Rotational Speed Analysis of Shipboard Turbo-generator Considering Efficiency Change after Sudden Load

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Abstract. Based on classical analytical process of cylinder efficiency, the mechanism of efficiency change during turbo-generator power adjustment is revealed, and the influence of cylinder efficiency change on calculation of generator loading limit is studied and tested by using PSCAD software. The result indicates that, efficiency deviation caused by sudden load is helpful for the recovery of system power balance, and that the negligence of power deviation caused by efficiency decrease under overload circumstances may reverse the analytical result. Reliable control of power station is the key to stable operation of shipboard power grid. The research between cylinder efficiency and generator power adjustment can provide reference for further operation design and coordinated control.

1. Introduction
Condensing steam turbine is often used to generate power in large ship power stations, and the active power output of the unit is coordinated and controlled by the boiler and regulating steam valve. In order to combine the classical model with practical engineering experience, scholars have conducted in-depth research in the field of turbine power generation control. In terms of mathematical model, literature [1-2] focused on the medium and long-term dynamic process of the interaction between power plant and power grid, and built an overall model by referring to the characteristics of each link of the unit. Literature [3-4] directly used De Mello differential equations to describe the time-domain characteristics of energy regulation of large turbo-generator sets, and then studied the control algorithm adaptive to its non-linearity. In the aspect of control strategy, power feedback control is widely studied in accordance with the prime mover's main function of providing active power. For example, literature [5-6] focused on the influence of power feedback control parameters on the damping characteristics of the unit, and literature [7-8] combined the control models to study the method of identifying model parameters by using the power response characteristics of the unit. Some scholars studied the power characterization of the regulating characteristics of the controlled mechanism of the unit based on the measured results of the unit operation, and further improved the description of the regulating system in the unit model. For example, literature [9-10] studied the influence of steam valve lift-flow characteristics on output power, literature [11-12] studied the characteristics of power grid frequency oscillation caused by boiler pressure pulsation. Literature [13] studied the operation characteristics of unit when boiler steam supply is cut off.

The research results have covered the structure and control method of large turbine generator sets. The research subjects of steam turbine are mostly large land steam turbine or marine propulsion steam turbine. There are few studies on marine power station steam turbine operating independently in an isolated network environment, and the variation of cylinder efficiency during unit operation is rarely mentioned. The efficiency of the cylinder varies with the power adjustment of the unit. Therefore, it is
helpful to improve the reliability and safety of ship power station regulation by using the feature of
efficiency change in unit working condition design and more comprehensively considering the non-
linear relationship between the state variables, such as speed, steam pressure and unit power.

Based on the classical calculation method of cylinder efficiency, the variation rule of efficiency in
the process of unit operation under variable working conditions is analyzed. The mechanism of the
influence of steam pressure and speed control of the unit is revealed. The correlation between the
variation of cylinder efficiency and unit transient stability after grid load mutation is studied by
applying PSCAD simulation. As the load rejection control strategy of a turbo-generator set is
relatively mature[14-15], only the case of sudden load increase is focused on.

2. Cylinder Efficiency and Unit Transient Regulation Process

2.1. Analysis of Efficiency

Cylinder internal efficiency $\eta$ usually includes two parts. One is the efficiency $\eta_s$ related to the unit
structure, such as baffle leakage, impeller friction, etc., which is less affected by the change of
working conditions, and is often regarded as a damping constant in the dynamic analysis as a whole
[16]. The other type is the wheel circumference efficiency $\eta_r$, which is affected by steam inlet
parameters, flow path structure and so on. Impulse turbine units are mostly used in marine power
stations. The wheel cycle efficiency of such units changes significantly with the speed ratio $x_a$. In
order to highlight the main differences before and after the variable working conditions of the units
and simplify the analysis, the influence of $\eta_s$ on the unit output power is ignored here. The
relationship between $x_a$, circumference velocity $u$, and ideal steam velocity $c_a$ can be seen in
formula (1). The typical relationship between $x_a$ and $\eta_r$ is shown in Figure 1. The dynamic change of
efficiency is studied based on the characteristics of this curve.

$$x_a = \frac{u}{c_a}$$  \hspace{1cm} (1)

Steam is regarded as an ideal gas and the enthalpy drop caused by steam transported by pipeline is
ignored. The relationship between the ideal velocity $c_a$ and the stagnation specific enthalpy drop $\Delta h^*$
is shown in equation (2)[17].

$$\frac{1}{2} c_a^2 = \Delta h^* = \frac{k}{k-1} RT_0 [1 - \left(\frac{p_r}{p_v}\right)^\frac{k-1}{k}]$$  \hspace{1cm} (2)

Where, $k$ is the steam isentropic index; $R$ is the vapor characteristic constant; $T_0$ is the initial
absolute temperature of steam; $p_r$ is the main steam pressure before cylinder; $p_v$ is the cylinder back
pressure. When the condenser works stably and the back pressure $p_v$ is constant, $x_a$ is positively
correlated with $u$ and negatively correlated with $p_r$.

