The application of hybrid photovoltaic system on the ocean-going ship: engineering practice and experiment research

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Abstract: The constant development of electronic inverter technology has played a key role in promoting the exploration and development of solar ships. For the large-scale ocean-going ship platform, the critical issue of applying solar photovoltaic (PV) system is integrating PV equipment into the ship power system (SPS) without changing its original structure. This paper compares the existent technical differences for applying the off-grid and grid-connected PV system in the SPS and proposes the basic design principles for marine integration applications. The 5000 PCTC ro-ro ship is set as the application object, on which a hybrid PV system with large-capacity lithium battery storage device is designed and installed as an independent subsystem. The typical feature of this hybrid PV system is that it can implement operation mode switching between off-grid and grid-connected, according to the evaluation on solar radiation resource, power load requirement and state of charge (SOC) in the lithium battery. The test results show that this PV system has a stable operation characteristic under the different operation modes. In addition, this ship-based PV power system has automatic and reliable operation management capability, which could effectively reduce manual control frequency and maintenance workload of marine engineer.

Key words: ship; ship power system; photovoltaic system; off-grid; grid-connected

1 Introduction

In the face of worldwide energy conservation, emission reduction and the pressure brought by international laws and regulations [1-3], the research institutes in many shipping country are beginning to explore new energy technologies such as wind, solar, nuclear, biomass and fuel cells to develop “*green ship*” [4], which is commonly regarded as a kind of environmentally friendly ship concept and/or technology with unlimited development potential. Solar ship, namely ship that use solar photovoltaic technology, are designed with the basic technical scheme that integrating the solar photovoltaic (PV) system into the ship power system (SPS) and utilizing this zero-pollution, zero-emission PV power as much as possible. Some case studies of actual ship application have shown that there is a significant reduction in the life cycle of fuel oil consumption and greenhouse gas emissions, and further claimed that the design power of diesel synchronous generator sets used in solar ship can be smaller than that of traditional ship[5], if the concept of energy balance and investment economy is taken into the consideration during the design stage of SPS. At present, the solar ship has become an important research direction for green ship technology development.

From the viewpoint of electric system standard, the ship-based PV system has two kinds of integration schemes, such as DC and AC power system. According to the ratio between the PV system capacity and the ship's power load demand, the PV system used in solar ship can be classified as the auxiliary power supply type and solar-powered type[6]. And, PV system design scheme can be further refined into off-grid, grid-connected and hybrid mode, when the power load demand and operating conditions of electrical load are comprehensive evaluated[7-9]. So far, much work has been reported mainly in the field of off-grid ship-based PV system of AC auxiliary power supply type and DC solar-powered type, e.g. “Solar Sailor” commercial ferry (Australia, 2008), “Auriga Leader” ro-ro ship (Japan, 2009), "MS Turanor Planet Solar" solar catamaran yacht (German, 2010) and

"Emerald Ace" ro-ro ship (Japan, 2012). Only a limited number of studies have considered the integration of a grid-connected PV system with SPS on ship platform, especially large scale ocean-going vessels. Ref. [10] introduced the only application case of grid-connected ship-based PV system, which is a 3.2 kW photovoltaic-diesel hybrid power system installed on a conventional cruise ship (South Korea, 2011). This proto-type green ship consisted of a diesel engine (20kW), battery energy storage (24V/19.2kWh), hybrid control system and PV generation system, within which there are two DC-DC converters (1.6kW×2) and DC-AC inverters (4kW, 22.5-30.8Vdc/220Vac standalone inverter; 4kW, 100-370Vdc/220Vac grid-connected inverter) respectively. Since the standalone inverter and grid-connected inverter can be put into utilization by the auto transfer switch (ATS) at the same time, this PV system is defined as a hybrid PV system. However, there is not any application research on the hybrid PV for any kinds of marine ship world-wide.

In this paper, the technical features of off-grid and grid-connected type ship-based PV systems are analyzed. From the viewpoint of engineering application, the corresponding critical technical and design principles are presented. A 5000 PCTC ocean-going ro-ro ship is set as the application object, and a kind of off-grid and grid-connected hybrid integrated PV system is designed and presented from topological structure, solar power management system and operating mode setting. In particular, there are two typical disparate points between this system and application cases mentioned above. Firstly, a large capacity energy storage device (iron phosphate-lithium power batteries) is used to deal with the problems of dynamic energy balance and smooth switching process, which is the key point for stable power output of inverter under any weather condition and/or operating modes; Secondly, there is only one PV inverter applied in this system, which means that the different pre-set operating modes containing off-grid and grid-connected can be carried out by one hardware circuit. That is quite different from the Korean case as mentioned above. Furthermore, this study also presents the assessment of the performance of this special ship-based PV system, and the system test are implemented under the operating mode of off-grid and grid-connected respectively.

2. The difference between off-grid and grid-connected photovoltaic system

Compared with "large inertia" conventional synchronous generator, solar PV system can be regarded as a "fragile power source" with "zero inertia" [11-13]. Since, it is a typical inverter power supply based on power electronic transformation technology, and its operating characteristics (such as active power-frequency characteristic, reactive power-voltage characteristic, frequency-response characteristic, power angle stability and fault response characteristic, etc.) are directly related to the component properties and logic driven control strategy[14][15]. As it is shown in Fig.1, the PV inverter is mainly composed of filter capacitor, Insulated Gate Bipolar Transistor (IGBT) module, filter reactor, measuring circuit, protection circuit and driving and controlling circuit. If the standard output ratings are designed at the same level, there would be not any special difference between the main power circuit of off-grid inverter and that of grid-connected inverter. Essentially, the key issue is concentrated on the selection of arithmetic program of control strategy, which is written into the digital signal processor (DSP) of driving and controlling circuit. The off-grid inverter is used as an independent power supply, so its alternating current (AC) voltage output of three phases should be stable. To meet this basic technical parameter requirement, the *v/f* control strategy is usually adopted to realize the driving and controlling process of three-phase full-bridge inverting circuit. The grid-connected inverter converts DC electrical power into AC power suitable for injecting into the power grid or parallel running with the synchronous generator. It must match the phase of the grid and maintain the output voltage slightly higher than the grid voltage at any instant for the purpose of electrical power feedforward. A high-quality modern grid-connected inverter has a fixed power factor setting stage by adopting the *PQ* control strategy, which means its output voltage and current are perfectly lined up and its phase angle is within 1 degree of the AC power grid.

