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Characteristic analysis of diesel generating sets under pulsed load

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Abstract: [**Objectives**] Pulsed load has a considerable effect on the power quality and stability of a system. The solutions are different due to the different operation characteristics of pulsed load. To this end, the working characteristics of a diesel generating set under pulsed load in a survey ship are researched. [**Methods**] Load which changes little in average power is the research object of this paper, and using the inherent mechanical energy storage of diesel generators to stabilize power fluctuation is proposed. Certain factors which influence the dynamic performance of a diesel generating set are analyzed and the stability of change and restoration of speed are attained. As such, the engineering summary of smooth power fluctuations in diesel generating sets is concluded. Based on the actual working conditions of a radar in a survey ship, the capacity and performance of diesel generating sets are calculated according to the formulas. [**Results**] This research shows that in the worst working conditions in which the load suddenly increases and fluctuates, the speed characteristics and change of the designed generators can meet the requirements. [**Conclusions**] The results of this research have guiding significance for the preliminary estimation of diesel generating sets under pulsed load.

Key words: pulsed load; diesel generating set; power quality; Integrated Power System (IPS)

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0 Introduction

Integrated power system (IPS) is the future development direction of ship power system, which integrates power generation, transmission, transformation and distribution to realize propulsive function. Moreover, it can meet the power demands of the communication and navigation systems on ships and the needs for energy management and automatic load control[1]. There are many power electronic devices on ships, and their nonlinear electric load will have a serious impact on power quality[2-4], especially the obvious periodic pulse transient characteristic of high-energy weapons, radars, etc. In view of the special energy requirements and operating characteristics of IPS, it brings opportunities for the development of ship power system while bringing new challenges to the stable operation of the system.

Many universities and research institutes in China have conducted research on the diesel generating sets under pulsed load. For example, for the applications where the pulsed load fluctuates greatly and there is a need to ensure high power quality, research is conducted to improve the speed drop of the sets, optimize the power supply frequency and voltage, and reduce the adverse effects of fluctuating load on the system. Yuan and Xing et al.[5-6] studied the factors affecting the performance of the sets, such as the determination of diesel engine power, design of flywheel for energy storage, performance matching of speed regulating system and supercharger matching design. Zhao et al. [7] analyzed the dynamic characteristics of the macroscopic performance parameters of the diesel generating set through the simulation model of the set under pulsed load, and described the dynamic thermal process of the diesel en-

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gine from the microscopic level. Li et al. [8]analyzed respectively the dynamic characteristics of the shaft system under the output torque and pulse torque of the diesel engine through the theoretical analysis model and the virtual prototype model, which laid the foundation for the set optimization design.

For the power supply under pulsed load, most of the references currently report two technical approaches: mechanical energy storage and capacitive energy storage. In the design process of two actual ship power systems with high-power pulsed load, the types and powers of radars are found to be different, and their operational characteristics, impacts and solutions are also very different.

In this paper, the pulsed load radar will be divided into two categories according to the power characteristics, so as to adopt different types of load solutions. Focusing on the first kind of equivalent constant load with little change in average power, it is proposed to use the mechanical energy storage inherent in the diesel generating set to stabilize the power fluctuation. Moreover, the dynamic characteristics of the rotation shaft in diesel generating set are also studied, so as to analyze the speed variation under load fluctuation before and after the intervention of speed regulator of the set and in the steady state, providing theoretical basis for the selection and configuration of generating sets in practical engineering application.

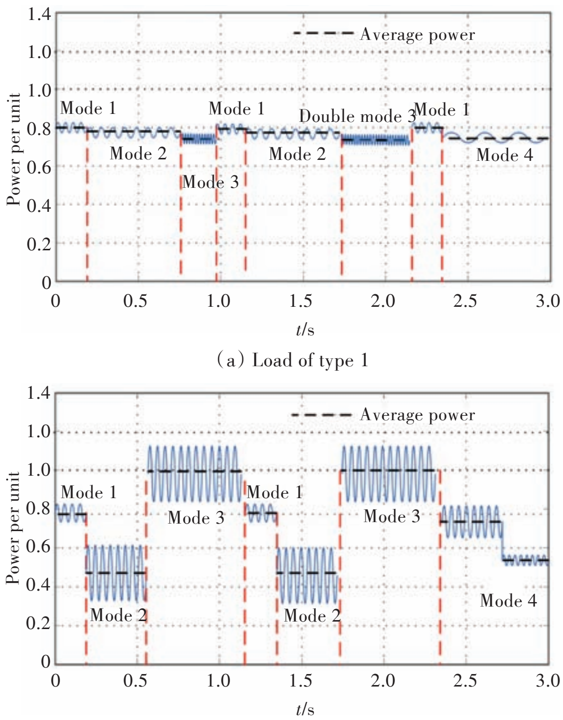
1 Analysis of radar load characteristics of survey ship generating set

1.1 Pulsed load running characteristics

The rapid development of large-scale power electronic equipment and electromechanical devices promotes the research and development of pulse energy and new devices for energy storage. The pulse energy demand is between tens of kilojoules and several gigajoules, and the instantaneous power is basically above the megawatt level. In the future, the ship may have many types of pulsed loads, such as laser weapons, electromagnetic launch, and high-power radars. The pulsed load studied in this paper is radar.

Since radar power sources in the past mostly use land-based power grids with very large capacity, and the general radar power is below 1 MW, the pulse power is directly absorbed by the grid. Traditionally, in ship power system with radars, radar power is small compared with generator power, and the impact of pulsed load is not particularly noticeable. Although there are not many cases of using large-scale radars above the megawatt level in the ship power system, there have been cases where the generating set cannot be connected to the grid due to the impact on generator frequency[9-10].

Radar load is a kind of high-frequency pulsed load, which is divided into two kinds according to the external characteristics of power fluctuation. One is equivalent steady load with little change of average power under different working modes of load. The other is the load that cannot be equivalent to a steady load due to the special working performance. Its fluctuation cycle and duty cycle of load power are uncertain and the average power varied greatly. The two kinds of radar load are shown in Fig. 1. The radar load with different external characteristics has different system solutions. This is because the rotating shaft of the diesel generator has the moment of inertia, which will dampen the fluctuation of the electromagnetic power. Therefore, in engineering applications, mechanical energy storage inherent in diesel generator is often used to stabilize the power fluctuation of the first kind of load. We study the first type of load in this research. The second type of load needs to be solved by capacitive energy storage, which will be studied in the future.



