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Real-ship application of composite energy storage DC energy management control technology for hybrid

System Integration & Hybridization

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ABSTRACT

A 4400HP twin-engine twin-propeller harbor tug adopts a hybrid power system in which the main engine and the shaft belt motor are connected in parallel, and the ship's power station is equipped with an energy storage device, a generator set, and a DC power distribution board. The DC energy management system can cooperate with the remote control system of the main engine and the remote control system of the motors to complete the free switching between the main engine mode, the shaft belt power generation mode, the BOOST mode, the purely electric propulsion mode, and the DC shore power charging mode of the vessel in different scenarios. In BOOST mode, the power station energy is used to propel the ship together with the main engine through the shaft motor; in pure electric propulsion mode, the energy of the energy storage device is used alone to realize pure green propulsion; and in DC shore power charging mode, the DC shore power is controlled to charge the energy storage device with high efficiency. The real ship verifies that the switching of each working mode is smooth, and the energy storage device has obvious effect of peak shaving and valley filling, which meets the user's demand.

REAL SHIP APPLICATION OF COMPOSITE ENERGY STORAGE DC ENERGY MANAGEMENT CONTROL TECHNOLOGY FOR HYBRID HARBOR TUGS

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Abstract: A certain type of 4400HP twin-engine and twin-propeller harbor tug adopts a hybrid power system in which the ME is connected in parallel with the M/G. Its power station is equipped with energy storage devices,DGs, and a DCMSB.The EMS can cooperate with the ME remote control system and the motor remote control system to freely switch the marine power system among the ME Mode, PTO Mode, and PTH Mode in different scenarios, and also switch the power station among the Pure Electric Mode, Diesel Electric Mode, Hybrid Mode, and AC Charging Mode. In the PTO Mode, the surplus energy of the ME is used by the M/G to supply power for the marine daily loads and charge the energy storage device. In the PTH Mode, the energy of the energy storage device is used alone to achieve pure green propulsion. In the AC Charging Mode, the shore power is controlled to charge the energy storage device with high efficiency.It has been verified by real ship that the marine hybrid power system and the power station can switch operating modes smoothly, and the energy storage device has an obvious effect of peak shaving and valley filling, meeting the user's requirements.

Key Words: Composite Energy Storage; Multi-Mode Switching; DC Energy Management; AC Shore Power Charge

1 INTRODUCTION

With the proposal and steady advancement of China's "Dual Carbon" strategy, maritime carbon emission regulations are expanding their coverage and becoming increasingly stringent. As a primary contributor to port carbon emissions, port-operated tugs possess significant carbon reduction potential[1][2]. The continuous development of electric propulsion systems and energy storage battery technologies, coupled with the emergence of new energy hybrid power solutions, has introduced innovative propulsion modes for harbor tugs operations[3]~[6].Concentrated in port operations, tugboats represent crucial emission sources. Conventional azimuth stern drive (ASD) tugboats predominantly employ diesel main engines for direct propulsion, with designs based on 100% ME power output to ensure robust towing or thrust. However, due to their operational characteristics, tugboats frequently operate under low-load conditions, resulting in incomplete diesel combustion, elevated fuel consumption, and suboptimal emission performance[7][8].

A certain type of 4400 HP harbor tug employs a hybrid power system combining a main engine with a shaft motor/generator. When the tug operates at high power, it works in the main engine mode (ME Mode) to provide towing or thrust. During low-power operations, it switches to the Power Take Out Mode (PTO Mode), utilizing excess energy from the main engine to power onboard systems and charge energy storage devices. When the tug is transiting to or from a port, it operates in the pure electric Take-Home Mode (PTH Mode), using energy from the storage devices for green propulsion. When docked, it operates in the AC Charging Mode, efficiently charging the energy storage devices from shore power. An energy management system (EMS) controls the power station to meet the demands of different operational modes.

