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DC Quick Charging Operation Assistant Development and Experiment in Taiwan

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Abstract

Electric Vehicle is widely used in passenger service gradually. It is a critical successful factor to have a sufficient electric energy supply. In order to solve the constraint of economical issue, the fast charging method can decrease the charging time such that the service time can be extended without dramatically increasing the battery numbers. This research develops a fast charging system which follows international regulation. The fast charging system includes a charging station simulation system, a battery loading simulation system, and a charging controller mounted on a fast charging vehicle. This system has completed connection tests with charging stations of ABB from Europe and Delta in Taiwan and also finished system verification with Japan HASETEC, which is a major company involving in CHAdeMO association affair. The developing charging controller undergoes several charging/discharging experiments for marine high capacity lithium ion battery module. The cells of the battery module still maintain reasonable balance status after charging process, which proves the developed charging controller of this research can safely and efficiently fast charge a lithium battery module via high voltage direct current. It is the goal for this research that promote adopting electric boat in touring water field for carbon emission reduction and water resource protection can be realized all at once.

Keywords: Electric boat, Li-Ion Battery, DC Quick Charging, CHAdeMO

1 Introduction

For the past few years, follow the discussion of energy exhaustion, the entire world starts focusing on the environment pollution improvement management and development of energy usage. For ships, the power source is mainly diesel or gasoline engine. The exhaust gas and leakage liquid create the pollution of air and water field, results in troublesome drinking water degradation and water ecological system unbalance. When ship cruising on water dam of city water or lake, or pollution sensitive water field like river, port, sandbank, and coast line, one must carefully monitor the influence brought by the ship. These days, some lakes in Europe already enforced a law, for which only allows a pure electric propulsion ship. Therefore, petroleum burning ship

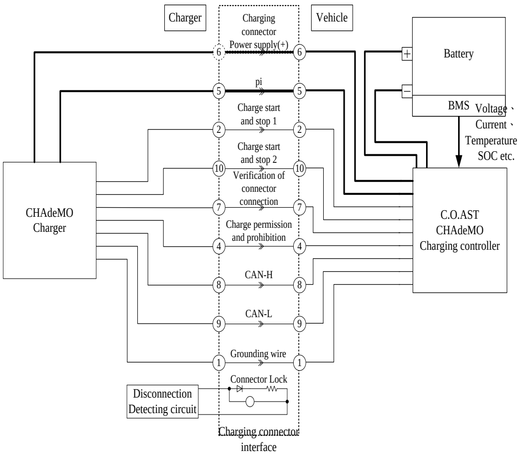


Figure 1: CHAdeMODC charging system configuration

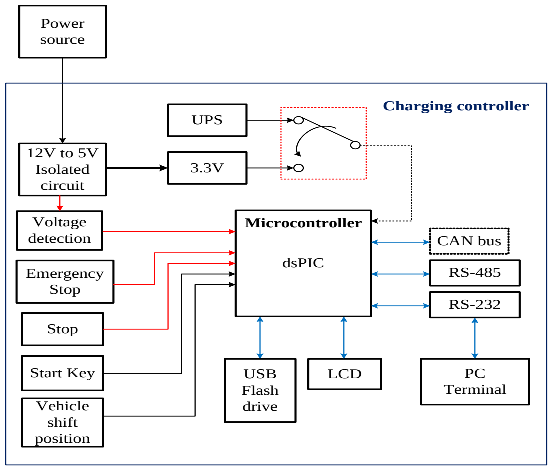


Figure 2: Controller hardware configuration schematic

Figure 3: Controller electric circuit board

cruising on this sensitive water filed will be gradually restricted [1].

Cruising radius becomes a bottle neck because the lithium battery technology so far only presents one tenth of the gasoline energy density. Using fast charging is a viable solution. There are three most common fast charging standards: Japan CHAdeMO[2], Europe & US SAE, and China national standard GB. Japan CHAdeMO standard has most widely adoption on charging station and vehicle.

Globally, the successful direct current charging feature of electric vehicle depends on the reliability and stability of "Vehicle Charging Controller". However, this technology is mostly controlled by car companies, for assuring the direct current fast charging system can apply on the domestic electric boat field, we SOIC (Ship and Ocean Industries R&D Center) attempts to develop a mobile test platform by ourselves in order to develop and test a "Direct Current Charging Controller" which compiles the standard. Thus, the domestic battery product and direct current fast charging station can be united for further promoting fast charging system.

