DEVELOPMENT OF THERMAL MANAGEMENT CONTROL SYSTEM OF ELECTRIC VEHICLE BATTERY CHARGING

BY

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ABSTRACT

Developing rapid charging protocols for lithium-iron-phosphate (LiFePo4) battery is a key issue for a wider deployment of electric vehicles. A combined experimental and analytical study has been performed to investigate the rapid charging and heat generation characteristics of lithium-iron power battery in the present work. The effect of the internal temperature of the battery has been investigated during the medium, fast, and rapid charge process. The main drawback of LiFePo4 battery is overcharge, overcurrent, extreme condition the separator will melt causing internal short-circuit, the battery will take longer time for charging, and high temperature which affects longevity, efficiency, and battery life cycle. Experimentally investigate the LiFePo4 battery charging characteristics and temperature rise behavior are carried out based on 1C, 2C, and 2.5C charging rate. Moreover, the constant current-constant voltage (CC-CV) charging method has been applied for medium, fast, and rapid charging and analyzing the battery internal temperature using N-type thermistor. Battery charging and thermal management system have been developed based on battery charging performances and levels of raised temperature. Refrigerant-134a cooling system is capable to maintain battery temperature within 20^{o}C~40^{o}C range. Battery charging voltage, current, SOC and battery rasing temperature has been monitor during the charge of LiFePo4 battery. On the other hand, MATLAB/Simulink based custom-designed tool was developed. A dynamic model of lithium-iron-phosphate battery is proposed in this research by considering the significant temperature and capacity fading effects. Results have shown that the LiFePo4 battery can be used for rapid charging up to 85% by maintaining the condition for lifespan of the battery and to shorten the charging time. The simulation results showed that the battery charging model can truly reflect the dynamic output characteristic of lithium-iron batteries. The simulation and experimental results show that the battery can be charged around 1 hour and 55 minutes for medium charging (SOC 100%), 56 minutes for fast charging (SOC 100%) and nearly 31 minutes for rapid charging (SOC 85%). In the experiment, LiFePo4 battery was tested with different charging rates (1C, 2C, and 2.5C). The prototype charger can control battery charging systems for different charging rates such as medium, fast and rapid charging and also able to monitor raised temperature of the battery. Additionally, high charging current has been used for rapid charging where the SOC is 85% due to battery performance. The developed model of a battery charging system shows good performances with several control methods. The LiFePo4 battery operating temperature range is 20^{o}C~40^{o}C where this range has been exceeded for fast, and rapid charging and the experimental battery temperature becomes nearly 47^{o}C. This is why the thermal management system has been developed for fast and rapid charging to control battery temperature. The Variable Frequency Driver (VFD) can control compressor motor frequency where the frequency range is 25Hz-60Hz. Battery average charging temperature has been kept below 25^{o}C, which helps battery performance and lifetime. The evaporator average surface temperature is 14^{o}C which helps for better performance while rapid charging. Experimental results have shown good agreement with simulation results where the maximum variation has been found around 7% only.

