Simulation of the transient processes of load rejection under
different accident conditions in a hydroelectric generating set

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Abstract. Load rejection test is one of the essential tests that carried out before the
hydroelectric generating set is put into operation formally. The test aims at inspecting the
rationality of the design of the water diversion and power generation system of hydropower
station, reliability of the equipment of generating set and the dynamic characteristics of hydro-
turbine governing system. Proceeding from different accident conditions of hydroelectric
generating set, this paper presents the transient processes of load rejection corresponding to
different accident conditions, and elaborates the characteristics of different types of load
rejection. Then the numerical simulation method of different types of load rejection is
established. An engineering project is calculated to verify the validity of the method. Finally,
based on the numerical simulation results, the relationship among the different types of load
rejection and their functions on the design of hydropower station and the operation of load
rejection test are pointed out. The results indicate that: The load rejection caused by the
accident within the hydroelectric generating set is realized by emergency distributing valve,
and it is the basis of the optimization for the closing law of guide vane and the calculation of
regulation and guarantee. The load rejection caused by the accident outside the hydroelectric
generating set is realized by the governor. It is the most efficient measure to inspect the
dynamic characteristics of hydro-turbine governing system, and its closure rate of guide vane
set in the governor depends on the optimization result in the former type load rejection.

1. Introduction
Load rejection refers to the transient process that the hydroelectric generating sets suddenly reject their
loads, which is an important way to ensure the safety of the sets when an accident occurs [1,2]. In
order to test the rationality of the design of the water diversion and power generation system of
hydropower station, reliability of the equipment of generating set and the dynamic characteristics of hydro-
turbine governing system, it is mandatory to carry out the load rejection test before the official
operation of hydroelectric generating sets.

For most of the recent studies on the load rejection transient process, they mainly focused on the
characteristics and simulation methods of the transient process during the load rejection test [3-6]. On
the other hand, the load rejection transient process is caused by accidents of the hydroelectric
generating sets. Hence, under different accident conditions, either within or outside the sets, the load
rejection transient processes are different, such as the control, characteristics and consequence of the
load rejection transient process. However, to the best of authors’ knowledge, there are fewer studies on
this aspect of the load rejection. Further, the following questions need to be answered. What are the characteristics of the load rejection processes under different accident conditions? How can the load rejection under different accident conditions be simulated? What is the relationship among the load rejection processes under different accident conditions? What are the effects of different load rejections on ensuring the regulation guarantee calculation, debugging and operation of hydropower station?

Starting with the different accident conditions of the hydroelectric generating sets, this paper describes the load rejection transient processes that correspond to different accident conditions. Then, the characteristics of different load rejection transient processes and the corresponding numerical simulation method which has been developed are elaborated. The accuracy of the numerical method has been verified with measured data from a hydropower station. Finally, according to the simulation results under different accident conditions, this paper reports the relationships among the load rejection transient processes and the consequence of load rejection on the hydropower station design and the load rejection test of the sets.

2. Load rejection transient processes under different accident conditions

Figure 1 shows the composition structure and working scheme of the hydro-turbine governing system of a hydropower station. Figure 2 shows the relationships between the working conditions and the transition processes of the microcomputer governor of the hydroelectric generating set. Note that: $f_c$ is the given frequency of the set; $f_g$ is the generator frequency of the set; $\Delta f$ is the frequency difference; $P_c$ is the given power output of the set; $P_g$ is the generator power output of the set; $\Delta P$ is the power output difference; $Y_c$ is the given guide vane opening (servomotor stroke); $Y_g$ is the guide vane opening (servomotor stroke); $y = (Y_g - Y_c)/Y_c$ is the relative stroke of servomotor, which equals the relative guide vane opening.

![Figure 1](image)

**Figure 1.** Composition structure and working scheme of the hydro-turbine governing system.
The hydro-turbine governing system carries out two functions. (1) To satisfy the supply-demand balance and frequency stability requirements, the governing system regulates the hydroelectric generating set according to the frequency regulation or the power regulation modes. During the operation, the microcomputer governor carries out the controlling function. (2) If there is an accident with the set, the set circuit breaker (i.e. oil breaker) separates the valves, and then the set rejects the load using the emergency shutdown valve or the microcomputer governor.

The microcomputer governor is the core component of the hydro-turbine governing system. In accordance with the regulation and control of the microcomputer governor on a hydroelectric generating set, the operation of the microcomputer governor can be divided into the following working conditions: wait at shutdown, no-load, load and phase modulation. Then, the transition processes that follow the working conditions are: start-up, load adjustment, load rejection and shutdown. The working conditions keep the hydroelectric generating set working under stable operation. The transition processes are the dynamic processes of the hydro-turbine governing system.