2 Development and design of charging controller hardware

Whether it is on an electric car or an electric boat, the concepts are the same, the developed direct current charging controller plays an important role of intermittent communication transformation in direct current fast charging process. Since direct current charging station and vehicle are connected via direct current charging controller, the communication flow and strategy design dramatically influence key factor of charging time and efficiency.

The hardware design focuses on electric power system and judgment of power-off behaviour. In a real vehicle application, the electric power can be manually disconnected because of external factor or malfunction. In order to investigate malfunction situation after the incident, the circuit has a design of three digital signals to judge the circumstances:

- The charging is not yet complete but terminated by normal manual stop.
- The external power is unplug or power is not enough.
- Malfunction occurs; an emergency stop button is utilized to terminate charging process.

Physically, CHAdeMO charger is connected with battery and charging controller (aka. ECU, Electronic Control Unit) on board via CHAdeMO connect interface (Fig. 4) which is defined by CHAdeMO association. Wherein, the connection line can be categorized by two different parts, power line and signal line. The power line connects battery, which allows highest voltage of 500V and highest current of 125A. The signal line connects ECU of electric vehicle. The control of

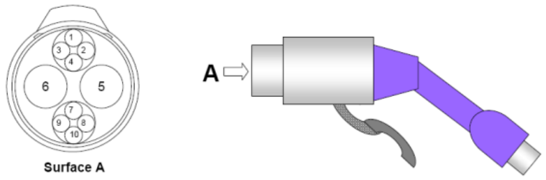


Figure 4: Charging plug layout

Figure 5: CHAdeMO DC fast charging controller

charging voltage and current is determined by the calculated result of signal line information. The safety mechanism in charging process, power shut off step, or power deliver procedure are also judged by signal line information. The appearance of a real fast charging controller is shown in Fig. 5.

3 CHAdeMO high voltage battery simulation technique

CHAdeMO high voltage battery simulation technique provides charging signal simulation and information verification for on board charging controller. The configuration schematic is shown in Fig.6. During the charging simulation process, a real battery module connection is not needed. A programmable electronic load and power supply can mimic battery status variation during charging process by program. Since the voltage and current control of a charging system is determined by signal line, it is very dangerous if a maximum 50kW charging system suddenly output huge power to battery before signal line function being fully verified. For example, if signal line control command is wrong, an over current or over charging situation might happen. The charging signal simulator can verify if charging controller

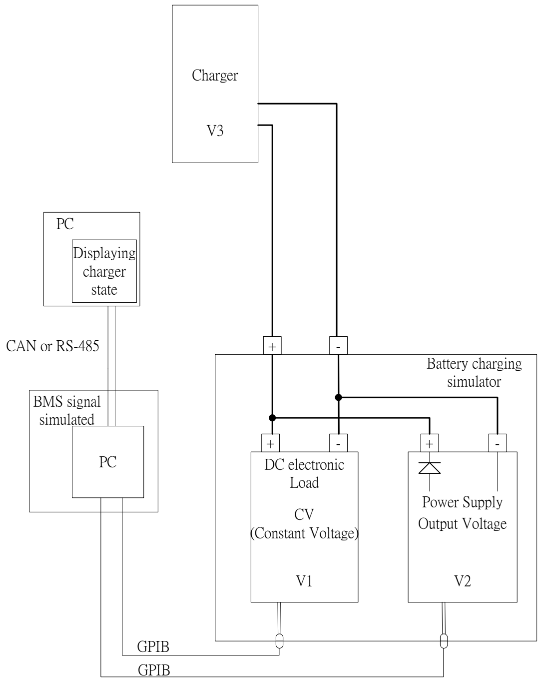


Figure 6: DC charging system signal simulator schematic

(ECU) on vehicle has correct function. Furthermore, voltage and current information signal of BMS on vehicle battery module are also simulated by the charging signal simulator. The charging signal simulator directly connects to the ECU on vehicle to simulate the BMS signal. With simulation and information verification pass, the charging controller can avoid potential dangerous of direct charging.

