The Dynamic Analysis of Hydropower House and Unit System in Coupled Hydraulic-mechanical-electric Factors

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Abstract A hydraulic-mechanical-electric and structures coupled model of hydropower station system including subsystem models of the penstock, hydro-turbine model, speed governor, synchronous generator as well as grid, rotor-bearing system and powerhouse structure is established. This model is used to simulate the small fluctuation transient process of 10% load-up in the part load condition for hydropower station. Mechanical eccentric force, unbalanced magnetic pull and vortex pressure fluctuation at inlet of draft tube are considered in the numerical calculation. The interaction between hydraulic-mechanical-electric coupled factors and structural vibration properties during the small fluctuation transient process is studied. The results indicate that the speed regulation for turbine has very litter impact on the transient process of generator. In the process of small fluctuation with loading method in this paper, structure of powerhouse is greatly influenced by vortex pressure pulse in the draft tube, and the vibration of unit is excited by loads which caused by itself rotating.

Key word: hydropower station system, small fluctuation, coupled-vibration characteristics

1. Introduction

One of the most environmentally friendly energy is hydroelectric power. It is a mutual coupling system with several subsystems for a comprehensive hydropower station. The hydropower station system is unsubstitutable component in the electric power system because of its unique role in the grid control. The studies of hydraulic, mechanical and electric transient process and structural vibration characteristics are important approaches to ensure the safe and stable operation for hydropower station system.

The operation of hydropower station system is a complex process. There was little academic attention for a global analysis on the system. The investigation was divided into two areas of maturing, which were stability studies of transient process\(^{(1-3)}\) and dynamic characteristics for structures\(^{(4,5)}\). The focus of transient process was to discuss the guideline for selection of regulating parameters\(^{(6)}\), which ensured the system stableness. The vibration behaviors of structures were concentrated on research of dynamic
characteristics of the generator unit and powerhouse under different load conditions. But the limitation of these achievements was also obvious, because the contents of this two parts were isolated and the connection between them was neglected. With the increased installed capacity of hydropower unit, the interaction between the transient process and structural vibration was aggravating. For example, during the hydraulic transient process, the changed pressure and discharge would influence the pressure pulse (which was the main load on the turbine and powerhouse) in the flow passage. When the fluctuation occurred with great amplitude, the dynamic response of structures would be impacted. Conversely, the uncontrollable vibration of unit would be affected the hydraulic transient process again.

In light of that, an analysis of structural vibration properties during small fluctuation process in a part-load condition is carried out. Firstly, a coupled model of hydropower station system is established, which can simulate the variation law of different loads during hydraulic-mechanical-electric coupled transient process. Secondly, some theoretical and empirical formulas are used to express the frequency and amplitude, which present the core characteristics of pressure fluctuation. Finally, the change laws for parameters of hydropower station system during small fluctuation process are studied by the coupled model. In addition to that, the vibration characteristics of structures which are influenced by pressure fluctuation in the transient process are analyzed.

2. Models

As core structures of the coupled model of hydropower station system, hydroelectric generator unit transforms hydraulic energy into electrical energy, while the powerhouse supplies support to the unit. The potential energy of water is converted into dynamic energy by penstock model with the difference of elevation. With load variation in the grid, the turbine output \( P_t \) is controlled by speed regulating with governor to follow the change of generator output \( P_e \), however, hydraulic and electric torque are applied on the unit in the opposite direction, a stable speed of rotating unit will be achieved when two torque are balanced. In this process, structures of unit and powerhouse are impacted because of the load producing by hydraulic, mechanical and electric sources. And the source would be unstable effecting by the dynamic response of structure. So, the operation stability and structural safety of hydropower station system would be influenced by this dynamic coupling process.

As above described, a complex and coupled nonlinear system for hydropower station is established as illustrated in Fig.1. It includes a 1D model of the penstock, a nonlinear model of water turbine, a PID
governor model, a third-order model of synchronous generator, a coupled structural model of shaft of unit and powerhouse and a nonlinear guide bearing model. In order to develop the mathematical model, the system was decoupled into 5 modules and then the dynamic nonlinear models are presented for each module as follow. The parameters in models can be found in the parameter list.