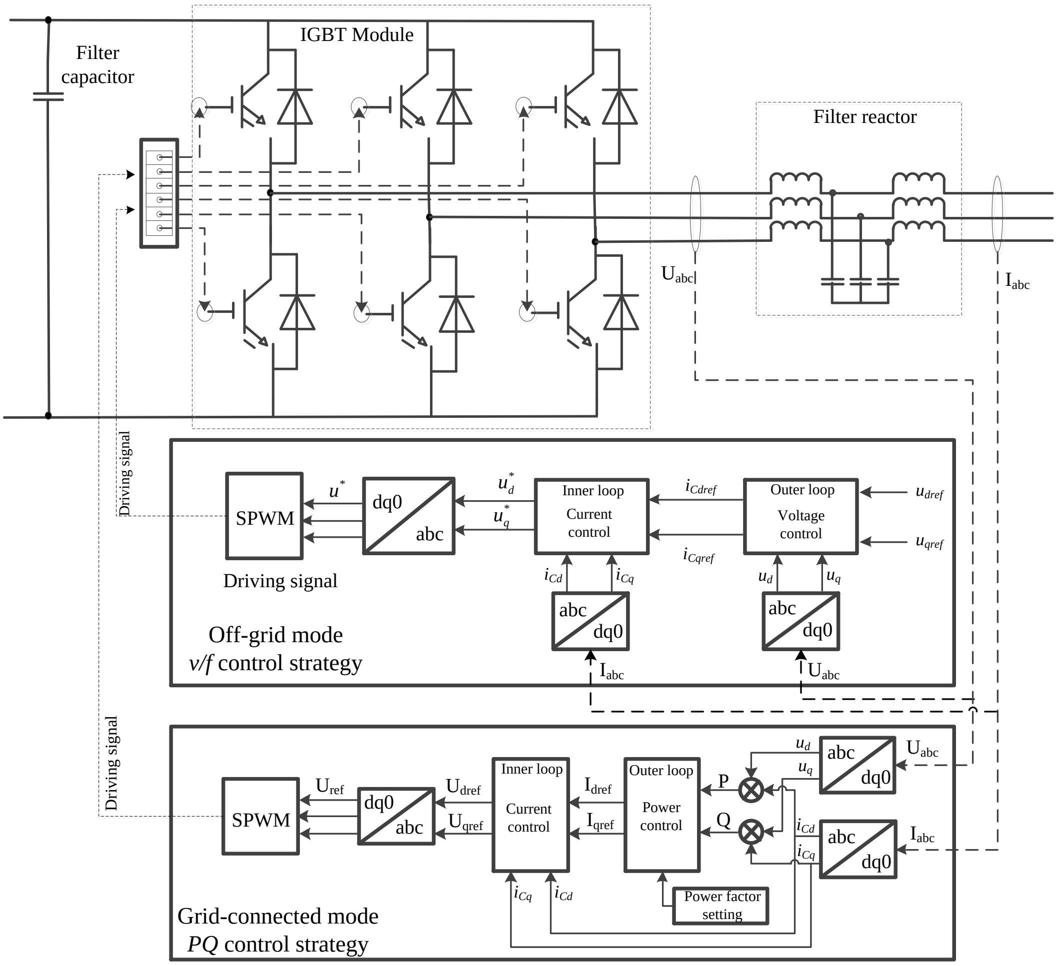

Fig. 1. The control system schematic diagram of PV inverter: off-grid mode and grid-connected mode

In the course of nearly 20 years of development of solar ship, the capacity of solar PV systems applied to various types of ship platforms has been continuously increasing. The design of system integration solutions has shown the trend of changing from off-grid to grid-connected and hybrid.

2.1. The off-grid type ship-based PV system

The off-grid PV system can supply the electrical power to the load directly, which means that it has no energy convergence with the SPS and has no impact on the security and reliability of the power grid. Thus, the transient stability of the SPS obviously depends on the power output characteristics of synchronous generators that run in parallel.

On the other side, there is a significant drawback existed in the off-grid PV system, no matter what kind of platform it is applied. Taking the average daily energy consumption of power load requirement and lowest power switching frequency between PV system and ship power station, it is ensured that an energy storage device with several times the capacity of the PV modules should be set up to achieve the static balance of power supply and load demand. This is a technical problem that is difficult to overcome in the off-grid PV system design. Besides, the output power of the off-grid inverter is limited by the total power of the load. If the connected load is operated at a low power level for a long time, it will cause the waste of power that has been converted by PV arrays.

2.2. The grid-connected type ship-based PV system

For the grid-connected type PV system integrated with the terrestrial power grid, there is no mandatory requirement for setting up energy storage system, but this design concept should be changed for the ship-based application. The reason is that there is a magnitude difference in the time response scale of power electronics and inertial physics system. The output power instantaneous fluctuation of PV system must be borne by the synchronous generator set. If this fluctuation is too large, it will be difficult for the synchronous generator to respond rapidly, and cause the over-excitation problem in the generator excitation device or overregulation problem in the speed governing device. Under the extreme condition, the stability of the entire SPS will be reduced to a low level. Thus, the energy storage system with the some capacity level of PV array should be integrated in any case. Only based on this kind of system structure or topology design, can the energy management system (EMS) of ship power station reasonable scheduling the output power of grid-connected type ship-based PV system, and realize the effective usage of PV power[16].