(b) Load of type 2

Fig.1 Power characteristics comparison of different radar loads

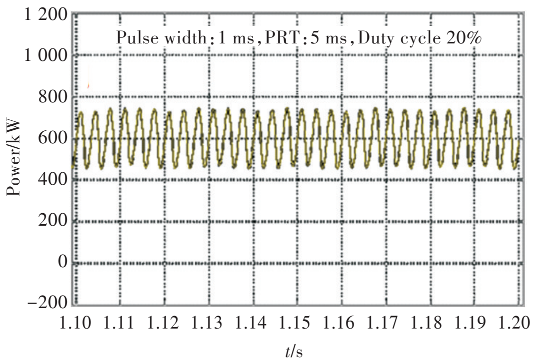
Table 1 shows the typical operating mode of the radar. When the radar T/R component works at a large pulse width and a small duty cycle, it will cause high-frequency power fluctuations in the power supply input to the radar system, which seriously affects the normal operation of the generating set. So radars will avoid running in such mode. It should be noted that in order to reduce the impact of the load on the system, the filtering unit and the storage capacitor are already included in the power supply device. Fig. 2 shows the power fluctuation of a module in the radar in a typical operating mode. In the figure, the PRT is the pulse repetition period.

Table 1 Typical operation modes of a radar unit

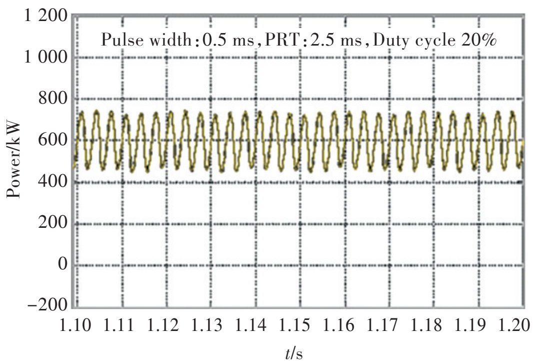
Mode	Pulse width/ms	Pulse repetition period/ms	Duty cycle/%	Blind zone/km	Maximum distance range/km
1	1	5	20	150	600
2	0.5	2.5	20	75	300
3	0.25	1.25	20	37.5	150
4	0.1	0.5	20	15	60

The radar system includes both stable power loads such as high-frequency cabin and water cooling and front loading of radar which leads to power fluctuation (hereinafter referred to as "front loading"). It can be seen from Fig. 2 that the external characteristic of the power fluctuation of the radar is that the power in one cycle fluctuates around the stable value, so it can be regarded as a steady load.

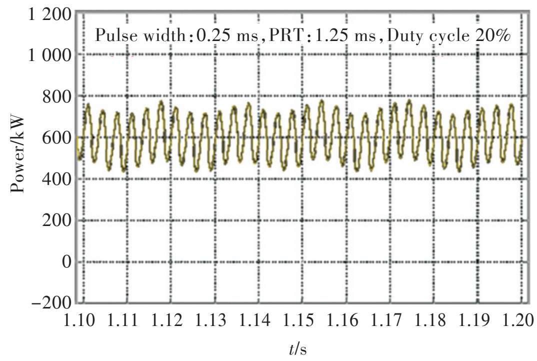
Reference [11] described the working characteristics of diesel generating set under pulsed load as follows: the load fluctuates periodically between



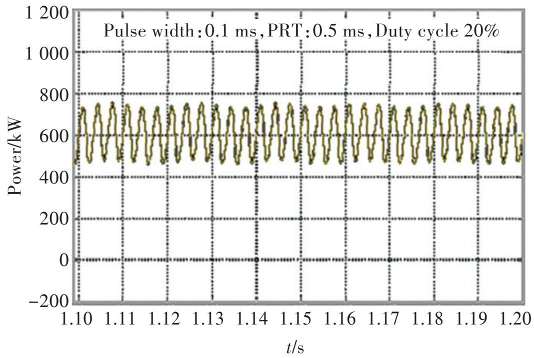
(a) Mode 1



(b) Mode 2



(c) Mode 3



(d) Mode 4

Fig.2 Power fluctuations of radar in four operation modes

no-load and on-load, the set runs in the dynamic process most of the time, and the load amplitude sometimes exceeds the rated load of the set. In fact, the load range of the set under pulsed load fluctuates not only between no-load and on-load, but also between low-load and high-load conditions. Low load may be no-load, relatively low load, or even the set load reverse towing. High load may be high load within the rated load of the set, or it may be much higher than the rated load, e.g., short-term continuous high load.

In this study, in order to explore whether the speed regulation of radar generating set and voltage adjustment of the generator can solve the load power change, two kinds of working conditions are considered.

1) The severe operation condition in which the load suddenly increases and fluctuates (operation condition 1).

Under the 1.2 MW stable load, the 4.25 MW load is suddenly added, and there is a load fluctuation of ±0.2 MW, with a fluctuation period of 15 ms. The total power consumption of load is 5.45 MW, and the fluctuation range is 5.25–5.65 MW, as shown in Fig. 3.

2) The operation condition with the worst fluctuation (operation condition 2).

