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The research progress of the medium voltage DC integrated power system in China

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Abstract: With the constant development of modern marine technologies, the vessel energy now can be distributed through an integrated power system, which is known as the third vessel power revolution. In this paper, the technical features of the first and second generation integrated power system are introduced. Next, based on the present domestic technical status, the research progress of the quasi second generation medium voltage DC integrated power system in China is presented, with the corresponding difficulties and problems analyzed, including the system model, electrical-magnetic transient simulation, the connected operator between the gas turbine generator set and the diesel generator set, the system steady analysis, and system layered protection. Finally, the solutions are proposed, which indicates that the developments are required on the medium voltage DC breaker, system energy storage, system safe operation, multi-time scale, and multi-objective system energy regulation.

Key words: integrated power system; medium voltage DC; energy regulation

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0 Introduction

The vessel integrated power system combines the two independent power system and electric power system in the traditional vessel together into one system, which provides the power for propulsion load, pulse load, communication, navigation and service equipment as a whole in the form of electrical energy, and realizes the comprehensive utilization of total vessel energy. The integrated power system can not only provide the power platform for vessel load, but also simplify the vessel power system structure, raise the vessel system efficiency, and reduce the noise level and the life cycle cost. These match with the development trend of informatization and intelligentization of vessel, which represents the future development direction of vessel power system[1-3], known as the third vessel power revolution after manpower, wind power, steam power, and nuclear power.

The U.S. , U.K. and other naval powers have begun the theory exploration and key technology research of integrated power system since the 1980s. U. S. Navy established the land-based test facility of warship integrated power system, and completed the onshore demonstration of full-scale integrated power system in 2001[4-5]. In 2003, U. K. and France set up the technology demonstration test field of electric warship, which is closely combined with the development of Type 45 destroyer. In July 2009, Type 45 destroyer became the first surface warship with integrated power system in the world[6]. In October 2013, U.S. Navy DDG 1000 destroyer was launched. The launching and service of these warships indicate that the naval powers such as the U. S. and U. K. have realized the engineering application of integrated power system on the surface warships[6-7].

The research basis of vessels with integrated power system is relatively weak in China. Compared with other countries in the world, the engineering application aspect lags far behind. The leading in the aspect

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of integrated power technology in China at present is the Vessel Integrated Electric Power Technology Key Laboratory of Naval University of Engineering (hereinafter referred to as the "laboratory"). In combination with domestic related research institutes, this laboratory has tackled the problems in key technology of integrated power, completed key technical validation test of medium voltage DC integrated power technology of quasi second generation vessel in China. The breakthrough results have been obtained, which provides the technical support for the engineering application of integrated power system.

The technical characteristics of integrated power system on the first and second generation vessel will be introduced in this paper. Combined with the technical status of integrated power system equipment in China, the research progress of medium voltage DC integrated power system of quasi second generation vessel is introduced, and the difficulties and solutions in system level are analyzed. The research work to be further developed is presented.

1 Integrated power system of first and second generation vessel

The vessel integrated power system consists of six subsystems including power generation, power transmission and distribution, electric transformer and distribution, propulsion, energy storage, and energy management (Fig. 1). The power generation subsystem consists of prime mover and generator, which can convert mechanical energy of prime mover into electrical energy. The power transmission and distribution subsystem is composed of cable, bus, circuit breaker and protection device, which transmits electric energy to the electric equipment, and has the functions of automatic identification and isolation of system failure. The electric transformer and distribution subsystem realizes the transformation of power model, voltage and frequency according to the electricity demand of electric equipment, so as to supply power for service equipment, pulse load and communication navigation equipment. The propulsion subsystem consists of propulsion frequency converter and propulsion motor. The propulsion frequency converter inputs electric energy for propulsion motor and controls its rotating speed so as to propel the vessel. The energy storage subsystem is used for storage and release of system power, and provides power for the system according to the pulse load demand, so as to ensure the safe and stable operation of the system. Energy management subsystem is used for monitoring, control and energy management of the system to achieve precise control of power flow by information flow of the system[2-3].