Different from the characteristics of synchronous generators that operate in parallel, the grid-connected photovoltaic system also has the features in followings: (1) Its AC voltage and current output of PV system are strictly regulated by the driving and controlling circuit, so there is no "loop current" between inverter and generator. Since, the generator is pulled into the synchronized operation entirely based upon the effect of this loop current, when the voltage, frequency or phase difference between it and power grid is within a given tolerance[17]; (2) Grid-connected inverter does not have the ability for supporting the grid voltage, and cannot withstand the high-level power load shock disturbance in the SPS [18]; (3) When the fluctuating range of power quality parameters (such as voltage, frequency, harmonic and reverse power) of a power grid exceeds the set point of grid-connected inverter, the sudden stop of the photovoltaic system will further aggravate the oscillation of the entire power system. This process is equivalent to reduce the system’s transient stability margin, which can easily cause the problem of out of synchronization among the synchronous generators. In extreme cases, the SPS will breakdown.

3. The design principles of ship-based PV system

No matter what kinds of ship-based PV system it is selected, such as off-grid, grid-connected or hybrid type, both the system design and technical specification should be evaluated in detail and corresponded to the classification specifications and ship design requirement. For new shipbuilding, it needs a comprehensive evaluation between the technical applicability, load balance, the initial cost of investment and safety requirements as well as some other factors of the ship-based PV system. However, for the ships which have been put into operation, in order to realize that the ship-based PV system merge with the ship power grid, safety monitoring system, ventilation system and fire alarm system, the ship hull structure and ship power system should be reformed.

3.1. Capacity matching between PV system and battery banks

The main technical parameters of the system architecture scheme, capacity of the battery banks, PV controller and grid inverter are determined by the PV system capacity, furthermore, its designed capacity seeks for a balance between the available deck area for installing the PV panels, charging and discharging characteristics of the battery, power load and daily running time. The basic principle is that installed PV panels as many as possible to increase the proportion of PV system to the capacity of the whole ship power station, which can maximize the benefits of energy saving. The maximum discharge depth of a single module should be considered in the design of battery capacity, and then calculates the optimal value matched with the capacity of PV panels under different operation modes. The capacity of battery banks in the off-grid PV system have to match with the capacity of the PV panels, meanwhile, it has to meet 24-hour uninterrupted operation requirements of the load (non-emergency load) to reduce the switching frequency of marine electric-PV electricity. Moreover, the capacity of battery banks in the grid-connected PV system should only matched with the capacity of PV panels (the condition of peak power under standard test). In general, the capacity of battery banks in off-grid PV system is several times more than that in grid-connected PV system, and the capacity of battery banks in hybrid off/connected grid PV system is decided by the larger one.

3.2. Photovoltaic array layout optimization

For the large ocean-going ro-ro ship, roll-on ship and bulk carrier, they all have the characteristics of flat-top deck structure and less deck machinery arrangements, no flammable and explosive substances onboard as well as low level of safety protection. In a word, the aforementioned characteristics make those ships suitable for installing PV arrays [19][20]. The PV arrays layout optimization methods should follow the basic guidelines: installation of regional concentration, which does not affect the overall style of the main deck of the ship; does not affect the bridge to observe sea conditions; does not affect the normal operation of the deck equipment; convenient for daily routine patrol inspection of battery components by the crew; satisfy the special requirements from the ship owner (such as set up awnings type array installation frame in the secure channel).

3.3. Ventilation and fire protection of battery banks

The security analysis and control are quite important and indispensable for the application of battery banks, no matter what kinds of a battery technology (lead-acid battery, lithium-ion ferrous phosphate battery, super-capacitor, etc.) it is selected or an electrical power system (ship-based PV system, micro-grid or regional power network) it is integrated with. At the very beginning point of the system design, all risk factors that involved in safety and reliability problems of battery energy storage system have been evaluated by our research group, such as overcurrent, overvoltage, overheating, internal short circuit, external short circuit, over-charging, over-discharge, recharge, drop, immersion wetting, electromagnetic interference, vibration, immersion wetting, electrical shock, ventilation and heat dissipation, gas combustion and open flame, etc. Technically speaking, these factors can be further classified into two groups, of which the boundary is whether or not it can be resolved by battery system itself. For example, the integration of BMS and main circuit protection devices is usually defined as a subsystem in the battery system, which has comprehensive functions of the operation control, energy management and active protection (for example overheating, over-charging and short circuit, etc.). For an engineering project of ship-based PV system, some higher level technical standards and risk counter measures should be taken into the consideration, responding to the extreme situation such as system failure, high temperature environment and cabin fire, which is beyond the effective control of the subsystem as mentioned above. Besides, this content has been defined as the mandatory requirement in "*Guideline of solar photovoltaic system and lithium-iron battery system inspection*" enacted by China Classification Society (CCS) [21]. Thus, the ventilation and fire protection of battery banks are represented as one of design principles in the paper, with the purpose of emphasizing the importance and necessity of extreme case analysis for the solution of the major engineering problem. Two essential requirements should be concerned, as follows:

(1) The mechanical ventilation or cabin ventilation system should be adopted in the battery banks room to avoid the excessive temperature around the battery banks, and ventilation port should be rainproof. For the lithium iron phosphate battery energy storage system, the cabin environment temperature should be set between 0-45℃.

(2) Since the extinguishing effect of conventional CO_2 fire extinguishing system is limited for the Li-ion battery, it is strongly suggested that the heptafluoropropane (HFC-227ea/FM200) extinguishant should be adopted in the fixed fire extinguishing system located in the batter room.