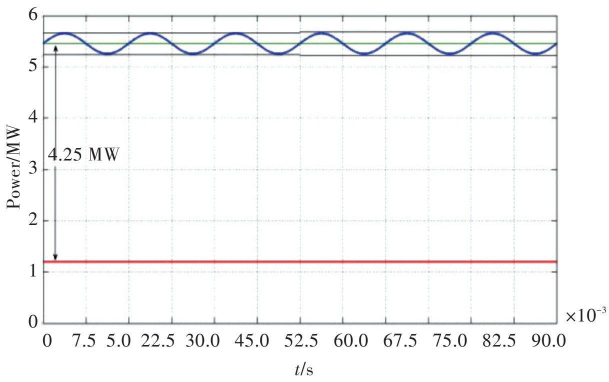


Fig.3 Front loading of radar in operation mode 1

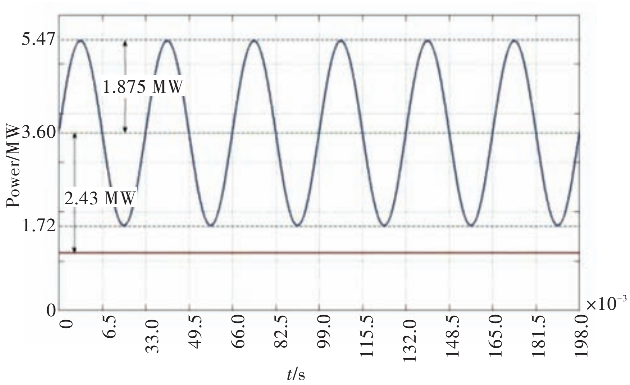


Fig.4 Fiont loading of radar in operation mode 2

Under the 1.17 MW stable load, the load of 2.43 MW is suddenly added, and the load fluctuation of ±1.875 MW is present, with a fluctuation period of 33 ms. The total power consumption of load is 3.6 MW, and the fluctuation range is 1.72–5.47 MW, as shown in Fig. 4.

1.2 System composition

The power station is equipped with six 5.8 MVA (1 000 kW) generating sets, and the radar power supply is connected to the 6.6 kV AC grid. Under the radar operation condition, a total of three generating sets supply power for the radar (i.e., diesel generator under pulsed load), with one set for daily service load and one set for propulsion load, as shown in Fig. 5. The maximum energy consumption of the radar front is 5 MW, which is powered by five power modules. The front is powered by DC. The voltage rating is 520 V, and the fluctuation range of DC voltage is from +6% to −10%.

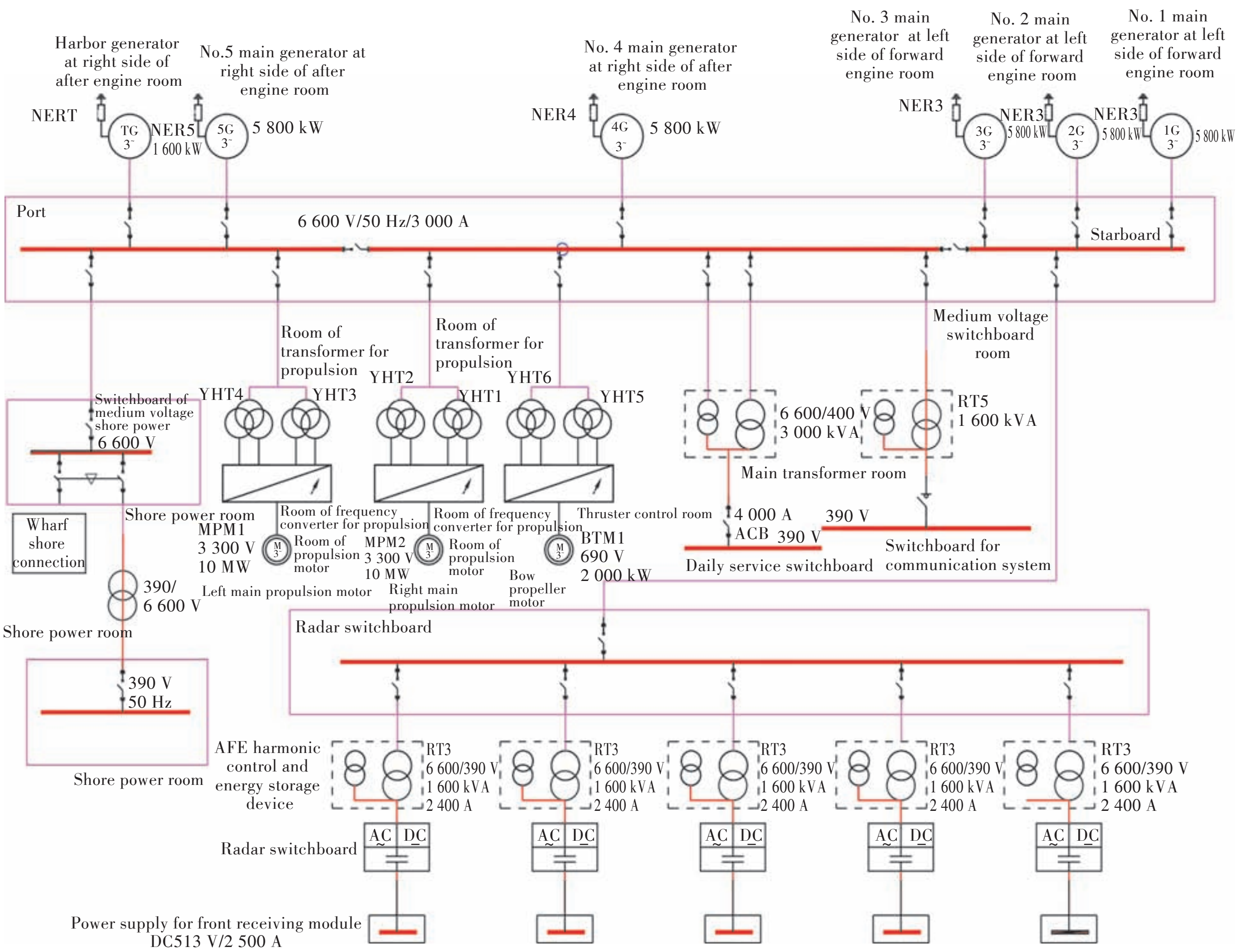


Fig.5 Schematic diagram of power system for a survey ship

2 Theoretical analysis of dynamic characteristics of diesel generating set

Taking the rotation shaft as the analysis object, the angular velocity fluctuation of rotation shaft under different loads is deduced theoretically.