For establishing a battery model, not only a BMS communication signal simulation is needed, a battery charging behaviour and voltage and current simulation is also needed. First, voltage model of a battery module has to be set up, next, set up initial state of charge (SOC) of the battery module, such that the voltage V_{BAT} of battery module can be determined. The formula is:

$$V_{BAT} = OCV(SOC) + I \times R(SOC) \qquad (1)$$

In the above formula, $OCV(\ )$ is the open circuit voltage of battery module. The degree of $OCV(\ )$ is a function of SOC. I is the charging current. $R(\ )$ is the internal resistance of battery module. The degree of $R(\ )$ is a function of SOC. The calculation formula of SOC is:

$$SOC = \frac{\text{stored electricity Ah}}{\text{battery capacity Ah}} \times 100\% \qquad (2)$$

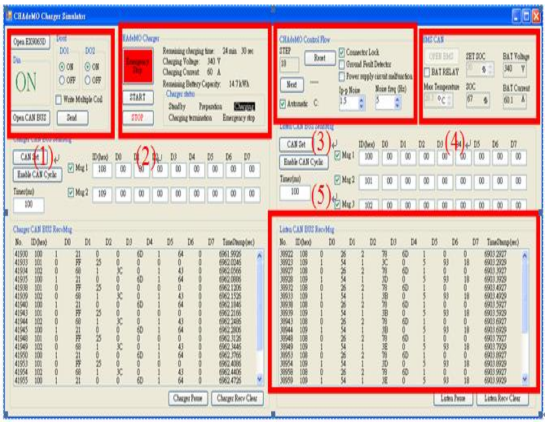


Figure 7: Human-machine interface of CHAdeMO charging simulation software function section

In the above formula, the Ah value of stored electricity can be represented by $Q_1 = \int I(t) \cdot dt$. The $I(t)$ is charging current. If a digital sampling method is used to acquire the charging current value, Q_1 calculation formula approximates to $Q_1 = \sum I[n] \cdot \Delta t$. During the charging simulation, the SOC will rise up, the battery voltage will change accordingly. In order to simplify the complexity of calculation, the curves of $OCV(\ )$ and $R(\ )$ are replaced by piecewise linear function.

The direct current charging system signal simulator must perform charging procedure and any malfunction processing procedure by CHAdeMO protocol. Fig. 7 is the human-machine interface of CHAdeMO charging simulation software. The function description is:

(1) The monitoring of I/O input-output status: one set for input, two sets for output.

(2) The interface of CHAdeMO charger: The typical CHAdeMO charger has three buttons which are “start”, “stop”, and “emergency stop”. The display is voltage, current, SOC, and remaining charging time.

(3) CHAdeMO flow monitor and malfunction simulation: The function of this section is for easily debugging. It shows the precise step in the flow. And, conditional simulation of malfunction fault. The vibrated amplitude and frequency of simulated output current can also be set up.

(4) BMS status simulation: Since the battery voltage model is a function of SOC, the input parameter of battery is SOC only. BMS signal is outputted according to the SOC status simulation.

Table 1: Testing Procedure

Verification item	Condition
Communication system connection test	Check list
Low current low voltage battery charging simulation	80V, 10A, SOC 30%~80%
High current low voltage battery charging simulation	80V, 120A, SOC 30%~80%
Low voltage battery charging over voltage protection	85V
Low current high voltage battery charging simulation	330V, 10A, SOC 30%~80%
High current high voltage battery charging simulation	330V, 120A, SOC 30%~80%
High voltage battery charging over voltage protection	365V
Emergency stop test	330V, 120A

(5) Monitor CHAdeMO charging communication system: Monitor CAN BUS connection which connects CHAdeMO charger and vehicle charging controller. The relative time of data transmission is also recorded to make the malfunction error-elimination easier.

CHAdeMO high voltage battery simulation technique can test charging controller according to the Table 1 verification items. Charging risk is minimized if the simulation test is passed before connecting real battery module and charger in test.

4 Charger simulation system

In order to simulate faulty signal in CHAdeMO communication protocol, a programmable power supply Chroma-62150H-1000S is used. This power supply has a maximize output of DC1000V/15A. With a circuit controlled by CHAdeMO charger communication protocol shown in Fig. 8, a 15kW power CHAdeMO charger is realized. A computer can control operation interface. CHAdeMO charger simulator is shown in Fig. 9.

