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Reliability and Availability Analysis of Lithium-Ion Batteries under Multiple Failures

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Energy storage solutions based on lithium-ion (Li-ion) batteries are becoming more popular. These batteries are progressively used because of their competitive performance compared to other battery types. It is an improved battery technology, and the lithium ion is the main factor of its electrochemistry. Li-ion batteries can have a very high voltage and charge storage per unit mass and unit volume, also have several benefits in comparison to other high feature rechargeable battery technologies. There are various applications of Li-ion batteries such as consumer electronics, electric vehicle, and light power industry etc. Li-ion batteries for such type of systems are the main components, which should be safe and reliable throughout the operating lifespan of the systems. The increasing energy density of Li-ion cells (Wh/L) and at the same time the increasing amount of stored total energy in various solutions accentuate the efforts on battery safety and measures to maintain a maximum on safety and reliability. The reliability of Li-ion batteries is directly related to the life and safe operation of electric drive products. For the accurate assessment of the reliability of Li-ion batteries, it is important to build a reliability model considering the dependency among cells for the overall degradation of Li-ion battery packs. This paper presents a broad summary of the reliability assessment of Li-ion batteries under multiple failures. Different reliability measures such as reliability, availability and expected cost have been investigated with the help of Markov process and supplementary variable technique.

Keywords: Electrochemistry, Reliability, Availability, Expected profit, Markov process.

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1. INTRODUCTION

Reliability plays an important role and a useful means for risk management and decision making for secure, efficient, effective design and process of complex engineering systems. The scope of reliability study is to help in decision making such as evaluation of prototype, categorization of main components, operation, and maintenance behaviors. Most of the organizations are aware about the cost of unreliability due to high failure cost under warranty and because of which customer face inconvenience. Reliability engineering is an engineering which accentuates on availability and reliability of the system in the life cycle management of the product. Significantly the literature of reliability has inclined to highlights the scientific and logical features of the subject, with the outcomes that reliability engineering is frequently measured by creators and others to be acquire mysterious subject. Lithium-ion battery is becoming the mount for lots of electronic gadgets like compact electronic products. These batteries are also an empowering technology for electrified transportation which is helpful in environmental sustainability considerably. The reliability of these batteries is a primary concern currently. Energy storage devices in which lithium-ion batteries are not only cause acute problem and massive alternative/restoration cost for the battery, but also these batteries are responsible for catastrophic effects such as: fire exposure and possible detonation be-cause of overcharging or high temperature [13].

A rechargeable lithium-ion battery is made up of one or more power generating compartments known as cells. Each cell consists of are four main components of lithium-ion battery they are as follows:

Anode: Anode works as a negative pole at the time of discharge and works as a positive pole at the time of charging. Its main purpose to store Lithium ions and to release them back into the external circuit for the electric current flow. 90 % of Lithium-ion batteries use graphene as the anode material for cost stability and high safety.

Cathode: At the time of discharge, cathode's poles contrast with anode poles. A conductive aluminum foil is normally used as a current collector after that a metal oxide which contains 'Lithium' is glazed with solvent, a binder, a conductive agent, and a little conductive material. The life of these batteries is linked to the material used in the positive electrode.

Separator: Separator is a non-conductor small plastic that separates cathode and anode. To avoid battery self-discharge and short circuit between the two poles, the microporous film made of Polypropylene (PP)/ Polyethylene (PE) and other plastics, placed between the plates to block the positive and negative electrodes.

Electrolyte: Electrolyte is commonly made of a Lithium salt (hexafluorophosphate), and its purpose to let the ions flow between the positive and negative electrode. State of charge and discharge has been shown in Fig. 1 and Fig. 2, respectively.

Reliability is the foremost concern for almost every engineering system, lot of good work has been done by a number of authors in this field such as Kumar et al. [1] evaluated fuzzy reliability of series systems to prevent hesitant fuzzy sets and triangular fuzzy number. In this work, the authors also assessed fuzzy reliability of par-

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allel and linear consecutive k-out-of-n systems by using the application of Weibull distribution and Markov process. Chopra and Ram [2] investigated the availability and reliability of the system containing two different units in the parallel network under copula. Goyal et al. [3] analyzed numerous reliability measures of a complex systems with three subsystems in series configuration. Bisht et al. [4] proposed an algorithm to compute the reliability indices of the network. In this work authors explored about the working of the universal generating function to solve the network related problems with exponentially distributed failure rates. Kumar et al. [5] obtained the reliability of k-out-of-n: F system of non-identical elements by using intuitionistic fuzzy concept and Weibull lifetime distribution.