1D model of penstock is expressed by the momentum equation and continuity equation. The head and discharge in penstock are calculated by finite differential method and method of characteristics with the equations which have the difference scheme as

\[
Q_{n+1}^i = \frac{1}{2} (Q_{n+1}^i + Q_{n}^i) - \frac{\Delta t Q_{n}^i}{2A\Delta x} (Q_{n}^i - Q_{n-1}^i) - \frac{\Delta t g}{2A\Delta x} (H_{n}^i - H_{n-1}^i) - \frac{f}{8DA} (Q_{n-1}^i + Q_{n}^i) \right] (Q_{n+1}^i + Q_{n}^i) \right]
\]  

\[
H_{n+1}^i = \frac{1}{2} (H_{n+1}^i + H_{n}^i) - \frac{\Delta t Q_{n}^i}{2A\Delta x} (H_{n}^i - H_{n-1}^i) - \frac{\Delta t a^2}{2A\Delta x} (Q_{n}^i - Q_{n-1}^i) - \frac{\Delta t g}{A} Q_{n}^i \sin \alpha 
\]  

The downstream boundary condition is

\[
Q_p = A(C_p - C_a H_F) \]

where, \( C_a = g/a \)

\[
C_p = \frac{Q_p}{A} - \frac{\Delta t}{A^2 \Delta x} (Q_M + Aa_M) (Q_M - Q_L) + C_a \left[ H_M - \frac{\Delta t}{A\Delta x} (Q_M + Aa_M) (H_M - H_L) \right] + g \left( S_0 - S_f \right) \Delta t \]

The upstream boundary condition is

\[
Q_n^{i+1} = A(C_n + C_a H_{F}^{i+1}) \]

\[
C_n = \frac{Q_n^i}{A} + \frac{\Delta t}{A^2 \Delta x} (Q_n^i - Aa_i) (Q_n^i - Q_L^i) - C_a \left[ H_n^i - \frac{\Delta t}{A\Delta x} (Q_n^i - Aa_i) (H_n^i - H_L) \right] + \frac{\Delta t g Q_n^i}{Aa_i} \sin \alpha - \frac{f \Delta t}{2DA^2} Q_n^i \left| Q_n^i \right| \]

Comprehensive characteristic curves are used to solve the transient process of hydro-turbine, the relationships of parameters in the curves are expressed as

\[
\tau = f(n, Q) \quad \eta = g(n, Q) \]

The third-order synchronous generator model is applied to calculate the transient process of generator

\[
\begin{align*}
T_m \frac{d\omega_e^*}{dt} & = \left( P_e^* - P_e \right) / \omega_e^* \\
\frac{d\delta}{dt} & = \omega_e^* (\omega_e^* - 1) \\
T_p \frac{dE^*}{dt} & = E_{md} - E_{md} - I_d (X_d - X_{md}) \\
U_{eq} & = E_{eq} - I_d X_{eq} \\
U_{gd} & = I_g X_q \\
U_{eq}^2 & = U_{eq}^2 + U_{gd}^2 \\
P_e & = U_{eq} I_q + U_{gd} I_d \\
U_{eq} & = U_{eq} + I_d R_e - I_q X_e \\
U_{gd} & = I_q R_e - I_q X_e \\
U_{eq} & = U_{eq} + I_d R_e + I_q X_e \\
U_{gd} & = I_q X_e + I_e R_e \\
\end{align*}
\]

The excitation regulation is controlled by the deviation of terminal voltage
A classical PID control strategy is applied in the model of governor \[10\]

\[ b_p K_p T_v y'' + \left( b_p K_p T_v + b_p K_p + 1 \right) y'' + b_p K_v y = K_p x'' + K_p x' + K_v x \]  \[11\]

The structural model of powerhouse includes the generator floor, fan cover, unit foundation, volute, draft tube and so on. On this basis, the water pressure pulsation can be applied on the powerhouse when the different conditions are considered. The bottom boundary constraints of the model are fixed and the others are free. The shaft of hydroelectric generating unit is modeled as a rotor-bearing system by finite element method (FEM). The beam 188 element of ANSYS software is employed to simulate the shaft of the rotor system. The rotor and the turbine are simplified as lumped mass that is simulated by mass 21 element in the model. The combine 14 element is used to simulate guide bearings. The dynamic characteristics of the bearings are equivalent to the stiffness and damping coefficients \((k_{ij}, c_{ij})\) of the element. The rotor system model is mounted on the model of powerhouse by constraint equations. A FEM model of tilting pad guide bearing is used in the rotor system \[11\].

