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Li-NMC Temperature Modelling Based on Realistic Internal Resistance

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ABSTRACT

Lithium-ion battery (LIB) produce heat when it is put under charging and discharging process. The heat generated during charging and discharging are directly related to the internal in the battery. This heat generation will cause the battery temperature to rise. The operating temperature for LIB is significantly important because its affect the performance and health of the battery. Gathering battery thermal behavior through experiment is a time consuming, high cost and a fussy process. The process can be made easier through battery thermal modelling. The purpose of this study is to provide a thermal battery model that can predict the battery thermal behavior at wide range of temperature by using realistic internal resistance value from experiment. In this study, a Nickel-Manganese-Cobalt Lithium-ion battery with capacity 40 Ah was discharged with 120 A (3C) and 160 A (4C) current continuously to heat up the battery until a set of targeted temperature achieved. The battery is then discharged with 40 A (1C) pulse current, and the voltage response is measured. The process was repeated until 80°C. From the voltage response data, the internal resistance for the battery was calculated and used as the main input in the thermal model based on heat generation equation to predict the battery temperature. The result shows that the developed thermal model managed to precisely predict battery thermal behaviour with a low average relative error of around 0.634 % to 5.244%. The significance of this study is to provide a battery model that can predict battery thermal behavior precisely at wide range of temperature. This information is important in designing a better battery management system (BMS) to prolong the battery lifetime, slowing degradation rate and avoid safety risk.

1. Introduction

The most popular power source in electrical circuit is battery [12]. There are variety of batteries available nowadays including non-rechargeable such as cadmium battery, nickel battery and rechargeable battery including Lithium-ion battery (LIB). Amongst rechargeable battery, LIB is widely used in electric vehicles, smartphones and laptops because LIB are stable with high power density and low self-discharge [9, 13, 20]. In fact, the usage of batteries in plug-in hybrid electric vehicle

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(PHEV) has reduced the dependency on petroleum as shown in simulation by Ibrahim *et al.,* [6] where fuel consumption greatly decreases with the combination of motor powered by battery. It is well known that LIB produce heat during charging and discharging process. In addition, the heat generated by LIB are non-homogenous whereby the areas particular to positive terminal experience greater heat production rather than areas particular to negative terminal and the centre of the battery [4]. To achieve long lasting performance from LIB requires a good cooling system whether it is from air-based or liquid-based or solid-based cooling system [5]. Operating LIB beyond its normal operating condition might leads to thermal runaway and ultimately can cause thermal hazard to the user and the system [10]. LIB are normally operated at temperature range of 40°C ~ 65°C [17, 24, 25]. The operating temperature for LIB is significantly important because temperature affect the performance and health of the battery [3]. When operating beyond normal condition, the probability for a LIB to undergo thermal runaway is high [8, 14, 22, 23]. This mean that a slight mistake in handling, the LIB will trigger the thermal runaway. The hazard of battery thermal runaway is a serious issue because it could cause burn injuries to consumer [1]. Main things to be taken extra careful are internal short-circuiting, external overheating, overcharged voltage and charging after over-discharge [7, 19, 23]. Charging and discharging a LIB cause the battery to generate heat because of the chemical reaction between the electrode and the electrolyte that have highly exothermic reaction nature [15]. When the exothermic reaction inside the cell reach critical temperature, thermal runaway occurs and the LIB started destroying itself [2]. As a summary, thermal runaway is a process where energy is release uncontrollably which accelerate the rise of temperature. There are numerous studies conducted in the scope of battery thermal modelling. Yoo & Kim [26] in their work uses equivalent resistant to do thermal analysis model for a Li-Ion battery based on the Joule-heating mechanism. The equivalent resistance was obtained from EIS test which was then validated via both theoretical analysis and thermal analysis. The thermal analysis successfully predicted temperature of the battery via simulation and agreed well with experimental results. Another study carried out by Noelle *et al.,* [11] about investigating the internal resistance and polarization dynamics to examine the joule heating regime of LIB. Their analysis includes how increasing ohmic or polarization resistance would affect the heating rate as well as their relevance to different timescale. They claimed that the results from their work could help in providing better strategies in mitigating thermal runaway. Apart of that, Sen and Kar [16] and Väyrynen and Salminen [21] was also pursuing the same idea in utilizing thermal management system to provide a safety battery design. Battery electro-thermal modelling helps to predict battery thermal behaviour for a better design of design battery management system (BMS) to prolong the battery lifetime, slowing degradation rate and avoid safety risk. The combination of governing equation for electrical model and thermal model makes up electro-thermal model. Gathering battery thermal behaviour through experiment is a time consuming, high cost and fussy process. The process can be made easier by using electro-thermal modelling and hence showing the significant of this study. This is also will be beneficial in the development of a suitable power source in electric and hybrid vehicle in term of efficiency of power delivery and battery safety. The objective for this paper is to develop an LI-NMC battery electro-thermal model based on realistic battery internal resistance data that can precisely predict the battery performance and thermal behaviour at wide range of operating temperature. This paper first will present the methodology used to develop the simulation model and then goes to tabulation of results with discussion and finally conclusion to summarize the research.