2 MARINE HYBRID POWER SYSTEM

2.1 System Configuration

The marine hybrid power system and power station system of a certain type of 4400HP port tug are shown in Figure 1. The main equipment of the power system includes main engines (ME) No.1-No.2, gear boxes (GB) No.1-No.2, propellers No.1-No.2, and shaft motor/generators (M/G) No.1-No.2.The main equipment of the power station includes the DC main switchboard (DCMSB), AC main switchboard (ACMSB), diesel generator sets (DG) No.1-No.2, and energy storage devices (battery) No.1-No.2. The DCMSB is composed of the EMS, AC/DC power converter modules (AC/DC) No.1-No.5, DC/DC power converter modules (DC/DC) No.1-No.2, and DC/AC power inverter modules (DC/AC) No.1-No.2, etc.

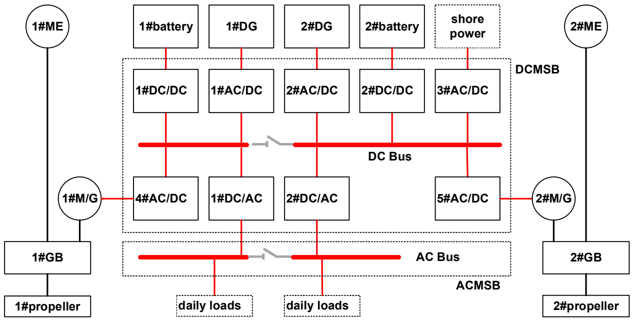

Figure 1. Configuration of the marine hybrid power system and power station system

Table 1 Parameter of the marine hybrid power system and power station system

Equipment name	parameter
ME	750rpm, 1618kW
GB	two inputs and one output, gear ratio of 1:1:1
M/G	0~750rpm,0~ 400kW
AC/DC	250kW
DC/DC	400kW
DC/AC	150kW
DG	250kW/1500rpm, 690V/50Hz
DCMSB	DC Bus voltage 1000V
ACMSB	AC Bus voltage 380V
battery	502.6kWh
shore power	AC690V,50Hz

2.2 Operating Mode

2.2.1 Hybrid Power System Operating Mode

The marine hybrid power system operating mode includes ME Mode、PTO Mode、PTH Mode.

① ME Mode,the ME drives the propeller independently through the GB.

② PTO Mode,the ME drives the propeller through the GB. In the generating mode of the M/G, the M/G converts the surplus energy of the ME into electrical energy, which is then supplied to the DCMSB for distribution to charge the battery and power the daily loads.

③ PTH Mode,the M/G independently drives the propeller. In the electric mode of the M/G, the electrical energy required by the M/G is taken from the DCMSB through the AC/DC.

2.2.2 Power Station Operating Mode

The power station operating mode includes Pure Electric Mode、Diesel Electric Mode、Hybrid Mode、AC Charging Mode.

① Pure Electric Mode,in the power station, only the battery are online, and supply electrical energy to the DC busbar through the DC/DC .

② Diesel Electric Mode,in the power station, only the DGs are online, and supply electrical energy to the DC busbar through the AC/DC .

③ Hybrid Mode,in the power station, the DGs are online, or the M/G are online and in the generating mode,the battery are online to supply electrical energy to the DC busbar.

④ AC Charging Mode,in the power station, the shore power AC/DC is online, converting the AC shore power into DC electrical energy to charge the battery.

3 DC ENERGY MANAGEMENT CONTROL STRATEGY

EMS not only needs to cooperate with the main engine remote control system and the motor remote control system to complete the switching control of the marine hybrid power system operating modes, but also needs to reasonably control the operating modes of the power station. This enables the power station to meet the propulsion requirements of the marine hybrid power system and ensures the stable operation of the ship.