2.2. Analysis of Efficiency with Transient Variation of Unit

It is generally believed that the frequency stability of marine power station generator sets is consistent
with the active power balance of the power grid, and the relevant description of the active power of the
steam turbine can be seen in equations (3) and (6)[18-21].

$$P_a = G \Delta h \eta_r$$  \hspace{1cm} (3)

$$G = k_v C_v (p_f - p_v)^{\frac{k}{2}}$$  \hspace{1cm} (4)

$$p_v = k_v C_v p_f$$  \hspace{1cm} (5)

$$\Delta h = \frac{k}{k-1} RT_0 [1 - \left(\frac{p_f}{p_v}\right)^{\frac{k-1}{k}}]$$  \hspace{1cm} (6)
Where, $G$ is the steam flow rate of classification; $\Delta h$ is the ideal specific enthalpy drop of classified steam. $k_r$ and $k_p$ are constant coefficients. $C_v$ is the opening degree of steam valve; $p_v$ is the classification vapor pressure.

During steady-state operation of the unit, $p_r$ is the rating value, $p_v$ varies with $C_v$ due to different load rate, and $\Delta h$ is positively correlated with $p_v$. When the working condition changes abruptly, the dynamic process of unit speed is shown in equation (7) and (8).

$$\frac{d\delta}{dt} = \omega - 1$$
$$T_j \frac{d\omega}{dt} = p_r - p_v - D(\omega - 1)$$

$$\frac{V}{RT} \frac{dp_v}{dt} = G^* - G$$

Where, $\delta$ is the unit power Angle; $T_j$ is the inertia time constant of the unit; $\omega$ is the rotational angular velocity; $p_r$ is the load power; $D$ is the equivalent damping coefficient of the rotor; $V$ is the total volume of boiler, pressure stabilizing chamber and pipeline; $T$ is the thermodynamic temperature of steam; $G^*$ is real-time flow rate of boiler.

Valve opening is controlled by speed deviation signal, as is shown in Figure 2. Where $R_v, T_1$ and $T_2$ are adjustment parameters of steam valve control signals; $T_{sm}$ is the regulating time constant of oil motor.

![Figure 1. Velocity ratio-efficiency curve](image1.png)

![Figure 2. Control block diagram of turbine valve](image2.png)

Boiler combustion quantity is controlled by steam pressure feedback, as is shown in Figure 3. Where, $T_s$ is the fuel treatment delay; $T_p$ is the combustion process time constant; $T_w$ is the time constant of water wall; $C_d$ is the drum time constant; $p_d$ is drum pressure; $C_{sh}$ is pipeline time constant; $K$ is pipeline flow coefficient.
Internal efficiency $\eta_t$ usually has a maximum value in the rated working condition. Affected by the setting of speed inequality, the steady-state speed of the unit is the minimum under rated working conditions, corresponding to the speed ratio $x_a$ at point B in Figure 1. If the light load steady speed is slightly higher than the rated working condition, $x_a$ may be set at point A in Figure 1. When the load $P_r$ increases suddenly, the speed $\omega$ decreases according to formula (7). Consequently, $C_t$ increases according to PID control; demand flow $G$ increases rapidly, and then the main steam pressure $p_t$ decreases according to formula (8) and $P_a$ decreases. From formula (2), it is obvious that the decrease rate of $p_r$ to $C_a$ is far less than the effect of rotation speed change on $x_a$. Moreover, the time constant of $p_r$ change is usually much higher than the inertia time constant $T_j$ of the generator set, so $x_a$ will be offset from point A to point B. According to the relevant requirements of “Rules for classification of sea-going steel ships”, the unit speed may drop by 7% after sudden loading. Considering this limit case, as long as the unit is pre-set so that $x_a$ does not cross point A’ in Figure 1, the efficiency change can play a positive role in the process of power balance restoration.

2.3. Cylinder Efficiency and System Overload Operation

The generator set of the ship power station should be able to withstand short overload operation. The design of overload condition is directly related to the vitality of the ship power grid under extreme environment. According to the analysis in the previous section, when the load of the unit is too heavy, the rotation speed will be lower than the design value of rated working condition, and the cylinder speed ratio $x_a$ may continue to move towards point C in Figure 1. If the response speed of the power regulation system is too slow, the unit may even be shut down in extreme cases, causing serious consequences.

