Research on Hierarchical Control Strategy of Aircraft Power Supply System

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Abstract. With the iteration and improvement of the combat capability of fighter jets, the power of airborne electrical equipment has been continuously improved. At the same time, various advanced high-power equipment has been equipped with new fighter jets, making the electrical load power of the aircraft continue to increase. Aircraft power supply systems have many problems by using traditional control strategies such as low system efficiency and high energy consumption when faced with high-power loads. And their limitations are becoming more and more obvious. In this paper, based on the F-35 fighter power supply architecture and the typical airborne power load profile, the hierarchical control method is used to optimize the power supply system control strategy. The important indicators, such as average power, energy consumption, average efficiency and heat dissipation of the aircraft power supply system are greatly optimized, which greatly eases the pressure on the onboard power supply.

Keywords: Hierarchical control strategy · Power supply system · High power load · Particle swarm optimization

1 Preface

Since 21st century, fighter jets have achieved the leap from the second and third generation aircraft to the fourth generation aircraft, and are moving towards a higher level. The continuous evolution of strategic combat requirements has led to the development of fighter jets.

One of the key technical points in the design of fighter aircraft is the power supply of the airborne power supply system and the heat dissipation of the whole aircraft. In the current fighter aircraft, the power is relatively low, and the energy requirements and heat dissipation requirements can also be satisfied under the current traditional design scheme. The use of high-power electrical equipment puts forward higher requirements on the power supply structure and heat dissipation capacity of the aircraft, while the traditional structure and its control strategy make the generator set work in the low-efficiency range for a long time. The overall efficiency is low which also means serious energy loss, and it increases the heat dissipation burden of airborne equipment. Therefore, the control strategy of the power supply system must be developed from uncontrolled to multi-source coordinated control to meet the bottleneck problems of power supply and heat dissipation caused by the above load changes, and to optimize the overall energy architecture within the boundary conditions of the airborne environment.

Chinese Society of Aeronautics and Astronautics: CASTYSF 2022, LNEE 972, pp. 420–432, 2023.
https://doi.org/10.1007/978-981-19-7652-0_39

2 Airborne Power Supply Architecture and Hierarchical Control Strategy

2.1 Aircraft Power Supply System

The early aircrafts were mainly based on AC parallel architecture [1], and the civil aviation passenger aircrafts were mainly based on AC power supply architecture. Boeing 787 mainly uses 235V and 115V alternating current for power supply, and then converts it into corresponding direct current through power electronic converter [2, 3].

Later, with the iteration of aircraft requirements, the problem of AC architecture gradually emerged [4], so AC power generation system is gradually replaced by high-voltage DC power supply system [5]. The DC power supply architecture built by scholars from the University of Nottingham has studied generator grid-connected characteristics and bus voltage characteristics of the DC power supply system in detail [6, 7]. At present, the power supply structure of the fourth-generation fighter jets in the world is dominated by high-voltage DC power supply systems. The earliest high-voltage DC power supply system design scheme has been fully tested in the United States in the F-22 and F- 35 [8]. Among them, the F-22 adopts dual independent channel 65 kW high-voltage DC generators to supply power to the whole machine load. The architecture also includes a variety of power electronic converters to convert the high-voltage DC into the required low-voltage DC.

Figure 1 is the architecture diagram of the power supply system of the F-35 fighter. The power system consists of two subsystems: the Electrical Power Generation System (EPGS) [9] and the Electrical Power Management System (EPMS).

The power generation system consists of a starter/generator (ES/G) which provides two independent 80 kW power outputs during normal operation. Two 160A rated voltage converters provide 28V DC for low power loads and critical loads. A 270V DC-115V AC inverter supplies the aircraft with 5.4 kVA of current (115V AC) for the F-35C’s weapon bay and folding wings.

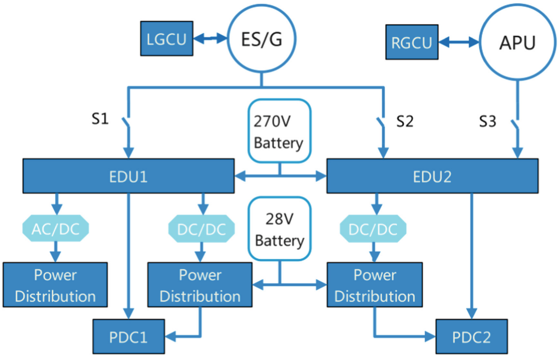

Fig. 1. Schematic diagram of the power supply system architecture of the American F-35 fighter jet

The 270V DC battery system consists of a Li-Ion battery and a charger/controller. The system provides auxiliary power for 270V flight critical loads and provides power for power and thermal management system self-starting.