3.1 Hybrid Power System Operating Mode Switching Control Strategy

The switching rules of the operating modes of the marine hybrid power system for the EMS are shown in Figure 2. Among all the switching rules for the operating modes, the EMS serves as a coordinator for mode switching. There are six types of operating mode switches in total for the marine hybrid power system that the EMS participates in:

① During the switching process from the ME Mode to the PTO Mode, the EMS takes over the control authority of the M/G. When the starting conditions of the M/G are met, the EMS controls it to start generating electricity and adjusts the power generation according to the rotational speed of the ME.

② During the switching process from the PTO Mode to the ME Mode, the EMS controls the M/G to stop generating electricity and releases the control authority of the M/G.

③ During the switching process from the ME Mode to the PTH Mode, the EMS controls the power station to enter the heavy-load state to meet the electric propulsion requirements of the M/G.

④ During the switching process from the PTH Mode to the ME Mode, the EMS controls the power station to exit the heavy load state.

⑤ During the switching process from the PTO Mode to the PTH Mode, the EMS controls the M/G to stop generating electricity and releases the control authority of the M/G. EMS also controls the power station to enter the heavy-load state to meet the electric propulsion requirements of the M/G.

⑥ During the switching process from the PTH Mode to the PTO Mode, the EMS controls the power station to exit the heavy-load state.the EMS also takes over the control authority of the M/G. When the starting conditions of the M/G are met, the EMS controls it to start generating electricity and adjusts the power generation according to the rotational speed of the ME.

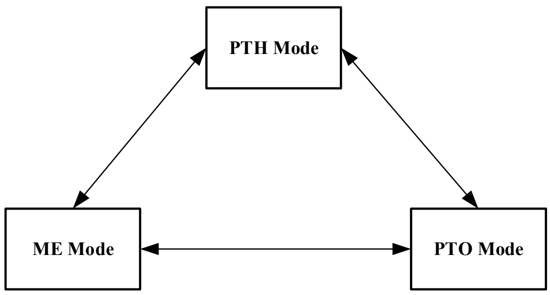

Figure 2. Operating mode switching rule of the marine hybrid power system

3.2 Power Station Operating Mode Switching Control Strategy

The switching rules of the power station operating modes for the EMS are shown in Figure 3. Among all the power station mode switching rules, the EMS acts as the initiator. Manual switching means that the mode switch needs to be initiated manually on its Human Machine Interface (HMI), but the entire switching process is automatically completed by the control program. Automatic switching means that the control program automatically initiates and completes the mode switching process when it detects that the conditions for mode switching are met. All power station modes can be manually switched arbitrarily according to the propulsion requirements. This paper only designs the automatic switching control strategy between the power station operating modes:

① The hybrid power system can operate in any operating mode,the power station is in the Pure Electric Mode, the EMS monitors the State of Charge (SOC) of the battery. When the SOC is less than 35% (adjustable), the first standby DG will be automatically started and connected to the grid, and the power station will automatically switch to the Hybrid Mode.

② The hybrid power system can operate in any operating mode, the power station is in the Hybrid Mode with one DG connected to the grid, the EMS monitors the SOC of the battery. When the SOC is less than 30% (adjustable), the second standby DG will be automatically started and connected to the grid, and the power station will maintain the Hybrid Mode.

③ The hybrid power system is in non-PTO Mode, the power station is in Hybrid Mode, the EMS monitors the SOC of the batteries. When the SOC exceeds 90% (the full charge value, adjustable), the DGs will be automatically stopped, and the power station will automatically switch to the Pure Electric Mode. This function is designed according to the actual needs of the ship.

④ The hybrid power system is in PTO Mode, the power station is in Hybrid Mode,the EMS monitors the SOC of the batteries. When the SOC exceeds 90% (the full charge value, adjustable), the M/G will be automatically stopped, and the power station will automatically switch to the Pure Electric Mode.

⑤ The hybrid power system can operate in any operating mode, the power station is in the AC Charging Mode,the EMS monitors the SOC of the batteries. When the SOC exceeds 90% (the full charge value, adjustable), the AC/DC will be automatically stopped,and the power station will automatically switch to the Pure Electric Mode.