In the overload condition, the forward transmission of the steam boiler to the generator set output power has a large time scale. Due to the delay caused by the time constants $T_s$, $T_p$, $C_a$, $C_{sw}$, etc., the response of the main steam pressure $p_t$ to the sudden load is slow, and the generator set will inevitably go through the low-frequency operation process. By the equal area method of generator unit transient analysis, the generator power characteristic curve is shown in Figure 4.

![Figure 3. Control block diagram of boiler pressure](image)

![Figure 4. Generator power characteristic](image)

Generally, the system operates at steady-state at point $a$, with power $P_a$. The working point moves towards point $b$ with the increase of unit torque. Meanwhile, the load power will also decrease due to the reduction of power grid voltage and frequency. Unit stability can be equivalent to deceleration area $S_a$ less than acceleration area $S_b$, and prime mover adjustment can be equivalent to translation characteristic curve in the longitudinal axis direction to increase the $S_b$ range, so that the unit can recover stability through the transition process. The characteristic of efficiency decrease with the rotational speed will weaken the adjusting effect of the prime mover and affect the critical value of loading.
The critical value of loading can be divided into two cases: upper limit \( P_e \) of transient loading and upper limit \( P_s \) of steady-state loading. For \( P_e \), the unit condition before loading is usually within the rated range; After loading, \( C_v \) is rapidly promoted to full capacity, the unit reaches an overload state, and the steam supply system leads to the torque balance of the unit. \( P_e \) value is related to the current load rate, speed and main steam pressure of the unit. If the load surge exceeds \( P_e \), the efficiency in the cylinder will be lower than the expected steady-state value due to the decrease of speed before the main steam pressure is raised to the expected steady-state pressure, thus the unit cannot transition to the expected steady-state. For \( P_s \), this limit is usually determined by the maximum value of the main steam pressure that a boiler can support. When the prime mover reaches \( P_s \), the speed reduction caused by arbitrary load of the power grid will lead to the efficiency value falling below the critical line, thus leading to the instability of the unit.

To sum up, the dynamic change of efficiency is closely related to the system performance when the unit is loaded, so it is necessary to consider the factor of efficiency change in the system modeling research. This will make the response characteristics of the system to load more real, and the results of model-based research will be more credible.

3. Sudden Load Analysis Considering Cylinder Efficiency

3.1. PSCAD Modeling Considering Cylinder Efficiency

In the traditional single-cylinder steam turbine modeling, the main characteristics are often described by cylinder volume time \( T_{vC} \), as is shown in Figure 5(a). The model considering efficiency change is shown in Figure 5(b), where \( \eta_v = f_v(p_T, C_v, \omega) \) and \( f_v(\ast) \) represents a functional relationship.

The simulation model of megawatt turbine generator set is established in PSCAD, as is shown in Figure 6. Efficiency module in the figure is \( f_v(\ast) \) computing module. Where the turbine cylinder volume time constant \( T_{vC} = 0.8s \), valve action time constant \( T_{SM} = 0.1s \), steam valve control parameters \( k_p = 30 \), \( k_i = 3 \), \( k_d = 1.8 \). The parameters of the steam pressure model, as is shown in Figure 3, were set as \( T_p = 0.25s \), \( T_k = T_w = 5s \), \( C_D = 60s \), \( K = 3.5 \), \( C_\omega = 5s \), and the steam pressure control parameters were consistent with the steam valve.

Figure 5. Single-cylinder turbine model

Figure 6. PSCAD simulation model

3.2. Load Simulation in Rated Working Condition

Set the load power factor 0.8 and initial load 0.25p.u., and then add a load suddenly to a 0.7p.u. at 20s. The change waveforms of rotational speed, valve opening, main steam pressure and efficiency are shown in Figure 7.
Figure 7. Simulation curve of sudden load in rated conditions

Figure 7(a) and 7(c) show that at the moment of loading, the rotational speed produces an amplitude fluctuation of 4% of the rated value, and that the main steam pressure drops by about 6% and then arrives at a steady state within 20s. From Figure 7(b) and 7(c), it is easy to conclude that the fluctuation of the main steam pressure caused by sudden load is consistent with the steam valve regulation in terms of time between the 20s and 30s. It can be seen from Figure 7(d) that the fluctuation between the rotating speed and the main steam pressure deviates the efficiency. In the 20s, the efficiency increases by about 0.3% with the decrease of the rotating speed, which is helpful for the rapid recovery of the rotating speed. As the speed amplitude is within a reasonable range, the speed ratio always oscillates slightly on both sides of point A in Figure 1 during the adjustment process, and the efficiency only produces a small fluctuation, with a amplitude of 0.4%. The new operating point is located between point A and B in Figure 1, and the new steady-state value is about 0.2% higher than the original value.