The simulation of the power supply architecture requires the flight profile load usage. This paper sets a typical combat load profile with a high-power load as the core. This profile reflects the load usage of the airborne system in Figure below. The simulation and analysis in this chapter are based on this flight profile (Fig. 2).

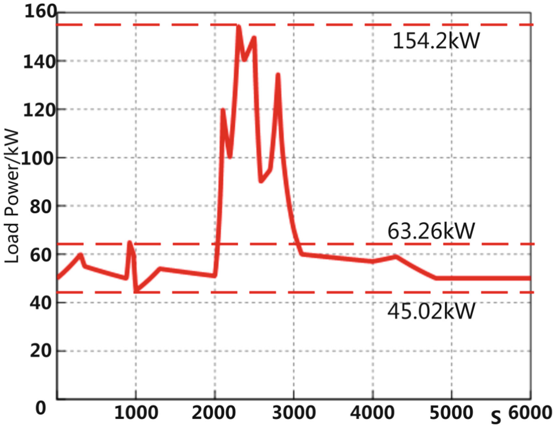

Fig. 2. Load variation curve of future fighter flight profile

The flight time of this mission profile is 6000 s. The peak power is 154.2 kW. The minimum power is about 45.02 kW and the average power is 63.26 kW.

2.2 Control Strategy Development and Hierarchical Control Strategy

At present, energy control strategies are mostly used in the hybrid energy power supply architecture of vehicles. The control strategies of the power supply architecture are mainly divided into two categories according to their characteristics. One is the rule-based energy management strategy, and the other is based on the optimization algorithm. Energy management strategy [10] and different control strategies have different scope of use and advantages and disadvantages. Rule-based energy management strategies include fixed rule control strategy, frequency division control strategy, fuzzy logic control strategy and predicted neural network control strategy. Energy management control strategies based on optimization algorithms include dynamic programming control strategies, transient optimization control strategies, Pontryagin's principle control strategies, swarm algorithm control strategies, and model predictive control strategies. Since the current sharing control strategy is mostly used for systerm control (hereinafter referred to as the "original strategy").

Hierarchical control strategy is a control scheme that is widely used in microgrids [11]. Scholars at home and abroad have done a lot of research and improvement work in power grid control optimization [12, 13], and continuously optimize the bus voltage operation quality from the control structure and control strategy [14, 15], so that the power grid maintains stable in different states. There are no specific requirements for the multi-layer control of the hierarchical control strategy. The hierarchical control strategy includes two to three control levels. Usually, the bottom layer is a component-level control layer, and the upper layer is a system-level control layer. There are also some layered control strategies in which the bottom layer is responsible for function implementation, such as droop control, the current sharing control mentioned above, and the master-slave control [16] method and so on. The upper layer test optimizes the algorithm of the underlying control strategy to make the underlying strategy more stable and responsive to run [17, 18].

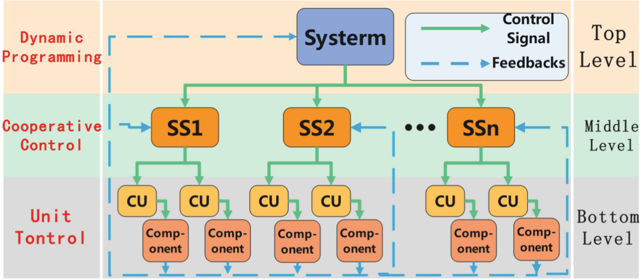

Fig. 3. Hierarchical control strategy of airborne power supply system

In this paper, the hierarchical control strategy controls power supply components such as generators and lithium batteries. The hierarchical control strategy is shown in Fig. 3. According to the system level, the control strategy is divided into system-level control strategy, subsystem-level control strategy and component-level control strategy. The component-level control strategy mainly analyzes the control strategy for the generator and lithium battery models, and ensures the stability of the bus power supply based on the combined power supply architecture of the generator and the lithium battery. The subsystem-level control strategy mainly studies the grid-connection of components, which mainly involves the grid-connection and power distribution of generators and the grid-connection and power distribution of DC/DC converters. Finally, the responsibility of the top layer, that is, the system-level control strategy, is to schedule the energy supply of the entire architecture. Based on the optimal efficiency of the entire architecture, the corresponding algorithm is used to provide the subsystem-level control strategy with specific instructions for grid-connected power distribution.