مُلخَّصُ البَحْثِ

قضية رئيسة LiFePo4 يُعَدُّ تطوير بروتوكولات الشحن السريع لبطارية ليثيوم فوسفات الحديد لانشار أوسع للمركبات الكهربائية .لقد تم استخدام الراسة التجريبية والدراسة التحليلية سوية للتحقق من مؤشرات الشحن السريع وتولد الحرارة في البطارية العاملة بطاقة الليثيوم والحديد في العمل الحالي .لقد تم اختبار تاثير الحرارة الداخلية للبطارية خلال عملية الشن المتوسط والسريع .ان العائق الرئيسي لشحن بطارية هو الشحن الزائد، والتيار الزائد والظروف الشديدة تؤدي الى ذوبان الفاصل وبالتالي يؤدي LiFePo4 الى حصول تماس كهربائي داخلي وان البطارية ستاخذ وقتا اطول في الشحن والى حرارة عالية يؤثران في طول عمر البطارية وكفاءتها، ودورة حياتها .تجريبيا تمَّ فحص سلوك خصائص بطارية ليثيوم فوسفات للشحن السريع للبطارية وارتفاع الحرارة اعتمادا على خصائص معدل (LiFePo4) الحديد اضافة لذلك لقد تم استخدام طريقة شحن بفولتية ثابتة وتيار ثابت..C,2C,1Cالشحن- 2.5 باستخدام شحن متوسط وسريع وتم تحليل الحرارة الداخلية للبطارية باستخدام ثرمستور (CC-CV) تم تطوير شحن البطارية وتطوير نظام ادارة الحرارة اعتمادا اداء شحن البطارية ومستويات . N نوع قادر على الحفاظ على درجة حرارة البطارية Refrigerant-134a الحرارة المرتفعة .ان نظام التبريد ودرجة حرارة البطارية SOC في نطاق 20 – 40 درجة مئوية تم مراقبة فولتية شحن البطارية والتيار و تم . MATLAB / Simulink ومن ناحية اخرى .تم تطوير اداة مصممة خصيصا باستخدام اقتراح نموذج ديناميكي لبطاريات ليثيوم فوسفات الحديد في هذا البحث بمراعاة الحرارة ذات الحد التاثير المعنوي وتاثير تلاشي القدرة وأظهرت النتائج بان بطارية ليثيوم فوسفات الحديد يمكن استخدامه للشحن السريع وبنسبة 85 %مع الحفاظ على حالتها فيما يخص فترة حياتها وتقليل الفترة اللازمة لشحنها .ان نتائج المحاكاةاظهرت أن نموذج شحن البطارية يعكس بصدق خصائص المخرجات الديناميكية لبطاريات ليثيوم فوسفات الحديد .لقد اظهرت نتائج المحاكاة والنتائج التجريبية بان البطارية يمكن شحنها خلال SOC) و56 دقيقة للشحن السريع ,(SOC 100%) ساعة و 55 دقيقة للشحن المتوسط تم اختبار بطارية ليثيوم فوسفات الحديد. (SOC 85%) و 31 دقيقة للشحن المتسارع ,(100% ان النموذج الاولي للشاحن بامكانه. C,2C,1Cخلال التجربة باستخدام معدلات شحن مختلفة 2.5

السيطرة على نظام شحن البطارية لمعدلات شحن مختلفة كالمتوسط والسريع والمتسارع وكذلك بامكانه مراقبة ارتفاع حرارة البطارية .اضافة لذلك فقد تم استخدام تيار شحن عالي في الشحن المتسارع عندما بسبب اداء البطارية .ان النموذج المطور لنظام شحن البطارية اظهر اداء وكفاءة جيدة(SOC 85%) مع طرق عديدة للسيطرة .ان حرارة تشغيل بطارية ليثيوم فوسفات الحديد كان في نطاق 20-40 درجة مئوية وفي حالة الشحن السريع والشحن المتسارع كانت حرارة تشغيل البطارية ترتفع خارج هذا النطاق وتصبح تقريبا 47 درجة مئوية .ولهذا السبب تم تطوير نظام ادارة الحرارة للشحن السريع والشحن المتسارع بامكانه السيطرة على مكثف (VFD) وذلك للسيطرة على حرارة البطارية .ان متحكم التردد المتغير محرك التردد حيث التردد في نطاق 60-25 هيرتز .تم المحافظة على معدل حرارة شحن البطارية تحت درجة مئوية بما يساعد على كفاءة البطارية وعمرها .ان معدل حرارة سطح المبخر كان 14 درجة 25 مئوية والتي تساعد على افضل اداء في حالة الشحن المتسارع .ان النتائج التجريبية اظهرت توافقا جيدا مع نتائج المحاكاة وكان اقصى حد للاختلاف بحدود 7 %فقط.

APPROVAL PAGE

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DECLARATION

I hereby declare that this thesis is the result of my own investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institutions.

Md. Sazib Mollik

Signature .... Date ....

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I dedicate this thesis to
my honourable parents and my wife
for their meticulous support, continuous inspiration, and unconditional love
till the very end of this journey.

