Stability Analysis of Different Regulation Modes of Hydropower Units

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Abstract: The dynamic characteristics of hydropower unit governing systems considerably influence the stability of hydropower units and the connected power system. The dynamic performances of hydropower units with power regulation mode (PRM) and opening regulation mode (ORM) are different. This paper establishes a detailed linear model of a hydropower unit based on the Phillips–Heffron model. The damping characteristic and stability of two regulation modes with different water inertia time constants $T_W$ were analyzed. ORM tended to provide negative damping, while PRM often provided positive damping in the major parts of the frequency range within the normal frequency oscillations when $T_W$ was large. Eigenvalue analysis illustrated that PRM has better stability than ORM. To validate the analysis, a simulation under two typical faults was conducted based on a nonlinear model of a hydropower unit. The simulation results illustrated that the responses of units with PRM are more stable in terms of important operating parameters, such as output power, rotor speed, and power angles. For hydropower units facing challenges in stable operation, PRM is recommended to obtain good dynamic stability.

Keywords: hydropower; power regulation mode; opening regulation mode; damping characteristic; dynamic stability

1. Introduction

With the strong demand for clean and green energy, hydropower energy has experienced rapid development in recent years. When adequate environmental flow is guaranteed and the ecological impact is controlled, hydropower is a superior renewable energy source [1,2]. Hydropower units are responsible for the regulation of frequency and power in power systems [3,4]. In a traditional large-scale power grid, where hydropower often provides a small proportion of total power input, the impact of hydropower units on power system stability is neglected. With the increasing momentum toward having flexible power systems based on renewables, hydropower is playing a more important role in power systems, and some hydropower-domain power systems have appeared [5,6]. In hydropower-domain power systems, such as the Colombian Grid, Nordic Grid, and power grids in the Chinese southwest, the dynamic characteristics of hydropower units have a significant influence on system stability [7–9], but it requires further detailed study of the dynamic characteristics of hydropower units.

Compared with thermal power units, controlling hydropower units is difficult due to the nonlinear characteristics of hydroturbines and the water hammer phenomenon [10]. The water hammer phenomenon makes the hydroturbine-governing system a non-minimum phase system. Strong nonlinear characteristics pose a challenge for the smooth and accurate control of hydroturbines. With such inherent defects, various unstable phenomena caused by hydropower units have been observed in hydropower-domain power systems, such as low frequency oscillations and power fluctuations. Scholars have searched for the factors that lead to unstable phenomena, and have proposed new control strategies to achieve stable regulation and operation. Many causes can result in frequency oscillations,
such as the induction generator effect, turbine damping, the inertia ratio, proportional-integral-derivative (PID) controller parameters, and the feed-forward controllers [11–15]. Hydraulic fluctuation is also a common cause of unstable regulation and operation in transient processes [16–18]. The proportion of hydropower in energy sources also affects the stability of a system [19]. Various methods, including the state space method, the extended equal area criterion theory, and the physical model experiment, can be used to analyze transient stability of hydropower system [15,20,21]. With the proportional-integral (PI) controller remaining as the main control method, many additional control strategies have been proposed. Controllers based on fuzzy control, neural network control, sliding mode control, and so on have been developed and applied [22,23].

Despite the many achievements, a number of unresolved questions remains. Few researchers have focused on the selection strategy of regulation modes that significantly influence the stability of hydropower units. Research on the dynamic characteristics of different regulation modes is required to provide some guidelines for the hydropower units in hydropower-dominant power systems.

For the grid-connected hydropower units, the hydroturbine governors often use open-loop regulation mode (ORM) or power regulation mode (PRM) [8]. PRM and ORM have different feedback signal sources. The feedback signal of ORM is the gate position control signal, or the gate position measured value. In PRM, the output power is the feedback signal. With different structures of closed-loop control systems, ORM and PRM have different dynamic characteristics. While little research has been conducted on the comparison of ORM and PRM, in most of the studies mentioned above, ORM was adopted for its simple closed-loop structure. Few studies concentrated on quantifying the characteristics of frequency oscillations while proposing a systematic tool to improve the regulation quality in both PRM and ORM, but without comparing the ORM and PRM [24]. In reference [25], ORM was found to have increased stability under a small load disturbance for hydropower units in an isolated system analysis. While this study was concerned with the isolated system and neglected the electromagnetic transient process, Chen et al. analyzed the stability of hydropower units with different regulation modes and found that the stability of pure power regulation modes are clearly superior to frequency regulation modes under the same conditions [26]. Whereas the pure power mode only aims to control power and regards the frequency deviation as unavailable in real power grids, in a previous study, characteristic analysis and comparison of ORM and PRM was far from sufficient.

