Seamless Shore Power Connection Circulating Current and f/P Control

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Keywords: voltage difference envelope; circulating current; f/P control; shore power connection; seamless connection

Abstract: When connecting the shore power, the different voltage, frequencies, and phases of ship power and shore power form a voltage difference envelop, and the control closing at the lowest point of the envelop is detected to realize the seamless connection of the ship power and shore power. The grid-connected circulating current of the ship power generator and shore power transformer has self synchronization effect on the generator, however, the excessive circulating current will cause protection action. The shorter the duration of envelope detection waveform over 0, the larger the circulating current. The simulation model of frequency and phase change envelope is established to analyze the envelop lowest point f/P control performance. The frequency difference and power change ratio control of closing at the lowest point of envelope is established to realize the ideal synchronous control of closing and transferring load. The above conclusions are confirmed by simulation and model tests. This paper solves the key problems of seamless shore power connection and load transfer.

1. Introduction

Shore power can realize the ship energy saving and port environmental protection. The grid-connected circulating current of the ship power generator and shore power transformer has self synchronization effect on the generator, however, the excessive circulating current will cause protection action. The signals of envelope voltage detecting ship power and shore power at different frequencies, different voltage effective values and different voltage phases are processed scientifically to form corresponding pulsating signals. Based on the shore power capacity, ship generator capacity, and ship power load, the pre closing operation voltage value of envelope relative low voltage is set up[1~7]. The shorter the duration of envelope detection waveform over 0, the larger the circulating current between ship power and shore power. The simulation.

model of frequency and phase change envelope is established to analyze the envelop lowest point *f/P* control performance. The frequency difference and power change ratio control of closing at the lowest point of envelope is established to realize the ideal synchronous control of closing and transferring load. The program control signal of the industrial personal computer(IPC) comes from the envelope closing signal of the single chip microcomputer. When shore power is needed to exit, the power off control signal will be sent after transferring the load to the ship power from the shore power. IPC can also display the information of shore voltage, current, power, power factor and frequency information before and after seamless shore power connection, as well as the information of electricity consumption and electric charge.

2. Grid-Connected Circulating Current of Shore Power and Ship Power

2.1. Active Self Synchronization of Circulating Current

The ship power generator and the shore power transformer are grid-connected. The circulating current of the ship power generator and shore power transformer has self synchronization effect on

  DOI: 10.25236/scmc.2019.102

the generator. When the voltage phase of the generator exceeds the voltage phase of the former transformer (or the frequency of the former is higher than the latter), the circulating current causes the generator to be in the state of generating electricity, the shaft is slowed down by braking force, and the output active power of the generator is positive. When the phase lags behind(or the frequency of the former is lower than the latter), the generator is in an motoring condition, the shaft is accelerated by the driving force, and the output active power of the generator is 0 or negative. In Fig.1, E_a is the transformer potential, E_b is the generator potential, the self synchronization of the circulating current accelerates the generator,the frequency and phase of transformer and generator are equal, the uniform voltage of the circulating current increases U_b, and the voltage of transformer and generator is equal, which meets the condition of parallel connection[1].

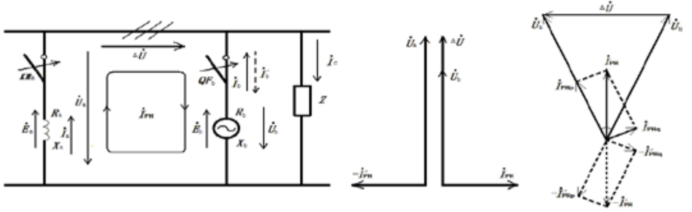


Fig.1. Circulating Current and Self Synchronization

2.2. Maximum Circulating Current Model of Shore Power(Fig.2)

The load is transferred within 0.1s of grid connection, and the output power of the generator is 0, equivalent to the disconnection of QF$_b$. Assuming that the load z of the ship power grid is short-circuited and the maximum circulating current flows between the shore power grid and the ship power grid. The short circuit circulating current model can be established by the transfer function(Fig.2).