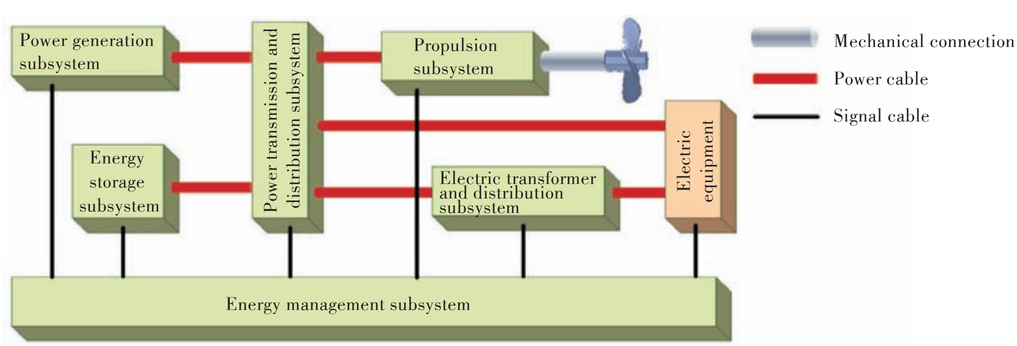

Fig.1 The composition of integrated power system

The six subsystems of vessel integrated power system are all with various technical schemes. And there is large difference in technical performance of different schemes. According to the iconic technical characteristics of subsystems, the vessel integrated power system is divided into the first and second generation integrated power system[2-3].

The integrated power system being used currently and widely in engineering over the world can be regarded as the first generation integrated power system, which is suitable for large tonnage vessels. The technical features of this system are as follows: the power generation subsystem uses medium voltage AC power frequency synchronous generator set; power transmission and distribution subsystem adopts medium voltage AC power frequency distribution network; electric transformer and distribution subsystem uses the medium voltage AC power frequency transformer or the DC zonal power distribution devices powered by medium voltage AC; propulsion subsystem adopts the advanced induction motor and its matched propulsion frequency converter based on IG-

BT/IGCT power electronic devices; there is no energy storage subsystem; energy management subsystem adopts the basic type of energy management system so as to achieve the monitoring of the whole system and the basic energy scheduling function.

With the rapid development of electrical materials, power electronic devices, control technology and computer technology, the research of second generation vessel integrated power system is actively carried on over the world so as to further improve the system performance, reduce the volume and weight of system. The second generation vessel integrated power system not only is suitable for large vessels, but also can cover the whole series of vessels with displacement below 3 000 t. The technical features of this system are as follows: the power generation subsystem uses high-speed integrated medium voltage rectifying generator set; power transmission and distribution subsystem uses the DC zonal power distribution devices powered by medium voltage DC; propulsion subsystem adopts the propulsion frequency converter based on the highly integrated component or wide-band gap semiconductor power device—silicon carbide; the propulsion motor uses the permanent magnet or high temperature superconductor motor; energy storage subsystem uses super capacitor energy storage integrated inertial energy storage or composite energy storage; energy management subsystem adopts intelligent energy management system so as to the realize the digital control of whole system and also the intelligent management function[2-3].

The U. S. Navy proposed three kinds of power network structure system in its technology roadmap of next generation integrated power system medium voltage AC power network, high frequency AC power network and medium voltage DC power network. In the case without the need of high power density, the vessel design can use medium voltage AC power network structure, and its transmission and distribution network uses medium voltage power frequency AC with the three-phase voltage of 60 Hz. The voltage can adopt three kinds of standard voltage: 4.16, 6.9 or 13.8 kV. The high frequency AC power network has high power density and its voltage frequency of power transmission and distribution network is one fixed frequency between 60 Hz and 400 Hz. Besides. The voltage can be 4.16 or 13.8 kV. The medium voltage DC power network has higher power density, and the DC voltage of its power transmission and distribution network can adopt the standard voltage between ± 3 000 and ± 10 000 V[7].