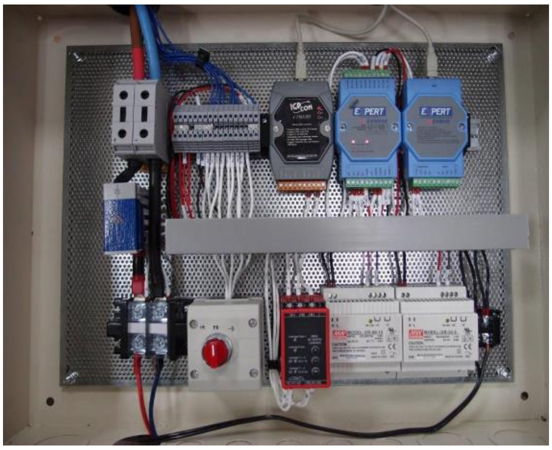


Figure 8: Circuit controlled by CHAdeMO charger communication protocol

Figure 9: CHAdeMO charger simulator

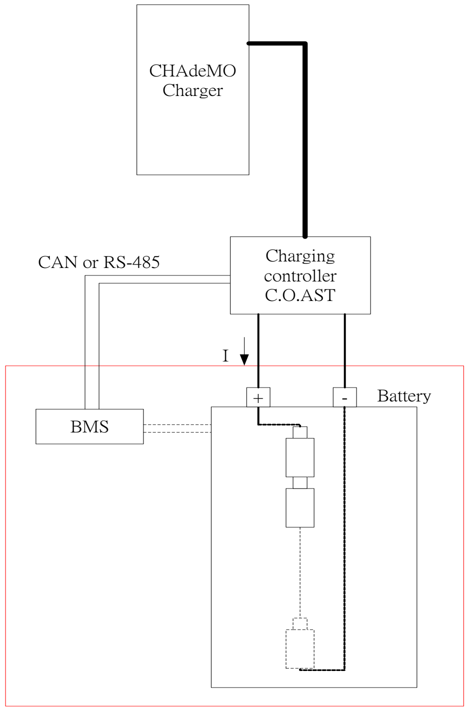


Figure 10: CHAdeMO charging test layout

Figure 11: TY DYNAMIC fast charging battery module

5 Direct current fast charging controller charging test

Fig. 10 is the CHAdeMO charging test layout. Except the charging controller C.O.AST which is developed by SOIC, it also includes Fast charge-discharge battery module and ABB Terra51 direct current fast charger.

Fast charge-discharge battery module is manufactured by TY DYNAMIC CO. LTD., and SOIC determines the specification. This battery is a fast charge-discharge battery module (Fig. 11) which is 22kWh capacity and 2C charge-discharge rate. It also passes multiple cell safety and vibration test verifications. This battery is designed under overall consideration of both performance and safety. It can also mount on a vehicle application directly. The communication function of battery BMS can output via CANBUS. The charging controller of SOIC can communicate with it directly and adjust charger output power according to the BMS signal.

ABB direct current fast charger (Fig. 12) is a CHAdeMO certified charger. It has a maximize output 50kW, voltage output 50~500V, adjustable current 0~120A. Its wide power variation range can deal with battery charging requirements of different vehicles. It can also perform user management by RFID card, and also integrated with internet communication and powerful back station management mechanism. With smart grid integrated feature and performance, this charger satisfies electric power management demand in the test.

Figure 12: ABB direct current fast charger

Table 2: Charging controller parameter setting

Setting item	Parameter
Charging current	120 A
Battery rated voltage	330 V
Charging voltage	360 V
Maximum charging voltage	370 V
Maximum protection charging voltage	365 V
Initial charging current	20 A
Start charging climbing rate	20 A/sec
End charging declining rate	200 A/sec
Charging to maximum SOC	100 %

This project develops a charging controller C.O.AST which passes simulation test first. Afterward, a charging pattern is designed according to battery charging profile. The battery in the test is TY DYNAMIC battery which is 20kWh/60A. The system test is operated in 2C charging degree which is about 120A. The parameters of charging controller are set up according to battery charging characteristic. These parameters are listed in Table 2.