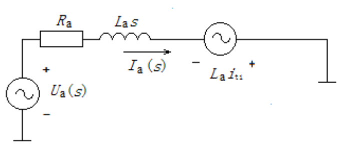


Fig.2. Maximum circulating current model circuit

$$U_a(s) = \frac{sU_a}{s^2+\omega^2} \tag{1}$$

$$I_a(s) = \frac{U_a(s)+L_a i_{t1}}{L_a s+R_a} = \frac{i_{t1}s^2+\frac{U_a s}{L_a}+\omega^2 i_{t1}}{(s^2+\omega^2)(s+\frac{R_a}{L_a})} = \frac{D_1}{s+\frac{R_{aa}}{L_a}}+\frac{D_2}{s+j\omega}+\frac{D_3}{s-j\omega} \tag{2}$$

In the above formula:

$$D_1 = \frac{i_{t1}(\frac{R_a^2}{\omega L_a}+\omega L_a)-U_a(\frac{R_a}{\omega L_a})}{(\frac{R_a^2}{\omega L_a}+\omega L_a)},\quad D_2 = \frac{U_a(\frac{R_a}{\omega L_a}+j)}{2(\frac{R_a^2+\omega L_a}{\omega L_a})},\quad D_3 = \frac{U_a(\frac{R_a}{\omega L_a}-j)}{2(\frac{R_a^2}{\omega L_a}+\omega L_a)} \tag{3}$$

The expression of short circuit circulating current can be obtained by Laplace inverse transformation:

$$i_a = D_1\exp(\frac{-R_a}{L_a}t)+2|D_2|\cos(\omega t+a\tan\frac{\omega L_a}{R_a}) \tag{4}$$

2.3. Maximum Circulating Current Simulation

The formula (4) is simulated in the short circuit maximum circulating current, and the simulation parameters are taken as follows:U_1=220V, U_2=220V, φ=30°, L_1=2.23mH, R_1=0.02Ω, L_2=1.78mH,

R_2=0.01Ω, L=3.0mH, C=50pF, R=0.012Ω, t_0=0s, t_1=0.1s.

From the simulation waveform, it is known that the peak value of current in steady period is about 9A, and the peak value of short circuit current can reach 35A[Fig.16 (a)]. Because of the external characteristic of transformer $\Delta U \approx 5\% U_N$, the internal impedance of the transformer is about 1/20 of the rated load impedance, and the peak value of the rated load current is 35/9×1/20≈1/5 short circuit peak value(7A), which is less than the peak value of the current 9A in steady-state period.

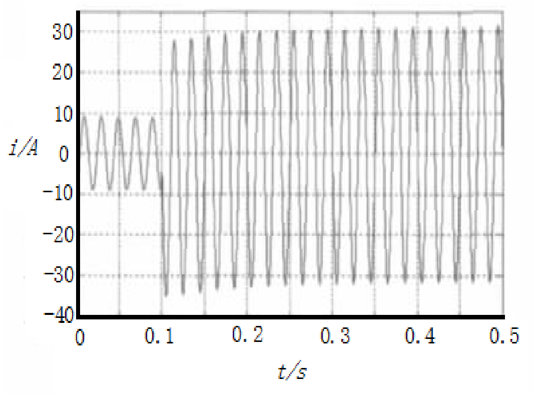


Fig.3. Simulation waveform of maximum circulating current model

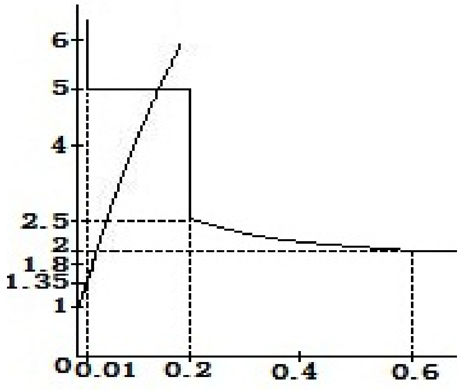


Fig.4. Circulating current and circuit breaker operating current and time

2.4. Circulating Current and Protection

Transformer impedance voltage ratio takes 4%,$I_N z$=4%U, the maximum short circuit current $I_d=U/z=25I_N$, transient maximum short circuit current $i_d=1.5\times25I_N$, transformer efficiency is 95%~98%, taking 98%, and the transformer iron loss is about equal to copper loss:

$$2\% I_N^2 2\pi fL = 2I_N^2 R \tag{5}$$

L/R=0.23, suppose the impedance of the transformer is equal to that of the generator, circulating current $I_P=25I_N/2=12.5I_N$, the transient circulating current is:

$$\begin{aligned} i &= 1.5I_N + 1.5\times(12.5-1)I_N(1-e^{-\frac{t}{\frac{L}{R}}}) \\ &= 1.5I_N + 1.5\times11.5I_N(1-e^{-\frac{t}{0.23}}) \end{aligned} \tag{6}$$

