Research on the Overall Framework of the Integrated Power System Fuel Economy Optimization Scheduling Strategy

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Abstract. Due to the differences in research objects, operational requirements and control methods, the fuel economy strategies of land-based power systems and traditional marine power systems cannot be directly applied to integrated power systems. Aiming at the energy optimization and regulation requirements of the integrated power system, a fuel economy optimization scheduling strategy model was established. By analyzing the operational requirements of the system under normal and abnormal conditions, the overall framework of the fuel economy optimization scheduling strategy for the integrated power system was established. The generator excitation adopts the master-slave control mode, which realizes the optimal dispatch of the generator output under the overall frame operation demand. Finally, the simulation test verifies the effectiveness of the proposed method.

1. Introduction
The ship integrated power system is a new power platform for the ship's power system. It integrates power generation and distribution with electric propulsion and other equipment, from power generation, distribution, substation, propulsion, energy storage and energy. It manages six modules and has the advantages of simplifying the power system structure, improving the efficiency of generator operation, and reducing energy consumption [1-2]. The second generation of ship integrated power system adopts the network structure of medium voltage direct current transmission and DC area power distribution. Compared with the medium voltage AC transmission scheme, the medium voltage direct current transmission scheme reduces the volume and weight of the system, eliminates the interaction between the prime mover speed and the bus frequency, and optimizes the efficiency and responsiveness. The weakening of the requirements for the speed regulation performance of the prime mover. The DC area power distribution system is a new type of ship power distribution system. It uses DC as the main form of power transmission and distribution to divide the power system of the whole ship. The integrated power system using DC area distribution can optimize the cost, volume and weight of the converter equipment, which is beneficial to the power flow regulation of the system [3]. The integrated power system in the form of medium voltage DC power supply DC area distribution represents the development direction of the ship power system.

The first generation of integrated power system uses AC synchronous generator as the power source and medium voltage AC grid as the transmission network. The transmission network power flow and
the distribution network power flow are coupled together, and it is difficult to realize the separate adjustment and control of the power transmission and distribution network power flow. The second-generation integrated power system uses a rectified generator as the power source, a medium-voltage DC grid as the transmission network, and a DC regional distribution system to supply power to the distribution network. The regional distribution converter has the function of isolating the tidal current, which makes the second-generation integrated power system transmission network tidal current and distribution network tidal current decoupling characteristics, and can realize the separate adjustment and control of the power transmission and distribution network tidal current. The network structure of the DC transmission and distribution system makes the system not transmit reactive power, and only needs to consider the adjustment control of the active power flow. The above characteristics make the second-generation integrated power system flow regulation relatively simple and more numerous. The second-generation integrated power system is different from the land-based power grid and the traditional marine power system. The research object is the medium-voltage DC system, while the land-based power grid and the traditional marine power system are studied in the AC system. In the case of land-based power grids, the proportion of disturbances is large, the sea conditions are bad, the storms are more, and the sudden or sudden load reduction is frequent, so the operation requirements are different; and the second-generation integrated power system and the land power system and the traditional ship power system are regulated. The means are also different. The transmission and distribution of land and conventional marine power systems cannot be decoupled and regulated, and the transmission and distribution of medium voltage DC systems can achieve decoupling regulation.

At present, the domestic ship energy optimization scheduling strategy mainly adopts the principle of increase and decrease. The principle of increasing the machine means that the reserve power is set to a constant value. If the system reserve power is less than the corresponding given value, add a generator set. The principle of reduction is that if one generator is disengaged and the average power of the generator is less than the corresponding set value, a generator set is dismissed [4,5]. Although this energy scheduling strategy can avoid the lack of system reserve power and the high energy consumption state of the generator running at light load, it does not consider the fuel consumption characteristics of the prime mover, and cannot realize the fuel economy optimization scheduling of the integrated power system.