Load rejection refers to the transient process that the hydroelectric generating set suddenly rejects its load, which is an important way to ensure the safety of the set when an accident occurs. According to the different types of accidents, there are two types of the load rejection: (a) load rejection due to an accident within the set, and (b) load rejection due to an accident outside the set.

(1) For the load rejection due to an accident within the set, during the normal power generation of a hydroelectric generating set, the set is separated due to a major accident within the set. The unit rejects the load and the guide vanes close quickly by a servomotor controlled by an emergency distributing valve. This results in the final shutdown of the set. As the set shuts down due to the internal accident, the load resistance torque becomes zero, the servomotor closes based on the prior given motion law of the emergency distributing valve, and the governor is not active in the regulation. This type of load rejection is an open loop control process.

(2) For the load rejection due to an accident outside the set, during the normal power generation of a hydroelectric generating set, when an oil breaker trips due to a line fault, the set rejects the load suddenly, and there is zero load as the servomotor closes by the main distributing valve. During the sudden load rejection process, the load resistance torque of the hydroelectric generating set becomes zero. First, the servomotor closes quickly according to the pre-set law and the rotate speed of the set rapidly increases. Then, as part of the regulation process, the governor tracks the rotate speed of the set. After a period of fluctuations in the speed, the set reaches a stable and no-load operation condition under the rated speed. This type of load rejection is a closed loop control process.

For accident that occurs outside the set, there is a special type of load rejection, in which the load rejection transient process is partly controlled by the governor. Generally, there is a safety limit in the rise of rotate speed of the set, such as 135% of the rated speed. As the set encounters an accident on the outside, the load is first rejected under the control of the governor. The main distributing valve then closes at a pre-set rate. Meanwhile, the rotate speed of the set increases. If the speed of the set is within the safety limit, the load rejection process is in the full control of the governor. However, if the speed exceeds the safety limit during the control of the governor, the emergency distributing valve becomes active and then the governor is no longer in control. The emergency distributing valve completes the subsequent load rejection process according to the pre-set shutdown law. Finally, the
servomotor closes and the set shuts down. This type of load rejection is an open loop first and then closed loop control process.

In summary, there are two types of accident conditions in the load rejection transient process of hydroelectric generating set. The load rejection can be due to an accident within the set or due to an accident outside the set. There are three ways the servomotor can be closed which are: closed by the emergency distributing valve, by the governor and by the joint control of the governor and the emergency distributing valve. Among these accident conditions and closing of the servomotor, the closing by the emergency distributing valve belongs to the load rejection due to an accident within the set. The closing by the governor and by the joint control of the governor and the emergency distributing valve belongs to the load rejection due to an accident outside the set. In Section 3, the developments of the mathematical models and numerical simulation methods for the load rejection transient processes under different accident conditions are described. The accuracy of numerical simulation method has been verified with measured data from a hydropower station.

3. Numerical simulation of load rejection transient processes

3.1 Mathematical models of load rejection transient processes

3.1.1 Basic equations for unsteady flow in pressurized pipeline

The basic continuity and momentum equations for unsteady flow in a pressurized pipeline which include the effects of the elasticity of the water and the pipeline wall are as follows [7,8]:

\[
\frac{Q}{A} \frac{\partial H}{\partial x} + \frac{\partial H}{\partial t} + \frac{a^2}{gA} \frac{\partial Q}{\partial t} + \frac{a^2}{gA} \frac{\partial A}{\partial t} - \frac{Q}{A} \sin \theta = 0
\]  

(1)

\[
gA^2 \frac{\partial H}{\partial x} + \frac{\partial Q}{\partial x} + A \frac{\partial Q}{\partial t} + \frac{fQ|Q|}{2D} = 0
\]  

(2)

where \( x \) is the distance along the pipeline axis; \( \theta \) is the angle between the pipeline and the horizontal; \( A \) is the cross-sectional area of the pipeline; \( a \) is the wave speed of water hammer; \( H \) is the pressure head; \( Q \) is the flow through the pipeline; \( f \) is the Darcy-Weisbach resistance coefficient; and \( D \) is the diameter of the pipeline. For a non-prism pipeline, \( A \) is a function of \( x \) and we have \( \partial A/\partial x \neq 0 \). For a prismatic pipeline, \( \partial A/\partial x = 0 \).