Generator and shore connection box circuit breaker is 200%~250% I_N, trips after 0.2~0.6s delay, greater than 5 times I_N, with 0.01s tripping. When 0.01s is put into the above transient action current, $i_P \approx 202\% I_N$. The envelope effective action current is $I_Q \approx 202\% I_N/1.5 \approx 135\% I_N$, setting $I=1.8I_N$ (Miss trip of impact load). 1200 V is the maximum peak voltage difference of the envelope, and the corresponding voltage difference of the envelope of the short circuit operation of the circuit breaker is about 1 200×1.8/12.5≈172.8V. When the grid is connected, the envelope requires that the closing voltage at the lowest point is within ±(172.8/2)V, and the closing time is within Δt±0.1s. 0.01-0.2s is the reliable range of the shore connection box circuit breaker. Fig. 4 is the MATLAB simulation of the operation current and time of the circuit breaker[2-3].

3. Grid-Connected Control of Shore Power and Ship Power

3.1. Frequency and Active Power Control

The frequency control of synchronous generator is realized by the rotor motion equation and prime mover governing equation. Assuming that the number of pole-pairs is 1, the mechanical angular velocity and electric angular velocity are equal, and the equation of rotor motion can be expressed as:

$$\begin{cases} J\dfrac{d\omega}{dt} = T_{m} - T - \beta\Delta\omega = \dfrac{P_{m}}{\omega_{N}} - \dfrac{P}{\omega_{N}} - \beta(\omega - \omega_{N}) \\ \dfrac{d\theta}{dt} = \omega - \omega_{N} \end{cases} \tag{7}$$

In the formula:ω_N and $\omega=2\pi f$ are rated and actual rotor angular velocities, respectively. T_m and T are mechanical and electromagnetic torque respectively. P_m and P are mechanical and electromagnetic power respectively: β is the damping coefficient, J is the moment of inertia, and θ is the power angle. Prime mover governing formula:

$$P_{m} = P_{a} + K_{a}(\omega_{N} - \omega) \tag{8}$$

In the formula: P_a is the given active power, K_a is the adjusting difference coefficient. Formula (9) can be obtained by combining formula (7) and (8).

$$\begin{aligned} &\frac{\omega_{N} - \omega}{P_{a} - P} = -\frac{1}{J\omega_{N}s + \beta\omega_{N} + K_{a}} = -\frac{k_{p}}{\tau s + 1}, \\ &\tau = \frac{J\omega_{N}}{\beta\omega_{N} + K_{a}}, \quad k_{p} = \frac{1}{\beta\omega_{N} + K_{a}} \end{aligned} \tag{9}$$

In the formula: P is the output active power, and τ and k_P are inertia time constant and droop coefficient of active frequency, respectively

3.2. Voltage and Reactive Power Control

U_{n}□θ_n(n□a,b) is the output voltage of marine synchronous generator and virtual synchronous generator of shore power transformer respectively[4]. θ_n is the phase difference between the two generators and the ship bus, Z_n is the output impedance of two generators respectively, and Z_L is the constant load impedance.

The generator given output voltage U_{a} can be obtained by reactive voltage droop relation. Its expression is:

$$U_{a} = U_{N} + k_{Q}(Q_{a} - Q) \tag{10}$$

In the formula: U_N is the rated voltage, k_Q is the reactive voltage droop coefficient, and Q_{a} and Q are the given and output reactive power respectively.

Classical second-order equation of synchronous generator:

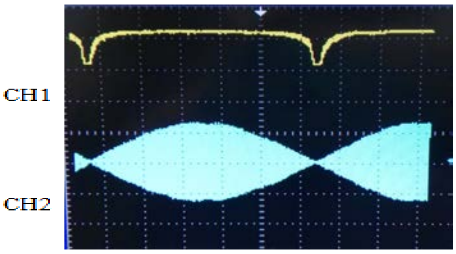
$$\begin{cases} u_{da} = -R_{a}i_{d} - L_{a}\dfrac{di_{d}}{dt} + \omega L_{a}i_{q} + U_{a} \\ u_{qa} = -R_{a}i_{d} - L_{a}\dfrac{di_{q}}{dt} - \omega L_{a}i_{d} + 0 \end{cases} \tag{11}$$