2.1 Relationship between the torque equation and the angular velocity of the rotation shaft

According to the torque equation, the sum of the torques T on the rotation shaft and the moment of inertia J constitute the change of the angular velocity ω, as shown in Eq. (1) [12].

$$\sum T = J\frac{\mathrm{d}\omega}{\mathrm{d}t} \tag{1}$$

The power P in the rotational motion is defined as the product of the torque and the angular velocity, as shown in Eq. (2).

$$P = T\omega \tag{2}$$

The simultaneous Eq. (1) and Eq. (2) can obtain the relationship between the sum of power on the rotation shaft and the angular velocity change, as shown in the Eq. (3):

$$\sum P = \sum T\omega = J\omega\frac{\mathrm{d}\omega}{\mathrm{d}t} = \frac{1}{2}J\frac{\mathrm{d}\omega^2}{\mathrm{d}t} \tag{3}$$

where the sum of the powers on the rotation shaft is the mechanical power P_{T} provided by the prime mover and the electromagnetic power P_{E} converted by the generator, as shown in the Eq. (4).

$$P_{\mathrm{T}} - P_{\mathrm{E}} = \frac{1}{2}J\frac{\mathrm{d}\omega^2}{\mathrm{d}t} \tag{4}$$

In the steady state, the mechanical power is offset against the electromagnetic power, so that the speed remains stable, as shown in Eq. (5).

$$P_{\mathrm{T0}} - P_{\mathrm{E0}} = 0 \tag{5}$$

In the transient state, the two constitute a change in angular velocity, as shown in Eq. (6).

$$(P_{\mathrm{T0}} + \Delta P_{\mathrm{T}}) - (P_{\mathrm{E}} + \Delta P_{\mathrm{E}}) = \frac{1}{2}J\frac{\mathrm{d}\omega^2}{\mathrm{d}t} \tag{6}$$

According to the simultaneous Eq. (5) and Eq. (6), since the steady state changes, the mechanical power increment ΔP_{T} and the electromagnetic power increment ΔP_{E} together constitute an angular velocity change, as shown in Eq. (7).

$$\Delta P_{\mathrm{T}} - \Delta P_{\mathrm{E}} = \frac{1}{2}J\frac{\mathrm{d}\omega^2}{\mathrm{d}t} \tag{7}$$

In view of the fact that the change of electromagnetic power is considered to be instantaneous and the mechanical power change of the prime mover has response time (t), ΔP_{T} = 0 when the speed regulator fails to respond and the fuel amount is temporarily unchanged. The variation of electromagnetic power required by front loading is shown in Fig. 6. In the figure, A is the fluctuating power, B is the power of sudden increase, and T_{p} is the fluctuating period.

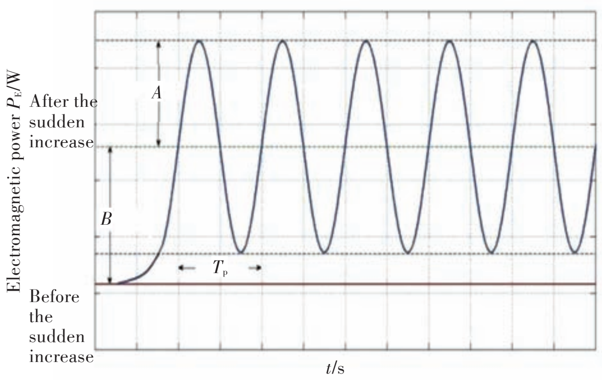


Fig.6 Sudden increase of front loading in radar

According to Fig. 6, the electromagnetic power consumed by the front loading can be expressed by Eq. (8), where ω_{p} is the fluctuating frequency.

$$\Delta P_{\mathrm{E}} = B - A\cos(\omega_{\mathrm{p}}t) = B - A\cos(\frac{2\pi}{T_{\mathrm{p}}}t) \tag{8}$$

The mechanical power increment (ΔP_{T} = 0) and the electromagnetic power increment are substituted into the torque equation Eq. (7), and the angular velocity fluctuation expression before the speed control mechanism of prime mover changes the fuel amount is as follows:

$$\frac{1}{2}J\frac{\mathrm{d}\omega^2}{\mathrm{d}t} = \Delta P_{\mathrm{T}} - \Delta P_{\mathrm{E}} = A\cos(\frac{2\pi}{T_{\mathrm{p}}}t) - B \tag{9}$$

After sorting, the differential equation for angular velocity is obtained as follows:

$$\frac{\mathrm{d}\omega^2}{\mathrm{d}t} = \frac{2A}{J}\cos(\frac{2\pi}{T_{\mathrm{p}}}t) - \frac{2B}{J} \tag{10}$$

After the integral of Eq. (10) is calculated for one time, there is the result as below.

$$\omega^2 = \int\left[\frac{2A}{J}\cos(\frac{2\pi}{T_{\mathrm{p}}}t) - \frac{2B}{J}\right]\cdot \mathrm{d}t + C = \frac{AT_{\mathrm{p}}}{\pi J}\sin(\frac{2\pi}{T_{\mathrm{p}}}t) - \frac{2B}{J}t + C \tag{11}$$

After the angular velocity ω_0 at the initial steady state is substituted into Eq. (11), the integral constant C can be obtained, where $C = \omega_0^2$. The analytical expression of the angular velocity before the change of fuel volume by the speed control mechanism of prime mover is shown in Eq. (12), which can be used for the quantitative calculation of the angular velocity change before the pilot valve adjustment.

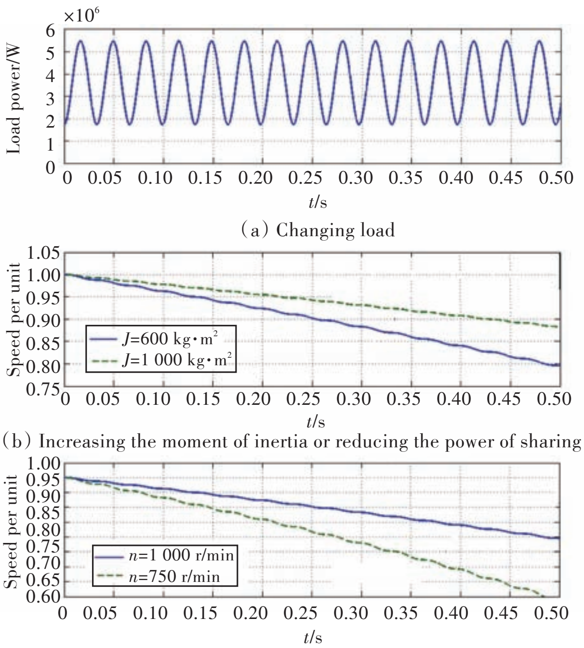
$$\omega(t) = \sqrt{\omega_0^2 + \frac{AT_{\mathrm{p}}}{\pi J}\sin(\frac{2\pi}{T_{\mathrm{p}}}t) - \frac{2B}{J}t} \tag{12}$$