3 Top-Level Control Strategy Based on Particle Swarm Optimization

The top-level control strategy of the hierarchical control strategy mainly realizes the whole-system dynamic planning and overall decision-making, and guides the system in which state to run on the basis of the middle-level power distribution control strategy. Therefore, the core of the outermost control strategy is to perform calculation and optimization according to the operating state of the system, so that the system can run optimally based on a specific index or specific index. For the power supply architecture, system energy consumption or system operating efficiency is an important indicator when the parameters of the system components are determined.

Particle Swarm Optimization (PSO) [19] was proposed in 1995, and scholars at home and abroad have done a lot of research and improvement work on it.

The expression of the basic particle swarm algorithm is as follows:

$$v_{i,d}^{T+1} = v_{i,d}^{T} + c_1 r_1 (p_{ibest,d} - x_{i,d}^{T}) + c_2 r_2 (g_{best,d} - x_{i,d}^{T}) \tag{1}$$

$$x_{i,d}^{T+1} = x_{i,d}^{T} + v_{i,d}^{T+1} \tag{2}$$

in, $d = 1, \cdots, n$; x_i^T is the position of the i-th particle in the T-th iteration; v_i^T is the velocity of the i-th particle in the T-th iteration.; c_1 is the self-perception coefficient; c_2 is the social cognition coefficient; r_1 or r_2 is a random number from 0 to 1; p_{ibest} is the individual optimal position of the i-th particle in the T iterations; g_{best} is the global optimal position obtained by all particles in T iterations.

The top-level strategy uses particle swarm optimization based on the fact that the generator efficiency changes with the output power of the generator, which makes it possible to optimize based on the system efficiency. The abscissa in Fig. 4 is the ratio of the generator output power to the rated power of the generator, dimensionless; the ordinate is the generator efficiency, dimensionless. It can be seen from the generator efficiency curve that the generator has the highest efficiency under the rated power. And the generator efficiency on both sides of the rated point shows a downward trend. When the output power of the generator is close to 0, the efficiency of the generator is extremely small. With the increase of the output power, the efficiency of the generator increases rapidly. When the ratio of the output power of the generator to the rated power of the generator increases from 0 to about 0.15, the generator efficiency rises from a very low value to more than 60%. After that, with the increase of the output power of the generator, the increase of the generator efficiency gradually slows down to the highest level, and the peak value of the generator efficiency at this stage is generally about 90%. Then, as the degree of overload of the generator increases, the generator efficiency gradually decreases. In addition, when the output power of the generator is 0, the input power of the generator is not 0. At the same time, the generator still consumes energy although it does not supply power to loads. In the architecture design of this paper, a high-speed clutch device is used at the front end of the generator, which can be controlled to cut off when the output power of the generator is 0 in a necessary stage, so that the input power of the generator is reduced to 0 and energy consumption is reduced. At the same time, it can be controlled and connected quickly when generator power is required.

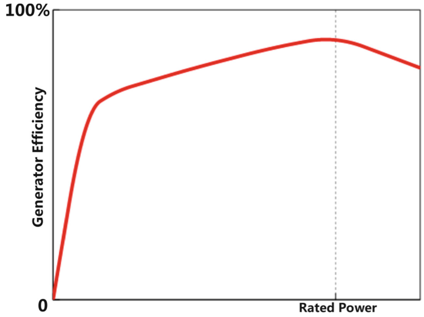

Fig. 4. Generator efficiency curve

Taking two permanent magnet synchronous generators with a rated power of 100 kW as an example, the particle swarm optimization simulation calculation is carried out. It is assumed that two generators need to provide electricity to a load of 130 kW at a certain time, and the optimization calculation is carried out through the particle swarm algorithm. In the quantum particle swarm algorithm of this paper, ten particles are initialized and the velocity and position information are randomly generated. In the constraints, the maximum power of the generator cannot exceed the load power and the generator cannot be overloaded by more than 2 times. Since the generator set uses two permanent magnet synchronous generators with the same rated power, the efficiency curves of the two generators are the same and are calculated using the line type in the above figure.

