論文
Paper

A Study on Battery System Design for Battery Ships Conforming to CHAdeMO*

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This paper discusses the configuration of battery system which is main power source of the battery propulsion ship conforming to CHAdeMO rapid charging protocol. A power consumption simulation on navigation and mooring of the battery ship ware developed to investigate a change of available energy in the battery. Based on the calculations, it was shown that SOC of the battery can be largely recovered while moored by designing the battery system voltage high. As a result, it is possible to operate the ship with sufficient leeway in SOC even with the same installed battery capacity. On the other hand, an efficiency of inverter get worse several % because of utilizing IGBT device with high rated voltage. This paper also mention the fact that a slight power dissipation increase at the inverter.

Nomenclature

SOC: State of charge in battery [%]
SOC_{Ah}: SOC based on integrated current value [%]
SOC_{Wh}: Percentile of available energy in battery [%]
v_b: Battery voltage [V]
$v_{b\text{-}open}$: Open voltage of battery [V]
p_{nav}: Propulsion power discharged from battery [W]
p_c: Charging power into battery [W]
P_{load}: Power consumed by onboard apparatuses [W]
T_{berth}: Time length while ship is moored at berth [sec]
T_c: Time length of charging battery [sec]
T_{nav}: Time length on voyage [sec]
W_{max}: Maximum energy in full charged battery [Wh]
W_{berth}: Increase and decrease energy during T_{berth} [Wh]
W_c: Charged energy into battery during T_c [Wh]
W_{ini}: Available battery energy at starting voyage [Wh]
W_{nav}: Consumed energy during T_{nav} [Wh]
W_{min}: Required surplus energy at finishing voyage [Wh]

1. Introduction

Battery propulsion ships are vessels that use electric motors for propulsion units with onboard storage batteries as the main power source. Battery propulsion ship ranges from small pleasure fishing boats like those used on lakes employing lead-acid storage batteries and small outboard electric motors (under 1.1 kW) to small passenger vessels and car ferries equipped with high-capacity, rechargeable lithium-ion batteries(1)(2). They are low-noise, low-vibration and no exhaust gas because the battery ships do not use internal combustion engines for propulsion (3). In addition to that, there is no oily odor as they do not carry fuel oil so that they enable passenger vessels to provide a high-quality on-board experience. For ships, cruising distance is largely dependent on the performance of the battery. For this reason, the rechargeable lithium-ion batteries are superior to other rechargeable batteries from the standpoints of high energy density, high charge-discharge rate and long service life(4)(5). However, the energy density of lithium-ion rechargeable batteries is only 1/20 that of liquid fuels such as diesel. It is unavoidable that the energy density is further reduced when ventilation paths for heat radiation are taken into consideration. In order to extend the cruising range, it is necessary to install an even larger number of batteries. However, the weight of battery cells is far greater than liquid fuel. The installation of high-capacity batteries leads to increased hull weight which in turn leads to greater hull's fluid-resistance. Although the price of rechargeable

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lithium-ion batteries is decreasing they are far more expensive than liquid fuel and not really comparable. Based on these characteristics, rather than battery ships being used as long-distance ocean-going vessels, they are expected to serve as short-distance passenger vessels.

In the moats and narrow waterways, the environment is calm. So the environmental impact such as wind, waves, river current, and tidal current are negligible. In these conditions, sight-seeing boats is not required to operate at high speed, the propulsion power requirements are low. Accordingly, the power consumption is not very high. The battery is charged to full at night. The charging is usually not done during the day or between trips.

On the other hand, under more rough environmental conditions such as sea or rivers, higher speed and larger propulsion power are required to ensure safe navigation. This means that high power electric motor and large batteries must be installed to commensurate with the navigation time length and the number of trips. This results not only in the technological problem of propulsion resistance due to increased battery weight but also higher building costs due to the larger battery capacity.