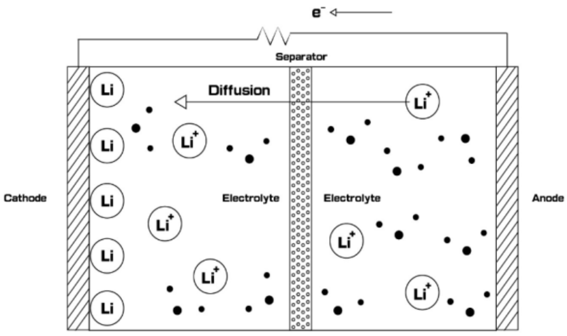

Fig. 1 – The state of charge

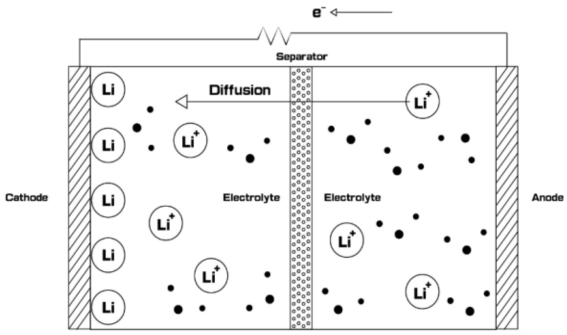

Fig. 2 – The state of discharge

Manglik and Ram [6] analyzed the various reliability measures of hydroelectric power plant under multiple failures with the help of Markov process. Manglik et al. [7] analyzed a reliability based mathematical model for multistate cloud computing transition system. Dai et al. [8] anticipated a different SOH (state of health) assessment method by using prior knowledge based neural network (PKNN) and Markov chain for a single lithium-ion battery. Meng et al. [9] discussed the diverse processes of internal failure of anode material for lithium-ion batteries. Wang et al. [10] presented a review on thermal runaway phenomenon and associated fire dynamics in single lithium-ion battery cells and in multi cell battery back. Gandomen et al. [11] presented impact of different failures on the reliability and safety of lithium-ion batteries in electric vehicles. Gandomen et al. [12] considered a case study for the assessment of reliability from practical and technical perspective.

This article presents, a scientific model of repairable lithium-ion battery due to the failure of its main components for different reasons. Primarily the battery was in good working condition it goes to failed state due to cathode failure because of dissolution loss in it, from where it is repaired. The battery goes to failed state due to the failure of anode because of overcharging, from here the battery is repaired again. It goes to failed state due to failure of electrolyte because of decomposition, from here also the battery is repaired again lastly it goes to failed state due to the failure of separator which is repaired from there. State transitions of the projected model has been presented in Fig. 3.

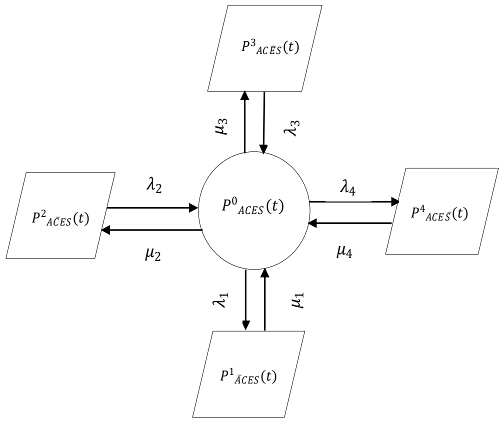

Fig. 3 – State transition diagram

2. ASSUMPTION AND NOTATIONS

The following assumptions have been taken throughout this work:

i. Primarily the battery is in good state.
ii. It has two states good and failed.
iii. All failure rates and repair rates are kept as constant.
iv. Repaired battery is assumed to work like a new one.
v. It can be repaired from failure mode.
vi. It is completely repairable.

$\lambda_1/\lambda_2/\lambda_3/\lambda_4$	Failure rates of anode /cathode /electrolyte and separator respectively
$\mu_1/\mu_2/\mu_3/\mu_4$	Repair rates from failed states S_1/ S_2/ S_3/ S_4 to good state S_0
$P_{ACES}(t)$	Probability of the battery in the good state
$P_{\bar{A}CES}(t)$	Probability of the battery in failed state due the failure of anode
$P_{A\bar{C}ES}(t)$	Probability of the battery in failed state due the failure of cathode
$P_{AC\bar{E}S}(t)$	Probability of the battery in failed state due the failure of electrolyte
$P_{ACE\bar{S}}(t)$	The probability of the battery in failed state due the failure of separator
$A(t)$	Availability of the battery in comprehensive state
$R(t)$	Reliability of the battery in comprehensive state
$E_p(t)$	Expected profit

