Analysis of open circuit voltage and state of charge of high power lithium ion battery

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Article Info	ABSTRACT
	Electric vehicles (EVs) are the emerging technologies in the transport sector around the world. EV runs using an electric motor with electricity which is stored in Li-ion batteries (LIBs). Because of its superior qualities LIBs become the market leader for the usage in EVs. With the increased penetration of LIBs in EVs, it is important to monitor the charging and discharging process of the batteries. Accurate estimation of state of charge (SoC) and open circuit voltage (OCV) is essential for the better control of EV. In the present study LIB of 40 Ah nickel manganese cobalt (NMC) cell chemistry has been used for estimation of state of charge at different C-rates as 0.3, 0.5, 1 and 2 C rates. The relationship between the SoC and OCV is nonlinear however relationship between SoC and Ah is linear. Slight rise has been observed in cell terminal temperature at lower C rating at higher C-rating it is found that temperature rise is more (around 10 ℃). Hence, it is important to consider the C-rate of the battery from SoC-OCV curve of the battery. Also, higher C-rate may lead to incorrect estimation of the SoC, reduction in battery life and may lead to potential safety risks.

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1. INTRODUCTION

Electric vehicles (EVs) are gaining popularity as they are more energy efficient, reduces air pollution and prevent climate change due to emissions. Electric vehicles are classified into three types as per the requirements: hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs), and BEVs are known as pure electric vehicles only. They derive all power from battery packs and hence have no combustion engine or fuel tank are needed in BEVs [1]–[3]. The battery management system (BMS) ensures that it works within the safety parameters which detects parameters such as current, voltage, temperature, state of health, and state of charge while charging or discharging the battery pack. BMS carries out thermal management, cell balancing, charge and discharge control, any abnormal fault and communication. BMS also estimate state of charge and state of health of battery pack. The safety of battery used in EVs is very important which includes mechanical, electrical, chemical and functional safety (correct function of electrical, electronic or programmable electronic system), and further measures (caution warning tags) are again controlled by BMS [4]–[8] which take decision on the basis of various parameters of battery in use.

The battery which is heart of EV has a great impact on the performance of vehicles, basically total energy stored in battery determines the drive range and other energy requirements of EV. As a consequence, the choice of the battery technology and its effective use the predominant importance. Li-ion batteries

technology is the choice of energy source in EV due to its high energy density, good power rating, and charge/discharge efficiency in pulsed energy flow systems [6], [9]−[11].

Out of all commercially available batteries Li-ion batterie (LIB) stands on top because of its high energy density, higher nominal voltag, better life cycles and has low self-discharge (5-10%/month) [7]−[9]. So it is clear that why LIBs are preferred over other types of rechargeable batteries. During the charging process, positive electrode (cathode) gives lithium ions, which moves through the electrolyte to the negative electrode (anode), and electron flows in external circuit at the same time. When the battery is discharging, the lithium ion moves back through the electrolyte to the positive electrode [10]−[16].

Various Li-ion cathode chemistries have been developed and are commercially available such as lithium cobalt oxide (LCO), lithium nickel oxide (LNO), lithium manganese oxide (LMO), lithium nickel cobalt aluminium oxide (NCA), lithium iron phosphate (LFP), and lithium nickel manganese cobalt oxide (NMC). Depending on the application and its requirements the particular LIB can selected. NMC chemistry LIBs stands on top as it has high energy density, high life cycle, high power density and low self-discharge than all other LIBs chemistry. State of charge (SoC) which is measure of remaining battery capacity and is important parameter which need to be monitored in order to optimize the battery performance and life cycle. If the SoC is inaccurate there will be inappropriate charging and discharging of li-ion battery which may lead to overcharging and deep discharge of LIB and cause a safety issue. LIB with different chemistry is very sensitive to overcharge and deep discharge, which may damage and harm the battery and there by shortening its lifetime and even causing hazardous situations. Hence it is necessary to take care safety of the LIB and to improve their performance by efficient and proper way of charging and discharging at different charging rates (C-rates). The SoC of battery pack in EV serves a similar function as that of petrol gauge in traditional vehicle based on IC engine. SoC estimation is must for optimization of the vehicle control and play an important role in collecting battery information, vehicle operation, utilization of battery capacity and preventing over-charging and deep-discharging which ensure the safety and service life of battery. There are various SoC estimation methods like model based approaches (electromagnetic interference (EMI), environmental chemistry methods (ECM), and EIM), data driven approaches (neural network, deep learning, support vector machine and fuzzy logic), lookup table method (open circuit voltage and AC impedance), hybrid method and coulomb counting method. Each method adopts different approaches to evaluate the performance of SoC. Among these methods, look up table method shows the direct mapping of relationship between the SoC and the external characteristics parameters such as the open circuit voltage (OCV), and impedance [17]−[21].