2. Experimental

2.1 Experimental Procedure

The goal of this procedure is to raise the battery temperature by discharging the battery with high discharge current using ITECH IT8514C+ Electronic Load. Since the capacity of the battery used in this experiment has 40 Ah capacity, 1C discharge current will be 40 A. For safety reason, the selected discharge current will be cap at 4C which is 160 A. But to consider SOC effect on the internal resistance, the SOC of the battery need to be maintained above 20%. Hence, for the normal operating temperature, 3C (120A) will be used to discharge the battery. For beyond normal operating temperature (>70°C), 4C (160A) discharge current will be used. The battery that will be discharge has been make sure to be in fully charged state. ITECH IT6502D power supply was used to slowly charge the battery until 100% SOC with 0.125C (5A) charging current at 4.20V constant voltage. The charging process will stop automatically when the battery voltage reached the charging voltage and no current flow (0A).

The temperature parameter at which the battery is tested will start from 40°C and increasing in 5°C until the highest achievable temperature that can be reached by the system or by the battery (which ever come first). Although the interested testing temperature parameter are at high temperatures range, several internal resistance data at low temperature are also needed as a result benchmark. For that, 26°C (room temperature) and 30°C are included as well. These data are essential to provide wide range of simulation results. Other than that, the time taken during high current discharge to raise the battery temperature are recorded simulation data. For gathering internal resistance data, the battery will be tested according to adjusted HPPC method by PNGV battery test manual 2001. 1C (40A) pulse current will be discharge from the battery to record the voltage respond. The before and after voltage respond data is analyzed to make internal resistance calculation. After all necessary data were taken, the battery is cooled by force convection to preserve the battery health and prevent faster degradation by heat.

2.2 Simulation Setup

The electro-thermal model will be developed to simulate the battery condition which will then compared to the experiment result. This model is composed of electrical model and thermal model. The inputs of the electrical model are initial SOC and discharge current. The outputs from electrical model will feed into the thermal model to calculate thermal respond respected to the input discharge current. Figure 1 shows the schematics of the electro-thermal model.

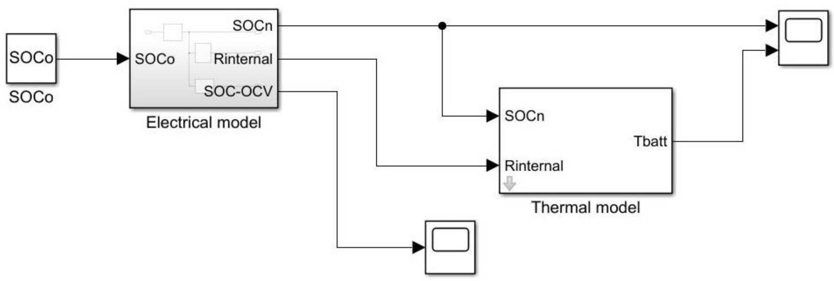


Fig. 1. Electro-thermal model schematic diagram

SOCn is calculated using SOC equation as stated Eq. (1) below where SOC_{init} is the initial battery SOC, I_{batt} is the battery discharge current and C_{init} is the battery capacity.