In order to charge the battery until 100%, except the first half section using 120A fast charging, when the battery reaches certain voltage value, the current must be lowered down, or it will exceed the charging voltage and results in a no-charge. Besides, this charger can only control output current, a constant-voltage current output of the charger is not possible. For lowering battery charging voltage, one must lower charging current. In the charging program of C.O.AST charging controller, when charged battery voltage reaches 357V, it automatically lowers output to 10A, such that the battery can be charged until 100%.

Figure 13: Boat charging controller connects charger imitated circumstance

Figure 14: Charging controller screen display

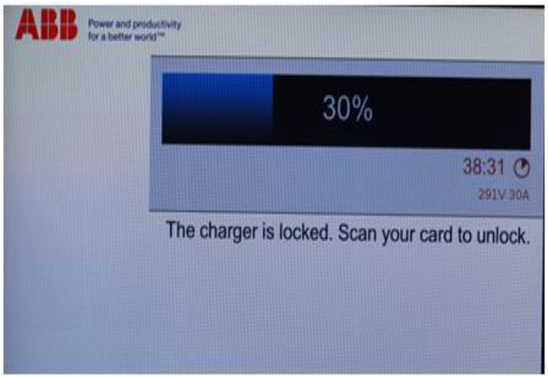


Figure 15: Charger panel displays screen

The appearance of charging controller imitated mounting on the boat is shown in Fig. 13. It has a LED screen which displays present charging information, it also provides boat personnel an emergency button switch for emergency stop charging process. When charging is under process, LED panel on the charging controller displays charging information, as shown in Fig. 14. The panel displays present battery voltage, current, and

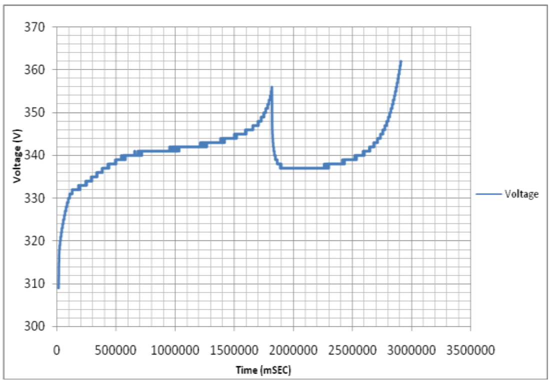


Figure 16: Battery voltage profile during charging

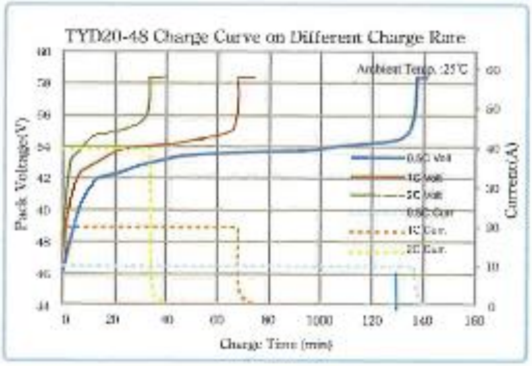


Figure 17: 48V battery charging voltage profile provided by TY DYNAMIC

present battery capacity. Fig. 15 is ABB charger display panel showing information which includes present battery capacity, charging voltage, charging current and remaining time.

When performs 2C charging, battery voltage changes like Fig. 16. Because the battery must accept high current charging, during high current charging, the battery voltage should gradually increase, which means the battery is gradually saturated. The characteristic of this battery is: one has to use low current to lower the battery voltage when battery voltage is in 357V, so that the battery slowly reaches full status. Fig. 17 is 48V battery charging profile provided by TY DYNAMIC. Compare it to charging profile provided by SOIC test battery, it is found that the profile can be divided into two sections. One section is fast charging 120A voltage profile which is the same with Fig. 17, the other section is transformed low current 10A charging voltage profile which is also the same with Fig. 17.