3.4. Safety and remote monitoring system

In order to minimize the power loss of the DC cables between the PV array and PV controller, the electrical equipment room which used to install the PV controller and the inverter should be arranged on top of the deck as far as possible. According to the China Classification Society “Solar Photovoltaic System and Lithium Iron Phosphate Battery Inspection Guide”, the PV power management system should set the monitoring and alarm devices which extend to the central control room and the drive control room [22]. Considering the crew lack of experience in maintenance management of the PV system, the 3G network or satellite network communication and internet-based data communication interface should be established so that the onshore technicians can monitor the real-time running condition of the PV system through the onshore-based data control center, which could provide timely maintenance suggestions to the crew.

4. Hybrid type ship-based PV system

According to the feasibility evaluation conclusions, a 5000 PCTC ro-ro ship "COSCO Tengfei" is confirmed as the project object. A hybrid type ship-based PV system is designed based on the original as-constructed drawing of hull structure, marine engineering equipment and electrical power system, which has two typical technical features, containing dual-mode switching function (off-grid mode and grid-connected mode) and with a large-capacity lithium battery storage device integrated. The topological structure, power management system and operation mode are represented respectively.

4.1. Topological structure design

As a retrofit project for installation of ship-based PV system, it is necessary to complement the comprehensive assessment on industry technical standard, ship structure safety, topology analysis of power networks and demand of electrical load condition, etc. The local measurement data shows that the unsheltered deck area is about 900 m^2 in total, which allows the PV array installed capacity of about 150 kWp according to the technical specification provided by PV module manufacturers. The average daily irradiation time is set at 5 h, so the average daily output power of photovoltaic system is about 750 kWh, without considering the effect factors such as DC cable loss, DC / DC converter, battery charge and discharge loss, DC / AC inverter and AC distribution cable loss, etc. Theoretically, it can meet the power load requirement of 30 kW uninterrupted running for 24 hours. For the grid-connected mode, it is only the consistency problem of electrical parameters between PV inverter and SPS, since the electrical power output is strictly regulated by driving and controlling circuit and associated strategy.

The system principle diagram of this hybrid type ship-based PV system is shown in Fig. 2. It mainly includes solar PV array, controller, lithium ion battery and BMS (Battery Management System), inverter, AC distribution cabinet and solar power management system, etc. The main functions of these equipment are defined as follows: (1) The PV arrays convert the sun radiation to DC current and output it into the controller; (2) In order to achieve the maximum utilization of DC energy, the PV controller has the multiply function containing maximum power tracking control (MPPT) and output voltage & current regulation, and its output terminal is connected to the input terminal of BMS and inverter, which means that these three components have the common DC bus; (3) the BMS has the abilities of overcharge and over discharge interlock protection, which are essential function for the normal operation of lithium ion battery. Through real-time monitoring the controller output voltage, battery voltage, State of Charge (SOC) and output current, BMS can dynamically change the charge and discharge status of the battery pack and achieve the dynamic balance of PV energy between the DC and AC terminal. And, this controlling process will be implemented uninterruptedly, unless the PV system is shut down. Any time if the SOC is 100% or a battery cell reaches the upper limit of the charging voltage, the charging relay in BMS will be disconnected, when the discharging relay remains closed. If the SOC drops to the 0% or a battery cell reaches the lower limit of the discharging voltage, the on-off status of these two relays changes correspondingly; (4) The DC to AC current transformation process is carried out by inverter, which also has the circuit protection functions such as reverse connection, short circuit, reverse power, overheating and overload, etc. The rated voltage and frequency is set at 450Vac/60 Hz, and these parameters have no relation with the off-grid photovoltaic and grid-connected operation mode both; (5) AC distribution cabinet is used to realize the manual mechanical interlock switching, in which an 450Vac /230Vac, 50kW step-down transformer is installed for providing the PV power to 4L-9L lighting distribution box (230Vac/60 Hz) under the off-grid mode. If the system is set at the grid-connected operation mode, the transformer is bypassed and the PV power (450Vac/60 Hz) will be directly distributed into the main switchboard (MSB).