It can be seen that the fuel economy strategy of the land grid and the traditional marine power system cannot be directly applied to the ship integrated power system, and it is urgent to study the fuel economy strategy applicable to the integrated power system. In this paper, based on the operation requirements of the integrated power system, a typical medium voltage DC integrated power system is used as the research object, and the fuel economy optimization scheduling strategy model is established. By analyzing the operational requirements of the system under normal and abnormal conditions, the integrated power system fuel is established. The overall framework of the economic optimization scheduling strategy, and the master-slave control method for the excitation of the rectifier generator, realizes the optimal dispatch of the generator output under the overall framework operation demand. Finally, the simulation test verifies the effectiveness of the proposed method.

2. The overall framework of the fuel economy optimization scheduling strategy for integrated power system

In the typical second-generation integrated power system model shown in Figure 1, the rectifier generator is used to supply power. The whole system includes three subsystems: medium voltage DC, low voltage DC and regional AC power distribution. The \( n_1 \) rectifier generator sets are connected in parallel to medium voltage. DC bus power supply, medium voltage DC bus to \( n_2 \) DC / DC converter, \( n_3 \) propulsion load PM power supply. Each DC/DC converter supplies power to the DC/AC inverter through a low-voltage DC bus, and the DC/AC inverter distributes the AC power distribution system. In order to improve the continuity and reliability of the power supply, the area The AC distribution system is equipped with an auxiliary synchronous generator [3].
The AC power system realizes the output control of the active power by adjusting the speed of the prime mover, and realizes the output control of the reactive power by adjusting the excitation of the generator. In contrast, increasing the excitation potential of a medium-voltage DC integrated power system generator increases its AC output voltage. Since the generator is connected in parallel through the rectifier diode, the ratio of the conduction time of the rectifier diode of the generator is increased, the output current is increased, and the output electromagnetic power is also increased. The increased electromagnetic power will inevitably lead to a decrease in the prime mover’s speed. Since the control objective of the prime mover speed control system is to maintain its speed as rated, the prime mover will gradually increase the output power until its speed reaches the rated value. Therefore, adjusting the excitation control of the rectifier generator can adjust its output power.

DC system rectifier generator power output has three control methods: master-slave control, voltage deviation control, and peer-to-peer control. Master-slave control refers to selecting a generator as the main generator, controlling the DC bus voltage to a given value, and the remaining generators as slave generators, controlling the output power to a given value. The main generator acts as a balancing machine and regulates its output power to maintain a constant DC bus voltage. The voltage deviation control is equivalent to the improvement of the master-slave control. After the main generator fails to lose the voltage control capability, the backup generator can detect the voltage offset and convert to the main generator control voltage to ensure the system continues to operate stably. Peer-to-peer control means that all rectifier generators have the same status in control, and there is no master-slave relationship between the controllers. Each power distribution source is locally controlled according to the voltage and frequency information of the access system point. Together to maintain system voltage and frequency stability, droop control is the main method of peer control. Compared with the master-slave control mode, the generator with peer-to-peer control does not depend on a main generator, which can easily realize the plug-and-play of the generator, which can avoid the failure of the master-controlled generator in the master-slave control mode. The system crashes, while reducing the dependence on the communication system and improving the reliability of the distribution system. However, the load power of the parallel generator controlled by the droop is distributed according to its rated power ratio, and cannot be directly used to optimize the operation of the rectifier generator [3].

Figure 1. The model of the integrated power system.
2.1. Establish a fuel economy model for integrated power system
Taking the rectifier generator as the droop control method as an example, the power flow equation of the system is given below. The \( n_1 \) generator sets are connected in parallel to supply power to the medium voltage DC bus. The DC bus voltage is \( U \), the supply current of the rectifier generator to the medium voltage DC bus is \( I_i \), the droop coefficient of the droop control of the rectifier generator excitation system is \( k_i \) plate, and the no-load voltage coefficient is \( U_r \), then:

\[
U + k_i I_i = U_r, i = 1, \ldots, n_1
\]  

(1)