The technical maturity of medium voltage AC power network structure is the highest with low technology risk. Because the cross-sectional area of transformer core is inversely proportional to the operating frequency approximately, the high frequency AC power network structure can reduce the volume of transformer and filter, and improve the power density of system. But there are shortcomings such as difficult parallel connection of generator sets and large voltage drop of system lines. Compared with the medium voltage AC system and the high frequency AC system, the medium voltage DC power system structure has the following advantages[7]:

1) The mutual influence between prime mover speed and bus frequency is eliminated. The prime mover can be directly connected to the generator without the use of reduction gear or overdrive gear. The speed of generator can break through the limit of 3 000 r/min, which improves the system efficiency and power density, and reduces the noise vibration level of equipment.

2) The propulsion transformer and power distribution transformer with large capacity are canceled, which means that the power conversion equipment can operate at higher frequency with a smaller volume and weight of the transformer.

3) The skin effect of current does not exist. And there is no need to transmit the reactive power, so the weight of cable is reduced.

4) The requirements for speed control performance of prime mover are low. The various types of generator sets with large differences in speed control performance, capacity and frequency can run stably in parallel.

There also exist some challenges in the vessel integrated power system powered by medium voltage DC power, and they are mainly as follows:

1) There is no natural zero crossing point in the short circuit current of DC system, and it is difficult to break the circuit breaker. And the performance index of medium voltage DC circuit breaker needs to be further improved[8-9].

2) The problem of static stability in medium voltage DC power supply system is outstanding. And the propulsion load has a negative incremental impedance characteristic, which is easy to cause system voltage instability[10-11]. If the input and output impedances are mismatched, with the cascade of power electronic convertor equipments, the system will be unstable or the dynamic response performance of system will be reduced[12-13].

The technical characteristics of medium voltage DC power network structure are quite different from those of the medium voltage AC and high frequency AC power network structure, with a larger technical risk. Both of the medium voltage AC and high frequency AC power network structures belong to the first generation vessel integrated power system. The medium voltage DC power network structure is the typical feature of the second generation vessel integrated power system. It has the higher power density and operational flexibility, and it also represents the development trend of integrated power system.

2 Integrated power system of quasi second generation vessel and its research progress

The performance of prime mover in China falls behind the foreign countries, especially the lack of optional types of large gas turbine, as well as the speed control performance. If tracking and imitating the technical route of medium voltage AC integrated power in developed countries, generator sets driven by different types of prime movers will not run stably in parallel due to the great difference in power level and speed control performance, which will seriously restrict the development of domestic integrated power system. Based on this, key laboratory of vessel integrated power technology of Naval Engineering University firstly put forward the technical route of medium voltage DC integrated power in the world in 2003. It contributed to the composition of quasi second generation integrated power system by adopting the network structure of second generation integrated power system to supply power for the subsystem equipment of the first generation integrated power system. In addition, the basic research on the integrated power technology was carried out and the problem of key technology was tackled. On the level of equipment, the high power density gas turbine power generation module, diesel power generation module, medium voltage DC power transmission module, high torque density propulsion module and DC zonal distribution module have been developed. On the system level, on the one hand, the problems involving the power network structure theory of quasi second generation integrated power system, system model and simulation, power split of parallel generators, system stability analysis and control, system layered coordination protection, system interface design and high power bottleneck technology were overcome. Meanwhile, the integration and performance test of the quasi second generation medium voltage DC integrated power system have been finished. In the following text, the main problems and solutions related to the quasi second generation medium voltage DC integrated power system will be introduced from the system level.

2.1 Power network structure of system

In order to improve the flexibility of system operation and meet the requirements of different navigation conditions, the unit power station of power generation system generally consists of large and small capacity generator sets. The prime mover of large capacity generator set is usually gas turbine or steam turbine, while that of small capacity generator set is usually gas turbine or diesel. The working frequency between large capacity generator set and the small one may be different. And also the speed control performance of their prime movers differs widely from each other. Especially, in the process of sudden loading and unloading, the speed stability time difference reaches more than an order of magnitude. The traditional AC generator sets not only fail to realize the parallel operation of generators with different frequencies, but also lead to the seriously uneven power distribution when different capacity generator sets run in parallel due to too large difference in speed control performance. Thus, the system cannot be operated stably in parallel.