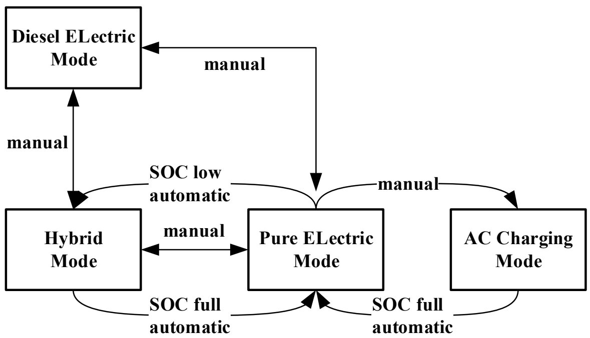

Figure 3. Operating mode switching rule of the power station

4 REAL SHIP TEST

4.1 M/G Power Generation Capacity Test

The hybrid power system is in PTO Mode, the power station is in Hybrid Mode,Test 1 and Test 2 are carried out respectively to verify the power generation capacity of the M/G:

Test 1: When the two ME are running at the same rotational speed, the starboard ME drives the M/G to generate electricity, while the port ME does not generate electricity. Record the rotational speed of the ME, the power generation of the M/G.

Test 2: When the two ME are running at the same rotational speed, the port ME drives the M/G to generate electricity, while the starboard ME does not generate electricity. Record the rotational speed of the ME, the power generation of the M/G.

This paper takes Test 1 as an example for a detailed description. The test data of the power generation capacity of the M/G driven by the starboard ME are shown in Figure 4 and Table 2. In Figure 4, the x-coordinate represents the rotational speed of the ME. From top to bottom, the first curve on the y-coordinate represents the power generation of the starboard M/G, the second curve represents the fuel consumption of the starboard ME, and the third curve represents the fuel consumption of the port ME. According to the EMS regulations, When the power of the M/G is positive, it means the M/G is consuming electricity; when it is negative, it means the M/G is generating electricity; when the power of the battery is positive, it means charging, and when it is negative, it means discharging; when the power of the DC/AC is positive, it means power consumption.

It can be seen from Figure 4 and Table 2 that the power generation rotational speed range of the ME is from 435 rpm to 680 rpm, and the maximum power generation at 680 rpm is 336 kW.

When the harbor tug is operating at low power and the PTO Mode is adopted, the M/G can generate electricity using the surplus power of the ME. This can fully leverage the advantages of the marine hybrid power system, increase the load of the ME to charge the battery, and provide the power required for the normal consumption of daily loads. It also avoids the drawbacks of the ME, such as incomplete combustion, high fuel consumption, and poor emissions at low loads.

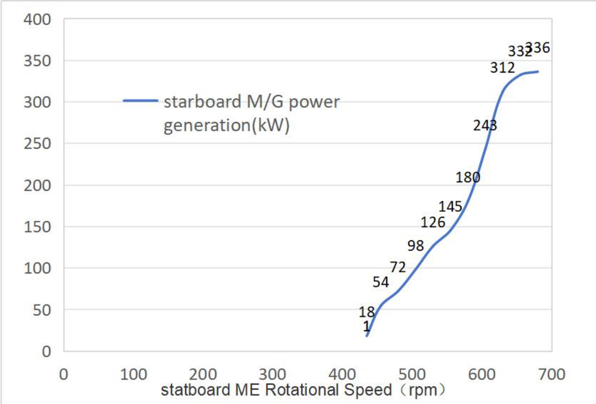

Figure 4 PTO Mode-starboard M/G generation

Table 2 PTO Mode-starboard M/G generation capacity data sheet

starboard ME rotational speed (rpm)	435	455	480	505	530	555
starboard M/G power generation(kW)	18	54	72	98	126	145
starboard ME rotational speed (rpm)	580	605	630	655	680	
starboard M/G power generation(kW)	180	243	312	332	336	

The hybrid power system is in PTO Mode, the power station is in Hybrid Mode,the real ship display effect of the HMI of the EMS is shown in Figure 5. The red arrows indicate the direction of energy flow.When the rotational speed of the starboard ME is 573 rpm, the power generation of the M/G is 183 kW, the charging power of battery No.1 is 58 kW, the charging power of battery No.2 is 86 kW.