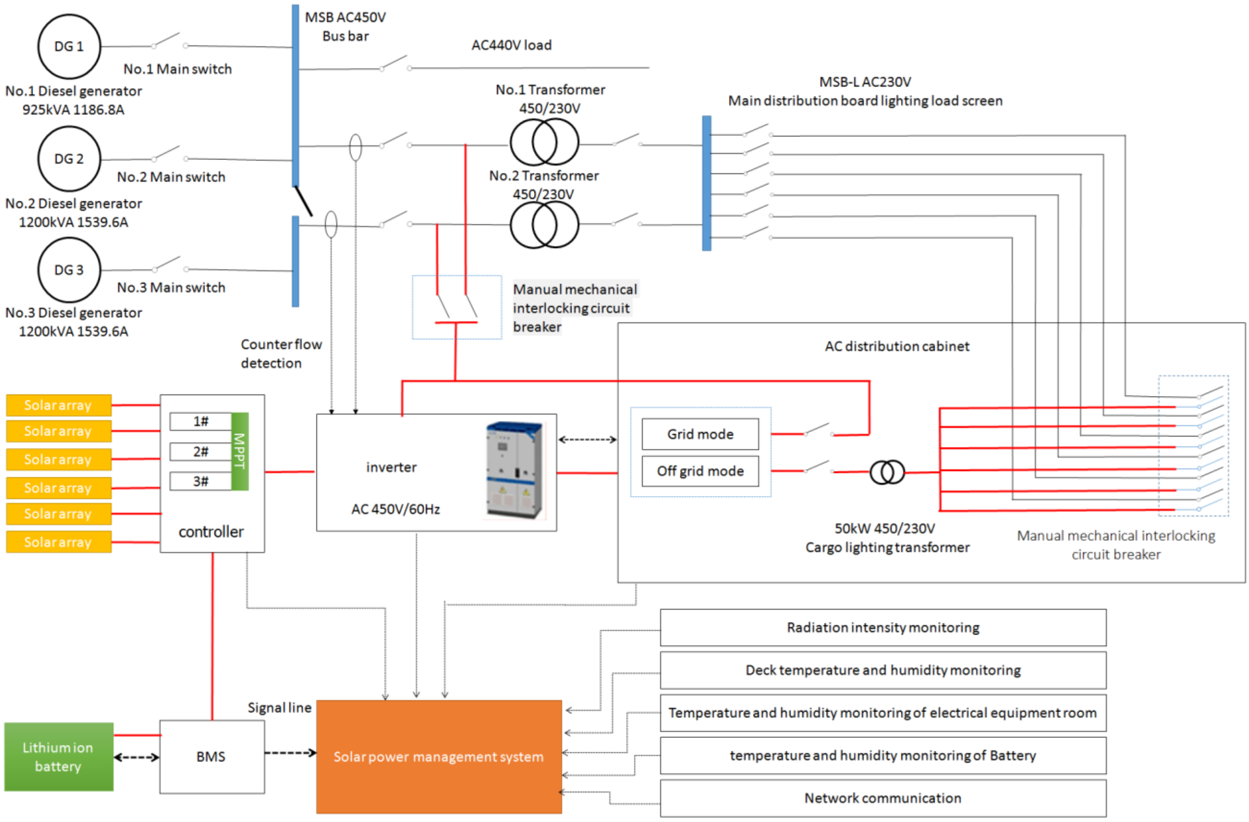

Fig. 2. The system principle diagram of hybrid type ship-based PV system

4.2. Solar power management system design

In order to ensure the safe and reliable operation of the hybrid PV systems on ship, a set of solar power management system is integrated as shown in Fig. 3., which has the functions such as environmental parameters acquisition, monitoring and display of state parameters of power system, power generation statistics, fault alarm, energy saving and emission reduction performance evaluation, etc.

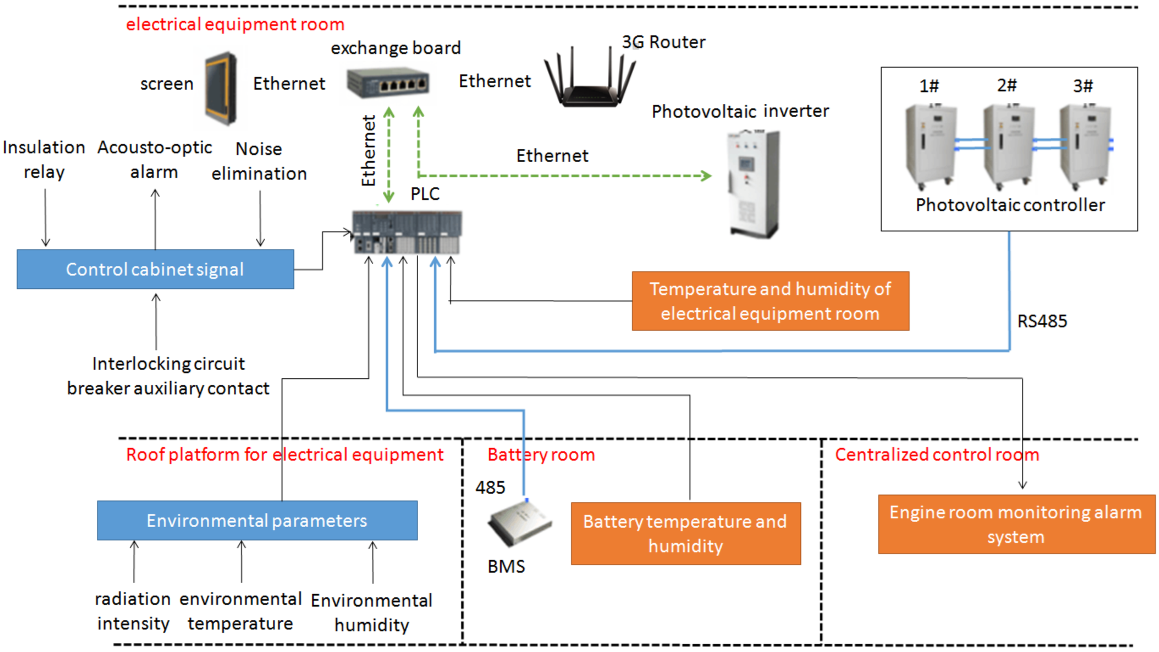

Fig. 3. Block diagram of solar power management system

According to the system safety protection strategy, the solar power management system can quickly respond and send out the safety control instruction to prevent system damage and dangerous accidents, which is completely based on the data from PV controller, BMS, inverter, reverse power protection device, ambient temperature and humidity sensor, smoke alarm sensor. In order to facilitate the historical data query and fault analysis, all of the data is stored in the host computer. The technicians of ship management department can remote login this system and acquire this data though the Web interface, which is established based on 3G network communication and shore-based Internet technology. Thus, it is possible for the researcher to evaluate the trend of operating condition and analyze the factors that can affect the system efficiency.

4.3. Operation mode setting

According to the route of solar radiation intensity, load power demand, economy and safety requirements as well as other factors, this ship-based hybrid PV system can be operated under the four setting operation modes.

(1) off-grid mode

The output power of the inverter running off-grid changes with the increase or decrease of the load, and the required power is shared by the photovoltaic cells and the accumulators. The output power fluctuation difference between PV controller and inverter is balanced by BMS by changing the state of charge and discharge of the battery. The three-phase AC output from the inverter is directly supplied to the lighting load after being stepped down by the transformer in the AC power distribution cabinet (three-phase load needs to be balanced). The power flow is as follows: Solar photovoltaic cell → PV controller (↔BMS and battery) → Off-grid /grid-connected integrated inverter (450Vac / 60Hz) → AC power distribution cabinet (450 / 230Vac, 60Hz, 50 kW lighting transformer) → 4 -9L sub-box → vehicle holding LED lighting load.