The rectifying generators operate in parallel through medium voltage DC network. The rectifying generators are not limited by system frequency, which means that the high-speed prime mover can be connected to the generators directly. In the AC power network structure, the prime mover governor is used to adjust the active power of generator, while the excitation system of generator is used to adjust the generator voltage and reactive power of generator. However, in the DC power network structure, higher DC voltage output by the parallel rectifying generator will lead to greater output power. Although the active power of generator is determined by the governor in the steady state, the dynamic response of generator power is decided by the excitation system of generator, which weakens the requirements for the speed control performance of prime mover to a great extent. Taking advantage of the characteristic in DC power network that the generator excitation control and the prime mover speed control are both applied to adjust the system active power, the poor speed control performance of prime mover can be improved by the rapid and precise excitation control. As a result, the parallel operation problems of different types of generators with great differences in power level and speed control performance can be systematically solved.

2.2 Mathematical modeling and electromagnetic transient simulation of system

The dynamic mathematical modeling of generator sets is the main problem in the modeling research of medium voltage DC integrated power system. The main reasons are as follows:

1) The gas turbine serves as prime mover for power generation, and its traditional thermodynamic model focuses on the analysis of internal physical characteristics of equipment. When the gas turbine is applied to the coupling analysis of the electromechanical performance of integrated power system, some problems appear, including complex model structure, high order, tight coupling of multiple physical quantities such as temperature, pressure, machinery, and electric, low computing efficiency and low accuracy.

2) The traditional rectifying generator with twelve phases mainly works in the DC side current continuous mode, and the existing model can only reflect the dynamic characteristics of generator in this mode. However, in the medium voltage DC integrated power system, three modes of this type of generator exist, including the DC side current continuous working mode, DC side current discontinuous working mode, and the transient process switching between the above two modes, which are beyond the application scope of the existing model. In addition, a large number of complex topological power electronic devices and multiple sets of multiphase motor make the modeling and electromagnetic transient simulation of medium voltage DC integrated power system very difficult. The following problems exist, such as the high order, strong nonlinearity, and poor convergence performance of electromagnetic transient calculation.

Therefore, the laboratory carried out the following experiments:

1) Under the premise of considering the volume inertia, action inertia of actuator, and some control links such as fuel flow limitation and fuel flow incremental restrictions, the simplified mathematical model of the compressor-turbine system, fuel system, governor and other components of gas turbine is built. In addition, the simplified mathematical model structure of gas turbine and its parameter identification method are put forward. In the commercial simulation software PSCAD/EMTDC, the simulation model of gas turbine is also established. In conclusion, tests show that this model can accurately describe the dynamic and static electrical performance of gas turbine generator set.

2) By taking twelve-phase AC generators as four three-phase AC generators equivalently and taking twenty four-pulse uncontrolled rectifier as six-pulse uncontrolled rectifier powered by four ideal power sources, the dynamic mathematical model of twelve-phase rectification generator is established within overall working conditions considering the dynamic characteristic of excitation system and twenty four-pulse uncontrolled rectifier. Moreover, the analytical model of twelve-phase rectifying generator considering line resistance is established when the DC side is in short circuit. Therefore, the time domain simulation and physical experiment proved that this model can provide the accurate description of the three working modes of DC side current of twelve-phase rectifying generator: continuous mode, discontinuous mode and short circuit mode[14-16].

2.3 Parallel connection of gas turbine generator sets and diesel generator sets

Gas turbine generator set and diesel generator set not only have different working frequencies, but also differ greatly in speed control performance. Especially in the process of sudden loading and unloading, the speed stability time difference reachesmore than an order of magnitude. The traditional AC generator set cannot achieve the parallel operation of generators with different frequencies. It is also easy to cause the uneven power distribution among the generator sets with different capacities in parallel connection when differences in speed control performance are too large. What's worse, the generator set cannot run stably in parallel. Aiming to solve the above problems, the following research is carried out.