$$SOC = SOC_{init} - \int \frac{I_{batt}}{C_{init}} dt \quad (1)$$

The final component in electrical model block is internal resistance block. The internal resistance data was calculated using the voltage responds from the discharge test prior simulation setup. The internal data is tabulated in table 1. Then, the internal resistance data were arranged in 1-D lookup table in Simulink. The lookup table will interpolate the value of internal resistance by referring to SOCn using Eq. (2).

Table 1
Internal resistance at different temperature

Temperature (°C)	Internal resistance (mΩ)
26	2.425
30	2.075
40	1.525
45	1.375
50	1.300
55	1.075
60	1.050
65	0.925
70	0.850
75	0.800
80	0.775

$$R_{int} = \frac{R_{int-n+1} - R_{int-n}}{SOC_{n+1} - SOC_n} * (SOC - SOC_n) + R_{int-n} \quad (2)$$

Figure 2 shows the heat generation block diagram. The main function for this thermal block is to calculate the amount of heat generated in the battery. Then by using heat transfer equation, the total heat generated is converted to temperature.

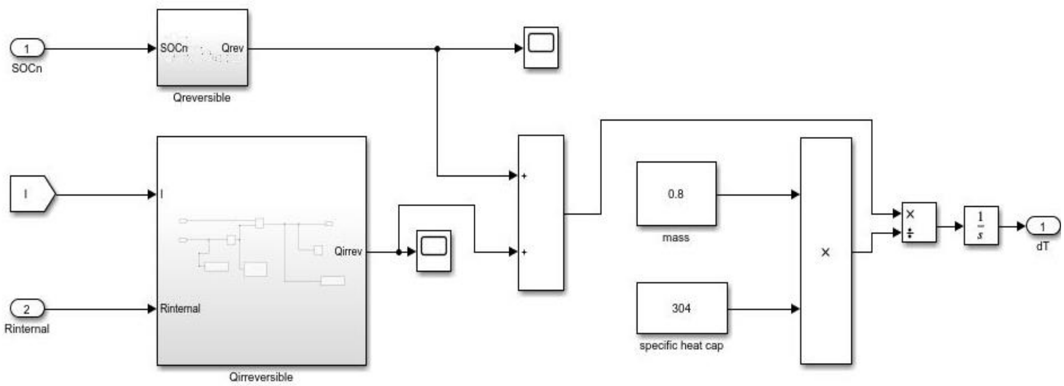


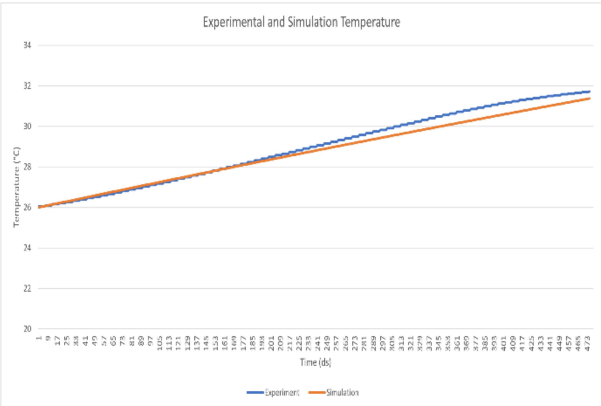
Fig. 2. Heat generation block diagram

The components in Figure 2 consists of reversible heat generation and irreversible heat generation. The convection heat is neglected in this study because during the discharge test, the experiment rig was shut closed and no airflow coming in or out of the rig. This means that natural convection gave insignificant impact on the battery heat generation. Plus, the RTD sensor used to measure the battery temperature are situated at the battery surface. Hence heat transfer through conduction gave the most significant impact on the temperature reading. Eq. (3) shows the generation equation used to construct the thermal block where I is the discharge current, R_{int} is the internal resistance, T is battery temperature, ΔS is the battery entropy, n is number of carrier, F is faraday constant, m is battery mass and C_p is battery specific heat capacity.