The current transient state when battery just starts charging is shown in Fig. 18. The blue line is current command, red line is the measured current by charger, and the green line is the measured current by battery side. The climbing rate is 20A/sec from 20A climbing to 120A. It is

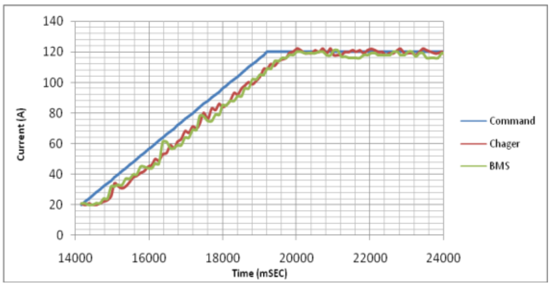


Figure 18: Start charging transient state profile

Figure 19: 120A charging transfers to 10A charging profile

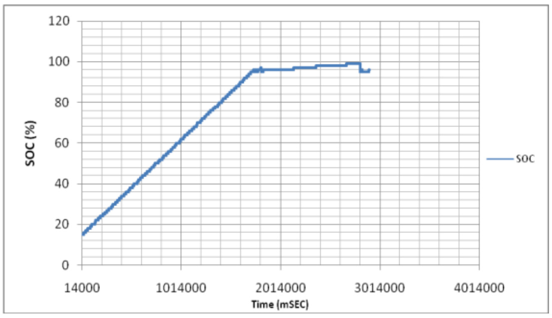


Figure 20: Battery remaining charge capacity profile

found that the battery side measurement result is very similar to the charger measurement result, and they agree all the way until 120A. When battery voltage reaches 357V, the current drops down to 10A from 120A as shown in Fig. 19. The decline rate is 200A/sec until 10A. Obviously, the charger quickly lowers current to 10A by following charging controller command.

In Fig. 20, the resulting battery capacity, it is shown that the time for charging to 80% SOC is around 1514 seconds, which is roughly 26 minutes, the time for charging to close to 100% is around 2914 seconds, which is roughly 50 minutes. The finished time for using 120A fast charging is around 30 minutes which roughly responses to battery capacity 95%. It is shown that TY DYNAMIC battery module can reach full charge status in 30 minutes only by 120A charging. Therefore, boat can launch again within roughly 30 minutes during operation period.

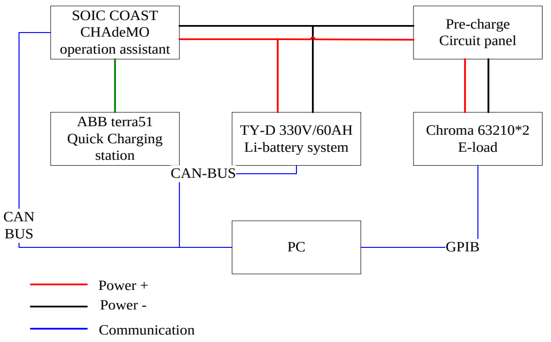


Figure 21: Durability test system block diagram

Figure 22: Programmable direct current electronic load

Table 3: Battery charging/discharging test condition

	Voltage (V)	Current (I)	Cut-off (V)	SOC (%)	Time (S)
CHG	320~345	120	365	54~100	1000
DSC	330~310	60	285	100~54	1800

6 Direct current fast charging controller durability test

For testing charging system durability, this project charges and discharges the same battery module for 50 times, and records the charge and discharge voltage value during process. We want to understand if the battery module characteristic is changed or varied after 50 times charge and discharge.

As shown in Fig. 21, the charging of fast charging battery module is accomplished by arranging charging controller connecting to direct current fast charger. PC computer collects battery signal via CANBUS communication, and uses GPIB (General Purpose Interface Bus) to communicative connect to electronic load. These connections complete communicative connection of test system. The discharge section is arranged by connecting the electronic load to battery, in which, between these two, a pre-charge protective circuit needs to be mounted to prevent the machine malfunction.

In the laboratory, Chroma electronic programmable direct current electronic load 63210 is used. Presently, SOIC equips with two loads and operates them in combination. The maximum power is 29kW, voltage limit is 500V, and maximum loading current is 150A. This type of equipment is widely applied in power supply test, battery capacity verification, and battery life cycle and durability test. All of these tests rely on this type of the test equipment.