The output power of the generator is \( P_{Gi} \), the efficiency of the power equipment on the DC bus is \( \alpha_{zi} \), and the outlet current is \( I_{Zi} \). The line resistance in the engineering practice is very small and can be ignored. The power of the propulsion load \( PM \) and the converter DC/DC are \( P_{mi} \) and \( P_{ci} \), respectively, which are available from the Kirchhoff circuit law and the power balance equation.

\[
\sum_{i=1}^{n_1} I_i = \sum_{i=1}^{n_2+n_3} I_{Zi}
\]

\[
P_{Gi} = UI_i, i = 1, \ldots, n_1
\]

\[
\alpha_{Zi} I_{Zi} U = P_{ci}, i = 1, \ldots, n_2
\]

\[
\alpha_{Z(n_2+i)} I_{Z(n_2+i)} U = P_{mi}, i = 1, \ldots, n_3
\]  

(2)

State variables in the power flow equation of a medium voltage DC system

\[X = \left[U, I_1, \ldots, I_{n_1}, I_{Z1}, \ldots, I_{Z(n_2+n_3)}, P_{G1}, \ldots, P_{Gn_1}\right]^T\]. By combining the above equations, the power flow equation of the medium voltage DC system is obtained. The number of equations is the same as the number of unknowns, which can be solved by the Newton-Raphson method. It can be seen from the power flow equation of the medium voltage DC system that the DC line resistance is ignored in the engineering practice. The DC bus has only one voltage value. This value can be realized by modifying the drooping coefficient \( k_i \) and the no-load voltage coefficient \( U_r \) of the rectifier generator, so that the DC bus voltage does not occur. The limit is exceeded. The DC system provides radiative power supply, and the DC line transmission power is consistent with the input power of the electrical equipment, so that the DC line transmission power does not exceed the limit [6, 7]. For the above reasons, in the fuel economy scheduling problem of the medium voltage direct current transmission integrated power system, the flow equation and the overshoot of the DC voltage and power can be ignored. The number of generators is \( n_1 \), the total system load is \( P_{0\alpha} \), and the fuel consumption characteristics of the generator are known. Now we discuss how to properly distribute the output power of \( n_1 \) generators to achieve the goal of minimum fuel consumption.

It is assumed that the ship has arranged different load tasks for multiple time periods before departure. Due to the change of the total load of the system in different time periods, under the premise of ensuring fuel economy, the number of generator sets invested may change, and the generator set has a start-stop problem. At this point you need to introduce the start and stop variables. Assume that the system only starts the shutdown group when the load changes, and based on this, establishes a fuel economy strategy model for the integrated power system considering the start and stop of the unit.
\[
\min \sum_{t=1}^{T} \min \left( \min_{j=1,\cdots,n_1} \left( f_i(P_{Gi}(t),t) \right) \right) u(t) P_{Gi}(t) + (1-u(t-1)) u(t) M_i \right) \\
\text{s.t.} \sum_{i=1}^{n_1} P_{Gi} = P_D(t) \\
P_{Gi1} \leq P_{Gi} \leq P_{Gi2}, i = 1,\cdots,n_1 \\
P_{Gj2} - P_{Gj} \geq P_b
\] (3)

Where \( P_{Gi}(t) \) is the output power of unit \( i \) at time \( t \); \( f_i(P_{Gi}(t),t) \) is the fuel consumption corresponding to unit \( i \)'s output power at time \( t \); \( T \) is the number of calculation periods; \( n_1 \) is the total number of units; \( j \) is the selected main generator; \( u \) is 0 or 1 integer variable, 0 means that the \( i \)-th unit is stopped during the \( t \) period, when it is 1 to indicate the start; \( M_i \) is the unit \( i \) after the stop period \( t \) Startup cost; \( P_D(t) \) is the total system load power at time \( t \). Constraint 1 is the power balance constraint, the sum of the generator output power is equal to the total load power. Constraint condition 2 is the upper and lower limit of power generation output power. It can be known from the above-mentioned increase and decrease principle that the ship operation requires the power system to have a certain reserve power \( P_b \), that is, the constraint condition 3, there is a generator whose output power upper limit and output the difference in power is greater than the reserve power \( P_b \).