1) By comprehensively analyzing the speed control performance of gas turbine and diesel, and the pressure regulating capacity of generator, the power generation technology scheme of medium voltage AC rectifying type is proposed to overcome the harsh conditions of the same frequency, phase and amplitude that the traditional AC generator sets in parallel require. This scheme shortens the parallel time of

generator sets from tens of seconds in traditional AC systems to hundreds of milliseconds.

2) On the basis of the excitation control strategy of AC rectificaiton generator of the voltage sag and double close-loop feedback control, the excitation control method adopting the current negative feedforward of diesel generator sets is proposed. It is verified by the experiment that this control method improves the average degree of transient power of gas turbine generator sets and diesel generator sets in parallel operation, and also decreases the overshoot of output current of diesel generator when the double-generator runs in parallel with the sudden load. After negative feedforward control is introduced, by regarding the ratio of maximum overshoot current and the current in steady state as the evaluation index, the overshoot declines significantly.

2.4 Stability analysis and control of the system

The main factor impacting the stability of integrated power system is the constant power property of propulsion load. In order to avoid the oscillation instability when generator has propulsion load, the system damping is usually enhanced by adding auxiliary control links with propulsion frequency converter in foreign countries. However, this method has many drawbacks such as the complexity in control of propulsion frequency converter, and susceptible control features. Another vital factor affecting the stability of integrated power system is the impedance mismatching in power electronic device cascading. There are cascade connection problems of a large number of complicated topological power electronic devices and the multi-stage power electronic devices in DC zonal electric transformer and distribution subsystem. Thus the accurate calculation of input and output impedance characteristic is essential for stability evaluation of this subsystem. Aiming to solve these problems, the following research is carried out:

1) The stability of medium voltage DC integrated power system was calculated by time domain simulation and eigenvalue analysis method based on state equation. The stability problem of the parallel operation of AC rectification generator with constant power loads was solved by setting parameters of generator and propulsion frequency converter reasonably[17-19].

2) The stability of DC zonal electric transformer and distribution subsystem was evaluated by the state space average mathematic model of this subsystem, and the phase margin and magnitude margin of Nyquist curve of input and output impedance ratio. It could be obtained from calculation that this subsystem could run stably under all working conditions.

2.5 Hierarchical coordination protection of system

The medium voltage DC integrated power system can be divided into three hierarchical networks, which are medium voltage DC transmission network, DC zonal electric transformer and distribution network and daily load power distribution network. In order to minimize the influencing region of short-circuit fault of different hierarchical networks and also improve the power supply continuity of load, the protection configurations of three hierarchical networks should match with each other. As a result, in our laboratory, the short-circuit fault characteristics of three hierarchical networks were analyzed, and the rapid extraction method of short-circuit fault was studied. Additionally, the hierarchical coordination protection strategy of medium voltage DC integrated power system was proposed, and the protection matching technique requirements and their corresponding solutions in and among these three hierarchical networks were proposed. The short-circuit fault experiments were carried out. And it was testified that the proposed protection strategy could realize the coordination protection in and among different hierarchical networks[20-21].

2.6 System interface design and cable arrangement

In the integrated design of integrated power system, besides the above problems in calculation and analysis of main circuit, it is also necessary to carry out the research on interface form of electric and information among different pieces of equipment. Taking standardization and modularization as design principle, the interface among the equipments of integrated power system is designed optimally in order to improve the transmission efficiency of energy and information of system. In order to advance the electromagnetic shielding property of cables and decline the dynamic magnetic field surrounding the cables, the electromagnetic shielding property of medium voltage cable and its surrounding dynamic magnetic field were studied, and the design and laying method of medium voltage DC cable were proposed in our laboratory. Also, the information interface design principle with the combination of information network, field bus and point-to-point hardwire connection was put forward so as to increase the speed and reliability of data transmission.

2.7 Experimental research of system

In our laboratory, the parallel operation between the gas turbine generator set and the diesel generator set was designed and built up, as well as the minimal medium voltage DC integrated power system which supplied power for propulsion subsystem and DC zonal electric distribution subsystem. The performance test of equipment and subsystem was completed. Besides, the following experiments were completed, such as the rated efficiency, steady-state power quality, dynamic performance, propulsion power limitation, continuous operation, fault protection, power management, electromagnetic compatibility, vibration noise, dynamic magnetic field and superconducting current limit. And the results all satisfied the technical index requirements of design.