In the formula, R_{a} and L_{a} are synchronous resistance and synchronous reactance respectively. Impedance suppresses the circulating current between marine synchronous generators and shore power transformers, Z□R_{a}□$j\omega L_{a.}$

4. Voltage Envelope Seamless Connection with Shore Power [5]

4.1. The Principle of Envelope Minimum Circulating Current Connecting Ship Power

The voltage difference of the envelope at the lowest point is 0 and the circulating current is the lowest. Fig. 5 is the detection waveform, Fig.6 is the grid-connected success waveform, the detection waveform signal fixed output is 0.3V, and the voltage envelope signal fixed output is 0V, indicating the synchronization and grid-connected success. The voltage envelope detection waveform in Fig.7 is the waveform when generator voltage is seriously unbalanced.



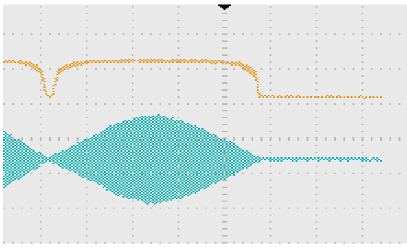
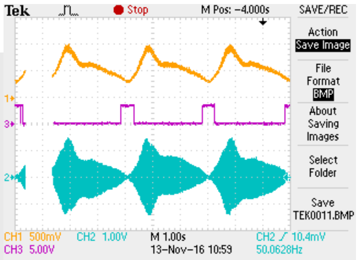



Fig.5. Detection waveform Fig.6. Successful grid connected waveform Fig.7. Ship voltage unbalance waveform

4.2. Simulation of Voltage Envelope Circulating Control

Suppose u_1 and u_2 are ship power voltage and shore power voltage respectively.

$$u = u_1 - u_2 = U_1 \sin(\omega_1 t + \varphi_1) - U_2 \sin(\omega_2 t + \varphi_2) \tag{12}$$

Suppose $U_1 = U_2 = U$

$$u = 2U \cos[\frac{1}{2}(\omega_1 t + \omega_2 t) + \frac{1}{2}(\varphi_1 + \varphi_2)] \times \sin[\frac{1}{2}(\omega_1 t - \omega_2 t) + \frac{1}{2}(\varphi_1 - \varphi_2)] \tag{13}$$

It can be seen that the envelope of voltage difference between ship power and shore power is composed of two parts: high frequency sine and low frequency cosine.

Based on formula (12) and (13), Matlab/Simulink software is used for simulation

4.3. Changing Frequency Envelope Waveform(Fig.8)

U_1=400V,f_1=50Hz,φ_1=0;U_2=400V,φ_2=0; From left to right: f_2=49.9Hz,49.8Hz, 49.7Hz,49.65Hz, 49.6Hz, 49.55Hz.

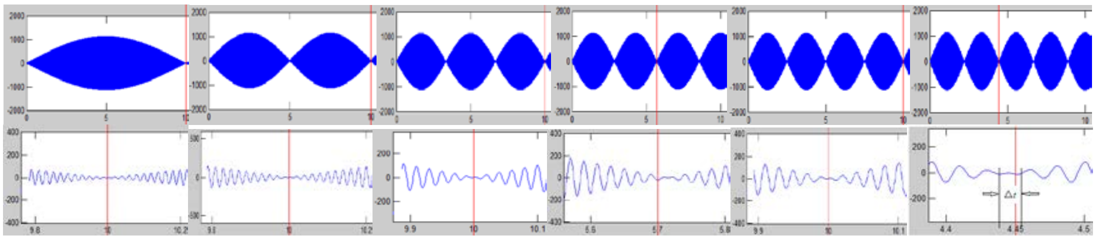


Fig.8. Changing frequency

The results show that the larger the frequency difference, the larger the number of envelopes in 10s. The shorter the duration Δt of the detection waveform over 0, the larger the circulating current.

4.4. Changing Initial Phase Waveform(Fig.9)

U_1=400V,f_1=50Hz,φ_1=0;U_1=400V,f_2=50Hz;From left to right:φ_2=0°,+15°(-15°same),+30°(-30° same),+45°,+60°,+75°.