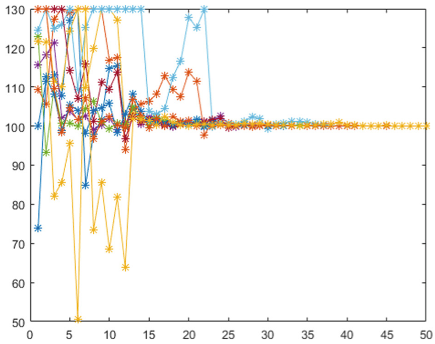

Fig. 5. Generator 1 particle swarm optimization process

Figure 5 shows the change curve of particle swarm when calculating the optimal power of generator 1 in the generator set. The particle position parameter cannot be higher than the injected load power value and greater than 0. The particles tend to aggregate after about 15 iterations, and the desired optimal solution is basically obtained after 35 iterations. The final power distribution particle swarm optimization result is that when the generator set supplies power to the load of 130 kW, the two generators output 100 and 30 kW of energy respectively, which can optimize the efficiency of the system.

4 Middle-Level Control Strategy and Bottom-Level Control Strategy

4.1 Middle-Level Control Strategy Based on Droop Control Strategy

In the power grid, the bus voltage is usually in a fluctuating state, and the fighter usually adopts a bus voltage 270V power supply scheme, so a control strategy based on the bus voltage is adopted. At the same time, in the case of multi-source grid connection, it is necessary to control the output power of each source. At present, the droop control method is relatively mature in practical application. The droop control mainly realizes the coordinated control of the parallel converter by introducing the droop coefficient and adjusting the output voltage reference value according to the magnitude of the output current.

When the droop control method is used to control the parallel system of DC/DC converters, the deviation of the output voltage will be caused. Therefore, the output voltage compensation control should be adopted in the secondary control to overcome the influence of the traditional droop control on the output voltage.

The mathematical model of droop control with output voltage compensation control is:

$$v_{refi} = v_{ref}^{*} - R_{di} i_{oi} + \left(k_{pv} + \frac{k_{iv}}{s}\right)\left(v_{ref}^{*} - v_{o}\right) \tag{3}$$

where $\mathrm{v_{refi}}$ is the actual output voltage reference value of the converter i; $\mathrm{v_{ref}^{*}}$ is the initial reference value of the output voltage; $\mathrm{v_o}$ is the actual bus voltage; $\mathrm{k_{pv}}$ and $\mathrm{k_{iv}}$ are the output voltage compensation PI adjustment parameters.

The droop control expression using voltage and current secondary compensation is:

$$v_{refi} = v_{refi}^{*} - \left(R_{di}^{*} - \left(k_{pi} + \frac{k_{ii}}{s}\right)\left(i_{oi} - \bar{i}_{o}\right)\right) i_{oi} + \left(k_{pv} + \frac{k_{iv}}{s}\right)\left(v_{ref}^{*} - v_{o}\right) \tag{4}$$

Comparing Eqs. (3) and (4), it can be found that the improved droop control is similar to the traditional droop control method. Because they both change the output voltage reference value of the converter to realize the coordinated control of the converter. However, different from the traditional droop control, when the output voltage reference value is given, the problem of output current unbalance and output voltage drop is considered in the improved droop control, and the output voltage command value of the basic converter unit is adjusted according to the unbalance degree of output voltage and the degree of bus voltage drop, so as to achieve Accurate distribution of output current and constant output voltage in parallel across the full range. The droop control simulation model of a single converter in the grid is shown in Fig. 6.

The lithium battery is connected to a DC/DC bidirectional converter, and then the power distribution can also be achieved by supplying such two groups in parallel. First, two lithium batteries are supplied with equal power, and the control strategy is changed in the first 0.5 s. The output power of the lithium battery pack supplies power to the load at a ratio of 2:1. The simulation results are shown in the Fig. 7 Simulation model output power variation curve. The functionality and stability of the droop control are both Guaranteed.