This study examines a use of a short time charging method as a means of minimizing installed battery capacity under the aforementioned conditions. The short time charging have to be implemented so that sufficient power is obtained for one day of navigation with limited installed battery capacity. Rapid chargers conforming to the CHAdeMO standard (JIS D61861-23, IEC61851-23:2014, IEEE Standard 2030.1.1TM-2015) are particularly suited to the short time charging as they are capable of high-power charging up to 50 kW. In addition, it is maintained by an CHAdeMO organization composed of lots of companies and industrial society groups. The organization is promoting standardization and technical innovation to ensure safety. As a result, the rapid chargers are being supplied by over 40 companies and this provides cost advantages.

Battery propulsion ships are expected to come into wider use in the future, and to have reference information for the design of these vessels. This paper discusses the composition of the lithium ion batteries which are the ships' main power source. The paper focuses in particular on the effects of battery system voltage in conditions where CHAdeMO chargers are used.

2. Power Consumption

In battery propulsion ships, batteries supply the energy to operate all of the equipment onboard. Power consumed for propulsion and power used for on-board equipments are examined separately.

2.1 Propulsion power requirements

Propulsion power requirements for ships vary according to the shape and size of the hull. However for non-planing, displacement-type ships, propulsion power is expressed as a function that is approximately the cube of the vessel's speed. Fig. 1 shows an example of actual measurement data of the relationship between log speed v_{log} [m/s] and total propulsion power for the battery boat “RAICHO N.” Measurements were taken in conditions of no wind to light breeze at a time when the tidal current was slowest. They were conducted on both legs of round trip voyages on a large calm body of water with little influence from river flow or tidal currents.

In actual operation, the propulsion resistance increases due to the effects of wind and tidal currents as well as fouling of the hull and the area around the propeller. Therefore, ships are generally designed with a power margin of about 15 to 20% with respect to nominal output as a sea margin(6). Main propulsion electric motors and inverters in battery ships must also satisfy this margin.

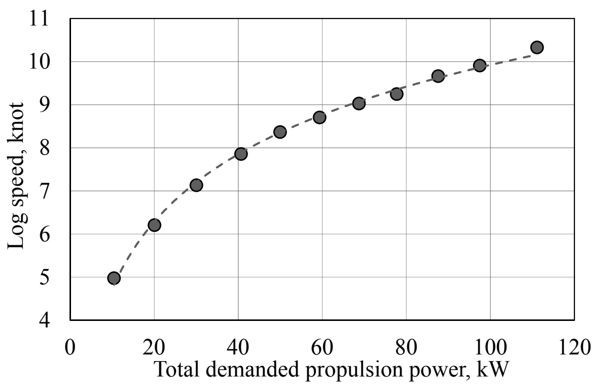

Fig.1 Relation between log speed and puropulsion power of battery boat “RAICHO N”

2.2 On-board power

When the battery propulsion ships are used as small passenger vessels, on-board apparatuses which includes contactor control, monitors, navigational instruments and air conditioner consume an almost constant electric power regardless of ship speed. Heating and cooling equipment used for food service, such as refrigerators and hot stands results in additional power consumption. When the vessel is moored, power is not required for propulsion motors and inverter. However, lighting and air conditioning, which account for much of the on-board power load, cannot be shut down. Therefore, the on-board power load can be considered to be constant both when the ship is moored and navigating. On-board power can be estimated on the basis of an electric power consumption table during shipbuilding in the same way as for standard marine vessels.