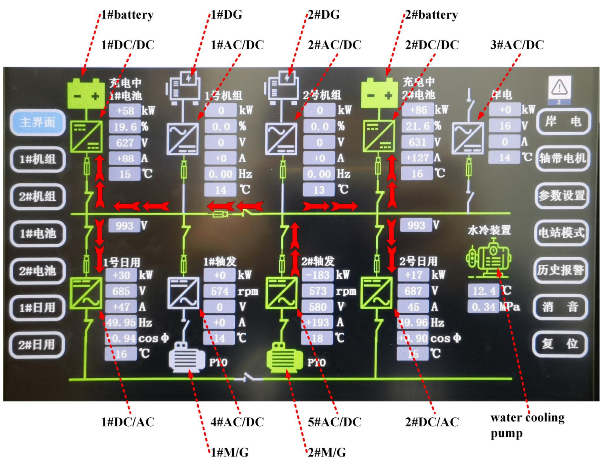

Figure 5 Effect of real ship for M/G power generation capacity test

4.2 Battery Peak Shaving and Valley Filling Energy Test

The hybrid power system is in PTH Mode, the power station is in Hybrid Mode,the EMS controls the battery for peak shaving and valley filling. A downstream test and an upstream test are carried out respectively, and the navigation speed is measured by the navigator.

This paper takes downstream navigation as an example for detailed description. The test data of the peak shaving and valley filling ability of the battery are shown in Figure 6 and Table 3. In Figure 6, the x-coordinate represents the ship's speed. From top to bottom, the first curve on the y-coordinate represents the propulsion power of M/G No.1, the second curve represents the propulsion power of M/G No.2, the third curve represents the power generation of DG No.1, the fourth curve represents the power generation of DG No.2, the fifth curve represents the power of battery No.1, and the sixth curve represents the power of battery No.2.

It can be seen from Figure 6 and Table 3, during the entire test process, the EMS controls the power generation of the two DGs to be stable in the range of 210 kW-220 kW, that is the load rate of the DG operates in the high efficiency range of 84%-88%. When the propulsion power of M/G is relatively small, the EMS controls the surplus power of the DG to charge the battery. When the ship's speed is 5 kn, the maximum charging power of the battery is 110 kW-119 kW (peak shaving). As the ship's speed increases, the power demand of M/G also increases, and the battery gradually changes from the charging state to the discharging state. When the ship's speed is 10.9 kn, the maximum discharging powe

r of the battery is 239 kW-240 kW (valley filling). The peak shaving and valley filling ability of the battery is obvious, which meets the operation requirements of harbor tug.