2.1 State Description

S_0	Represents that the battery is in operating condition
S_1	Represents that the battery is in break down condition due to cathode failure (dissolution loss)
S_2	Represents that the battery is in break down condition due to anode failure (overcharging)
S_3	Represents that the battery is in break down state due to electrolyte failure (decomposition)
S_4	Represents that the battery is in break down state due to separator failure

3. MATHEMATICAL FORMULATION

$$\left[\frac{\partial}{\partial t}+\lambda_1+\lambda_2+\lambda_3+\lambda_4\right]P^0_{ACES}(t)=\mu_1 P^1_{\bar{A}CES}(t)+ +\mu_2 P^2_{A\bar{C}ES}(t)+\mu_3 P^3_{AC\bar{E}S}(t)+\mu_4 P^4_{ACE\bar{S}}(t) . \quad (1)$$

$$\left[\frac{\partial}{\partial t}+\mu_1\right]P^1_{\bar{A}CES}(t)=\lambda_1 P^0_{ACES}(t) , \quad (2)$$

$$\left[\frac{\partial}{\partial t}+\mu_2\right]P^2_{A\bar{C}ES}(t)=\lambda_2 P^0_{ACES}(t) , \quad (3)$$

$$\left[\frac{\partial}{\partial t}+\mu_3\right]P^3_{AC\bar{E}S}(t)=\lambda_3 P^0_{ACES}(t) , \quad (4)$$

$$\left[\frac{\partial}{\partial t}+\mu_4\right]P^4_{ACE\bar{S}}(t)=\lambda_4 P^0_{ACES}(t) . \quad (5)$$

Initial condition $P^0_{ACES}(t)=1$ at $t=0$ and rest state probabilities are zero primarily. On taking Laplace of equations (1-5), we get:

$$\left[s+\lambda_1+\lambda_2+\lambda_3+\lambda_4\right]\overline{P}^0_{ACES}(s)=\mu_1\overline{P}^1_{\bar{A}CES}(s)+ +\mu_2\overline{P}^2_{A\bar{C}ES}(s)+\mu_3\overline{P}^3_{AC\bar{E}S}(s)+\mu_4\overline{P}^4_{ACE\bar{S}}(s) \quad (6)$$

$$\left[s+\mu_1\right]\overline{P}^1_{\bar{A}CES}(s)=\lambda_1\overline{P}^0_{ACES}(s) , \quad (7)$$

$$\left[s+\mu_2\right]\overline{P}^2_{A\bar{C}ES}(s)=\lambda_2\overline{P}^0_{ACES}(s) , \quad (8)$$

$$\left[s+\mu_3\right]\overline{P}^3_{AC\bar{E}S}(s)=\lambda_3\overline{P}^0_{ACES}(s) , \quad (9)$$

$$\left[s+\mu_4\right]\overline{P}^4_{ACE\bar{S}}(s)=\lambda_4\overline{P}^0_{ACES}(s) , \quad (10)$$

$$\overline{P}^0_{ACES}(s)=\frac{1}{\left(H-\lambda_1\mu_1-\lambda_2\mu_2-\lambda_3\mu_3-\lambda_4\mu_4\right)} , \quad (11)$$

$$\overline{P}^1_{\bar{A}CES}(s)=\frac{\lambda_1}{A}\overline{P}^0_{ACES}(s) , \quad (12)$$

$$\overline{P}^2_{A\bar{C}ES}(s)=\frac{\lambda_2}{B}\overline{P}^0_{ACES}(s) , \quad (13)$$

$$\overline{P}^3_{AC\bar{E}S}(s)=\frac{\lambda_3}{C}\overline{P}^0_{ACES}(s) , \quad (14)$$

$$\overline{P}^4_{ACE\bar{S}}(s)=\frac{\lambda_4}{E}\overline{P}^0_{ACES}(s) , \quad (15)$$

where

$$H=\left(s+\lambda_1+\lambda_2+\lambda_3+\lambda_4\right), A=\left(s+\mu_1\right), B=\left(s+\mu_2\right),$$
$$C=\left(s+\mu_3\right), E=\left(s+\mu_4\right).$$

Laplace transform of the probabilities that the battery is in the active or inactive state (i.e., either good or failed state) at any time is as follows:

$$\overline{P}_{UP}\left(s\right)=P^0_{ACES}(s) , \quad (16)$$

$$\overline{P}_{DOWN}(s)=\overline{P}^1_{\bar{A}CES}(s)+\overline{P}^2_{A\bar{C}ES}(s)+\overline{P}^3_{AC\bar{E}S}(s)+\overline{P}^4_{ACE\bar{S}}(s) . \quad (17)$$

4. NUMERICAL ILLUSTRATION

4.1 Availability Analysis

It is the probability of a system which states about system's availability for operation under the specified working conditions.