3. Charging

3.1 SOC

In rechargeable lithium-ion batteries, its terminal voltage $v_{b\text{-}open}$ can be expressed as a fuction of SOC (the State Of Charge) which means the remaining battery level.

$$v_{b-open} = f(SOC) \qquad (1)$$

Depending on the SOC, the value of $v_{b\text{-}open}$ of rechargeable lithium-ion batteries will vary, in some cases by about 20%. For this reason, the input/output electric power varies depending on the SOC value, even if the same current is input/output. Battery capacity is generally represented in Ah units, and SOC is calculated using actual measurement value taken with a current integration meter which is called as coulomb meter in general. Therefore, SOC based on the current integrated value [Ah] is not a precise indicator of the percentage of available energy [Wh] remaining in the battery. Figure 2 shows the relationship between available energy in the battery and the conventional SOC in standard Ah units generally obtained from the rechargeable lithium-ion battery supplier. To discriminate these two values, the general SOC based on the integrated current is tentatively named as SOC_{Ah} [%]. SOC_{Wh} [%] is defined as the percentage of available energy in battery tentatively. It is calculated as a value of remaining battery energy devided by maximum energy at fully charged condition. As is clear from this figure, there is a slight difference between SOC_{Ah} and SOC_{Wh}.

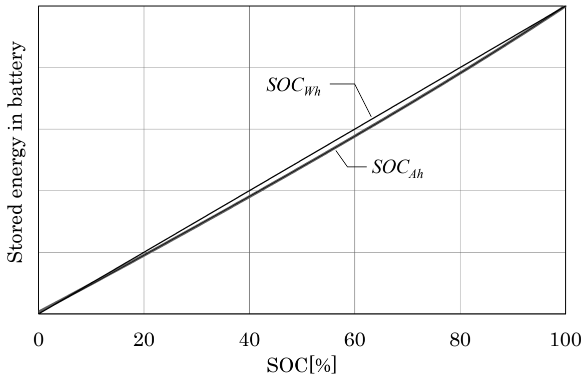

Fig. 2: SOC and available remaining energy

3.2 Internal impedance

The regular service ship for sightseeing driven by the battery power will either consume energy or charge battery while it is moored. Thus the batteries are almost never released from the main circuit. The voltage between terminals v_b rises higher than $v_{b\text{-}open}$ when the battery is charged since there is internal impedance in the rechargeable battery. On the other hand, its voltage tends to decrease during discharge. The increase and decrease of terminal voltage during charging and discharging varies depending on the charge/discharge rate per cell. Therefore, the cell's terminal voltage is defined as a function of SOC_{Ah} and the charging current i_{charge} [A].

$$v_b = f(SOC_{Ah}, i_{charge}) \qquad (2)$$

As a result, the charging power p_c [W] is slightly higher than the power calculated by $v_{b\text{-}open}$.

$$p_c = v_b \cdot i_{charge} > v_{b-open} \cdot i_{charge} \qquad (3)$$

3.3 CHAdeMO compliant limit and charge control

As shown in Fig. 3, CHAdeMO compliant high-speed chargers have some electrical limittations. The output voltage is limitted up to 450 V. The maximum charging current is 125 A. The maximum output power is 50 kW. In order to charge much more energy in a shorter amount of time, it is necessary to use charge control such as the following.

When the voltage of the battery system is lower than 400 V, constant current control is used to maintain a steady charging current of i_{charge}=125 A. At the point the battery system voltage rises above 400 V, the charging method switches to constant power control to maintain a steady charging power of p_c=50 kW. As mentioned before, the voltage across terminals increases with a large charging current due to the internal impedance of the battery. Constant voltage control is carried out so that the battery system voltage during charging does not exceed the preset voltage at the last stage of charging. Preset voltage is the value obtained by derating the maximum charging voltage if necessary.

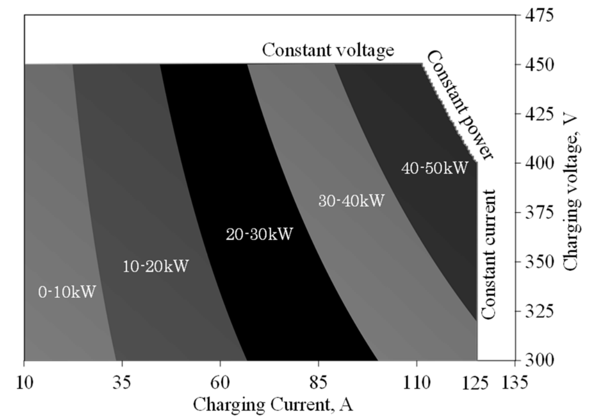

Fig. 3: Output range of CHAdeMO charger.