The charge/discharge behaviour of high Li-ion battery can be used to estimate the SoC by measuring OCV of battery and grouped accordingly, which are, look up table method, coulombs counting method, and model based estimation method, data driven estimation methods and hybrid method. The model based SoC estimation, which is also known as white box models, approaches are designed using the knowledge of background processes. The data driven method which is also known as black box model, are new approaches which is possible with the big data and with the help of powerful computers. This method requires little knowledge or no knowledge of the background process. The drawback of these data is that they require huge data which should be readily available, this method doesn't give much benefits in the absence of the data. The coulomb counting method and hybrid methods are based on modelling and simulation studies. Whereas look up table method is based on experimental test results generated at laboratory and the huge data will be collected through bitrode life cycle tester for studying OCV-SoC characteristics [13], [22]−[25].

In this paper, the charge/discharge behavior of LIB of NMC chemistry has been studied at different C-rates in order estimate the SoC of battery by using open circuit voltage and ampere-hour data by look up table method. The rise in temperature has also been monitored in order to understand the effect of charging current on battery temperature. During the discharging process at constant current mode battery was halted to measure the OCV of the battery at various steps of SoCs, which can be use the load voltage to estimate the SoC by tabulating the data. The OCV of a LIB has an approximately linear relationship with SoC. Using this relationship between OCV vs SoC by the look-up table method which involves putting the battery parameters into tables and linking the parameters, SoC of the battery can be predicted and discussed in this paper.

2.   EXPERIMENTAL

A cylindrical Li-ion NMC-LTO battery cell has been used in this experiment which has nominal voltage of 2.3 V and rated capacity of 40 Ah. The cell has been connected with the battery tester to monitor the key parameters including current, temperature, voltage, power, and Amp-hour during the charging and discharging process of cell. The developed experiment bench model contains two sections: one is the hardware section and other is the software section, as shown in Figure 1. The hardware section includes Li-ion NMC battery, a segment of LCN bitrode module with control conditions through visual LCN software. In the software section of the set-up, various charge/discharge steps for charge, discharge and rest steps are used to know the

accurate OCV. Thermocouple is placed at the terminal of LIB to measure the temperature of cell during charge and discharge cycle at different C-rates. The cell is initially kept for rest before beginning the experiment. The tests are conducted by charging and discharging the cell with current pulse at different current rating (0.3 C, 0.5 C, 1 C, and 2 C rates). The cell is charged with constant current - constant voltage (CC-CV) method. The cell is charged till the voltage reaches to upper limits of 2.8 V and similarly discharged to the lower limit of 1.5 V.

The pulse train needs to be carefully designed in order to maximize the information that can be extracted from the limited data points. The pulses are injected at every 10% SoC. The voltage behavior for the current pulses of discharge cycle is given in Figure 2. The advantage of giving the current pulses is that it contains rest period after charge/discharge and thereby it helps the OCV to stabilize after every 10% of SoC, which gives us the accurate OCV for respective SoC.
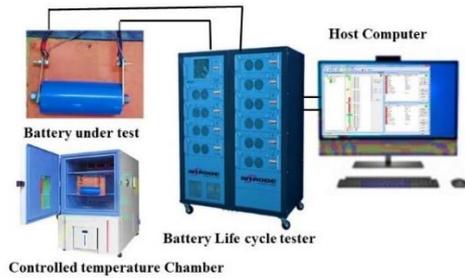

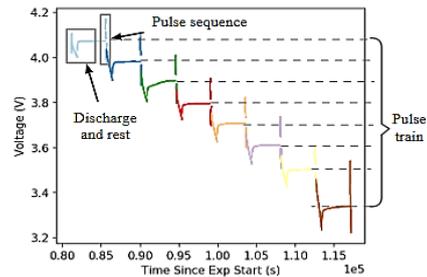Figure 1. LIB experiment bench model configuration for SoC estimation