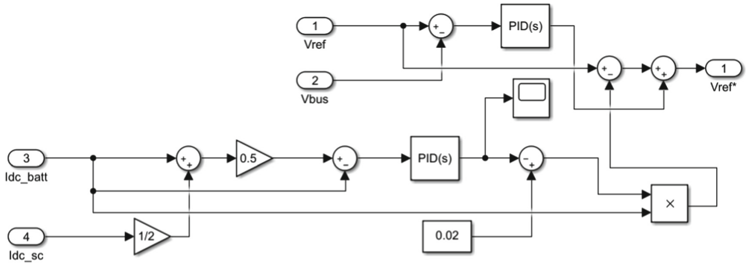

Fig. 6. Droop control simulation model

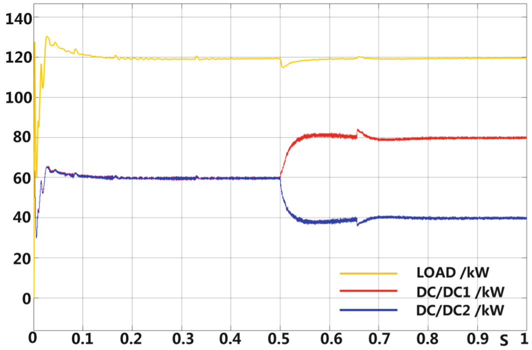

Fig. 7. Simulation model output power variation curve

4.2 The Underlying Control Strategy

The underlying control strategy mainly involves the control strategy of components such as generators and lithium batteries. The generator is generally equipped with a generator controller. For the simulation model, the dual-loop control strategy is a classic control strategy. Regardless of the control strategy used, the goal of the underlying control strategy is to make the generator work stably according to demand.

The underlying control strategy also includes a control strategy for lithium batteries. In the underlying control strategy, this paper set a threshold for the lithium battery. When the load power exceeds the threshold, the lithium battery discharges to reduce the power supply pressure of the system. When the system power is lower than a certain threshold or the SOC of the lithium battery is lower than a certain value, the lithium battery switches to the charging mode. Through the control of the lithium battery and the generator, the correct operation of each component in the system is realized, and the application of the upper-layer strategy is guaranteed.

5 Simulation Experiment and Result Data Analysis

According to the simulation load profile and layered control strategy set in the previous section, the simulation analysis is carried out based on the power supply architecture of the F-35 fighter. The simulation in this paper uses SimulationX software, and the simulation model is shown in Fig. 8.

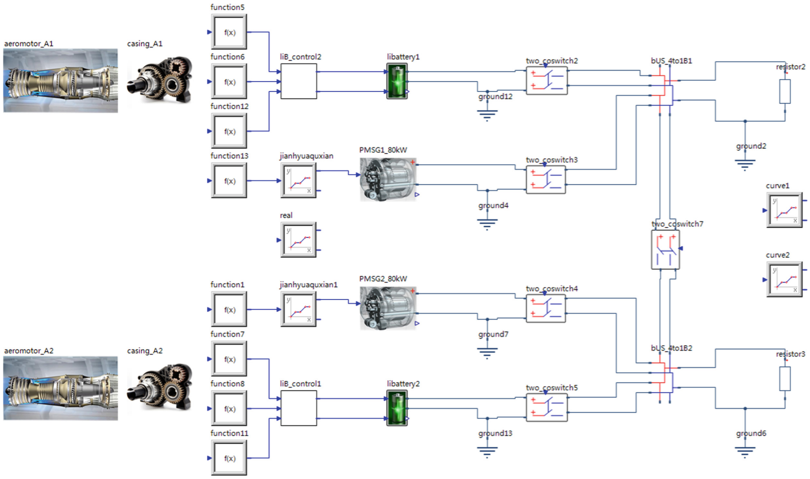

Fig. 8. Power supply system and its strategy simulation model

Through simulation and data analysis, the following results are obtained.

When the load is lower than a certain value, one of the generators in the generator set stops working (implemented by a special clutch device), and the other generator completely supplies power to the load according to the optimal solution criterion for system efficiency. The output power of the two generators is shown in Fig. 9. After the top-level control strategy calculates the optimal power distribution solution, the middle-level and bottom-level control strategies are implemented. It can be clearly seen in Figure that the output power of the two generators is no longer evenly distributed which is different from traditional architecture, whether in a low load power state or a high load power state. They are controlled in real time according to the load state. Regulation, in order to achieve the optimization of system energy consumption.

Figure 10 is a comparison of the efficiency curve of the system efficiency of the basic architecture and the system efficiency of the layered control architecture. The layered control strategy greatly improves the average efficiency of the system compared with the original strategy, from 76.82% to 84.84%. The improvement of efficiency means the reduction of energy consumption. In addition, it can be seen from Figure that the efficiency of the layered control architecture is relatively stable during the operation process, and the system efficiency is adjusted within a certain range.