4. Calculation of the amount of power

4.1 Power consumption during navigation

Ship speed varies throughout a voyage. For example, it will be slow in narrow waterways and be high when the ship sails in open sea. Assuming that every voyage follows the same route, ship speed v_{OG} can roughly be considered to be a function of time t.

$$v_{OG} = f(t) \qquad (4)$$

where, the time of departure is 0.

The propulsion power p_{nav} [W] which is required to reach ship speed v_{OG} can be estimated from fluid resistance diagrams at the hull design stage. Because it is assumed that the battery ship is a sightseeing ship, it is not necessary to take an unloaded situation into consideration. Therefore, the relationship of v_{OG} and p_{nav} at fully loaded condition is expressed by a certain function.

$$p_{nav} = f(v_{OG}) \qquad (5)$$

On the other hand, electric power counsumed by onboard apparatuses P_{load} [W] is a constant. Therefore minimum required energy for a single voyage W_{nav} [Wh] can be expressed by the following equation.

$$W_{nav} = \frac{1}{3600}\int_0^{T_{nav}} (p_{nav} + P_{load})dt \qquad (6)$$

where, T_{nav} [sec] represents the navigation time.

In case that the battery ship is operated for sightseeing, it is necessary to remain the enough energy in the battery to achieve safe and secure passenger transfer when the ship arrives at the destination.

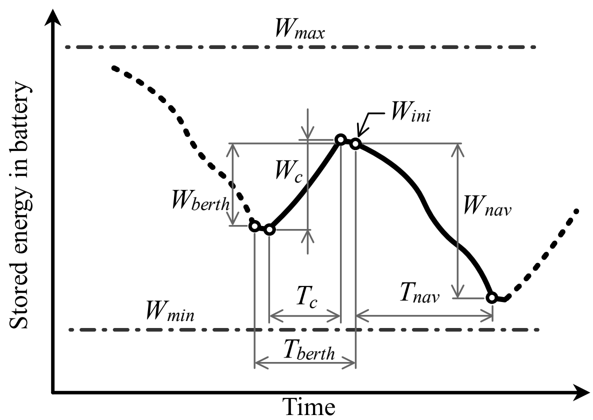

Fig. 4: Remaining battery energy over time

How much surplus energy should be reserved in the battery depends on the ship owner's requirement. Here, W_{min} [Wh] represents the required surplus energy for maintaining speed for a certain amount of time at finishing voyage. If the remaining energy in the rechargeable lithium-ion batteries immediately before the voyage is W_{ini} [Wh], the following inequality must hold (see Fig. 4).

$$W_{ini} - W_{nav} \geqq W_{min} \qquad (7)$$

4.2 Charging and consuming power while moored

The relationship between SOC_{Wh} and SOC_{Ah} as shown in Fig. 2 varies depending on electrode and electrolyte materials of battery. The product data obtained from the battery cell supplier clarifies this relationship.

$$SOC_{Ah} = f(SOC_{Wh}) \qquad (8)$$

By substituting equation (8) into equation (2), it is possible to calculate equation (3). At this time, the amount of power W_c [Wh] that can be charged in the charging time T_c [sec] is given by the following equation.

$$W_c = \frac{1}{3600}\int_0^{T_c} p_c \, dt \qquad (9)$$

The onboard demanded power P_{load} [W] can be regarded as constant while ths ship is moored too. For this reason, the increase or decrease in the amount of power W_{berth} is given as followings.

$$W_{berth} = W_c - \frac{P_{load} \cdot T_{berth}}{3600} \qquad (10)$$

where, T_{berth} means time when the ship is moored at berth.

4.3 Calculation of change in remaining battery level

Calculation was done by applying power consumption calculations to “RAICHO N,” a battery boat owned by Tokyo University of Marine Science and Technology. “RAICHO N” has a charging control function compliant with the CHAdeMO standard. The boat's main specifications are shown in Table 1.