Figure 2. Pulse train with intermediate discharging and rest [6]

Program steps for different C rates for both charging and discharging cycles are as follows: initially the LIB is completely discharged so as to bring the cell to 0% SoC. After LIB is fully discharged to 0% SoC, it is charged using constant current (CC) for every 10% of SoC following by a rest periods for fix duration till the OCV is stabilized and again it is charged using constant current (CC) for another 10%. This procedure is repeated till the battery attains 100% SoC. After the LIB reaches 100% SoC it is kept at rest for 5 minutes and followed by discharging cycle at CC with rest periods. This procedure is continued till the battery is fully discharged to 0% SoC. Once the look up table is established, measuring the instantaneous OCV of LIB gives the SoC level. Following that, the relation between the OCV and SoC is mapped. Further voltage drop (ΔV) during this process has been analysed for each state of charge during charging and discharging cycles and analysed to understand the open circuit voltage at various SoCs.

Also, the current which should be given to the cell changes with C-rates. The calculated current to be given to the cell, time to charge/discharge for each 10% of SoC, and total time to be taken for completing the experiment (which includes rest period in between charge or discharge cycles) for different C-rates are given in Table 1. The program steps remains same for all the C-rates but the only difference is values of current, time required for charge/discharge cycles and total time as mentioned above. The experiments are carried out for 0.3 C, 0.5 C, 1 C, and 2 C rates and the test results are collected.

Table 1. Current, time to charge/discharge and total time to be taken to complete experiment at different C-rates

C-rate	Current (A)	Time to charge/discharge for each 10% of SoC (min.)	Total time taken for complete experiment (min.)
0.3 C	12	21	520
0.5 C	20	12	340
1 C	40	6	220
2 C	80	3	160

3. RESULTS AND DISCUSSION

A single cell of 40 Ah has been used in this study and charged and discharged at 0.3 C-rate at constant current (CC with 12 A) charging. The cell is charged and discharged with 12 A of current with rest period of 5 minutes for each 10% of SoC followed by a rest period. The protocol for the voltage behavior and the current pulses applied and corresponding charge and discharge cycles are demonstrated in Figure 3. The Y-axis shows the voltage and current and the x-axis shows the time for charge, discharge and rest period. The charging continues till the voltage reaches the upper limit of 2.8 V (100% SoC). After reaching 2.8 V, the discharge cycle starts with 12 A of current and continues till the voltage reaches 1.5 V (0% SoC).
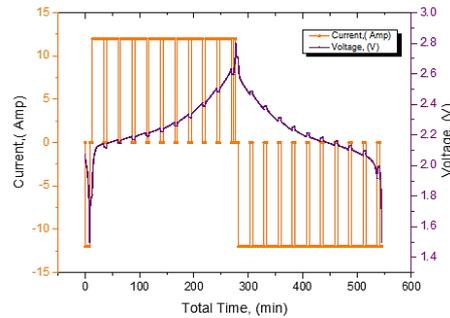
Figure 3. Protocol of charge and discharge for 0.3 C-rate

SoC of the cell was increased by steps of 10% for each cycle of charge and followed by rest period. The SoC keeps increasing by steps of 10% till full capacity of 100%. The OCV increases continuously for every 10% of SoC and value of OCV is recorded after stabilization. It is observed that there is a drop in OCV during rest period. Initially open circuit voltage of cell gradually increased at initial stages of SoC and faster at final stages of SoC. At 100% SoC the battery reaches almost its full capacity and kept under rest for 5 minutes for stabilization of OCV.

After reaching 100% charging, discharge is carried out at the same C-rate of 0.3 C. The OCV drops continuously with different rates at every 10 percent of SoC. The minus sign for current values indicates that the cell is discharging. Taking the OCV at different SoC percentage points of a single cell, the voltage reading and corresponding value of the SoC are shown in table in Table 2. The look up table involves the parameters which are linking to SoC, where accuracy of estimation depends on the size of data recorded.