3. Water pressure fluctuation and other loads

The rotating frequency of helical vortex rope in the draft tube is the frequency of pressure fluctuation \[12\], while the frequency is concerned with inlet vortex circulation of draft tube. The inlet vortex circulation is supposed to be equal to the outlet vortex circulation of turbine for simplification, \[13\]

\[ \Gamma = 2\pi r_2 V_{a2} = 2\pi r_a V_{ma} \]  \[12\]

According to the velocity triangle of turbine runner,

\[ V_{a2} = kV_2 - V_{ma} \text{ctg} \beta_2 \]  \[13\]

Substitute \( V_2 = 2\pi r_2 n/60, \ V_{ma} = Q/F \),

\[ V_{a2} = \frac{2\pi k r_2}{60} n - \frac{Q}{F} \text{ctg} \beta_2 \]  \[14\]

As the definition of the frequency,

\[ f_r = \frac{V_{ma}}{2\pi r_u} = \frac{V_{a2} r_2}{2\pi r_u^2} = k \left( \frac{r_2}{r_u} \right)^2 \frac{n}{60} - \frac{r_2}{2\pi r_u^2} \frac{Q}{F} \text{ctg} \beta_2 \]  \[15\]

The equation for amplitude of pressure fluctuation is derived in paper \[13\],

\[ P = 2\pi r_u V_{ma} e_r \left( r_u^2 - r_v^2 \right)^{-1} \]  \[16\]

In order to express the pressure fluctuation caused by vortex rope, according to the analysis from the experiment results \[14\], the eccentric of vortex is supposed as
\begin{equation}
\begin{aligned}
    e_v &= 0 & P'_t \leq 0.3 \\
    e_v &= 0.5P'_t - 0.15 & 0.3 < P'_t \leq 0.5 \\
    e_v &= -0.5P'_t + 0.375 & 0.5 < P'_t \leq 0.7 \\
    e_v &= 0 & 0.7 < P'_t \leq 0.85 \\
    e_v &= 0.075P'_t - 0.06375 & 0.85 < P'_t \leq 1.25
\end{aligned}
\end{equation}

The unbalanced magnetic pull is derived from paper\textsuperscript{[15]}.

4. Numerical calculation and analysis

\begin{table}[h]
\centering
\begin{tabular}{cccccccc}
\hline
Nominal value of Turbine & Length/diameter of penstock (m) \\
\hline
$H$(m) & Weight (t) & $e_v$(mm) & $Q$(m\textsuperscript{3}/s) & $S$(kVA) & $n$(r/min) & \\
\hline
116.2 & 207 & 4.5 & 90.57 & 103.4* & 150* & 495/8.5 \\
\hline
\end{tabular}
\caption{Data of models}
\end{table}

A numerical example for a signal machine with load is calculated. The transient process is suddenly load-up operation of 10\% rated power at 55\% rated power condition. There are two groups of parameters for speed governor as: (a) a stable process of small fluctuation, (b) an unstable process of small fluctuation, which is noted in Table 1 and in the figures of result analysis. The eccentric force and UMP are acted on the rotor and turbine, while the pressure pulse is only applied on the shell of straight part of draft tube.
The change laws for parameters of hydropower station system are depicted in Figure 2. As shown in Figure 4(a), because of sudden-up of electric power ($P_e$), the terminal voltage ($U_G$) is suddenly decreased, and then returns to rated value after a short-term fluctuation by the excitation regulation. For the same reason, the speed of unit is decreased because the electric power is larger than turbine power ($P_t$) at first. So gate opening ($\tau$) is regulated by governor to increase turbine discharge, then, the turbine power is increased and balanced with the electric power gradually. Finally, the system is stable at the 65% rated power condition. However, in Figure 4(b), for the reason for ineffective regulating parameters of speed governor, turbine power is unstable in a long time, the system is operated around the 65% rated power condition. From the change laws in (a) and (b), it illustrated that the $P_e$ and $U_G$ are stabilizing because of excitation regulation with unchanged parameter $K_V$, which leads to a conclusion that the speed governor regulation has no influence on the regulation of $P_e$ and $U_G$.

**Figure 2.** Variation laws of parameter during small fluctuation

UMP is shown in Figure 3. The value of UMP changes fast and with big range because terminal voltage fluctuation caused by sudden load-up. Then the filed current is unchanged when the terminal voltage

![Figure 3. Change of UMP](image)
achieved the rated value, the UMP is balanced with small variation, it is because the value of UMP is influenced by axis displacement of rotor.

The pressure fluctuation’s frequency and amplitude are described in Figure 4. The pressure pulsation caused by vortex rope is belong to the low frequency fluctuation.

![Figure 4](image)

**Figure 4** Pressure fluctuation and its frequency

The displacements of rotor and turbine are presented in Figure 5 ~ 6. The vibration of rotor and turbine are influenced by the changed UMP and pressure pulse during the small fluctuation process. The total displacements of rotor and turbine in Figure 5(a) ~ 6(a) has a larger oscillation before 25s, and then became stable in dynamic. Nonetheless, in Figure 5(b) ~6(b), they always maintain a large fluctuation. This phenomenon is caused by the variation of pressure fluctuation in Figure 4. Because the different changing of frequency, the pressure value has different trends.