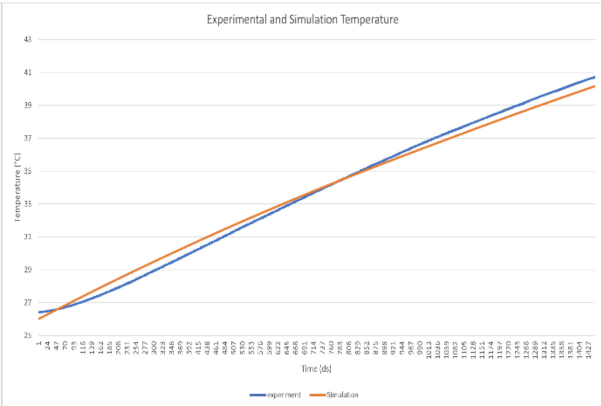
$$\frac{\partial T}{\partial t} = \frac{I^2 R_{int} + IT\frac{\Delta s}{nF}}{mC_p} \tag{3}$$

3. Results and Discussion

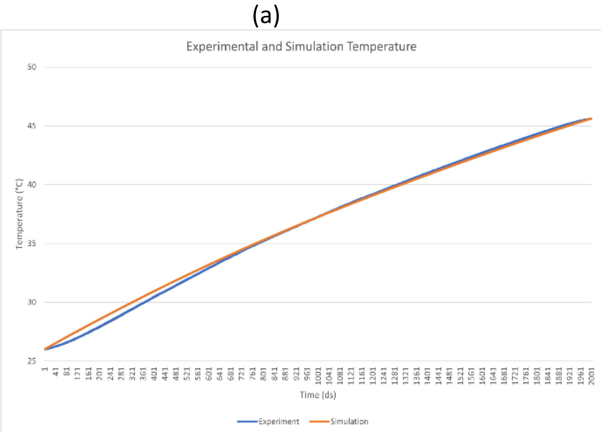
The discharge test was run 30°C, 40°C, 45°C, 50°C, 55°C, 60°C, 65°C, 70°C, 75°C, 80°C. A total of 10 voltage responds successfully recorded for internal resistance calculation data. These internal resistance data will be feed into simulation input to model the battery temperature. Simulation model successfully predicted all the discharge test temperature profile. The results of temperature simulation, orange plot for simulation and blue plot for experiment are depicted in Figure 3(a) to Figure 3(j) for 30°C, 40°C, 45°C, 50°C, 55°C, 60°C, 65°C, 70°C, 75°C, 80°C respectively. Relative error for each individual simulation result for discharge test are calculated to validate the result. Table 2 shows the relative error with respect to each temperature simulation. On top of that, average relative errors were also calculated to compare the highest and lowest error for each simulated temperature result.



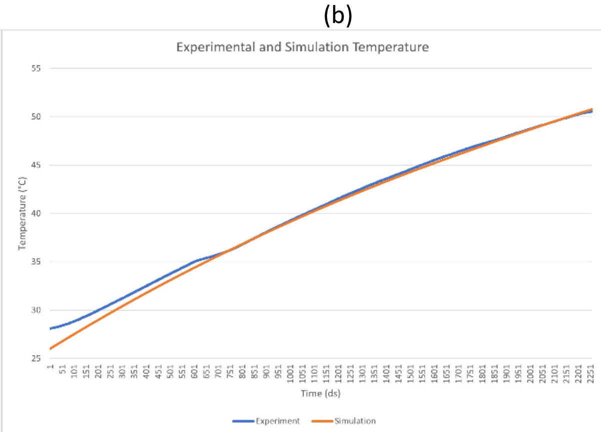
(a)



(b)



(c)



(d)