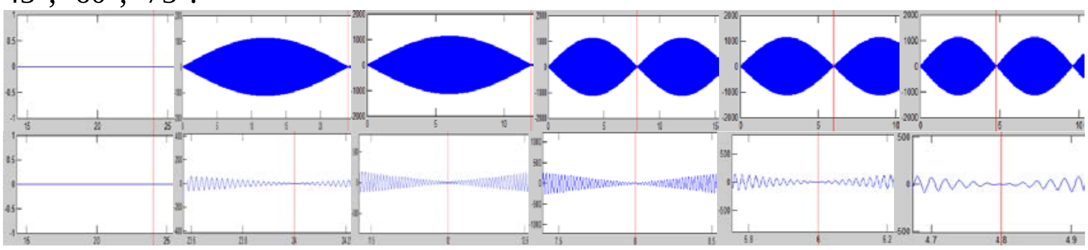


Fig.9. Changing initial phase

When the phase difference increases, the number of envelopes increases in a certain period of time; when the phase difference is constant, the positive and negative phases of the initial phase do not affect the envelope; when the phase difference is zero, it is a horizontal line (the voltage is the same). The smaller the initial phase, the shorter the duration Δ*t* of the detection waveform over 0, the larger the circulating current. The phase difference is the important influence factor of Δ*t*.

4.5. Changing Frequency Waveform when the Power Factor is 0.85(Fig.10)

U_1=400V,f_1=50Hz,φ_1=0; U_2=400V,φ_2=32°; From left to right: f_1=49.49Hz,49.52Hz,49.55Hz, 49.58Hz,49.61Hz,49.64Hz.

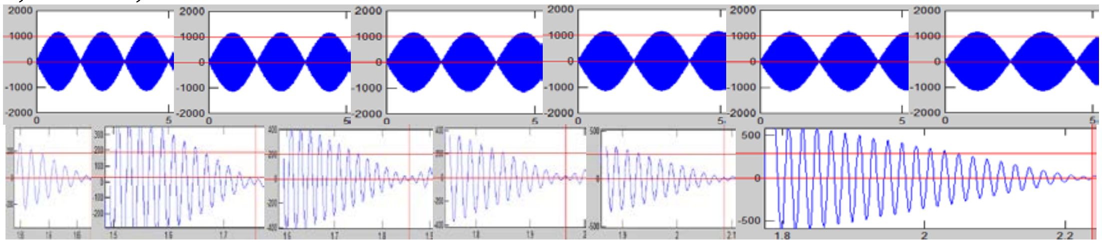
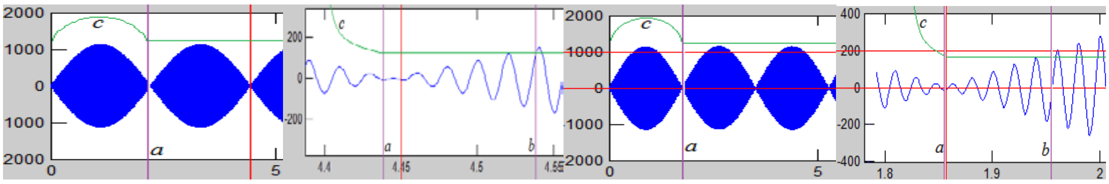


Fig.10. Changing Frequency Waveform when the Power Factor is 0.85

From 49.49 to 49.64Hz, its envelope rises from 0 to the peak value 200V, and the number of wave peaks increases from 4 to 6, indicating that the phase difference affects the speed of charge and discharge of detection, and the speed changes with frequency. The larger the frequency difference, the faster the charge and discharge. The harder the detection, the larger the circulating current. When the power factor is 0.85, the waveform fluctuation of detection over 0 is more serious than that of 0.

4.6. Control Analysis of Voltage Envelope Detection



(a) (b) (c) (d)

Fig.11. Control analysis of voltage envelope detection

Fig. 11 (a) (b) are the voltage envelopes of pure resistive load measurement and control with frequency difference Δ*f*=0.45Hz. Fig (c) and (d) are the load measurement and control voltage envelopes with frequency difference Δ*f*=0.48Hz and power factor *cosφ*=0.85.