3.3. Simulation under Overload

3.3.1. Upper Limit Simulation of Transient Loading. On the basis of 20s loading in the above section, 40s is added with active load 0.35p.u. When the efficiency is not considered, the speed waveform is shown in Figure 8. After considering the changes in efficiency, the rotational speed, main steam pressure, valve opening and efficiency waveforms are shown in Figure 9.
According to Figure 9(c) valve opening waveform, 0.35p.u. is loaded into the unit for overload operation. In Figure 8, the maximum decrease of rotation speed is 7%, and then it gradually recovered and stabilized with the main steam pressure. However, in Figure 9(a) and (d), the rotation speed drops sharply, resulting in the efficiency falling below the required level for stability, and then the unit becomes unstable. Referring to the characteristic curve at the left of point C in Figure 1, within the speed ratio range, the torque increase caused by the decrease of speed ratio is not high enough to compensate for the power reduction caused by the decrease of speed ratio, so the system cannot be restored to equilibrium.

Considering that slow recovery of steam pressure and too low rotating speed are the main causes of unit instability, the 40s loading 0.35p.u. is changed to loading 0.23p.u. and 0.12p.u. respectively in the 40s and 60s to reduce the impact of single loading on the rotating speed. The corresponding waveforms of speed, main steam pressure, valve opening and efficiency are shown in Figure 10.
It can be seen that the 0.35p.u.’s loading after adjustment does not cause instability of the unit, indicating that the upper limit of transient load $P_t^*$ of the simulation unit under 0.7p.u.’s load steady-state is between 0.23p.u.’s and 0.35p.u.’s. If the efficiency variation is not taken into account, $P_t^*$ of this steady state may even reach more than 0.6p.u., which is inconsistent with actual situations. Therefore, when the unit load rate is high, the transient efficiency cannot be neglected in load design.

3.3.2 Steady-state Loading upper Limit Simulation. To test the upper limit of steady-state loading of the unit, 0.001p.u. is loaded at the 120s on the basis of the above-mentioned 0.35p.u. loading, and the efficiency waveform is shown in Figure 11(a). If 0.001p.u. is loaded again at the 130s, the efficiency waveform is shown in Figure 11(b).

The long recovery time of main steam pressure is fully considered in this load test. If it is only slightly loaded at 120s, the power balance of the system can still be maintained. But after the load at 130s, the output power of the unit decreases by 0.03% per minute. Since the steam valve and main steam pressure of the unit have reached the regulation limit, the unit will eventually lose stability with the continuous decrease of efficiency. Therefore, it can be concluded that after the 120s loading, the unit speed has reached the lower limit allowable by the balance, and that the upper limit of static loading $P_s^*$ is located between the corresponding unit load rate of two 0.001p.u. loads.
Combined with Figure 8, it can be seen that when the change of efficiency is not taken into account, the estimation of the maximum bearing capacity of the unit will be optimistic. Therefore, the efficiency factor should not be neglected in the study of unit limit load characteristics.

4. Conclusion
By analyzing the mechanism of the internal efficiency of the cylinder with the transient variation of the unit, the model of the unit considering efficiency variation is established, and the relationship between the efficiency deviation and the load limit of the unit is studied. The main conclusions are as follows:

(1) Turbine wheel cycle efficiency is a function of speed ratio, and the influence of unit speed on speed ratio is more significant than that of main steam pressure. Within the rated working condition, the load adjustment of the unit is dominated by the control of the steam valve, and the quick adjustment of the steam valve can ensure that the speed of the unit is within a reasonable range. At this time, the speed ratio is located in the monotone decreasing range of efficiency. The speed reduction caused by sudden load increase will increase the efficiency, which is conducive to the recovery of unit speed.

(2) The dynamic process of unit overload operation is regulated by the boiler, and the boiler regulation time constant is significantly higher than the steam valve, which is not conducive to power balance. In case of overload, the speed ratio is usually in the monotone increasing range of efficiency, and the sudden increase of load will lead to the decrease of efficiency. When the efficiency reduction caused by loading exceeds the allowable limit of power balance, the unit will be unstable. However, this instability mechanism is rarely studied in the loading characteristics of traditional turbo-generator sets.

PSCAD simulation results verify the above conclusions. The mechanical and furnace network system has complex structure and many parameters. In the future, the relationship among various factors affecting the regulation process of a turbo-generator set will be further studied based on the working mechanism of each link of the system and the operation characteristics of different loads, so as to provide references for the design and coordinated control of the unit operating conditions.

5. References
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