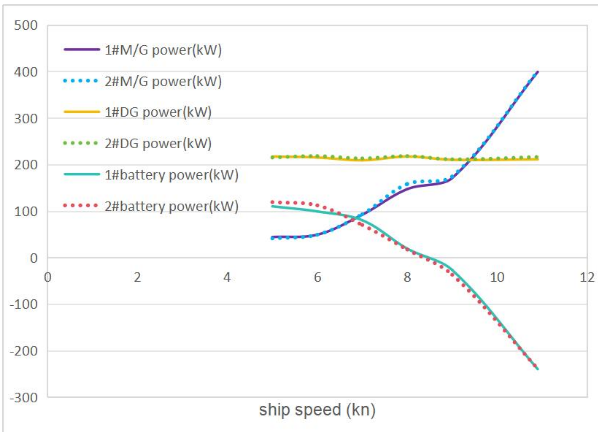

Figure 6 PTH Mode-the battery peak shaving and valley filling

Table 3 PTH Mode-the battery peak shaving and valley filling data sheet

ship speed (kn)	5	6	7	8	9	10.9
1#M/G power(kW)	44	49	92	147	171	399
2#M/G power(kW)	41	49	93	158	174	400
1#DG power(kW)	217	215	209	217	210	211
2#DG power(kW)	215	218	213	218	211	216
1#battery power(kW)	110	99	80	19	-27	-240
2#battery power(kW)	119	112	70	17	-37	-239

The hybrid power system is in PTH Mode, the power station is in Hybrid Mode,the real ship display effect of the HMI of the EMS is shown in Figure 7. The red arrows indicate the direction of energy flow.The power generation of DG No.1 is 146 kW, that of DG No.2 is 161 kW. The discharge power of battery No.1 is 165 kW, and that of battery No.2 is 180 kW. The propulsion power of M/G No.1 is 143 kW, and that of M/G No.2 is 406 kW.

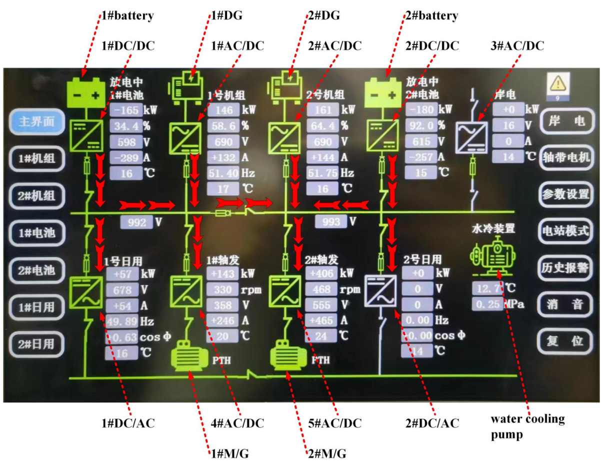

Figure 7 Real ship effect of the battery peak shaving and valley filling

4.3 PTH Mode Sailing Capacity Test

The hybrid power system is in PTH Mode, the power station is in Pure Electric Mode,the EMS controls the battery to discharge evenly. Downstream and upstream tests are carried out, and the navigation speed is measured by a navigator.

The test data of the sailing ability in PTH Mode are shown in Figure 8 and Table 4. In Figure 8, the x-coordinate represents the test time. From top to bottom, the first curve on the y-coordinate represents the ship's speed, the second curve represents the SOC of battery No.1, the third curve represents the SOC of battery No.2, the fourth curve shows the propulsion power of M/G No.1, and the fifth curve shows the propulsion power of M/G No.2. It can be seen from Figure 8 and Table 4, during the entire test process, the propulsion power of the M/G is stable in the range of 240 kW-265 kW. The ship's upstream speed is stable between 6.9-7.6 kn, and the downstream speed is stable between 10-11.3 kn. The EMS controls the two batteries to discharge evenly. When the SOC of the batteries decreases from 99% to 23%, the ship can sail continuously on pure electricity for about 70 minutes, which meets the requirements of the harbor tug for green departure and return in the port.

