leading to potential failure effect to improve design reliability. Secondly, the failure effect is caused by multiple factors' interaction, while the factors in this paper is limited by product design and manufacture features in this specific scenario, so the failure modes published in this paper is not sufficient enough. DFEMA analyser should use diverse ways to identify different failure modes under various scenarios, then establish failure chain and reasonably derive failure causes to effectively propose improvement measures for the product development.

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