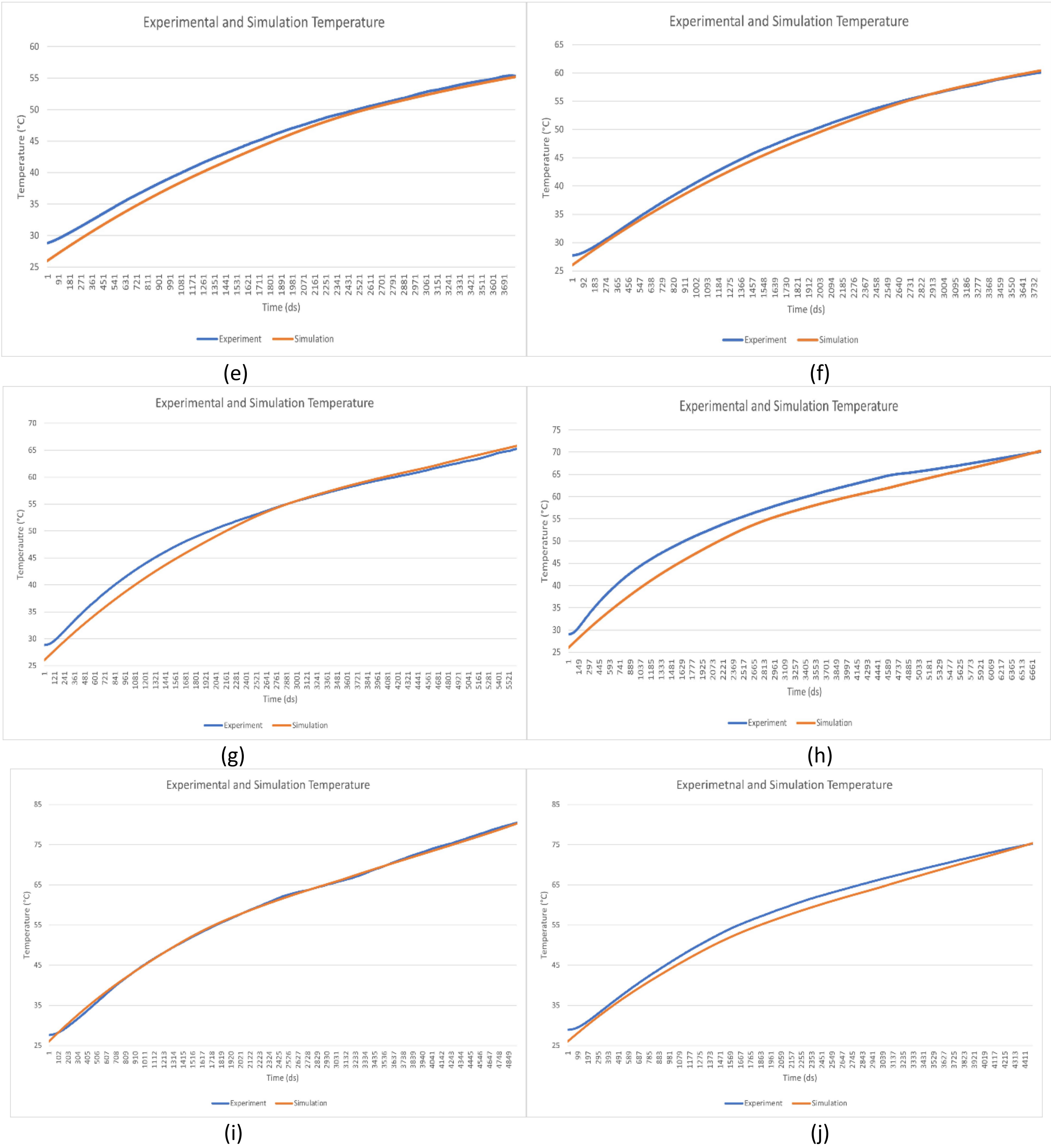


Fig. 3. Experimental vs Simulation graph; (a) 30°C; (b) 40°C; (c) 45°C; (d) 50°C; (e) 55°C; (f) 60°C; (g) 65°C; (h) 70°C; (i) 75°C; (j) 80°C