For evaluating the availability of the lithium-ion battery, using the values of different failure rates as $\lambda_1=0.06, \lambda_2=0.07, \lambda_3=0.08, \lambda_4=0.09$ and all the repair rates as 1 in equation no. (16) and then taking the inverse Laplace transform, we get

$$A=0.7692307692+0.2307692308e^{-1.300000000t} . \quad (18)$$

Now by varying time t, we get Fig. 4, which signifies the variation of availability of the system with respect to time.

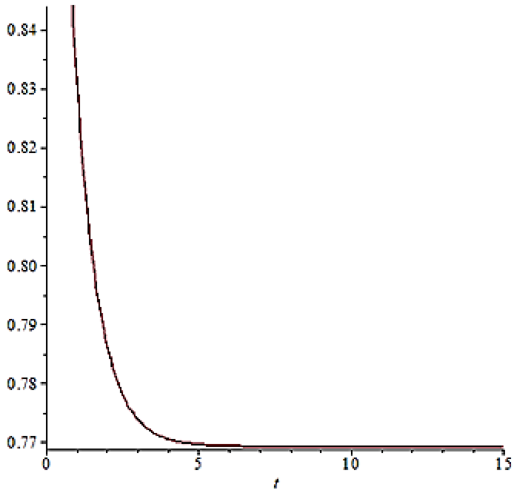

Fig. 4 – Availability versus time

4.2 Reliability Analysis

It is the probability of a system which performs its function effectively for the period anticipated under specified working conditions. Reliability can be evaluated by using the various failure rates as $\lambda_1=0.06, \lambda_2=0.07, \lambda_3=0.08, \lambda_4=0.09$ and repair rates as 0 in Eq. (16), we get:

$$R = e^{-3000000000t} . \tag{19}$$

By fluctuating the time t, we can get Fig. 5, which represents the variation of reliability of lithium-ion battery with respect to time.

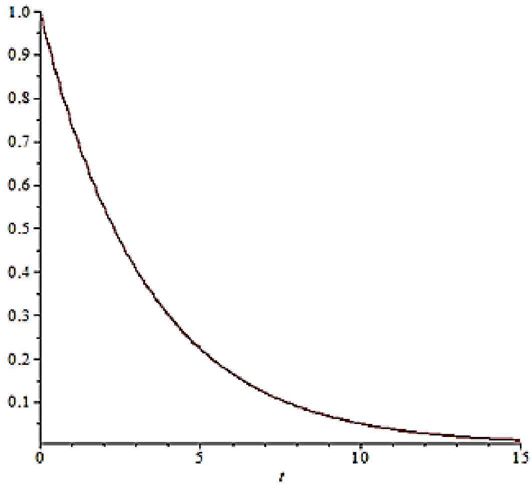

Fig. 5 – Reliability versus time

4.3 Expected Profit

The expected profit for the system in the interval (0, t] is given by below mentioned equation:

$$E_p(t) = K_1 \int_0^t P_{UP}(t)dt - tK_2 . \tag{20}$$

By using Eq. (18) in (20), the profit function for the same set of failure/repair rates is given by:

$$E_p(t) = K_1 \cdot \begin{pmatrix} -0.1775147929e^{-1.300000000t} \\ +0.7692307692 + 0.1775147929 \end{pmatrix} - t \cdot K_2 . \tag{21}$$

Table 1 – Expected profit

Time	$K_2 = 0.001$	$K_2 = 0.0015$	$K_2 = 0.002$	$K_2 = 0.004$	$K_2 = 0.006$
0	0	0	0	0	0
1	0.8973671373	0.8968671373	0.8963671373	0.8943671373	0.8923671373
2	1.700791672	1.699791672	1.698791672	1.694791672	1.690791672
3	2.478613862	2.477113862	2.475613862	2.469613862	2.463613862
4	3.249458598	3.247458598	3.245458598	3.237458598	3.229458598
5	4.018401756	4.015901756	4.013401756	4.003401756	3.993401756
6	4.786826674	4.783826674	4.780826674	4.768826674	4.756826674
7	5.555110355	5.551610355	5.548110355	5.534110355	5.520110355
8	6.323355545	6.319355545	6.315355545	6.299355545	6.283355545
9	7.091590244	7.087090244	7.082590244	7.064590244	7.046590244
10	7.859822084	7.854822084	7.849822084	7.829822084	7.809822084

By putting revenue as 1 and varying service cost K_2 as 0.001, 0.015, 0.002, 0.004, 0.006, respectively, after that varying time t in (21), we get Table 1 and Fig. 6 which shows the trend of expected profit with respect to service cost and time.