Equations (1) and (2) are quasilinear hyperbolic equations, which can be solved by many existing numerical methods. Currently, the most widely used method is the method of characteristics.

3.1.2 Boundary conditions and initial conditions

The most important boundary condition of the numerical simulation of hydropower station is the hydroelectric generating set. The basic equations of this boundary condition are presented as follows.

(1) Basic equations of a reaction hydroelectric generating set [9-11]

Continuity equation:

\[ Q_p = Q_s \]  

(3)

Flow characteristic equation inside the turbine:

\[ Q_p = Q_{n1} D_1^2 \sqrt{(H_p - H_s)} + \Delta H \]  

(4)

Characteristic line equations:

\[ C^+ : Q_p = Q_{CF} - C_{QH} H_p \]  

(5)

\[ C^- : Q_p = Q_{CF} - C_{QH} H_p \]  

(6)

Characteristic curve equations of turbine:

\[ n_{n1} = nD_1 / \sqrt{(H_p - H_s) + \Delta H} \]  

(7)

\[ Q_{n1} = f_1(n_{n1}, y) \]  

(8)

\[ M_{n1} = f_1(n_{n1}, y) \]  

(9)

\[ M_p = M_{n1} D_1^3 (H_p - H_s + \Delta H) \]  

(10)
First-order equation for generator:
\[ \frac{30}{\pi} \frac{dn}{dt} = M_r - M_s - \frac{30e_\gamma P_r}{n^2 \pi} \Delta n \]  
(11)
where, \( H_p, Q_p \) are the head and flow rate at the inlet side of turbine; \( H_s, Q_s \) are the head and flow rate at the outlet side of turbine; \( n_i \) is the unit rotate speed; \( Q_i \) is the unit flow rate; \( M_i \) is the unit torque; \( M_s \) is the kinetic torque of turbine; \( M_r \) is the load resistance torque; \( J \) is the moment of inertia; \( e_\gamma \) is the coefficient of load damping; \( D_1 \) is the diameter of runner; \( \Delta H = (\alpha_p / (2gA_p^2) - \alpha_s / (2gA_s^2))Q_s^2 \). \( \alpha_p \) is the correlation coefficient of kinetic energy at turbine inlet, \( \alpha_s \) is the correlation coefficient of kinetic energy at turbine outlet, \( A_p \) is the section area of turbine inlet, \( A_s \) is the section area of turbine outlet; \( n \) is the rotate speed, \( P \) is the power output, the subscript “r” represents the rated values.

(2) Basic equation of governor
Equation (12) is the differential equation for a parallel proportional-integral-derivative (PID) type governor [12-14], as follows:
\[ b_pK_pT_s \frac{dy}{dt} + (b_pK_pT_s + T_s + b_pK_d) \frac{d^2y}{dt^2} + (b_pK_pT_s + b_pK_d + 1) \frac{dy}{dt} + b_pK_s y = -(K_d \frac{d^2x}{dt^2} + K_i \frac{dx}{dt} + K_s x) \]  
(12)
where \( K_p \) is the proportional gain; \( K_i \) is the integral gain; and \( K_d \) is the derivative gain; \( b_t \) is the temporary droop; \( T_s \) is the damping device time constant; \( b_p \) is permanent droop; \( T_i \) is servomotor response time constant; \( x = (n - n_i) / n_i \).

Model A: For the load rejection due to an accident within the set, the load resistance torque of the hydropower generating set is zero. So, Equation (11) can be rewritten as
\[ \frac{30}{\pi} \frac{dn}{dt} = M_s \]  
(13)
In this case, as the governor is not active in the regulation process, the motion law of the servomotor stroke can be pre-given and expressed by \( y = f(t) \). Then, Equations (3)-(10), and (13), and \( y = f(t) \) can be used to develop the mathematical model for the load rejection due to an accident within the set.

Model B: For the load rejection due to an accident outside the set and the servomotor is closed by the governor, Equations (3)-(12) can be used to develop the mathematical model.

Model C: For the load rejection due to an accident outside the set and the servomotor is closed by the joint control of the governor and the emergency distributing valve, the Model B can be used for the initial stage in which the governor always tracks the rotate speed of the set. Once the speed of the set reaches the pre-set safety limit, the Model A can be used.

The other boundary conditions, such as reservoir, surge tank and branch pipe, are introduced in [7,9].

The initial conditions are the values of all the parameters when the hydropower station is at the steady flow state.