3 Key technologies of system to be further studied

With the continuous development of vessel function requirements and integrated power technology, the system capacity is larger and larger, even up to several hundred megawatts, which brings great challenges to the medium voltage DC circuit breaker. At the same time, the vessels will be equipped with pulse load. Because of the properties of pulse load such as large power, short time, capacity of gigawatt, and greater load capacity than generating capacity, the system is always in the short-time repeated non-periodic transient limit state, and the energy density, power density and their impact on system are all extremely large. So, this type of load needs to be equipped with appropriate energy storage system. The electromagnetic transient and electromechanical transient of integrated power system equipped with energy storage system and pulse load are closely coupled. The pulse load greatly impacts the system. The system energy regulation is featured by multi-time scale characteristics. And the operating characteristics of the system will be changed from simple periodic steady state to the combination of periodic and non-periodic transient state. Also, the system mathematical model presents the characteristics such as time varying, strong nonlinearity, high order, and strong rigidity. So, this model is difficult to be convergent with numerical simulation method. These characteristics of integrated power system make it necessary to further study the following key technologies on the system level.

3.1 Medium voltage DC circuit breaker

In order to improve the power density of quasi second generation integrated power system, the super transient impedance design value of generator is very low. Moreover, the feeder line is relatively short. So the DC short circuit current increases quickly and will also be large when the system short circuit happens. The quickness indicators of removing fault with DC circuit breaker is far higher than that with the AC circuit breakers, which is usually about 20 ms. With the development of integrated power system, the system capacity is larger and larger. This leads to higher demands on the rated voltage, rated current, breaking capacity and other indicators of DC circuit breakers, which brings about huge challenges to the development and test of medium voltage DC circuit breaker. There are two kinds of technical schemes for medium voltage DC circuit breaker in general: medium voltage DC air circuit breaker and medium voltage DC vacuum circuit breaker.

If the medium voltage DC air circuit breaker is used in the medium voltage DC integrated power system, the arc extinguishing of air circuit breaker needs to be solved firstly. When the DC main network is short-circuit, there is no natural zero crossing point in short circuit current, and then the air circuit breakers would directly use hard breaking to achieve short circuit protection, which will lead to high energy arc. Because the main network DC voltage is high, the effective arc extinguishing technology which means the arc energy is absorbed effectively, is the key to determine whether the air circuit breaker can be broken effectively.

If the medium voltage DC vacuum circuit breaker is used in the medium voltage DC integrated power system, the design of reverse pulse circuit needs to be solved firstly. When the DC main network is short-circuit, DC vacuum circuit breakers superpose the reverse pulse current in the vacuum arc extinguishing chamber to produce artificial zero crossing point, then the short circuit current is broken. When the vacuum contact is open, the arc energy, contact distance, recovery voltage, and arc time of arc extinguishing chamber are closely related to the reliability of the turn-off of vacuum arc extinguishing chamber. Therefore, it is very crucial and difficult to select the appropriate reverse pulse circuit parameters and the input timing of the reverse current[22-23].

3.2 Composite energy storage device

The composite energy storage device significantly improves the energy regulation capacity of integrated power system. On one hand, energy storage devices such as superconductor and super capacitor, take the advantages of high power density (2–18 kW/kg), low energy density (1–10 (W·h) /kg), fast response (1 s–10 min), long cycle life (50 000–100 000 times), high conversion efficiency (90%–100%) and so on. By using this type of energy storage device with fast energy handling capacity, the start and stop of the pulse load can be effectively supported. Combined with such energy storage device as battery, which has low power density (75–300 W/kg), high energy density (30–50 (W·h)/kg), slow response speed (1 min–3 h), the combination scheme for composite energy storage is formed. By studying the coordination control method, and designing the capacity optimization and topology optimization allocation strategy, the running characteristics of pulse load can be further advanced. What's more, the impact of pulse load on integrated power system is reduced sharply so as to maintain the safe and stable system operation. On the other hand, the access of energy storage device can also completely improve the operating economy of system under normal operating conditions, which is beneficial to improve the power quality of the system[2–3,24–25]. In case of fault, the energy storage can provide power to the important load of vessel, and improve the continuity of power supply.