![Figure 5](image)

**Figure 5.** Total displacement of rotor

![Figure 6](image)

**Figure 6.** Total displacement of turbine

FFT for rotor axial x-displacement is shown in Figure 7, FFT of turbine axial displacements has the same basic frequency which is rotating frequency. It indicates that the main forces of unit vibration are eccentric force and UMP, the pressure fluctuation has little influence because of its way of load application.
Generator floor is the typical component of powerhouse structure. The maximum displacements of generator slab in three directions are illustrated in Figure 8. The amplitude of displacements in (b) is larger than that in (a), especially in z-direction. Obviously, it is caused by the pressure pulse in the
unstable small oscillation.

FFT for floor displacements are shown in Figure 9. The basic frequency in horizontal direction is rotating frequency, while there are also many other frequencies. And the basic frequency is a high frequency in z-direction. It indicates that the main source of floor vibration is pressure fluctuation.

5. Conclusion

The coupled model of hydropower station system is established to study the operation characteristics during small oscillation process. The conclusions are as follows:

(1) The speed regulation has little impact on the transient process of generator.
(2) The excited resources of rotor and turbine are from the rotation of unit, while the UMP has a greater effect.
(3) The main vibration source of generator slab is pressure fluctuation which is caused by vortex rope in draft tube in this paper, especially in the vertical direction.

Acknowledgment

This research is supported by the National Natural Science Foundation of China (No.51379030).

Appendix

a-water hammer wave velocity

$b_p$-permanent droop

$b_t$-temporary droop

c,b,c,r-clearance of bearing, rotor (air-gap length)

$D,A$-the cross section diameter and area of penstock

$D_1$-the diameter of water turbine

$E^t$-transient EMF(electromotive force)

$e,e_c,e_r$-eccentricity of turbine, rotor centre

e,e_c,e_r- eccentricity of vortex rope

$E_0d$-imaginary open-circuit EMF generated by field voltage

$E_q$-open-circuit terminal EMF

$E_{q'}$-q-axis transient EMF

$F$-section of turbine outlet

$H$-head in penstock at the node i

$H_{np}$-net water head of turbine

$I,I_d,I_q$-stator current, its d and q-component

$I_f$-field (excitation) current and voltage

$J$-inertia moment of unit in direction of rotation

$k$-correction coefficient of absolute velocity of flow

$k_{y,x},c_{y,x}$-stiffness, damping coefficients, i=x,y; j=x,y

$K_p,K_i,K_d$- governor gain

$M_n,M_e$-mechanical torque and electric torque

$n,n_1$-water turbine’s mechanical and unit speed

$P_e$-electric power (active output)

$P_n,P_r'$-power and unit power of water turbine

$Q_r'$-water turbine’s unit discharge

$Q$, discharge in penstock at the node i

$R_a,R_e$-radius of shaft and rotor

$R_d$- journal radius

$R_s,R_{Li}$ -resistance of transmission and system

$r_s,r_d$ -radius of turbine outlet, draft tube inlet

$T_d$-reset time or dashpot constant

$T_{d0}'$-d-axis open-circuit transient time constant

$T_e$-time constant of excitation

$T_{w}$-water turbine inertia time constant

$T_{w}$-accelerating time constant

$T_{w}$-water inertia time constant

$T_y$-servomotor response time constant

$U_{L}$-system voltage

$U_{Gh},U_{Gd},U_{Gq}$- terminal voltage, d-, q-component

$V_2,V_{a2},V_{m2}$-absolute velocity of flow of turbine outlet, its circumferential and axial plane component

$V_{au}$-circumferential velocity of flow of draft tube
inlet

\( X_{L} \) - reactance of transmission and load

\( X_{d}, X_{q} \) and d axis synchronous reactance

\( X'_{d} \) - d-axis transient reactance

\( y, \Delta y \) - water turbine servomotor stroke and its deviation value

\( \beta_{a} \) - blade outlet angle of turbine

\( \Gamma \) - flow circulation

\( \delta \) - torque-angle/power-angle

\( \rho \) - water density

\( \tau \) - gate opening

\( \omega_{m}, \omega_{e} \) - mechanical speed and electric speed

\( \omega_{ms}, \omega_{es} \) - mechanical/electric synchronous speed

the superscript * represent the per-unit parameters

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