3.2 Example calculation
Three existing hydropower stations have been selected for the verification of the proposed numerical simulation method in Section 3.1: namely Station A, Station B and Station C. A load rejection test due to an accident within the set has been carried out at Station A. Station B carried out a load rejection test due to an accident outside the set and the servomotor was closed by the governor. Station C carried out a load rejection test due to an accident outside the set and the servomotor was closed by the joint control of the governor and the emergency distributing valve. Using the mathematical model and the numerical simulation method developed in Section 3.1, the load rejection tests for Stations A, B, and C are simulated, and the results have been compared to the measured data. The basic information of Stations A, B, C are shown in Table 1, and the corresponding load rejection test conditions are shown in Table 2. The comparisons between the simulation and measurement results of the three load rejection tests are shown in Figures 3-5. The comparisons of the extremes of the volute pressure and the rotate speed of the set and their relative errors of the three load rejection tests are shown in Table 3.
Note that: the volute pressure and the rotate speed of the set are determined by $H_P$ and $n$, respectively. The wave velocity is selected based on the pipeline material.

**Table 1. Basic information of the selected hydropower stations.**

| Basic information       | Station A                                      | Station B                                      | Station C                                      |
|-------------------------|------------------------------------------------|------------------------------------------------|------------------------------------------------|
| Layout form             | Two sets in one tailrace tunnel                | Two sets in one tailrace tunnel                | Two sets in one diversion tunnel               |
| Rated head $H_r$ (m)    | 80                                              | 128                                            | 46                                             |
| Rated flow $Q_r$ (m$^3$/s) | 506                                            | 225                                            | 122.33                                         |
| Rated power output $P_r$ (MW) | 367                                            | 256.5                                          | 51.28                                          |
| Rated rotate speed $n_r$ (r/min) | 100                                            | 166.67                                         | 136.4                                          |

**Table 2. Load rejection test conditions.**

| Basic information       | Station A                                      | Station B                                      | Station C                                      |
|-------------------------|------------------------------------------------|------------------------------------------------|------------------------------------------------|
| Load before rejection   | 50%$P_r$                                       | 50%$P_r$                                       | 75%$P_r$                                       |
| Closure law of guide vane | Straight-line law                              | Straight-line law                             | Broken-line law                                |
| Safety limit of rotate speed | /                                              | /                                              | 115%n_r                                        |

**Figure 3.** Comparison between simulation and measurement results for load rejection test at Station A.

**Figure 4.** Comparison between simulation and measurement results for load rejection test at Station B.
Figure 5. Comparison between simulation and measurement results for load rejection test at Station C.

Table 3. Comparisons of the extremes of the volute pressure and the rotate speed of the set and their relative errors.

| Values          | Station A | Station B | Station C |
|-----------------|-----------|-----------|-----------|
|                 | $H_t$ (MPa) | $f_g$ (Hz) | $H_t$ (MPa) | $f_g$ (Hz) | $H_t$ (MPa) | $f_g$ (Hz) |
| Simulation result | 1.116 | 54.95 | 1.446 | 59.83 | 0.701 | 60.56 |
| Measurement result | 1.089 | 54.62 | 1.425 | 59.29 | 0.713 | 60.04 |
| Relative error (%) | -2.479 | -0.604 | -1.474 | -0.911 | 1.683 | -0.866 |

Note that: In the practical engineering, the extremes are most concerned. Hence, only the extremes of the volute pressure and the rotate speed are listed in the above table.

Figures 3-5 and Table 3 show that for the three load rejection tests, the simulation results are basically the same as the measurement results. The variation law and trends of the guide vane opening, volute pressure and rotate speed of the set are all in good agreements. For the extreme and its occurrence time, the simulation and measurement results are close to each other. The relative error of the extreme of volute pressure is less than 2.5% and the relative error of rotate speed of the set is less than 1%. These comparison results show that the mathematical models developed in this study can be used as a simulation tool which can accurately reflect the load rejection transient processes of a hydropower station under different accident conditions.

The discrepancies between the simulation results and the measurement results mainly caused by the following aspects: the transformation method of characteristic curve, the congruent relationship between guide vane opening and the stroke of servomotor, settings of steady parameter, such as head loss, rotational inertia and wave velocity.

4. Discussion

(1) Load rejection due to an accident within the set

The load rejection transient process due to an accident within the set is the foundation for the regulation guarantee calculation of a hydropower station [9,15]. During the load rejection process, both the volute pressure and rotate speed of the set increase. They are associated with the closure rate of the servomotor, while the variations are in opposite directions. Therefore, for a hydropower station,
the closure law of the servomotor has to be optimized so that the opposing variations can be coordinated and make them satisfy the requirements of specification [16].