(2) The grid-connected mode

The output power of the Inverter connected to the grid is constant. However, the output power fluctuation of the PV cells is balanced by the batteries. The three-phase AC output from the inverter is incorporated into the main distribution panel of the ship and a backflow prevention device is installed to avoid energy backflow. The power flow is as follows: solar photovoltaic cell → photovoltaic controller (↔ BMS and battery) → off-grid/grid-connected integrated inverter → main bus.

(3) Marine electric power supply mode when PV power is insufficient

When the PV system output power is not sufficient for a long time and the residual capacity of the battery is not enough to support the power consumption of the load, the power is switched to the bypass of the marine power supply and the marine power is supplied to the lighting load via the AC power distribution cabinet of the photovoltaic system. When the solar radiation intensity continues to increase, the PV system will automatically switch back to off-grid / grid-connected mode when the battery is charged to its recovery voltage node.

(4) Marine electric power supply mode when photovoltaic power is under maintenance

When the PV system is shut down for maintenance, the switch between the PV inverter and the main switchboard should be disconnected to completely cut off the PV system. After switching on the marine power-PV power interlock switch on the AC distribution cabinet, the lighting load is supplied from the ship main transformer. The power flow is as follows: main bus → main transformer （1#与 2# Manual mechanical interlocking）→ 4-9L sub-box → vehicle holding LED lighting load.

5. Installation project and system test

5.1. Installation project of PV system

Installation project for installing the PV system on "COSCO Tengfei" ship was completed in March 2014, the structure layout of PV array, electrical equipment and battery room and the corresponding main equipment are shown in Fig. 4.

Fig. 4.Floor planbattery array, electrical equipment and storage battery

The peak power of PV module is 265 W, and the method of connecting wire is set at 18 in series and 30 in parallel, so the rated output voltage is 384 Vdc; the rated voltage of lithium iron battery is 3.2 V, rated capacity 100 Ah, with 120 in series and 17 in parallel; BMS is designed as one master & three slaves structure, which can realize the function of group management and uniform charge & discharge control; Three DC/DC modules are integrated into the PV controller (input voltage range 350-780 Vdc, maximum input current 150 A), and each module is connected with 10 sets of parallel PV arrays; The sinusoidal pulse width modulation (SPWM) technology is adopted in the PV inverter control for the purpose of pure sine wave output, and the power factor is set to 0.99 under the off-grid and grid-connected mode.

5.2. Off-grid mode test

Off-grid mode operation test takes the way of fixed load and variable load condition, and focuses on the stability of the system under steep and steep load conditions. Fig. 5-8 show a set of operating data (the abscissa is the test time) in the repeated comparison test. The test conditions are as follows: (1)the operation stage starts from no-load to full-load 150 kW, with the test period of constant load in each stage being 5 min, and then increase the three-phase load by 15 kW step by step. (2) The full load is reduced to the no-load operation stage with decreasing 30 kW stage by stage and each stage with certain load lasts 2 min.