2.2 Speed change of the set during the three processes

2.2.1 Speed drop before the intervention of speed control mechanism

In the initial state, the speed control mechanism has not been involved in the work, so the kinetic energy of the rotation shaft consumed at this time is converted into electromagnetic power, and the rotation shaft is in a pure deceleration state. Calculation is continued according to Eq. (12). The duration of this equation depends on the response speed of the pilot valve and the control time of the speed regulator. After the delay, the speed control mechanism starts to work, and the pilot valve is switched for fuel supply and the next stage is entered.

The parameters of the set in Eq. (12) have typical values, and the parameters related to the front loading are known, so preliminary theoretical calculations can be performed. By adjusting the moment of inertia and rated speed n of the set, the speed drop characteristics before the intervention of speed control mechanism can be changed, as shown in Fig. 7. As can be seen from the figure, the large moment of inertia of a single set, or the great number of parallel sets, or the increase of the rated speed of the set can slow down the speed drop and improve the transient characteristics.



(a) Changing load

(b) Increasing the moment of inertia or reducing the power of sharing

(c) Reducing speed

Fig.7 Speed drop without the speed control mechanism

It can also be seen from Fig. 7 that the increased fluctuating component does not have a significant impact on the sudden load, and it only brings about some ripples to the original waveform of sudden increase. Moreover, the overall trend has not changed, and it will not affect the role of the speed regulator, so the characteristic of sudden increase of front loading can be approximated as sudden increase.

2.2.2 Transition process after the intervention of the speed control mechanism

In the transient state, the speed control mechanism intervenes, the oil supply via the pilot valve changes, and the $G(t)$ term is added to indicate the cumulative amount of mechanical energy generated by the governor actuator from the change of the pilot valve. Eq. (12) can be modified to the universal expression Eq. (13) in the whole speed regulation process. However, since the $G(t)$ term cannot be expressed analytically, Eq. (13) can only be used for qualitative analysis.

$$\omega(t)=\sqrt{\omega_0^2+\frac{AT_{\mathrm{p}}}{\pi J}\sin\left(\frac{2\pi}{T_{\mathrm{p}}}t\right)-\frac{2B}{J}t+\frac{2}{J}G(t)} \quad (13)$$

In the equation, the first term in the radical expression is the initial angular velocity; the second term is the amount of mechanical energy change caused by the power fluctuation generated by the array; the third term is the mechanical energy gap generated by the sudden power of array; the fourth term $G(t)$ is the mechanical energy supplemented by the speed control mechanism through increasing the fuel supply. When $G(t) = 0$ before the speed control mechanism responds, Eq. (13) is simplified to Eq. (12).

It should be noted that after the radical expression in the Eq. (13) is opened and the left and right sides of the equation are multiplied by $J/2$, the equation is physically equivalent to the law of conservation of energy.

After fuel is increased, when $G(t) > 0$, the rated speed drop of the set begins to ease, while when $G(t) > B \cdot t$, the newly added mechanical energy exceeds the suddenly increased electromagnetic power, and the speed starts to rise. During this process, the amount of change in speed affects the speed detection, but the overall trend does not change.

2.2.3 Speed fluctuation after steady state

In the steady state, the pilot valve is constant, and the power generated by the newly added fuel is offset by the steady-state increment. The third term and the fourth term in Eq. (12) disappear, and the second term of power fluctuation causes the angular velocity to change periodically. Eq. (12) is transformed as follows:

$$\omega(t)=\sqrt{\omega_0^2+\frac{AT_{\rm p}}{\pi J}\sin(\frac{2\pi}{T_{\rm p}}t)} \tag{14}$$

At this time, the maximum angular velocity $\omega_{\max}$ is as below:

$$\omega_{\max}=\sqrt{\omega_0^2+\frac{AT_{\rm p}}{\pi J}} \tag{15}$$

while the minimum angular velocity $\omega_{\min}$ is as shown in Eq. (16).

$$\omega_{\min}=\sqrt{\omega_0^2-\frac{AT_{\rm p}}{\pi J}} \tag{16}$$

After the Eq. (14) is slightly simplified and the angular velocity is expanded in the first order at $t=0$ by Taylor series, Eq. (17) can be obtained:

$$\omega(t)=\sqrt{\omega_0^2+\frac{AT_{\rm p}}{\pi J}\sin(\frac{2\pi}{T_{\rm p}}t)}=$$

$$\omega_0\cdot\sqrt{1+\frac{AT_{\rm p}}{\pi J\omega_0^2}\sin(\frac{2\pi}{T_{\rm p}}t)}\approx$$

$$\omega_0\cdot\left[1+\frac{1}{2}\cdot\frac{AT_{\rm p}}{\pi J\omega_0^2}\sin(\frac{2\pi}{T_{\rm p}}t)\right] \tag{17}$$

From the above equation, the upper bound of the angular velocity change rate δ can be obtained as follows:

$$\delta=\left|\frac{\omega(t)-\omega_0}{\omega_0}\right|=$$

$$\left|\frac{AT_{\rm p}}{2\pi J\omega_0^2}\sin(\frac{2\pi}{T_{\rm p}}t)\right|\leqslant\frac{AT_{\rm p}}{2\pi J\omega_0^2}=\frac{450}{\pi^3}\cdot\frac{AT_{\rm p}}{Jn^2} \tag{18}$$

$$\delta_{\max}\propto\frac{AT_{\rm p}}{Jn^2} \tag{19}$$

From Eq. (19), it can be seen that the upper bound $\delta_{\max}$ of the angular velocity change rate δ is proportional to the fluctuating power A and the fluctuation period $T_{\rm p}$, and is inversely proportional to the moment of inertia J and the square of the rated speed n of the set. In other words, when the J is larger, the angular velocity change rate δ is smaller; when A is larger, δ is greater; when the $T_{\rm p}$ is smaller, δ is smaller; the larger rated speed n of the set corresponds to the smaller δ. However, the J of the general high-speed machine is small, so the two are contradictory. The Jn^2 of the specific model should be comprehensively calculated to compare the performance.