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A	Exponential zone amplitude (V)
Ah	Ampere hour
A_S	Total surface area
B	Exponential zone time constant inverse (Ah)-1
C	Heat capacity of the battery pack
C_{cell}	Heat capacity of a cell
D	Duty cycle
dt	Time difference of charging
E	Internal voltage
E_0	Battery constant voltage (V)
f_s	Operating frequency
G	Mass velocity (ms^{-1})
h	Heat temperature coefficient
h_{tp}	Two-phase heat transfer coefficient (Wm^{-2}K^{-1})
i	Battery resistance (Ω)
i^*	Filtered current (A)
K	Polarization constant
m_{evp}	Rate of evaporation (kgm^{-3}s^{-1})
$\dot{m}_v$	Mass flow rate of vapour (kgs^{-1})
mV	Output Ripple
Nr	Rotor speed
Ns	Motor synchronous speed

n	Motor speed in RPM
P	Number of poles
VFD	Variable frequency driver
V_{batt}	Battery voltage (V)
V_{exp}	Exponential zone
V_{full}	Fully charged voltage
V_{nom}	Nominal zone
Vs	Supply voltage
P	Pressure (Pa)
Q	Battery capacity
Q_{gen}	Overall heat generation inside the cell
Q_p	Heat generation due to chemical reaction
q_{elec}	Electrochemical reactions
q_{pres}	Polarization resistance
R	battery resistance (Ω)
SOC_{inti}	Initial SOC of battery
T	Temperature (K)
T_{amb}	Ambient temperature
T_{cell}	Battery temperature
T_{EVA}	Evaporator temperature
T_{sat}	Saturation temperature (K)
ρ_l	Density of liquid refrigerant (kgm^{-3})
ρ_v	Density of vapour refrigerant (kgm^{-3})
ρ_s	Density of solid (kgm^{-3})

LIST OF ABBREVIATIONS

4S2P	Four series and two parallel
LiFePo4	Lithium iron phosphate
ANOVA	Analysis of variance
BEV	Battery-operated electric vehicles
BTMS	Battery thermal management system
CC	Constant current
CCS	Charge control system
CI	Confidence interval
CV	Constant voltage
DOD	Depth of discharge
EV	Electric vehicles
EDV	Electric Drive Vehicles
IC	Integrated circuit
ICE	Internal Combustion Engine
IDE	Integrated development environment
NTC	Negative temperature coefficient
OCV	Open circuit voltage
PCM	Phase change material
PHEV	Plug-in hybrid electric vehicles
PWM	Pulse width modulation
R-11	Refrigerant-11
R-134a	Refrigerant-134a

SOC	State-of-charge
TMS	Thermal management system
VFD	Variable frequency drive
VCR	Vapor compression refrigeration
VOF	Volume of fluid

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND

A number of battery modules in electric vehicles (EVs) are connected in series to provide a high system voltage. From the early stage of EV development, it has been found that the initial capacity varies little between battery modules, but differences in the capacities become greater with charge and discharge cycling of the batteries. Battery modules with higher capacity deviations from the others should be overcharged or over-discharged to balance the modules at the end of recharge and discharge, respectively (B. H. K. Lee, Sun Wook, 2002; J. Shen, Dusmez, & Khaligh, 2014). In this case, the performance of the batteries could become worse on repeated overcharge or over-discharge. In order to solve this problem, all of the battery modules must be managed individually during recharge and discharge.

Driving range information in EVs is important for drivers not only to avoid breaking down on the road but also to improve the utilization of battery with maximization of available capacities which is strongly related to the accurate calculation of the state-of-charge (SOC) of the batteries. For providing accurate battery SOC information, available capacity, self-discharge rate, and ageing factors should be considered under all conditions that the EVs could be driven. The available capacity of a battery decreases rapidly with drop in temperature and larger discharge currents. Thus, it is assumed that the battery SOC and the driving range of an EV are highly dependent on environmental conditions, especially ambient temperature and driving patterns of the vehicle. In addition, the capacity of the battery decreases naturally due to self-discharge when the EV is parked for a long period of time(L. Lu, Han, Li, Hua, & Ouyang, 2013).

The rate of self-discharge is dependent on both the storage temperature and the stand period: the higher the temperature and the longer the stand period, the greater is the rate of self-discharge. Such energy loss must also be considered for accurate calculation of the battery SOC. The battery capacity tends to decrease with an increasing number of cycles. For example, the available capacity after 300 cycles is somewhat less than that after 10 cycles. With respect to the ageing effect, this must also be taken into account when determining the battery SOC (Xing, He, Pecht, & Tsui, 2014).