By the numerical simulation model developed in this study, the load rejection due to an accident within the set can be simulated and then optimized to obtain the closure law for the servomotor that can satisfy the regulation guarantee design. Then, the closure law can be achieved by the emergency distributing valve, and it is also the closure law of guide vane. It can also be used to regulate the closure rate of the servomotor when the load is rejected due to an accident outside the set. Through the calculation for the load rejection transient process due to an accident within the set, the closure law of servomotor achieved by the emergency distributing valve can be optimized into different types, including the straight-line closure law and broken-line closure law. Currently, the broken-line closure law has been widely accepted in practical engineering. Through careful selection of the break point location, the opposing variations in the increases of the volute pressure and the rotate speed of the set can be better coordinated.

Since the closure law of the servomotor has been optimized through the load rejection transient process due to an accident within the set, and this law is realized by the emergency distributing valve. Further, the optimized closure law of the servomotor is applied to regulate the closure rate of the load rejection due to an accident outside the set which is controlled by the governor. As such, the optimization process has to take into account the quick action of the governor so that the upper limit of the closure rate of the servomotor can be satisfied.

(2) Load rejection due to an accident outside the set

The load rejection due to an accident outside the set is also the corresponding load rejection transient process for the load rejection test of a hydropower station. After rejecting load, the set is in the state of no-load stable operation rather than in the shutdown state, which is mainly based on the following considerations:

(a) Since most electrical faults are temporary, such as the flashover short circuit of an insulator in air that is caused by the thunder striking on an overhead line, if the circuit breaker trips and stops transmission, the arc disappears and the insulation recovers, resulting in re-transmission. Only by rapidly keeping the set under the no-load operation condition, can the rapid grid-connected power generation be achieved, which can shorten the outage time and improve the reliability of power supply.

(b) For the grid-connected sets that supply power to themselves at the same time, it is important that these sets are not shut down after a load rejection. Hence, these sets must be maintained at the no-load operation, so that electricity can be supplied for their own use.

The closure of the servomotor during such load rejection condition is realized by the governor. The closure law used for the servomotor is the optimized closure law based on the load rejection process due to an accident within the set. In this way, the regulation guarantee parameters, such as the volute pressure and rotate speed of the set, can be ensured to satisfy the requirements. In addition to the maximum increase in the rotate speed and pressure of water hammer that has been determined by regulation guarantee calculation, the quality indices of the load rejection dynamic process need to be further investigated.

In Article 4.4.2 of China National Standard “Specifications of governors and pressure oil supply units for hydraulic turbines. GB/T 9652.1-1997” [17], there are the following clauses:

1) After rejecting 100% of the rated load, during the variation process of the rotate speed, the number of curve peaks exceeding 3% of the rated speed should not be more than two times.

2) After rejecting 100% of the rated load, the period between the first move of the servomotor to the opening direction and the time when the swing of the set does not exceed ±0.5% should be less than 40 s.

3) As the speed and order signal changed according to the pre-set forms, the servomotor dead time has the following requirements: no more than 0.2s for electric modulation and no more than 0.3s for machinery modulation.
Meanwhile, Article 4.13.2 of IEC 61362 (1998) "Guide to specification of hydraulic turbine control systems." has defined the dynamic quality of hydroelectric generating set after rejecting 100% of rated load [18].

The dynamic quality during load rejection transient process can be optimized through reasonably tuning the parameter of the governor.

5. Conclusions

(1) For hydroelectric generating set, there are two types of accident conditions in the load rejection transient process: load rejection due to an accident within the set, and load rejection due to an accident outside the set. There are three ways the servomotor can be closed which are: closed by the emergency distributing valve, by the governor and by the joint control of the governor and the emergency distributing valve. The closing by the emergency distributing valve belongs to the load rejection due to an accident within the set. The closing by the governor and by the joint control of the governor and the emergency distributing valve belongs to the load rejection due to an accident outside the set.

(2) The mathematical model and simulation method developed in this paper can accurately reflect the load rejection processes of hydropower station under different accident conditions.

(3) The load rejection transient process due to an accident within the set is the foundation for the regulation guarantee calculation of a hydropower station. The load rejection due to an accident outside the set is the most direct method to verify the dynamic characteristics of the governor system, but the closure rate used by the load rejection due to an accident outside the set depends on the calculation results of the load rejection transient process due to an accident within the set.

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