Figures 4(a) and 4(b) shows the relationship between OCV (V) and SoC (%) for 0.3 C-rate for charging and discharging cycles respectively. The plots generated from the collection of test results received from the experiment, where it clearly shows that the charge and discharge profile of NMC based chemistry cell is not linear. OCV of cell slowly increased initially up to 50% of SoC and then increased at faster rate beyond 50% SoC.

Table 2. SoC %, current and voltage values for charging and discharging cycles

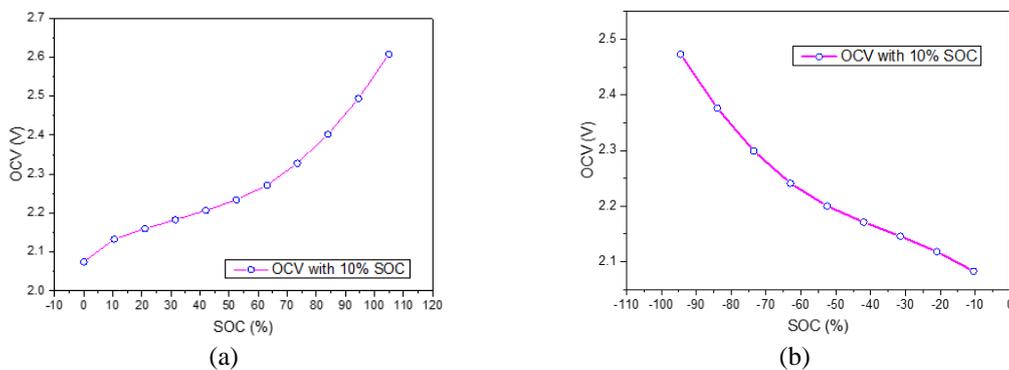|	Charging cycle			Discharging Cycle	
SoC (%)	Current (A)	Voltage (V)	SoC (%)	Current (A)	Voltage (V)
0	12	1.500	100	-12	2.473
10	12	2.133	90	-12	2.376
20	12	2.160	80	-12	2.299
30	12	2.183	70	-12	2.241
40	12	2.207	60	-12	2.200
50	12	2.234	50	-12	2.171
60	12	2.272	40	-12	2.146
70	12	2.328	30	-12	2.118
80	12	2.402	20	-12	2.083
90	12	2.494	10	-12	1.999
100	12	2.608	0	-12	1.500

(a)

(b)

Figure 4. OCV (V) vs SoC (%) for 0.3 C rate (a) charging and (b) discharging

Similar behaviour has been observed between OCV (V) and capacity (Ah) for 0.3 C rate charging and discharging cycles as demonstrated in Figures 5(a) and 5(b), where Ah indicates the amperage of a battery can provide for one hour. Figures 6(a) and 6(b) shows the relationship between capacity (Ah) vs SoC (%) for 0.3 C rate charging and discharging cycles. This relationship between SoC and Ah indicates that the availability of Ah of the cell for any given value of SoC (charge left out in the cell) and it is found linear for both charging and discharging cycles. Thus by measuring OCV and total Ah used for driving the car, SoC of the battery or battery pack can be predicted during the operation of vehicle and total left driving range can be predicted.
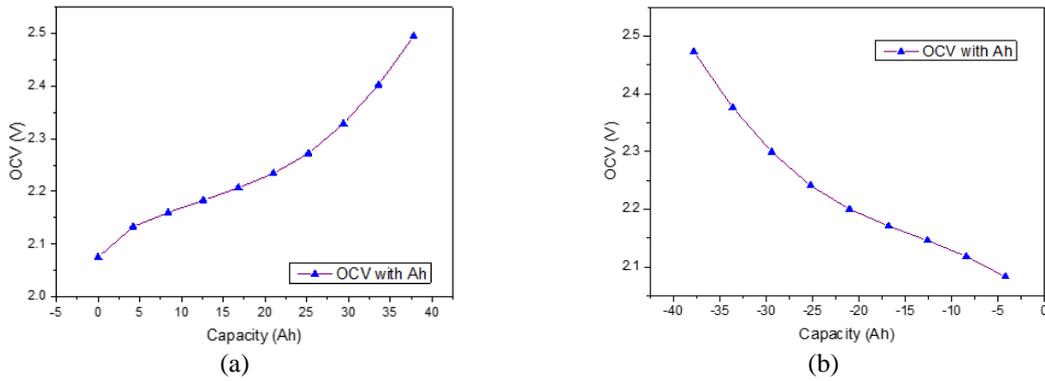