“RAICHO N” was placed into the role of a regularly-scheduled sightseeing ship navigating a 5.7 mile course of the Sumida River estuary as the model route. In order to take approximately 50 minutes for the cruise, the course was divided into several different sections and scheduled cruising speeds were set for each section. During the experiment, the wind speed was a 1.3 to 4.5 m/s (average wind speed: 3.2 m/s). The wind direction was north-northwest to northwest. The tide started ebbing immediately before the start of the experiment and continued ebbing at a constant rate until the end of the experiment.

Fig. 5 shows the propulsion power requirements and changes in boat speed for one example trip. In order to simulate a scheduled cruise on a regularly-scheduled sightseeing ship, the boat speed was kept as close scheduled speed as possible. However, there were slight variations due to the necessity of maneuvering to avoid colliding with other ships because the course was placed in congested waterways with a large number of water bus and work boats.

As the figure shows, there was a difference between the calculated and measured power. The propulsion power was estimated by log speed in calculation. In environments affected by the flow of rivers and tide levels as in this experiment, it was necessary to increase or decrease the log speed in order to achieve the scheduled speed. The log speed is affected by various environmental factors such as the direction of the current, current strength, and wind. Consequently the measured power differed from the estimated power which is expected at planning stage of navigation.

The power consumption for a single cruise was 25.2 kWh, which is 1.2 kWh greater than the calculated value of 24.0 kWh.

It is likely that the power consumption difference of

Table 1: Specifications of battery boat “RAICHO-1”

Length	10 m	Propulsion motor (IPM type)	45 kW×2	
Beam	2.2 m		4,500 rpm	
G/T	9.1 ton	Main battery	P	60 kWh
Draft	1.0 m		St.	72.2 kWh

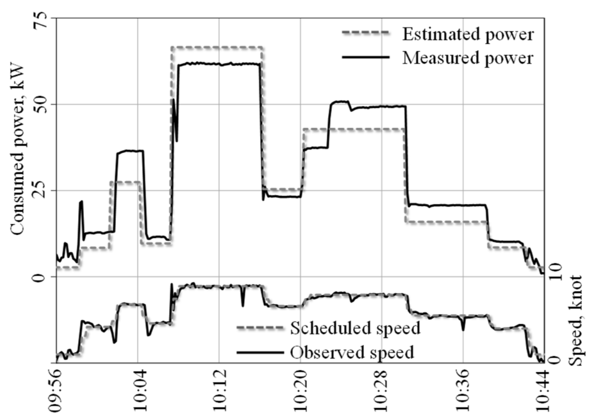

Fig. 5: Changes of speed and required propulsion power during a cruise

the entire route was reduced because the cruise start and end points were the same,

5. Examination of the battery system configuration

5.1 Effect on SOC recovery during charging

As described in 3.3, CHAdeMO chargers have certain limitations on output voltage, current and power. In particular, because the maximum charging current is 125 A, if the battery system voltage is less than 400 V, it cannot be charged at the maximum charging power of 50 kW. However, by creating conditions where the battery system voltage exceeds 400 V, it is possible to draw the maximum charging power of 50 kW. Nominal voltage of battery system can be designed high by increasing the number of cells in series. What the number of cells is increased in series is an effective design approach to utilize high performance of CHAdeMO charger. As a result, it is possible to increase the SOC in a short time. The charging performances differing by the number of cells were compared based on the calculation.

To clarify the short time charging performance, the calculation of SOC recovery was done in a condition that the battery system is charged by CHAdeMO charger from SOC = 50%. Table 2 shows the parameters varied in the calculations. The nominal voltage of the “RAICHO N” battery system is 331 V. It consists of a total of 3168 cells with 144 cells connected in each series and a total of 22 series connected in parallel. Using that as a reference point, configurations combining parallel and series count in various ways were chosen in order not to change the number of cells significantly. Figure 6 shows the calculation results.