3 Operation condition analysis and simulation

Based on the theoretical analysis of the dynamic characteristics of the diesel generating set, the specific calculations of the two operation conditions mentioned in Section 1.1 are carried out. The Matlab software is used as the simulation platform, and the generator adopts the third-order synchronous generator model that comes with Simulink software. The classical Woodward speed regulating model and IEEE AC type1 excitation controller model are used to carry out the simulation research on ship power station. The input of pulsed load uses three-phase full-bridge uncontrolled rectifier to convert the alternating current into direct current, and with the controlled current source as the core component, the output current is controlled by the output power and voltage of the pulsed load. In addition, using the land-based joint measurement data of the same type of set, the parameters of the excitation voltage regulator and the speed regulator are identified, so that the external characteristics of three-stage loading on the simulation model are consistent with the experimental ones.

3.1 Operation condition 1—operation condition with the worst sudden increase

The set type of operation condition 1 is 10L32/44CR, and other input parameters are shown in Table 2.

Table 2 Parameters of working condition 1

Set parameters	Value	Parameter of front loading	Value
Set power P/ MW	5.8	Power of sudden increase B/MW	4.25
Rated speed of the set n/(r·min^{-1})	750	Fluctuating power A/MW	0.2
Moment of inertia J/(kg·m^2)	> 600	Fluctuating period $T_{\rm p}$ /ms	15.5

From the analysis in Section 2, it can be seen that the front loading of radar can be approximated as a sudden load, and the fluctuation has no obvious influence on this. The input provided by the manufacturer of prime mover is shown in Fig. 8. According to Fig. 8, the speed drop of the sudden load can be calculated, as shown in Table 3. The system configurations of schemes 1, 2 and 3 respectively refer to one 5.8 MW generator, two 5.8 MW generators and three 5.8 MW generators.

According to the analysis in Section 2, the rate of change of the single generator speed in steady state is solved. According to Eq. (14) and Eq. (18), the change rate of the speed of the single generator can be calculated. The rated speed of the 10L32/44CR set is n = 750 r/min, which is 78.5 rad/s in total.

$$\omega_{\max}=\sqrt{\omega_0^2+\frac{AT_{\rm p}}{\pi J}}=78.55\ {\rm rad/s}\text{ ,totaling 750.1 r/min}$$

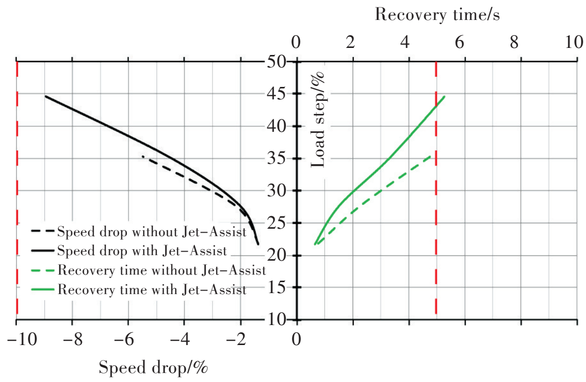


Fig.8 Speed regulation characteristics of 10L32/44CR diesel engine

Table 3 Speed changes of different unit configurations at sudden load of 4.25 MW

Scheme	Total system power/MW	Share rate of sudden increase/%	Speed drop percentage/%	Recovery time/s
Scheme 1	5.8	73.3	Out of range	Out of range
Scheme 2	11.6	36.6	4.5 ~ 5.5	3.5 ~ 5.0
Scheme 3	17.4	25.3	1.7	1.0~1.5

$$\omega_{\min} = \sqrt{\omega_0^2 - \frac{AT_p}{\pi J}} = 78.53 \text{ rad/s ,totaling } 749.9 \text{ r/min}$$

$$\delta_{\max} = \frac{450}{\pi^3} \cdot \frac{AT_p}{Jn^2} =$$

$$\frac{450}{\pi^3} \times \frac{0.2 \times 10^6 \times 15.5 \times 10^{-3}}{600 \times 750^2} = 0.013\%$$

For the case of multiple generators, the fluctuating power A of the two generators is reduced by half, and the fluctuating power A of the three generators is reduced to 1/3. According to the theoretical calculation results, the operation condition 1 with the front loading of radar and more than two diesel engines can satisfy the speed characteristics at the time of sudden increase, and the rate of change is negligible.

The simulation check of operation condition 1 is carried out, and the result is shown in Fig. 9. At this time, the speed of each generator drops by about 5%, which is close to the calculated analytical value, and the instantaneous voltage fluctuation rate is about 5%.

3.2 Operation condition 2—the operation condition with the worst fluctuation

The other input parameters in operation condition 2 are shown in Table 4. According to Fig. 8, the speed drop at the time of sudden load can be calculated, as shown in Table 5.

According to the analysis in Section 2, the change rate of the speed for single generator in steady state is solved. According to Eq. (14) and Eq. (18), the speed change rate of single power system can be calculated. The rated speed of the 10L32/44CR set is n = 750 r/min, which is 78.5 rad/s in total.