In the improvement of energy regulation and control capacity of integrated power system by composite energy storage, the main technical difficulties exist in the following aspects.

Firstly, because there exist great differences among the power density, energy density, response time in one single energy storage element, it is difficult to simultaneously meet all kinds of control targets of the integrated power system under different operating conditions, such as pulse power output (high power demand, low energy demand, and short response time) and energy balance maintenance (low power demand, high energy demand, long response time). Therefore, it is very important to establish composite coordination configuration model suitable for various energy storage ways with apparent differences and design the corresponding coordination control scheme so as to fully meet the needs of electrical characteristics of integrated power system under different operating conditions. Secondly, the reasonable energy storage capacity and location allocation can effectively improve the electrical performance of integrated power system under different operating conditions. However, on one hand, the electrical structure of integrated power system is complex, and there are many optional schemes for grid connection point of energy storage, and the type and capacity of energy storage. On the other hand, the operating conditions are also flexible, and the optimal allocation of energy storage devices needs to meet more optimization objectives at the same time. So it is really difficult to solve this optimization problem with multi-objectives and variables. In addition, considering the relatively limited space of vessels and strict requirements on security indicators, the constraints and computation will be more complicated. However, if the conventional intelligent algorithm is used to solve this optimization problem, the problems such as the low computation efficiency and misconvergent result may arise. Therefore, it is necessary to study the composition and control strategy of composite energy storage device, the optimal allocation method of energy storage device and also the control method of system energy.

3.3 Safe operation analysis of system

In order to consider the power demand of pulse load and the performance improvement of system operation, the energy storage device of integrated power system will develop from the centralized energy storage specially used for pulse load emission at present to the distributed energy storage considering all operational needs of system. This leads to direct effects of instantaneous power impact properties of pulse load on the integrated power system. If there is something wrong with the distributed energy storage allocation and its coordination control, the power quality of integrated power system, as well as the safe and stable operation of the system, will be seriously affected. The impact mechanism of pulse load on power quality and safe and stable operation of integrated power system is not clear yet, which makes it hard for the system designers to put forward measures to improve the power quality and the safe stability of system pointedly. Thus, the operational characteristics of pulse load and its influence mechanism on the power quality and safe stability of integrated power system must be studied in depth.

With the different system operating conditions, the type and quantity of equipments that are put into operation by integrated power system with distributed energy storage are also different, which makes the inherent frequency of equivalent circuit of system being with multi-spectrum features. If the system presents weak damping characteristics under the inherent frequency of one certain working condition, the instantaneous impact of pulse load may cause the system harmonic amplification at the inherent frequency and sideband, which affects the system power quality. Compared with the traditional power system, the integrated power system has a large number of power electronic devices, which makes its multi-spectrum resonant characteristics more serious. So it is urgent to establish one mathematical model of system power quality influence factors under multi-spectrum resonance condition, and then conduct quantitative analysis .

The vessel integrated power system includes distributed energy storage device and pulse load. When the pulse load is emitted, it is in the state of alternating operation with charging and discharging in short time and repetition, which leads to a result that the vessel integrated power system no longer has one balance point, but presents alternating cyclical process of a series of operating points. The static voltage instability of land-based power system mainly results from system reactive power shortage caused by the mismatch among load characteristics of induction motor, negative voltage regulation characteristics of transformer with on-load voltage regulation and excitation limit of generator. The voltage instability of power system is monotonic instability mostly when the load capacity of power system reaches limit. The basic model of the static voltage stability analysis method is the continuous power flow model of power system, which essentially takes the critical power flow solution as the limit of voltage stability. The instability mechanism of vessel integrated power system is the mismatch between negative resistance characteristic of the constant power load and the impedance of the power electronic device cascade system. The system static voltage stability not only requires one balance point of system, but also requires that the balance point is small disturbance stability. Therefore, it is necessary to study the influence mechanism of pulse load on the stability of vessel integrated power system, and establish the analysis method of system safe operation.