As shown in Table 2, the overall variation range of the battery system voltage is raised by connecting a larger number of cells in series. It increases the charging power during the short time charging (see Fig.6). Therefore it is clearly better to recovery much more SOC in operating conditions using short time charging,

If the nominal voltage is 405 V, however, the battery system voltage will reach to 458 V when the SOC = 100%. CHAdeMO compliant chargers can only output up to 450 V due to the limits of the standard. For this reason, it is not possible to make SOC to 100% under these conditions.

Thus, it is possible to charge much more energy during the short time charging by increasing the battery system voltage within the permissible range when the system complies with CHAdeMO standard.

Table 2: Configuration of main battery system

Number of cells			Voltage of main battery system		
Series	Parallel	Total	Min	Nominal	Max
132	24	3168	275	304	344
138	23	3174	287	317	359
144	22	3168	300	331	375
151	21	3171	314	347	393
158	20	3160	329	363	412
167	19	3173	347	384	435
176	18	3168	366	405	(458)*

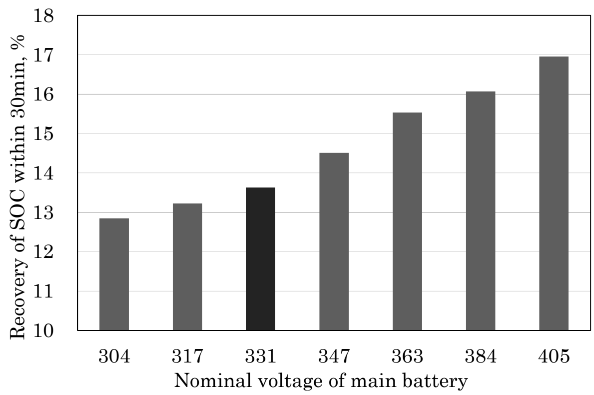

Fig. 6: Recovery of SOC within 30 minutes

5.2 Disadvantages of increasing the number of cells in series

As the number of battery cells in series in the battery system is increased, the battery system voltage becomes high. DC input voltage of the inverter for propulsion motor inevitably raises as well. Generally, the DC input voltage of the inverter is about 50 to 60% of the rated voltage of the IGBTs used in the inverter circuit. The main inverter circuit of “RAICHO N”employs IGBT devices with a rated voltage of 600V because the nominal voltage of the battery system is 331 V. For example, if the number of cells in series is increased and the nominal voltage is raised to 384 V, the maximum voltage will reach 435 V. IGBTs with a rated voltage of 600 V would not usually be chosen in this situation. Apart from the small IGBTs used in home appliances, the standard lineup of IGBTs for industrial applications generally have voltage ratings of 600 V, 1200 V and 1700 V. Consequently, IGBT with the rated voltage of 1200V will be used in this situation. Generally speaking, the switching speed of IGBTs with higher voltage ratings becomes slower and switching losses tend to increase. Furthermore, the increased saturation voltage have a negative impact on conduction loss. The power conversion efficiency decreases for these reasons. This may possibly result in the batteries being diminished quicker. In this paper, an electric power loss analysis was conducted to evaluate this effect.

Fig. 7 shows the rate of increase of power loss that occurs when the nominal voltage of the battery system is increased from 331 V to 384 V. Regardless of the output power or the SOC, the power dissipation at the inverter increases several percentage points. The main reasons for this are the switching loss accompanying the increased battery system voltage and the increased conduction loss due to the use of high rated voltage IGBT devices.