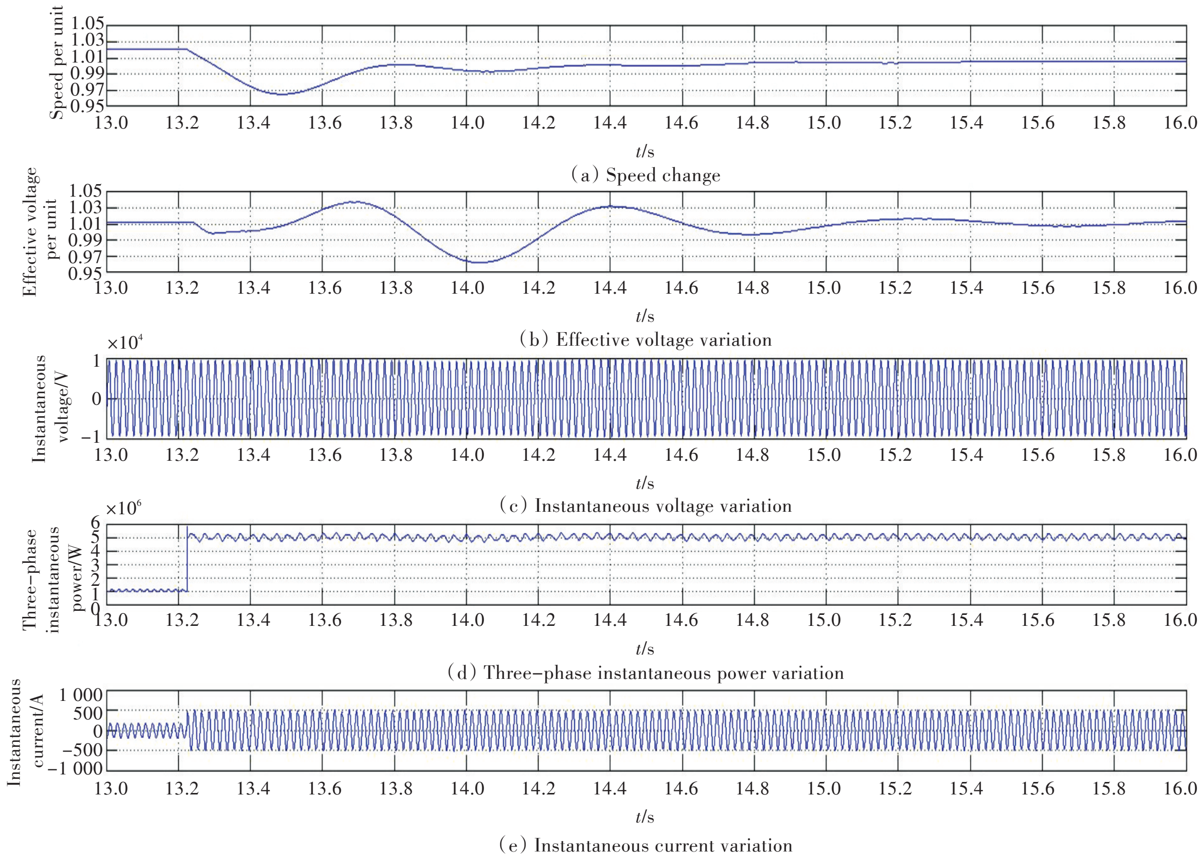


Fig.9 Fluctuations of two power systems in working condition 1 of two generators

Table 4 Parameters of working condition 2

Set parameters	Value	Parameter of front loading	Value
Set power P/ MW	5.8	Power of sudden increase B/MW	2.43
Rated speed of the set n/(r·min^{-1})	750	Fluctuating power A/MW	1.875
Moment of inertia J/(kg·m^2)	> 600	Fluctuating period T_p /ms	33

Table 5 Speed changes of different unit configurations at sudden load of 2.43 MW

Scheme	Total system power/MW	Share rate of sudden increase/%	Speed drop percentage/%	Recovery time/s
Scheme 1	5.8	41.9	6.7	4.5
Scheme 2	11.6	20.9	1.3	0.5
Scheme 3	17.4	14.4	1.0	< 0.5

$$\omega_{\max} = \sqrt{\omega_0^2 + \frac{AT_p}{\pi J}} = 78.75 \text{ rad/s}, \text{ totaling } 752 \text{ r/min}$$

$$\omega_{\min} = \sqrt{\omega_0^2 - \frac{AT_p}{\pi J}} = 78.33 \text{ rad/s}, \text{ totaling } 748 \text{ r/min}$$

$$\delta_{\max} = \frac{450}{\pi^3} \cdot \frac{AT_p}{Jn^2} = 0.26\%$$

For the case of multiple generators, the fluctuating power A of the two generators is reduced by half, and the fluctuating power A of three generators is reduced to 1/3. Due to the large fluctuating power of the operation condition, the simulation check based on Simulink and theoretical calculation is carried out, as shown in Fig. 10. The angular velocity change rate of the simulation results is 0.29%, which is basically similar to the theoretical calculation value.

The envelope of the instantaneous current amplitude fluctuation shown in Fig. 10(e) is the fluctuating power shown in Fig. 10(d). In this case, the system current will generate a large fractional harmonic, and the flow path of harmonic source fluctuating load is from the fluctuating load to the power supply unit, so it is necessary to pay attention to the impact of fractional harmonic on other equipment (especially the relay protection device).

In short, at this time, the operation condition 2 of one diesel engine with front loading of radar can satisfy the speed characteristic at the time of sudden load, and the theoretical value and simulation value of the speed change rate are also within the allowable range. It can also be seen from the simulation results that the system voltage characteristics also