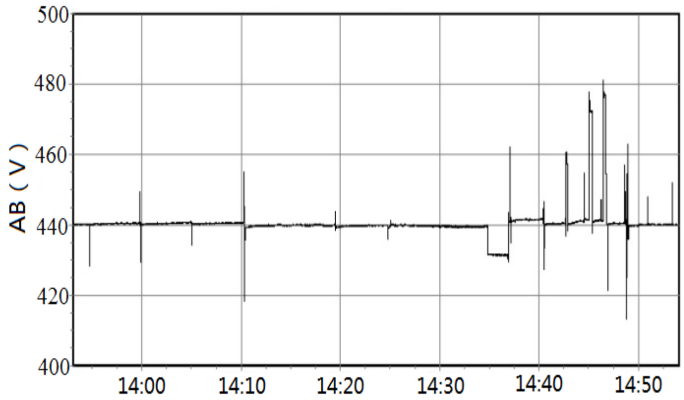

Fig. 5. Off-grid mode: AB line voltage

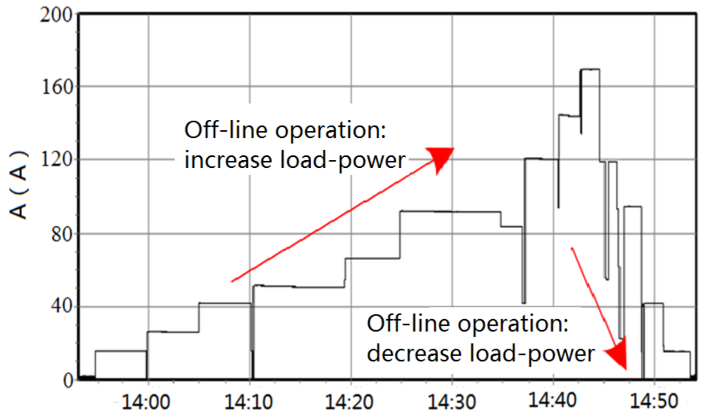

Fig. 6. Off-grid mode: A phase current

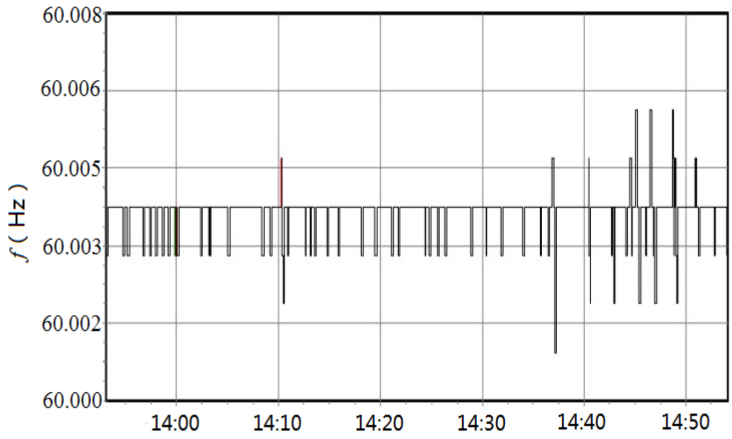

Fig. 7. Off-grid mode: frequency

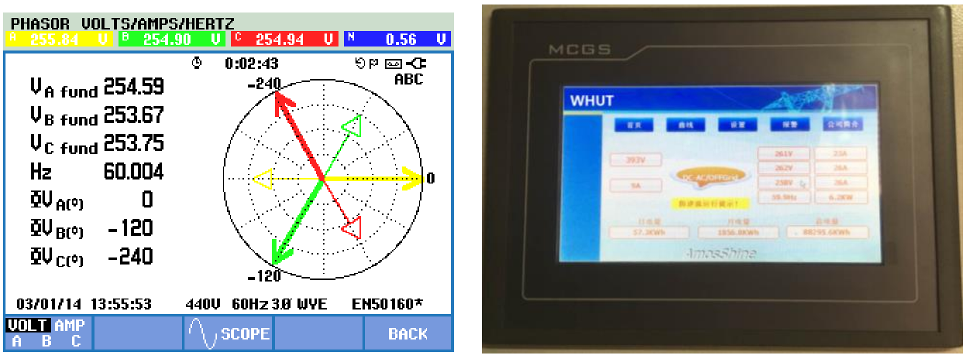

Fig. 8. Off-grid mode: three-phase voltage & phase, electric energy production

The results show that the phase voltage is stable at 440.0 Vac (the manual load power is reduced rapidly, and the error of transient voltage fluctuation is within ± 9%), the frequency stable at 60 Hz (the amplitude range is ± 0.01 Hz), the THD value stable below 2.5%, and the phase angle difference constant.

5.3. Grid-connected mode test

The grid-connected mode operation test is carried out under loading and unloading conditions of the docked ships. Repeated comparative tests includegrid-connected reliability, stability of load and variable load conditions, system steepness, steep drop of grid-connected output power and impacts of the steep stop on the power quality of the power grid, as shown in Fig. 9 - 14 (abscissa represents the test time).