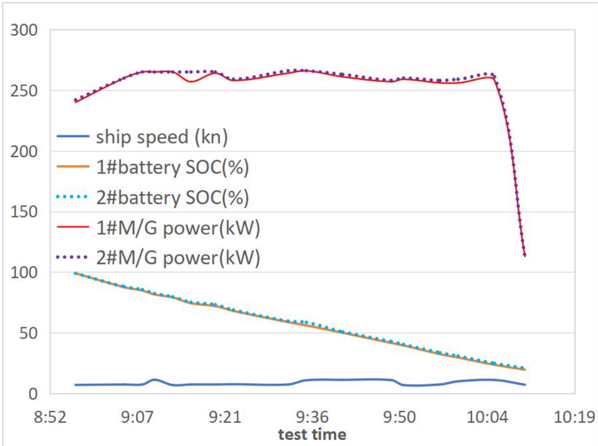

Figure 8. Pure Electric Mode sailing capacity test

Table 4 Pure Electric Mode sailing capacity test data sheet

time	8:57	9:05	9:08	9:10	9:13	9:16
water flow	upstream	upstream	upstream	downstream	upstream	upstream
ship speed (kn)	7	7.4	7.4	11.3	6.9	7.4
1#battery SOC(%)	99	87.6	84.8	81.6	79.2	74.4
2#battery SOC(%)	99	88	85.6	82.4	79.6	75.2
1#M/G power(kW)	240	260	265	265	265	257
2#M/G power(kW)	242	260	265	265	265	265
time	9:20	9:23	9:32	9:35	9:41	9:49
water flow	upstream	upstream	upstream	downstream	downstream	downstream
ship speed (kn)	7.4	7.6	7.4	10.9	11.2	11
1#battery SOC(%)	72	68	58.8	56.1	50	41.6
2#battery SOC(%)	73.2	68.8	59.6	58.6	50.8	42.8
1#M/G power(kW)	264	258	264	266	261	257
2#M/G	265	259	266	266	263	258

power(kW)					
time	9:51	9:57	10:00	10:06	10:11
water flow	upstream	upstream	downstream	downstream	upstream
ship speed (kn)	6.9	7.4	10	11.1	7.2
1#battery SOC(%)	39.6	32.4	29.6	23.6	19.6
2#battery SOC(%)	40.4	33.6	30.8	24.8	20.8
1#M/G power(kW)	259	256	256	258	113
2#M/G power(kW)	260	258	259	261	113

The hybrid power system is in PTH Mode, the power station is in Pure Electric Mode,the real ship display effect of the HMI of the EMS is shown in Figure 9. The red arrows indicate the direction of energy flow.The discharge power of battery No.1 is 297 kW, and that of battery No.2 is 318 kW. The propulsion power of M/G No.1 is 263 kW, and that of M/G No.2 is 262 kW.

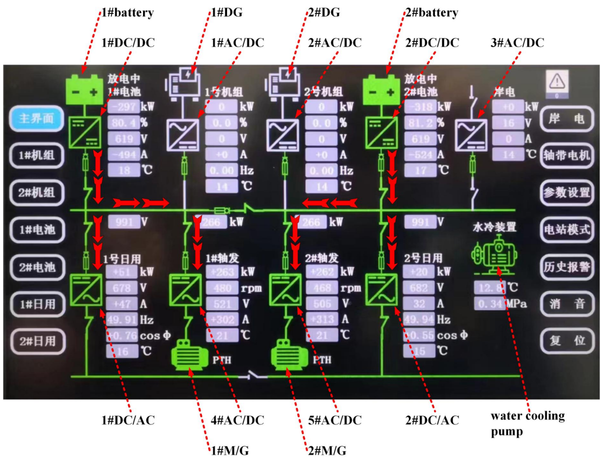

Figure 9. Effect of real ship in Pure Electric Mode sailing capacity

4.4 Diesel Electric Mode Sailing Capacity Test

The hybrid power system is in PTH Mode, the power station is in Diesel Electric Mode, and the navigation speed is measured by a navigator. The real ship test data are shown in Table 5. The rated power of the DG is 250 kW, the power generation of the DG is approximately 244 kW, and the propulsion power of the M/G is approximately 194 kW. The ship's downstream speed is 8.8 kn, and the upstream speed is 8 kn, which meets the user's requirements.