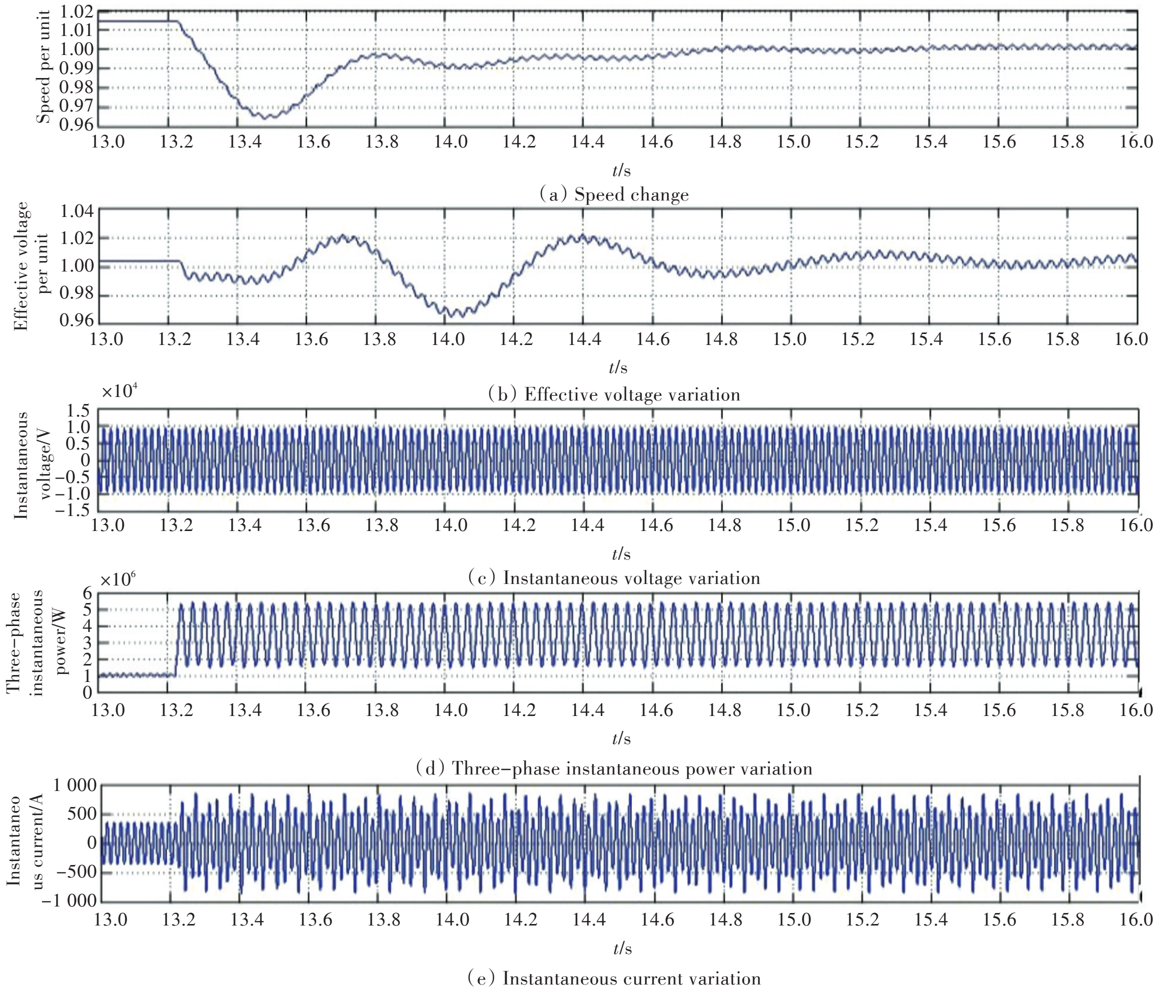


Fig.10 Fluctuations of single power system in working condition 2 of two generators

meet requirements.

4 Conclusions

In this paper, the pulsed load radar is divided into two categories according to the power characteristics. The solutions to different types of load are different. The first type of load is mainly studied, namely the load that had the average power not changing much in different operation modes and can be equivalent to a stable load. And it is proposed to use the mechanical energy storage inherent in the diesel generating set to stabilize the power fluctuation. Taking the survey ship as an example, the dynamic characteristics of the rotation shaft of diesel generating set for powering the high-power radar are analyzed. The speed drop and recovery law before and after the speed control mechanism intervention and the speed change rate during steady state are deduced theoretically. The simulation calculations of two typical operation conditions are carried out and the results are compared with the theoretical results. The following conclusions are obtained:

1) Under the operation condition with the worst sudden increase, for more than two diesel engines with front loading of radar, the power and speed characteristics at a sudden load under the operation condition can be met, and the rate of change is negligible.

2) Under the operation condition with the worst fluctuation, for one diesel engine with front loading of radar, the speed characteristics at a sudden load can be met, and the speed change rate is within the allowable range. At the same time, the voltage characteristics of the system also meet the requirements.

On the basis of theoretical analysis, the capacity and performance indexes of the configured diesel generating set are calculated according to the load characteristics of the survey ship radar in actual operation condition, and the correctness of the theoretical derivation is verified through simulation. The research results can provide quantitative criteria for suppressing the power fluctuation of this type of pulsed load with the inherent mechanical energy storage of the diesel generating set, and form a systematic theoretical engineering summary.

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脉冲性负荷柴油发电机组特性分析

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摘　要:[**目的**]舰船系统的电能质量会受到脉冲性负荷的极大影响。脉冲性负荷种类、功率不同,其运行特性、影响及其解决方法也会有很大差异。为此,针对平均功率变化不大、可等效为恒稳负荷的雷达,[**方法**]提出采用柴油发电机组固有的机械储能来平抑其功率波动,通过对柴油发电机组工作特性进行研究和分析,找到调速器介入前、后的转速跌落、恢复规律和稳态过程转速的变化率,以得出利用柴油发电机组固有的机械储能来平抑负荷功率波动的量化标准。基于测量船雷达的实际工况,按照得到的量化标准计算出所配置柴油发电机组的容量及其性能指标,并通过2个典型工况仿真来验证理论推导的正确性。[**结果**]研究结果说明:在突加最严重工况下,对于2台柴油机以上带雷达阵面的负荷, 在该工况下可满足突加功率时的转速特性,变化率可忽略不计;在波动最严重工况下,1台柴油机带雷达阵面的负荷, 在该工况下可满足突加功率时的转速特性,转速变化率在允许范围内,且系统电压特性满足指标要求。[**结论**]研究结果对于该类脉冲性负荷柴油发电机组在设计时的初步估算具有一定的指导意义。

关键词:脉冲性负荷;柴油发电机组;电能质量;综合电力系统

[*Continued from page* 30]

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浮体浅水波浪载荷数值计算方法研究

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摘　要:[**目的**]在浅水环境下,对波浪中浮体的响应进行求解时,其主要难点在于对有限水深格林函数及其偏导数的准确求解和快速计算。[**方法**]为此,利用改进的Gauss-Laguerre积分法,提出一种可精确计算有限水深格林函数及其偏导数的方法,结合循环矩阵原理,给出对称性的处理方法和简化的级数求解公式。并将所提方法与其他商业软件计算结果进行对比分析。[**结果**]结果表明,所提计算方法精确度较高。[**结论**]该方法可用于准确评估浅水中的浮体运动和波浪载荷。

关键词:浮体;浅水;格林函数;波浪载荷;对称