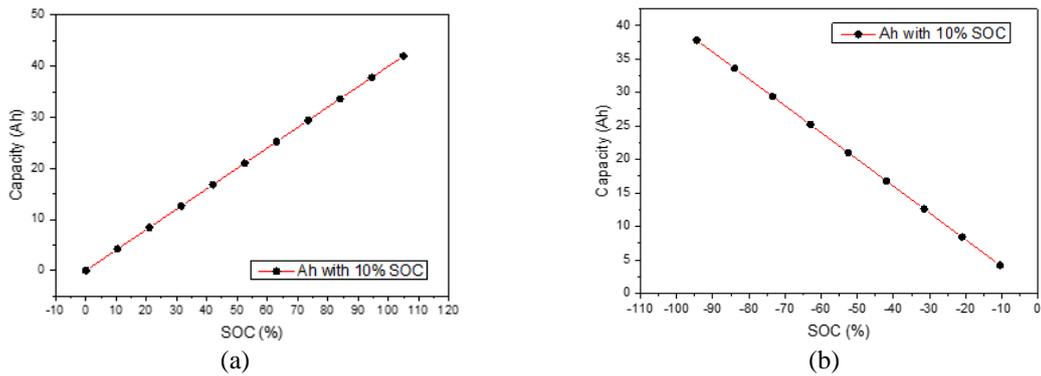Figure 5. OCV (V) vs capacity (Ah) for 0.3 C rate (a) charging and (b) discharging

Figure 6. Capacity (Ah) vs SoC (%) for 0.3 C rate (a) charging and (b) discharging

The measured values of Ah for different SoC % during charging and discharging cycles are given in Table 3. The amp-hour of the NMC based chemistry cell is increasing @ 4.2 Ah for every 10% of SoC for 0.3 C-rate charging cycle and the relationship is linear. Similarly, during discharging cycle also amp-hour found decreasing @ 4.2 Ah for every 10% SoC and it is also linear. Thus, when we are charging/discharging, if we know the SoC, we can find out the amp-hour of the cell and vice versa.

Table 3. Ah values during charging and discharging cycles at 0.3 C rate

Charging cycle		Discharging Cycle	
SoC (%)	Ah	SoC (%)	Ah
0	0.00	100	41.99
10	4.20	90	37.79
20	8.40	80	33.59
30	12.60	70	-29.39
40	16.80	60	-25.20
50	21.00	50	-21.00
60	25.20	40	-16.80
70	29.39	30	-12.60
80	33.59	20	-8.40
90	37.79	10	-4.20
100	41.99	0	0.00

During charging and discharging cycles, the change in temperature (℃) of the cell terminals vs SoC (%) is given in Figures 7(a) and 7(b). It is found that there is slight change in the temperature as it is low current (12 A) for 0.3 C rate charging and discharging cycles. As the C-rate is lesser than 1 C, the slow charging or discharging has taken place. The maximum temperature reached is only 28 ℃ from the room temperature of 24.5 ℃. This indicates that at lower C-rate, cell terminal temperature doesn't increase much and hence no effect on cell performance due to small rise in temperature.