In formula (2), the frequency difference between f_1 and f_2 has a significant effect on the envelope cosine period, but the charge and discharge of the detection circuit *RC* only affects the detection period, and has no effect on the detection of the key envelope minimum point, because the detection and envelope are in the same period control. The sinusoidal quantity of the frequency difference between f_1 and f_2 determines the duration Δ*t* over 0. The larger the frequency difference is, the more severe the turbulence is, the shorter the duration over 0, and the larger the circulating current. When the phase difference increases, the sinusoidal quantity increases, the duration over 0 of envelop obviously shortens, and the circulating current increases. When the phase difference is large, the envelope almost fluctuates at 0 point, which affects the detection effect over 0. The above Fig.(b) compares with Fig.(d) in obtaining the closing and parallel connection of the prosecution signals over 0 on line a. The action time of ordinary contactor is 0.1s, the duration is from line a to line b, the line c passes near line b, and frequency difference and phase difference act together. In Fig.(d), the peak voltage is close to 200V, and the circulating current is large, and in Fig(b), the peak voltage is much less than 200V. The phase difference inductive load inductance energy effect in Fig(d) is more serious, and the electronic switch with action time of 0.20ms should be adopted.

5. Load Distribution Experiment of Voltage Envelope Grid Connection

Fig.12. f/P control experiment of grid connection of voltage envelope

f/P control experiment of grid connection of voltage envelope in Fig.12: The capacity of three synchronous generators was 20kVA respectively, the rated frequency of two generators was 50Hz, the rated line voltage was 400V, and the adjustment rate of generator *f/P* droop control[6-7] was 3%. Parallel operation and load transfer between two generators or shore power transformers of the same capacity can be carried by synchronous table of generator control bank and parallel bank[8]. Three phase 15KW+6KVar of load bank was adjustable, shore power supply capacity was 20kVA, and three phase line voltage 380~420V was adjustable. IPC controlled the voltage envelope prosecution circuit board, the IGBT quick switch switched on in 20ms, and the oscilloscope showed the prosecution signal and the voltage envelope.

Table 1 f/P control experimental data

Load bank before grid connection P (W) /cosφ	Generator control panel before grid connection f(Hz)	Shore power supply bank after grid connection P (W) / cosφ	Generator control panel after grid connection P (W) / cosφ
1 077/0.999	49.84	3 700/0.857	Inverse power/0.72
1 079/0.999	49.94	1 000/0.563	0/0.4
3 540/1	49.62	10 300/0.962	Inverse power/0.92
3 540/1	49.80	3 000/0.693	0.2/0.3
7 183/0.99	49.55	14 100/0.986	Inverse power/0.87
7 162/0.99	49.66	7 800/0.951	Inverse power/0.4
7 180/0.99	49.77	4 800/0.833	1 800/0.49
7 159/0.99	49.85	3 800/0.85	3 000/0.75
7 165/0.99	49.91	1 300/0.553	5 600/0.89
10 450/0.957	49.67	9 500/0.97	500/0.4
10 490/0.957	49.83	3 400/0.952	6 600/0.85
13 980/0.956	49.75	4 200/0.962	9 500/0.89

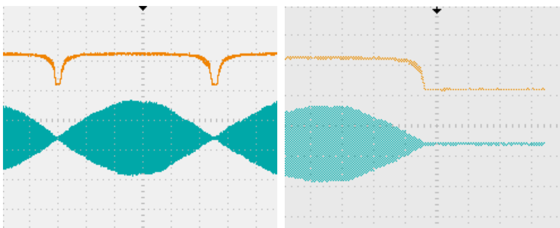


Fig.13.Measurement waveform

Fig.13 shows the waveform of 7KW load and the waveform of successful experiment of grid-connection. Fig.14 is the grid-connected load distribution experiment. 20KW generator supplies 7KW load. The grid connection of ship power and shore power is carried out at the lowest point of voltage envelope. The ship power is set as 49.71Hz in the range of 49.50~49.95 Hz, the load is transferred within 0.1s when connecting grid, the output power of the generator is 0, and the diesel generator set can be shut down intelligently.

Fig.15 is the frequency difference and 0 power, a, b, and c are experimental data, m and n are experiment conclusions. It shows that the 20KVA generator supplies 0~20 KW load, the grid is connected at the lowest point of voltage envelop, the generator load is changed to 0, and it also shows the relationship between the shore power 50Hz and frequency difference controlled by generator by reducing frequency. Approximate ratio control can be applied in 15% to 90% load, $k_{cm}=\Delta f_{cm}/\Delta P_{cm}$.