3.4 Multi-time scale and multi-objective energy control strategy

The structure and dynamic process of vessel integrated power system are very complicated, which include the fast electromagnetic transient process (microsecond level) caused by switching action, the electromechanical transient process caused by motor speed control and high power transient impact process (millisecond level) when pulse load starts or stops, the charging dynamic process of energy storage equipment (second level) and vessel maneuvering control process (minute level), as well as the long-term steady-state change process of corresponding vessel cruise (hour level). The structure and dynamic process of vessel integrated power system have the property of multi-time scale. The vessel integrated power system also has multi-objective requirements such as the vessel cruising ability, power supply ability of pulse load, power supply continuity of load, vessel maneuverability, and reconfiguration ability after system fault.

There are four challenges in the automatic generation of multi-time scale and multi-objective energy control optimization strategy:

1) With the different working conditions, the requirements of vessel integrated power system for automatic generation control differ greatly. Specifically, the centralized optimization is used to improve fuel economy under normal conditions; the decentralized control is used to ensure the basic performance when the abnormal conditions such as the blocked communication and system failure lead to the failure of centralized control. Therefore, different control frameworks and optimization methods need to be designed so as to satisfy the demands of integrated power system under different working conditions.

2) According to the emission demand of pulse load, the following control of high-power short-time scale is carried out, which demands that the energy scheduling optimization control algorithm have advantages over real-time solution and quick response, and energy scheduling coordinates the low-power short-time scale energy requirements such as continuous emission of pulse load and electric propulsion load adjustment.

3) Because both the failure destruction and fault partition isolation will cause the system to deviate from original operation state and result in a large transient impact, the dynamic security problem is prominent in the emergency self-healing and reconstruction of vessel integrated power system.

4) It is necessary for the energy scheduling of vessel integrated power system to adjust the real-time weight of multi-objective according to the mission re-

quirements of vessel. The multi-objective optimization scheduling of vessel integrated power system should be able to transform the objective function weight constantly to realize the switching of operation mode, and also ensure the stability of system under frequent switching, which is different from the multi-objective optimization solution of land-based power system in one single time section[26-27].

The automatic generation of multi-time scale and multi-objective optimization control strategy of integrated power system is the core function of intelligent energy management system. The intelligent energy management system makes the automatic generation control for generator sets by taking fuel economy as goal to achieve the efficient utilization of energy. At the same time, this intelligent system can also produce the power scheduling strategy corresponding to the different task requirements by taking the pulse load maximum emission capacity and maneuvering performance as the goal. Also, in case of fault, this intelligent system can ensure the maximum survivability of system through the rapid network reconfiguration and a series of emergency control measures by taking the power supply continuity of key equipment as the goal. The intelligent energy management needs to be able to optimize and control the dynamic process of integrated power systems in multi-time scale and multi-objective dimension so as to ensure that the economy, maneuverability and security always tend to be optimal.

4 Conclusions

This paper introduces the progress of medium voltage DC integrated power system in China. This system uses the network structure of the second generation integrated power system to supply power for the first generation integrated power system, which constitutes the quasi second generation integrated power system. In addition, the difficulties in this system in modeling simulation, parallel connection of different types of sets, system stability analysis and system protection are analyzed. Also, the solutions to these difficulties are put forward. Moreover, the further research of medium voltage DC integrated power system is pointed out.

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我国舰船中压直流综合电力系统研究进展

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摘　要：舰船综合电力系统可实现全舰能量的综合利用，被誉为是舰船动力的第三次革命。介绍了一代和二代舰船综合电力系统的技术特征。结合我国综合电力系统设备的技术现状，介绍我国一代半舰船中压直流综合电力系统的研究进展，分析了系统层面存在的难点，主要包括：系统建模和电磁暂态仿真、气轮机发电机组和柴油发电机组并联、系统稳定性分析和分层保护等，并给出了解决的方法，指出中压直流综合电力系统需要在中压直流断路器、系统储能、系统安全运行和多时间、多目标能量调控方面进一步开展研究。

关键词：综合电力系统；中压直流；能量调控