Table 5 Diesel Electric Mode sailing capacity test data sheet

ship speed (kn)	1#M/G power(kW)	2#M/G power(kW)	1#DG (kW)	2#DG (kW)	water flow
8.8	193	195	244	242	downstream
8	194	194	244	244	upstream

The hybrid power system is in PTH Mode, the power station is in Diesel Electric Mode,the real ship display effect of the HMI of the EMS is shown in Figure 10. The red arrows indicate the direction of energy flow.The power generation of DG No.1 is 244 kW, and that of DG No.2 is 242 kW. The propulsion power of M/G No.1 is 193 kW, and that of M/G No.2 is 195 kW.

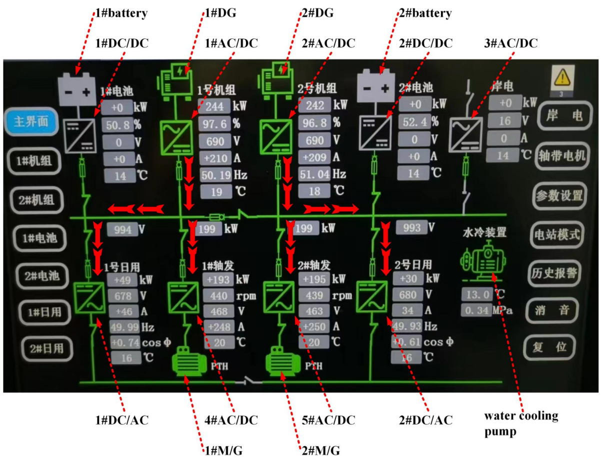

Figure 10. Effect of real ship in Diesel Electric Mode sailing capacity

4.5 AC Charging Mode Capacity Test

The hybrid power system can operate in any operating mode,the power station is in the AC Charging Mode,the real ship display effect of the HMI of the EMS is shown in Figure 11. The red arrows indicate the direction of energy flow.After the power station enters the AC Charging Mode, the AC shore power charges the batteries through the AC/DC. The charging power increases linearly from 0 kW to the full power charging level, achieving a safe and efficient charging function that meets the user's requirements. It can be seen from the figure, in this mode, the power of the AC shore power is 398 kW, the charging power of battery No.1 is 185 kW, and the charging power of battery No.2 is 195 kW.

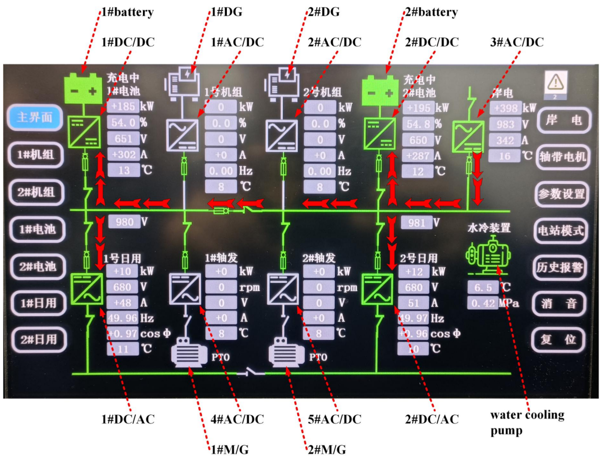

Figure 11. Effect of real ship in AC Charging Mode full power charge

5 CONCLUSIONS

The EMS can cooperate with the main engine remote control system and the motor remote control system to realize the switching control of the marine hybrid power system operating mode, and can achieve the manual/auto switching control of the power station operating mode according to the ship's requirements. During the low-power operation of the ME, it controls the M/G to generate electricity, enabling the ME to operate in the high-efficiency load area.The power station is in Hybrid Mode, it controls the battery to smooth out the peak and fill in the valley of the power station, with obvious effects. The power station is in Pure Electric Mode, the sailing ability meets the requirements for the harbor tug's green departure and return. The power station is in the Diesel Electric Mode, the sailing ability meets the design requirements. The power station is in the AC charging Mode, it can safely and efficiently charge the battery, meeting the user's requirements.

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