Because the ship does not change the operating state frequently in consideration of the actual situation, the climbing rate and minimum opening and closing time constraints of the unit are not considered. The above problem is a discrete, non-convex dynamic mixed integer nonlinear optimization problem involving discrete variables and continuous variables [7]. Based on the hierarchical optimization algorithm, this paper simplifies the solution of the problem and solves the model by exhaustive method. Firstly, according to the total system load of different time periods, enumerate all the unit combinations, then consider the choice of the main generator, and finally consider whether there is a unit start and stop when the state is replaced, so that the global optimal solution can be obtained.

2.2. Analysis of the operational requirements of the fuel economy optimization scheduling strategy for integrated power systems

The fuel economy optimization scheduling strategy under normal operating conditions is carried out in two steps:

1) Offline optimization according to the planned average total load. According to the mission requirements, the ship determines the average power according to the speed and sea conditions, and arranges the shutdown group according to the plan.

2) Online real-time correction optimization. When the unit is started, the genset excitation control is implemented by pressing down. After the system runs stably, it switches to the master-slave control, collects the load signal every 5 minutes during the scheduling period, optimizes the output power of each generator and the main generator according to the total load of the collected system and the minimum fuel consumption. Select to correct the generator's output power in real time.

Fuel economy optimization scheduling strategy under abnormal operating conditions:

3. A generator suddenly trips

1) If the difference between the total rated power and the reserve power of the remaining units in the network is greater than the total load, the excitation master-slave control can be directly switched to the droop control to prevent the main generator from taking up insufficient power and causing its overload.
operation, and then in a dispatch. The load signal is collected once every 5 minutes, the excitation droop control is switched to the master-slave control, and then the fuel economy scheduling strategy is operated under normal operating conditions.

2) If the difference between the total rated power and the reserve power of the remaining units in the network is less than the total load, in order to ensure the safe operation of the system, power limit or tripping of the propulsion load is required at this time, so that the load power is rapidly decreased to ensure the stability of the system power supply. Switch to droop control again, and the subsequent control is the same as the previous step.

By limiting the load power value not greater than the difference between the total rated power of the remaining units and the reserve power, the master-slave control is switched to the droop control. If the system has a standby unit, the standby unit is started. After the start is completed, the thrust load power limit is released, and the system is stable. After the operation, according to the fuel economy scheduling strategy under the normal operation of the above system, if the system has no standby unit and the trip unit cannot restore the power supply, the load power limit is reserved, and the droop control is adopted first. After the system is stably operated, the fuel economy is followed. The scheduling policy is scheduled [9].

4. Start large load
In the system, high-power electrical equipment such as electric propellers, large-scale fire pumps and large-scale winches are activated, which may cause serious power failures. Before starting any such high-power equipment, you should ask the generators in advance. Whether the existing power meets the startup requirement, this function is the overload inquiry function.

The overloaded query function mainly includes the following two aspects:

1) Allow start signal: Detect the power headroom of the grid generator set and compare it with the capacity of the starting power equipment. If the power demand is met, the energy management system issues an allowable start signal, and the high power equipment can be started. If the power demand cannot be met, the start-up is not allowed. In this case, the control system needs to start more generator sets to ensure sufficient power headroom.

2) Blocking signal: If you do not know when a high-powered electrical equipment sends an inquiry, according to the important level, the high-powered electrical equipment with high importance level will be overloaded and inquired, and at the same time, the blocking command will be issued to other high-power electrical equipment. After the system is running stably, the total system load is collected every 5 minutes, and the fuel economy optimization scheduling strategy is optimized [10].

5. Sudden disturbance
Ships operating sea state disturbances frequently encounter large disturbances may cause insufficient system reserve power, resulting in power failure. In the case of sudden large disturbance, similar to the sudden trip of a certain unit mentioned above, it is necessary to realize rapid load shedding, limiting the difference between the propulsion load power value and the total rated power of the remaining units and the reserve power, and switching the excitation given control to the conventional one. Sagging control, if the system has a standby unit, the standby unit is started. After the completion of the system, the propulsion load power limit is released. After the system is stably operated, the fuel economy optimization scheduling strategy under the normal operation of the system is optimized; if the system has no standby unit, the propulsion load power limit is retained, and then the total system load is collected every 5 minutes in a scheduling period, and the fuel economy optimization scheduling strategy is optimized.