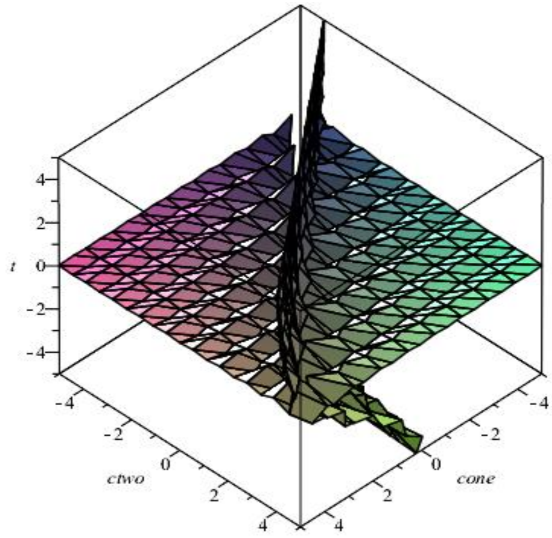

Fig. 6 – Expected profit

5. RESULTS AND DISCUSSION

In this article, various reliability measures considering all the parameters which are required to plot the availability, reliability, and expected profit functions are analyzed by the authors. These functions are represented by Fig. 4, Fig. 5 and Fig. 6, respectively.

Fig. 4 represents the availability of the battery with respect to time. From the graph it can easily be observed that the availability of the system decreases with increase in time.

Fig. 5 shows the trends of reliability of the lithium-ion battery with respect to time by taking fixed values of the parameters. It is observed from the graph that the reliability of lithium-ion battery decreases abruptly in comparison to availability.

Table 1 and Fig. 6 represent the cost function with respect to time. From the graph one can easily get that the increase in cost results in decrease in expected profit. Analysis shows that minimize service cost leads to maximum profit.

6. CONCLUSIONS AND FUTURE WORK

This article presents the concept of reliability of repairable lithium-ion battery. To understand the concept of reliability, failure of four main components is considered. The cycle life of lithium-ion battery is closely related to the material used in positive electrode. The introduction of additives can improve the battery safety into the positive electrode process also the silicon-based anode materials can improve the energy density of the battery. Improvement in the formation of electrolyte and electrolyte additives can also maximize the performance of lithium-ion batteries. To overcome the challenges on reliability it's important to investigate the different failure rates. The MTBF (mean time between failures), sensitivity analysis with respect to the failures and uncertainty can be included as future work.

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Аналіз надійності та доступності літій-іонних акумуляторів під час багатьох відмов

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Рішення для зберігання енергії на основі літій-іонних (Li-ion) акумуляторів стають все більш популярними. Ці акумулятори широко використовуються через їх конкурентоспроможність порівняно з іншими типами акумуляторів. Це вдосконалена технологія акумуляторів, а іон літію є головним фактором її електрохімії. Літій-іонні акумулятори можуть мати дуже високу напругу та запас заряду на одиницю маси та одиницю об'єму, а також мають ряд переваг порівняно з іншими високофункціональними акумуляторами, що перезаряджаються. Літій-іонні акумулятори застосовуються в різних сферах, наприклад, у споживчій електроніці, електромобілях, легкій енергетиці тощо. Літій-іонні акумулятори для такого типу систем є основними компонентами, які повинні бути безпечними та надійними протягом усього ресурсу роботи. Збільшення густини енергії літій-іонних елементів (Вт·год/л) і водночас зростання кількості загальної запасеної енергії, що зберігається в різних розчинах, посилюють зусилля щодо безпеки акумуляторів та заходи для підтримки максимальної безпеки і надійності, яка безпосередньо залежить від безпечної експлуатації електроприводів. Для точної оцінки надійності літій-іонних акумуляторів важливо побудувати модель надійності, враховуючи залежність між елементами для загального погіршення якості літій-іонних акумуляторів. У статті представлено загальний підсумок оцінки надійності літій-іонних акумуляторів за численних відмов. Різні показники надійності, такі як безпосередньо надійність, доступність і очікувана вартість, були досліджені за допомогою процесу Маркова та техніки додаткових змінних.

Ключові слова: Електрохімія, Надійність, Доступність, Очікуваний прибуток, Процес Маркова.