Table 2
Tabulation of relative error for each temperature

Temperature (°C)	Largest error (%)	Smallest error (%)	Average error (%)
30	1.887	0.001	0.844
40	2.083	0.006	1.078
45	2.384	0.003	0.718
50	7.523	0.001	1.143
55	9.769	0.288	2.652
60	6.179	0.001	1.450
65	9.767	0.001	2.602
70	11.744	0.002	5.244
75	10.04	0.03	2.853
80	5.811	0.001	0.634

The relative error for all simulation results can be average into one result as in Figure 4. Comparison for all average relative error shows that the average relative error for all simulation results is between 0.634 % to 5.2%. This error may come from two sources which are battery memory effect and internal resistance interpolation method.

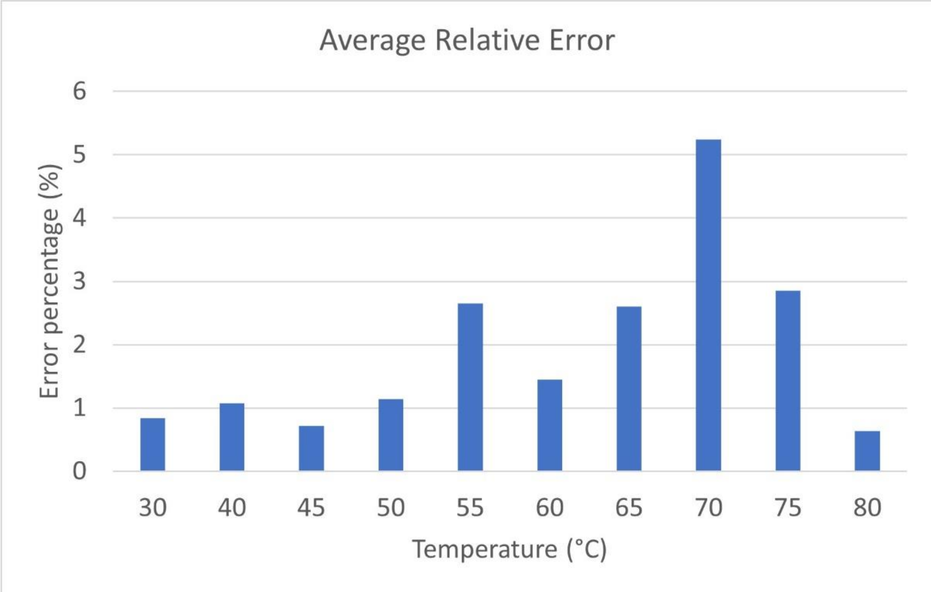


Fig. 4. Average relative error

Sleigh, Murray, & McKinnon, [18] in their works demonstrated that battery cell behaves differently on their first cycle compared to the subsequent cycle. This "memory effect" makes the battery heat generation and voltage, independent from its cycle history. Thus, showing slightly different results for each cycle. Meanwhile it is a different case for simulation model, where the model can generate same result based on the equation that it is built from. Because of the memory effect, there will always be a slight error in simulation and experiment data.

The second error source was possibly coming from the determination of internal resistance by interpolation method used in the simulation thermal block. Since the internal resistance data relative to its temperature are in 5°C increment, interpolation method is needed to determine the internal resistance value in between the temperature point. However, the simulation results still showing low percentage of average error for the entire simulation indicating that this simulation can approximately imitate real world systems and indirectly validated this simulation.

5. Conclusion

In conclusion, a total of 10 battery temperature has been conducted. The electro-thermal model used in this simulation showed a positive result. The methodology in this research which was using realistic internal resistance data to model LI-NMC battery temperature was able to prove it is applicable. In terms of thermal behavior, the ability of the simulations in this study to predict the temperature showed almost accurate results with a very low percentage of average error around 0.634% to 5.244%. In addition, the simulation consisting of electro-thermal models in this study can help to build a better battery management system that can control battery performance on a wide range of battery temperatures. This study can be continued for future works by expanding the study to various types of batteries other than lithium ions. The methodology used in this study can certainly contribute to worthful research findings.

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