The experiment has been repeated for charging and discharging cycles for NMC battery at different C-rates i.e. 0.5, 1, and 2 C rates. The relationship between OCV (V) and SoC (%) values for charging and discharging cycles at different C rates are given in Figures 8(a) and 8(b) respectively. From the Figures 8(a) and 8(b), it is observed that OCV-SoC curve at different C-rates are different, especially under high and low C-rate. Achieving an accurate SoC is the key issue for assessing remaining energy for use and hence it is important to measure accurate OCV for different conditions such as C-rate and temperatures. At different C-rates, it is observed that higher is the C-rate, the lower is the discharge cu-off voltage of cell. The OCV-SoC characteristic curve shows a whole downward shift for discharge cycle as shown in Figure 8(b). It is observed that lower the C-rate is, higher the discharge cut-off of cell. It is important to note down that at low SoC interval, SoC-OCV curves are different without any trends. The difference of OCV values is higher at initial stages of SoC and the OCV values are closer at last stages of SoC.
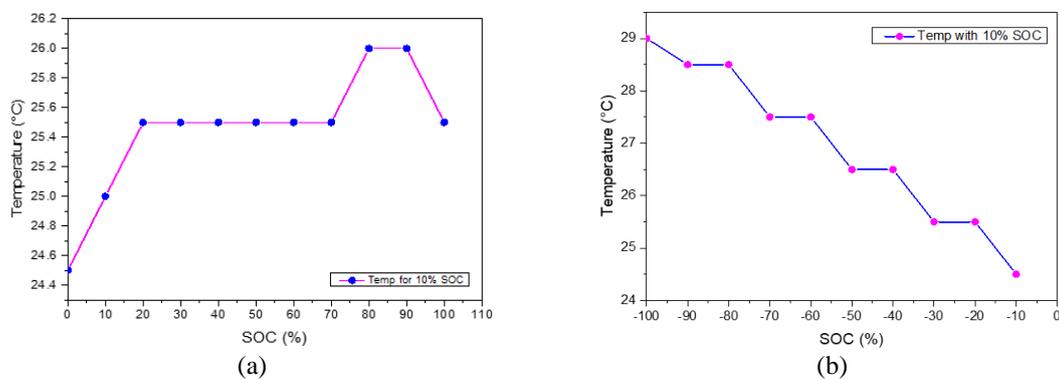

Figure 7. Temperature ℃ vs SoC (%) for 0.3 C rate (a) charging and (b) discharging
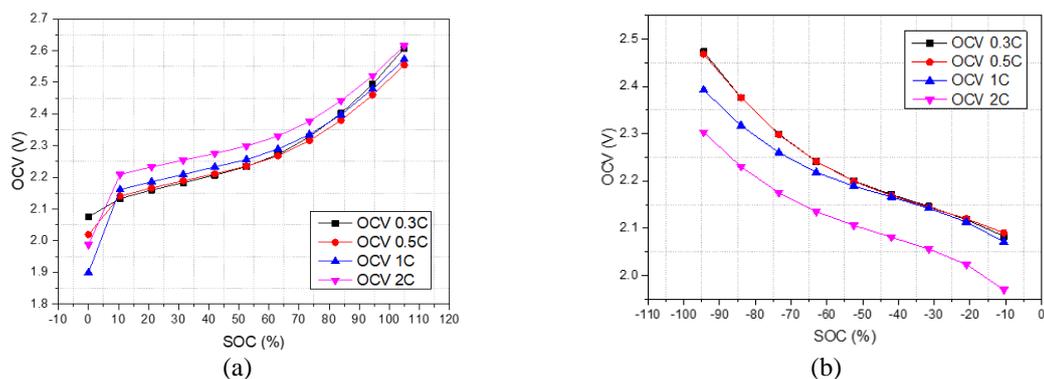

Figure 8. OCV (V) vs SoC (%) for different C rates (a) charging and (b) discharging

4. CONCLUSION

This work focuses on the study of the OCV-SoC characteristics of high power cell based on NMC-LTO chemistry under the influence of different C-rates and at ambient temperature. The result shows the OCV-SoC characteristic curve is greatly influenced by the change in C-rate. The results shows that the OCV-SoC characteristics curve gives the remaining capacity of batteries for particular voltage level. The relationship of SoC and OCV of lithium ion battery with different C-rates are investigated in detail. The relationship between the SoC and OCV is nonlinear however relationship between SoC and Ah is linear and indicates the availability of Ah of the cell for any given value of SoC for both charging and discharging cycle. Slight change has been observed in cell terminal temperature at 0.3 C, 0.5 C, and at 1 C rating, however

temperature of cell terminal rises from 24.5 to 34.0 ℃ for higher C-rate i.e. 2 C-rate. Besides, it is important to consider the C-rate of the battery for SoC-OCV curve of the battery. It is must to consider other factor such as working temperature otherwise it will lead to incorrect estimation of the battery SoC. And also it will accelerate the degeneration of battery life and will lead to potential safety risks. Thus in future study, the OCV-SoC curve adjustment method needs to be considered at different temperatures and more spread for percentage of SoC in order to predict accurate value of SoC.

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