6. Examples and Simulation.
Assume that there are six diesel generators on the DC bus, four of which are 8MW and two of which are 13.5MW. According to the literature, the generator consumption characteristic curve is a quadratic curve. The values of each parameter and the operating conditions of the system are shown in Table 1.
Table 1. Integrated power system parameters and operating status.

| Number | Rated power(MW) | Consume Characteristics(t/h, \( P(MW) \)) | Power lower limit(MW) | Power cap(MW) |
|--------|-----------------|------------------------------------------|----------------------|--------------|
| 1      | 8               | 0.033\( P^2 + 2.63P + 2.26 \)           | 1.6                  | 8            |
| 2      | 8               | 0.034\( P^2 + 2.64P + 2.26 \)           | 1.6                  | 8            |
| 3      | 8               | 0.035\( P^2 + 2.65P + 2.26 \)           | 1.6                  | 8            |
| 4      | 8               | 0.036\( P^2 + 2.66P + 2.26 \)           | 1.6                  | 8            |
| 5      | 13.5            | 0.019\( P^2 + 2.44P + 3.42 \)           | 2.7                  | 13.5         |
| 6      | 13.5            | 0.020\( P^2 + 2.45P + 3.42 \)           | 2.7                  | 13.5         |

Example 1: Assume that the total system load is 41.3MW, which is 70% of the total system load, and Unit 1 is in the shutdown state. The power reserve required by the system is 4MW, and the DC bus voltage is 6kV. Through the quadratic programming algorithm, the No. 4 unit is selected as the main generator, and the excitation control is controlled by maintaining the bus voltage, and the remaining four are slaves. Before 4s, the slave excitation control adopts the droop control mode. After 4s, the slave excitation control adopts the master-slave control mode. At 6s, the system suddenly encounters a large disturbance, and the total system load is 46.3MW. At this time, the difference between the total rated power and the reserve power of the network unit is 47MW and the total load is 46.3MW, then the excitation master-slave control can be directly switched to the droop control. Avoid the main generator to bear the power shortage and cause its overload operation, and then collect the total system load in the new scheduling period, assuming that the total system load collected at this time is 46.3MW, and optimize the operation according to the fuel economy optimization scheduling strategy. The parameters in the system running process are shown in Table 2.

Table 2. System operation process parameters of Exp.1.

| Running time(s) | 0-4 | 4-6 | 6-8 | 8-10 |
|-----------------|-----|-----|-----|------|
| DC bus voltage(V) | 5924 | 6000 | 5898 | 6000 |
| Unit 2 output power(MW) | 6.48 | 5.30 | 7.26 | 7.83 |
| Unit 3 output power(MW) | 6.48 | 5.00 | 7.26 | 7.47 |
| Unit 4 output power(MW) | 6.48 | 4.00 | 7.26 | 4.00 |
| Unit 5 output power(MW) | 10.93 | 13.50 | 12.26 | 13.50 |
| Unit 6 output power(MW) | 10.93 | 13.50 | 12.26 | 13.50 |

The above excitation control mode and power optimization distribution are realized by MATLAB/Simulink simulation. The DC bus voltage simulation waveform is shown in Figure 2, and the output power simulation waveform is shown in Figure 3.
Example 2: On the basis of the first example, assuming a large disturbance at 6s, the total system load becomes 47.3MW. At this time, the difference between the total rated power and the reserve power of the network unit is 47MW and the total load is 47.3MW. In order to ensure the safe operation of the system, the power limit of the propulsion load should be limited at this time, and the limit load power value is not more than 47MW of the total rated power and the reserve power of the network unit to ensure the stability of the system power supply, and then switch to the droop control, and The system has no standby unit, and needs to reserve the propulsion load power limit, and then re-acquire the total system load in the next scheduling period. It is assumed that the total system load collected at this time is 46.3 MW, and the fuel economy optimization scheduling strategy is optimized. The parameters in the system running process are shown in Table 3.
Table 3. System operation process parameters of Exp.2.