Electric vehicles have not been commonly used by people nowadays. One of the reasons is a lack of charging infrastructure especially when cars are on the road, which is not possible to wait for six hours for charging the cars (Yilmaz, 2013). By enhancement in battery charging scheme that allows fast charging with high performance, efficiency, and safety, the utilization of the electric vehicles may be greatly enhanced.

In addition, based on a survey conducted by United States Department of Transportation (USDOT), about 78% of the population drives an average of 40 miles (64 km) or less in their daily commuting as shown in Figure 1. (Aubin, 2011; Hannan, Lipu, Hussain, & Mohamed, 2017; Mi, 2011). Thus, by only overnight slow charging at residential, most of the people could go to and from work by electric vehicles easily on a single charge. On top of that, fast charging might be required for a long journey in order to extend the range where a single charge could not support. With fast charging, only less than one hour is required to recharge the battery up to 80% of its capacity and this waiting period is reasonable.

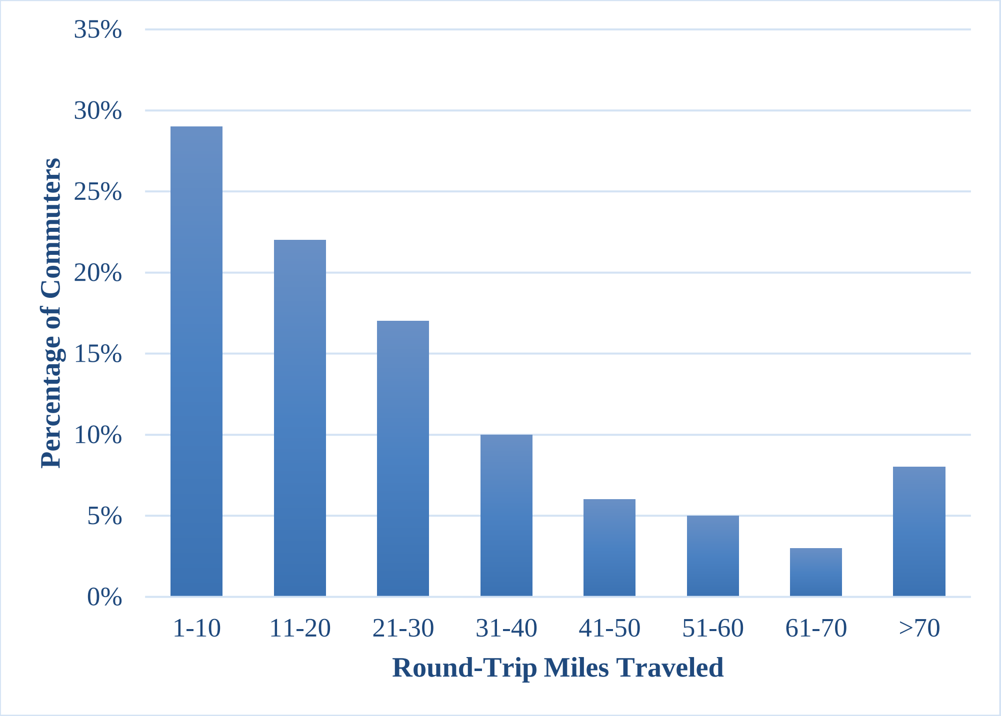

Figure 1.1: USDOT survey shows that 78% of the US population travel less than 40 miles daily (Mi, 2011)

1.1.1 History of Electric Vehicles

The first practical electric road vehicle was developed by Thomas Davenport in the United States in 1834 or by Robert Davidson in Edinburgh in 1842. However, both of these vehicles used non-rechargeable batteries for limited travel range. As a result, the vehicles were not accepted by the customers (Sulaiman, 2015). When the battery technology drastically improved between the years 1890 to 1910, many companies started to develop their electric vehicles. In 1897, Walter Bersey had developed cars for the London Electric Cab Company, which used 40-cell battery and 3-horsepower electric motor, and could be driven for 50 miles (Sulaiman, 2015). The electric vehicle then becomes popular in the market where about 38% of the cars sold were powered by electricity in 1900 (Berecibar et al., 2016; Santini, 2011).