The condition of 50 times cycle test of battery is shown in Table 3. The temperature upper limit is 50 degree C, 365V is charging upper limit voltage in charging, current is 120A for 2C charging until the BMS of battery module responds SOC being 100%, and then stop the current. Discharge termination point is 60A for 1C discharge in 30 minutes, and discharge protective voltage is set in 285V when SOC is roughly 54%. As shown in Fig. 23, V1 is the first test. In the early test part, the profiles of battery module do not agree compared with the late test part. After 50 times of test, like V10~V50, the voltage profiles are rather overlapped. By variation observation, one can find out that the battery overall voltage is gradually toward decline. This phenomenon relates to this fast charging test because constant voltage CV mode charging is not performed, such that "adding charge" balance mechanism is not completed.

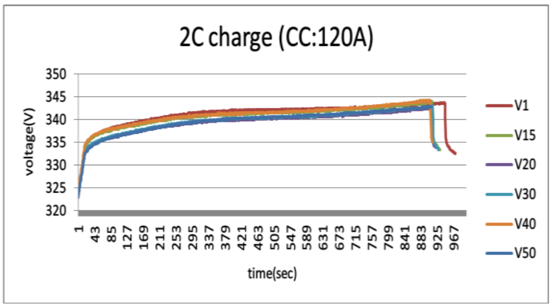


Figure 23: Battery charging voltage variation profile

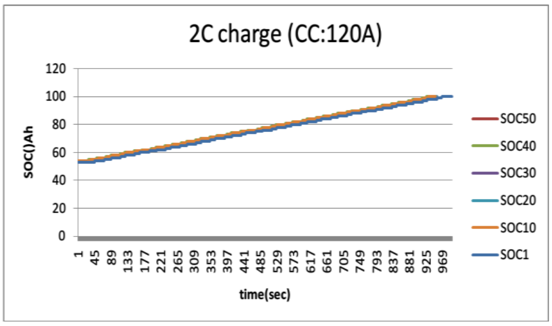


Figure 24: Battery charging SOC variation profile

The remaining charge capacity (SOC) does not change a lot after 50 times of short period fast

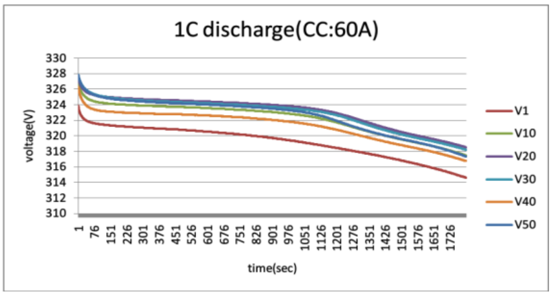


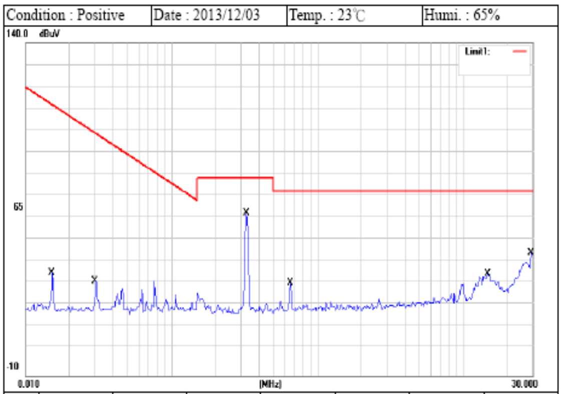
Figure 25: Battery discharge voltage variation profile

Figure 26: DELTA fast charger test photo

Figure 27: Cooperated with HASETEC engineers in fast charging test photo

charge- discharge cycle test, which means the uniformity of battery module and performance of BMS (current and capacity estimation) are quite well. This battery module demonstrates outstanding quality.

As shown in Fig. 25, V1 is the first test. In the early test part, the profiles of battery module do not agree compared with the other late test part. After 50 times of test, like V10~V50, the voltage profiles are rather overlapped. By variation observation, one can find out that the battery overall voltage is gradually toward decline, which reveals slight variation of battery discharging capacity, this also has a positive correspondence with battery temperature in



No.	Frequency (MHz)	Reading (dBuV)	Detector	Corrected dB	Result (dBuV)	Limit (dBuV)	Margin (dB)
1	0.0153	35.79	QP	0.57	36.36	111.99	-75.63
2	0.0307	32.30	QP	0.16	32.46	98.88	-66.42
3	0.3258	63.16	QP	0.10	63.26	79.00	-15.74
4	0.6578	31.56	QP	0.12	31.68	73.00	-41.32
5	14.5942	34.32	QP	0.46	34.78	73.00	-38.22
6	29.2031	44.65	QP	0.68	45.33	73.00	-27.67

Figure 28: Conducted Emission test (Positive)

immediately discharging. This phenomenon relates to this fast charging test because constant voltage CV mode charging is not performed to complete "adding charge" balance mechanism.