| Running time(s) | 0-4   | 4-6   | 6-8   | 8-10  |
|-----------------|-------|-------|-------|-------|
| Excitation control mode | Droop control | Master-slave control | Droop control | Master-slave control |
| DC bus voltage(V) | 5924  | 6000  | 5895  | 6000  |
| Unit 2 output power(MW) | 6.48  | 5.30  | 7.37  | 7.83  |
| Unit 3 output power(MW) | 6.48  | 5.00  | 7.37  | 7.47  |
| Unit 4 output power(MW) | 6.48  | 4.00  | 7.37  | 4.00  |
| Unit 5 output power(MW) | 10.93 | 13.50 | 12.44 | 13.50 |
| Unit 6 output power(MW) | 10.93 | 13.50 | 12.44 | 13.50 |

**Figure 4.** DC bus voltage.

**Figure 5.** The number 2-6 generator output power.
The above excitation control mode and power optimization distribution are realized by MATLAB/Simulink simulation. The DC bus voltage simulation waveform is shown in Figure 4, and the output power simulation waveform is shown in Figure 5.

7. Conclusion
In this paper, based on the operation requirements of the integrated power system, a typical medium voltage DC integrated power system was used as the research object, and the fuel economy optimization scheduling strategy model was established. By analyzing the operational requirements of the system under normal and abnormal conditions, the integrated power system fuel was established. The overall framework of the economic optimization scheduling strategy, and the master-slave control method for the excitation of the rectifier generator, realized the optimal dispatch of the generator output under the overall framework operation demand. Finally, the simulation test verified the effectiveness of the proposed method.

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References
[1] Ma Weiming. A survey of the second-generation vessel integrated power system [C]//The International Conference on Advanced Power System Automation and Protection. Beijing, China:IEEE, 2011: 1293 - 1302. W. Strunk Jr., E. B. White, The Elements of Style, third ed., Macmillan, New York, 1979.
[2] Ma Weiming. Development of vessel integrated power system [C]. The 14th International Conference on Electrical Machines and Systems. Beijing, China: IEEE, 2011.
[3] Xiao Runlong, Wang Gang, Li Zimeng, Xiong Youxing. Static estimation of the integrated power system with medium voltage DC and DC zonal distribution system [J]. Transactions of China Electrotechnical Society, 2018, 33 (13): 3023 - 3033.
[4] GONG Xiwen, ZHENG Yuanzhang, SHI Linlong. Research on design and key technology of ship PMS controller [J]. Journal of Shanghai Institute of Shipping and Transportation, 2010, 33 (2): 83 - 87.
[5] Shi Linlong, Gong Xiwen, Guo Chen, He Wei. Energy Dynamic Priority Management Technology for Integrated Power Ships [J]. China Navigation, 2013, 36 (3): 19 - 22.
[6] B. Zahedi, L. E. Norum, K. B. Ludvigsen. Optimized efficiency of all-electric ships by DC hybrid power systems [J]. J.Power Sources, 2014, 255: 341 - 354.
[7] Damir Radan. Integrated control of marine electrical power systems [D]. Department of Marine Technology, Norwegian University of Science and Technology, 2008.
[8] Wang Ke, Liu Jiantao, Li Yaping, et al. An adaptive power control strategy based droop feedback for VSC-HVDC [J]. Power System Protection and Control, 2014, 42 (9): 48 - 53.
[9] Xiao Xiong, Wang Jianxiang, Zhang Yongjun, et al. An optimized master-slave model predictive torque control scheme for the dual motor [J]. Transactions of China Electrotechnical Society, 2018, 33 (24): 5720 - 5730.
[10] Li Ming. Research on energy management strategy of marine electric propulsion system [D]. Harbin Engineering University, 2016.