The energy consumption comparison curves of the two architectures and loads are shown in Figure below. Both architectures use the same load profile, which has a total

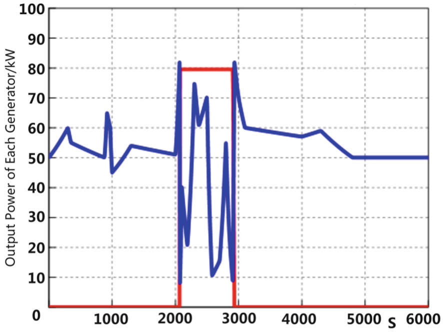

Fig. 9. The output power change curve of the two generators in the left generator set

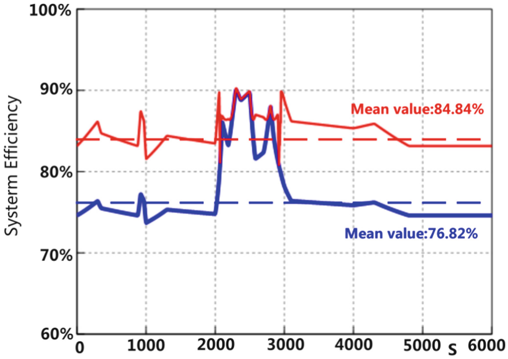

Fig. 10. Comparison of the efficiency change curves of the two-architecture systems

energy consumption of 379.55MJ. The energy consumption of the system under the original strategy and the hierarchical control strategy is 486.85MJ and 444.90MJ, respectively, and the energy consumption efficiency of the system is 77.96% and 85.31%, respectively. In this simulation, compared with the original strategy, the hierarchical control strategy achieves a reduction of more than 8% in system energy consumption (Fig. 11).

Table 1 summarizes the key parameters of the system simulation under the two strategies as follows.

The system load under the two strategies consumes 379.55MJ of energy, the energy consumption of the system using the original strategy is 486.85MJ, and the energy consumption efficiency is 77.96%; Compared with the conventional architecture, the data energy consumption is reduced by 8.62%, and the energy consumption efficiency is increased by 9.43%. From the point of view of power supply, the layered control strategy achieves a substantial optimization of the energy supply system of the system, and the average efficiency of the system is 10.44% higher than that of the system using the original strategy.

The reduction of the energy consumption of the whole machine not only means saving electric energy, weight and space cost, and improving the power supply capacity.

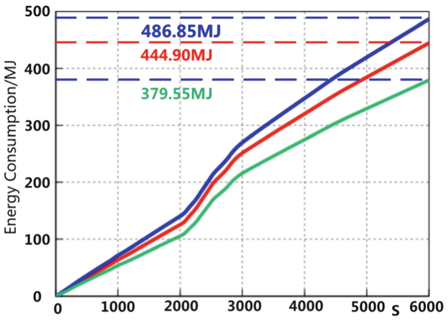

Fig. 11. The energy consumption curve of the two-type power supply system architecture

Table 1. Comparison of simulation results between two power supply architectures and control strategies

	Original strategy	Hierarchical control strategy
Total load energy consumption/MJ	379.55	379.55
Total system energy consumption/MJ	486.85	444.90
–	Benchmark	↓ 8.62%
System Energy Efficiency	77.96%	85.31%
—	Benchmark	↑ 9.43%
System calorific value/MJ	107.30	65.35
–	Benchmark	↓ 39.10%
Average efficiency	76.82%	84.84%
–	Benchmark	↑ 10.44%

Considering the full-function thermal system, the reduction of the energy consumption of the whole machine also means the reduction of the heat dissipation pressure of the whole machine. We assume that the energy dissipated by each component and unit in the power supply architecture due to the efficiency problem is radiated in the form of thermal energy, then it can be obtained by calculation that the calorific value of the system using the original strategy is 379.55MJ, and the calorific value of the system using the hierarchical control strategy is 444.90MJ. The heat is 65.35MJ, and the system heat production is reduced by 39.10%, which is a huge optimization for the airborne environment with extremely strict temperature control requirements, which greatly reduces the pressure on the airborne heat sink. It may bring about secondary energy and weight saving and from the system level.

6 Conclusion

Based on the use of high-power equipment on fighter aircraft, this paper adopts the layered control strategy of the power supply architecture to solve the problems of insufficient power supply capacity and low efficiency of the next-generation aircraft power supply architecture. The layered control strategy is studied and simulated in detail. The main conclusions are as follows:

(1) The layered control strategy is realized based on the characteristics of the relationship between the generator efficiency and its output power.
(2) The use of the hierarchical control strategy can optimize the system energy compared with the conventional current sharing control strategy. And the parameters such as system efficiency and energy consumption can be greatly optimized in the case of a unified load profile in the same architecture.
(3) The layered control strategy can reduce the heat dissipation of the system, so as to ease the design and operation pressure of the airborne heat dissipation system, and greatly reduce the airborne heat dissipation problem.

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