So far, above 50 times fast charging cycle test is completed. Based on this, initial battery durability is constructed. Assume one day one fast charging, roughly 3 months usage is achieved. By evaluating charge- discharge profile, one can realize that increasing charge-discharge times results in the slightly variation of battery charge capacity. At this moment, charging controller charges battery module from CC constant current transferred to CV constant voltage mode. This mode change can effectively decrease single cell capacity inconformity after battery module experiencing fast charge-discharge, and refill single cell charge capacity timely.

The test result proves the battery can be charged above 95% SOC in about 32 minutes by 2C charging rate. This tells us that good charge-discharge operation strategy and correct specification indeed proves viability of fast charging, not like the common misunderstanding which implies fast charging will damage battery directly. Nevertheless, battery fast charging surely needs good control and wastes some battery energy.

In the research and development process of SOIC, in order to guarantee the correctness and stability of the charging controller, not only an ABB direct current fast charger is used, a DELTA electronic developing fast charger is also used for system test (Fig. 26), and also engineers travel to Japan HASETEC for technology exchange (Fig. 27).

Figure 29: Sun Moon Lake Ita Thao dock CHAdeMO charger station

HASETEC is a major manufacturer of CHAdeMO association charger.

Direct current fast charging controller also takes Electromagnetic Interference (EMI) and Electromagnetic Compatibility (EMC) into consideration. This includes part selection inside circuit, filter capacitor mounted, four layers electric circuit board accumulated, and the final electric circuit board pattern developing and parts soldered. It passes a series of design and error-elimination process to complete the circuit. And, it is also sent to Electronics Testing Center Taiwan for IEC-60533 test. Fig. 28 is Conducted Emission test (Positive) result according to IEC-60533 standard.

In view of the 50 times cycle test is not sufficient, long term 500 times cycle test is under planning in the future for this battery module. This long term test can further verify the viability and durability of the fast charging test. All this effort helps develop green energy electric boat and promotes engineer integration design ability of SOIC, as well as increasing user confident approval.

7 Real boat application

In middle of December 2013, Sun Moon Lake Ita Thao dock has mounted two CHAdeMO chargers. This dock has two charging berths as shown in Fig. 29. Sun Moon Lake has 139 boats, one of them is Ta-Chuang number One, it is a pure battery power boat, equips with 70kWh lithium ion battery. The Sun Moon Lake cruise mode consumes 20kWh in every single trip of one hour. Before the charger stations were mounted, it can only serve three times of the cruise trip, and then the battery is almost depleted. After the charger stations was mounted, boat operator uses lunch rest interval to do a 30~40 minutes fast charging which quickly replenishes 30kWh to 40kWh battery capacity. This lunch fast charging increases cruise trips to 4 times, and the battery still remains extra capacity for user to run a flexible passenger transportation mode.

8 Conclusion

The direct current fast charging system of this project not only provides a vehicle charging controller following CHAdeMO charging protocol, but also effectively cuts down charging time of suitable fast charging high voltage battery module. It is hope that introducing this direct current fast charging system will benefit user’s demand of electric vehicle performance upgrade, such that a widely system adoption can be realized. Finally, accomplishes energy saving and carbon reduction and water source protection.

Once a fast charging system is ready, it presents a demand for suitable fast charging high voltage battery module. The created software and hardware for the research further help battery performance and capacity examination and test. It also assists battery manufacturer to quickly develop and examine fast charging high voltage battery module of vehicle. The result is more and more business players would join the development and research of electric vehicle core element as well as supporting earth protection.

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Mr. Chung held a M.S degree from NTU. He is now working in ship and ocean industries R&D center, the head of system development section. He has much experience in both marine and mechanical engineering field.