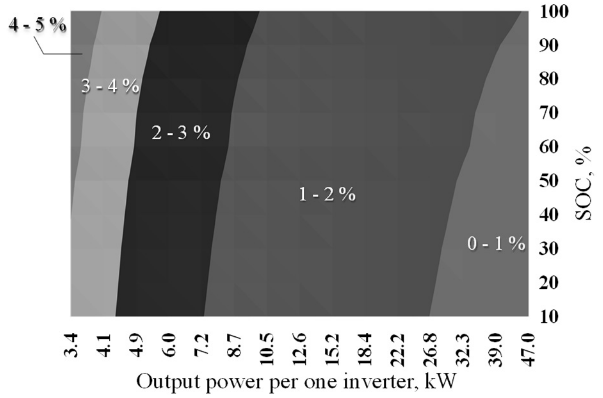

Fig. 7: Increase of power loss in inverter of condition A comparing to condition B

5.3 Continuous navigation simulation

When the battery system voltage is increased, the short time charging ability is improved and SOC recovery is quick. On the other hand, the SOC is diminished more quickly during navigation as a result of the lower inverter efficiency. In order to evaluate these effects, a regularly-scheduled cruise simulation was conducted. The conditions of the simulation are shown in Table 3. The simulation consisted of five regular cruises on the same route on a single day. Batteries were charged to 100% during night, and short time charging was conducted when moored a total of four times. Fig. 8 shows the changes in SOC at those times. In condition A (nominal voltage 331 V), the SOC was 24.0% at the end of 5 cruises (see Table 4). In condition B (nominal voltage 384 V), it was 36.6%.

Therefore, the characteristics of Condition B are superior from the standpoint of safe operation for a regularly-scheduled sightseeing ship. However, Condition A consumed 221.7 kWh for 5 cruises while Condition B consumed 224.3 kWh. Therefore, from the standpoint of energy conservation, Condition A, which uses IGBTs with a rated voltage of 600 V in the inverter, has slightly better characteristics.

Table 3: Simulation conditions

Items	Condition A	Condition B
Nominal voltage of main battery system	331V	384V
Maximum volotage of main battery system	375V	435V
Rated voltage of IGBT	600V	1200V
Rated current of IGBT	300A	300A

Table 4: Simulation results

Item	Condition A	Condition B
SOC margin at the end of 5th Nav.	24.0%	36.6%
Consumed electric power by 5 navigations	221.7 kWh	224.3 kWh

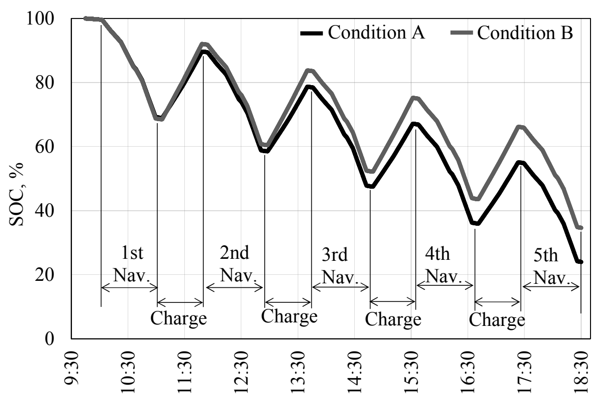

Fig. 8: SOC changes on one day operation

6. Conclusion

This paper examined the battery system for battery propulsion ships used in regularly-scheduled sightseeing applications such as water bus. This paper evaluated the effect of battery system voltage on SOC recovery during short time charging and on the power conversion efficiency of the inverter in battery ships. In particular, it was assumed that the charging system was compliant with the CHAdeMO standard. The calculation conditions were set with several cruises and short time chargings in a single day. When a battery ship is put into service as a regularly-scheduled sightseeing ship, it must have sufficient remaining battery power to ensure safe navigation. When utilizing a CHAdeMO compliant charging system, it is possible to increase amounts of SOC recovery during short time charging by raising the battery system voltage within the permissible range. As a consequence, it is possible to operate the ship with sufficient leeway in the SOC even with the same installed battery capacity. On the other hand, it is necessary to raise the rated voltage of the IGBT devices in the inverter if the battery system voltage is increased. In consequence, the conduction loss and the switching loss were increased in IGBT devices. This was found to result in slightly greater electric power dissipation.

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