Fig.16 is the grid-connected load analysis of ship synchronous generator G and shore power transformer M: The curve is shifted from H to D through the speed regulation device before the grid connection, f_G=49.71Hz, $P_d= P_G$=7KW, P_M=0. Closing and grid connection is carried out at the lowest point K_2 of voltage envelope. After successful closing: $f_G=f_M=f$=50Hz, P_G=0, P_M =7KW.

The speed of synchronous generator is low ($f_G<f_M$), and the rotor is in electric state. Under the action of driving force, the time required for the generator to rise from d to 50Hz along the speed regulation characteristics is as follows:

ΔT=1/Δf=1/(50-49.71)Hz=1/0.29Hz=3.45s

Switch closing time T=0.1s. At this point, $\Delta T>T$. It is impossible for the generator to increase from d to 0 load along the speed regulation characteristics and transfer it to the shore power transformer.

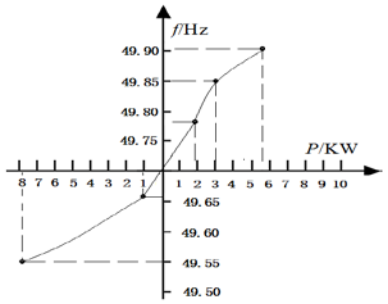


Fig.14. Grid-connected load distribution

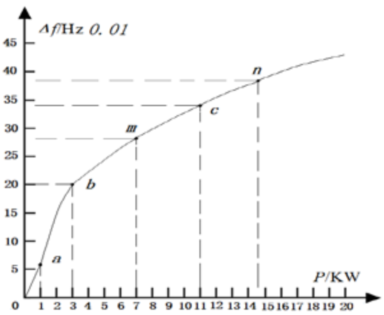


Fig.15. Frequency difference and 0 power

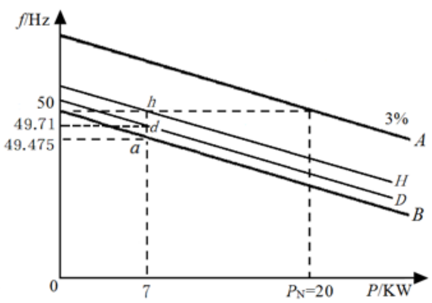


Fig.16.Grid-connected *f/P* relation

The rotor motion formula (7) can determine: P_{d1}=7KW×(50-49.71)/(50-49.475)=3.87KW.The internal circulating current is provided by shore power transformer,At the same time, the load P_{d2}=7-3.87 =3.13KW of the generator along the speed regulation characteristic from d to 50Hz and the mechanical power $P_m=1/3P_N$ of the generator itself are determined. The ratio of power is supplied by the generator and shore power transformer within the switch closing time T=0.1s.

The formula (7) also proves that: P_G=0, Δf=0.29Hz; The curve is shifted from H to B, Δf=0.825 Hz, and P_G=-7.5KW is seriously reverse power.The formula (7) can be used to calculate the β damping coefficient and J moment of inertia with 2 groups of experimental parameters.

6. Conclusions

The detection device of voltage difference envelope includes voltage difference acquisition circuit, absolute value conversion circuit and shaping detection circuit. The control components include single chip microcomputer and IPC. The envelope signal of voltage difference between ship power and shore power is obtained and converted to periodic positive pulse signal. Taking the lowest point of the periodic positive pulse signal as the datum point, T time is taken before and after the datum point, and the 2T time is set as the docking period, where $0\leq T\leq 0.01$s. If the current time is within the docking time, the ship power can be connected with shore power. Before the docking of ship power and shore power, the ship power frequency is measured by setting the precise frequency table on the ship power distribution device and the engine throttle is adjusted manually or automatically to adjust the ship power frequency to make the ship power frequency lower than shore power frequency, and then carry out the docking of ship power and shore power. Under the classical load, when the ship power and shore power frequency different Δf is the fixed value, closing is carried out at the lowest point of the envelope. Suitable circulating current between ship power and shore power transforms the ship power supply into shore power supply, and the output power of ship generator is 0 after load transfer, which realizes the ideal synchronous control of switching on and transferring load. The model test further confirms the above conclusion.

Acknowledgment

Fund Projects: Special Fund Project of Applied Science and Technology Research and Development in Guangdong Province (2016B020243012); Guangzhou University Innovation and Entrepreneurship Education Project(201709P09).

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