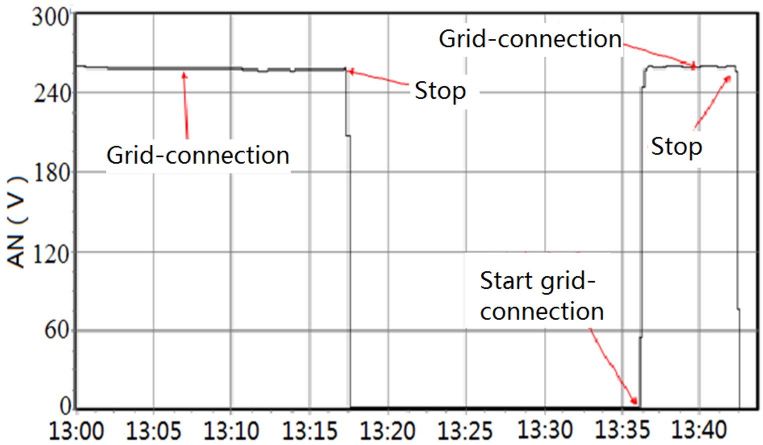

Fig. 9. Connected-grid - A phase voltage

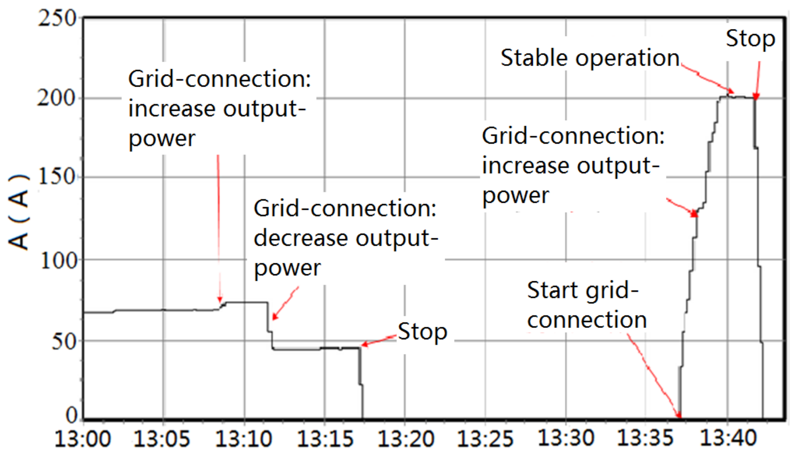

Fig. 10. Connected-grid - A phase current

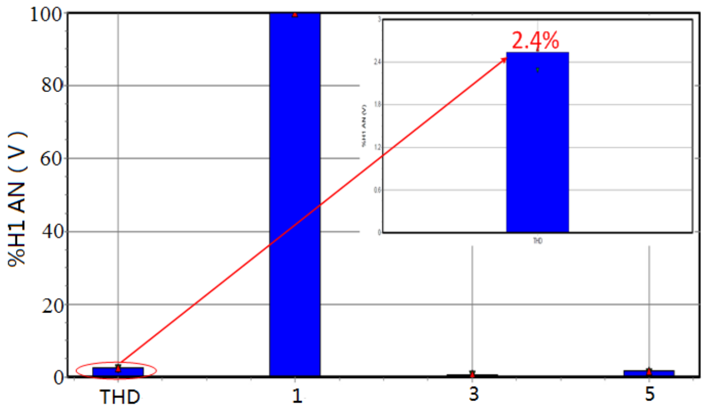

Fig. 11. Connected-grid - A phase voltage THD

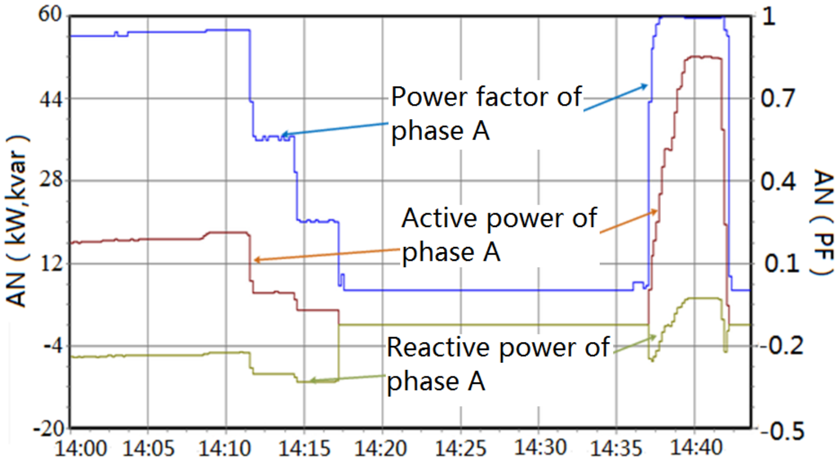

Fig. 12. Connected-grid -A phase active, reactive power and power factor

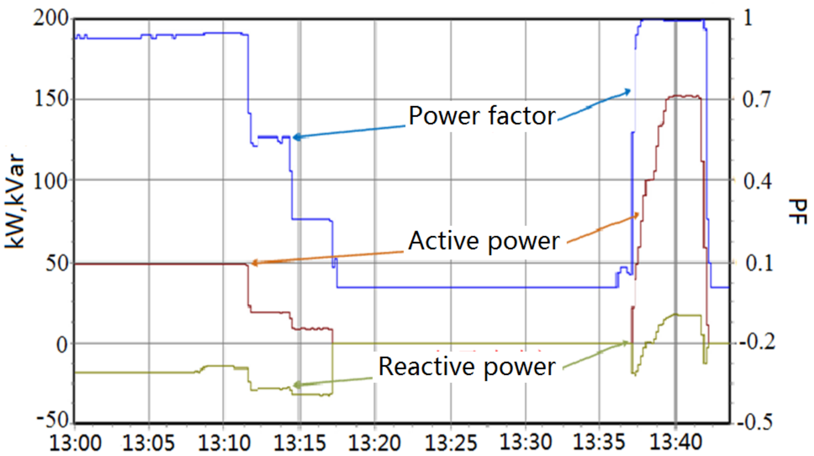

Fig. 13. Connected-grid - three phase active, reactive power and power factor

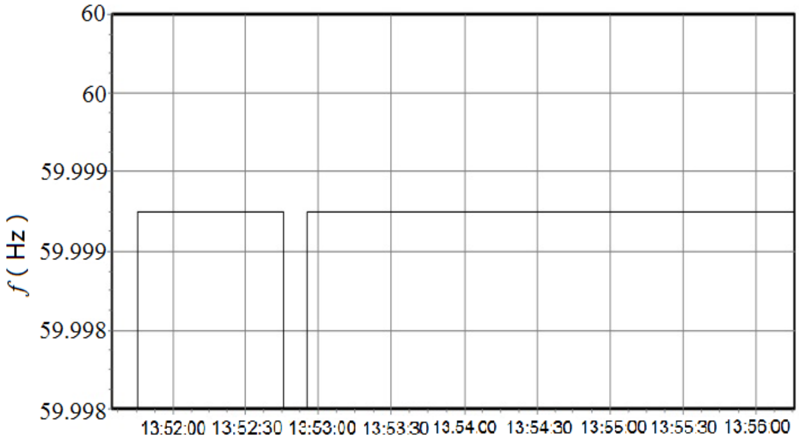

Fig. 14. Connected-grid - three - phase frequency

The results show that the phase voltage and line voltage of the inverter can be maintained at 260 Vac and 450 Vac at a constant frequency of about 59.999 Hz from the start-up to the stop-down phase (the 435-II Fluke power quality analyzer has been used in the repeated comparison test Frequency and power parameters, so the calibration time is different), THD value is stable below 2.4% (classification society requires less than 5% of the specification);with the increase and decrease of the set grid output power, the inverter power factor also increases accordingly, which reduces to 1 at a rated output power of 150 Kw; an increase of 1 kW/s in output power from instantaneous start of grid-connected operation rises up to rated output power; output from down to zero during rated output power output. The rate of change of power is 5 kW / s. During the grid operation and shutdown, the PV system has no significant effect on the power quality of the main power network of the ship.

6. Conclusions

In this paper, the existent technical differences for applying the off-grid and grid-connected ship-based PV system is analyzed and the basic design principles for marine application are proposed. The hybrid PV system with large-capacity lithium battery storage device that installed on 5000 PCTC ro-ro ship is illustrated form three aspects the topological structure, power management system and operation mode. Actually, it is the first attempt for Chinese shipping industry to applying photovoltaic technology on ocean-going vessel. Based on the system test data, operational monitoring data (navigation on China–Europe route and China-U.S. route during 22 months) and crew feedback information, conclusions are as follows:

(1) The integrated application of solar photovoltaic system can play a role in large ocean-going ship power systems which can expand the available energy range of ships;

(2) The output power quality of hybrid type ship-based PV system can effectively meet the requirements of the relevant rules that approved by China Classification Societies (CCS). Especially, there is no significant impact on the SPS when the output power is sharply fluctuated under the grid-connected operation mode;

(3) The solar power management system can realize the system-wide safety monitoring, alarm and protection functions. Not only can it ensure the whole system to be automatically operated at a high-level of safety and reliability under the operation condition of off-grid / grid-connected mode, but also the daily maintenance workload of the crews is effectively reduced.

(4) The ship-based PV system design principles, system architecture and operation mode settings can be directly used to guide the conceptual design of a new-style solar ship, which means that the PV system design can be integrated within the hull structure and power system design stage. This kind of improvement can greatly expand the range of potential application objects and significantly reduce the initial investment cost.

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