In engineering, ORM is widely used in the hydropower-domain grids, such as the Sichuan grid, Chongqing grid, and Xizang grid in China. The feedback link of ORM is in the governor. The hydroturbine and generator are not in a closed-loop control system. Free from external disturbance, ORM is considered to have better stability. Since the feedback of PRM is the output power, which is sensitive to external disturbances, PRM is thought to produce negative damping. However, this simple inference is lacking detailed theoretical deduction. Further research and validation are necessary to construct a criterion for regulation mode selection.

We analyzed and compared ORM and PRM through theoretical analysis and numerical simulation. In this study, the system of a hydropower unit in ORM and PRM was established. The damping characteristics and stability of two regulation modes were analyzed. The PRM was found to have better stability. The numerical simulation, based on real nonlinear models, proved the results.

2. Damping Characteristics of ORM and PRM

In the regulating process of hydropower units, the damping characteristic is determined by a governing system and an excitation system. In the 1960s, the Phillips–Heffron model was proposed to study the damping provided by excitation systems in electromechanical oscillation in the infinite-bus system [27]. Based on the Phillips–Heffron model, we analyzed the damping characteristic of governing systems with PRM and ORM in electromechanical oscillation in the infinite-bus system.
Assuming the power system stabilizer is equipped, the transient exciting potential, \( Eq' \), is unchanged. The electromagnetic torque increase caused by the change in transient exciting potential \( Eq' \) is neglected. The electromagnetic torque increase caused by the change in power angle \( \delta \) is calculated. The diagram block of the hydropower unit is shown in Figure 1.

**Figure 1.** Structure of a hydropower unit.

\( K_p \) and \( K_i \) are the scaling coefficient and integral coefficient, respectively; \( b_p \) and \( e_p \) are the temporary droop and permanent droop, respectively; \( \Delta y_c \) is the increase in the gate opening position control signal; \( \Delta y \) is the increase in the gate opening position; \( \Delta T_M \) is the increase in the hydroturbine output torque; \( \Delta T_e \) is the increase in electromagnetic torque; \( \Delta \omega \) is the increase in rotor speed; \( \Delta \delta \) is the increase in power angle; \( \omega_0 \) is the rated angular frequency; \( K \) is the transfer coefficient from the power angle to electromagnetic torque; \( D \) is the damping coefficient; and \( T_a \) is the inertia time constant of the generator.

### 2.1. Mathematical Models of the System

1. The governor

The governor consists of a PI controller and a servo system. The difference between PRM and ORM is the feedback signal of the PI controller. The transfer function of a PI controller is written as:

\[
G_{PI}(s) = \frac{K_ps + K_i}{s}. \tag{1}
\]

The assistant servomotor is adopted in the servo system. The transfer function of a servo system is written as:

\[
G_{servo}(s) = \frac{1}{T_{yB}s^2 + T_ys + 1} \tag{2}
\]

where \( T_{yB} \) and \( T_y \) are the time constant of the assistance servomotor and main servomotor, respectively.

In most hydropower stations, \( T_{yB} \) and \( T_y \) are small. In IEC61632 standards, \( T_y \) is less than 0.25 s and larger than 0.1 s. In most cases, \( T_{yB} \) is less than 0.05 s. Thus, \( T_{yB} \) is regarded as 0.

\[
G_{servo}(s) = \frac{1}{T_ys + 1} \tag{3}
\]

2. The hydroturbine and division system
The hydroturbine is a nonlinear component. In stability analysis, a hydroturbine is assumed as working in a small region where it is approximately linear. The linear equation of a hydroturbine is written as:

\[
\begin{cases}
T_M = e_y y + e_h h + e_x x \\
q = e_y y + e_h h + e_q x 
\end{cases}
\]  

(4)

where \( e_y, e_x, \) and \( e_h \) denote the partial derivatives of the hydroturbine torque \( T_M \) with respect to guide vane opening \( y \), speed \( x \), and head \( h \), respectively; \( e_qy, e_qx, \) and \( e_qh \) denote the partial derivatives of the flow \( q \) with respect to gate opening \( y \), speed \( x \), and head \( h \), respectively.

In this paper, we consider the Francis turbine. For the Francis turbine, \( e_qx = 0 \). \( e_x \) is combined with a load frequency adjusting coefficient.

The inelastic water hammer model is adopted:

\[
h(s) \overline{q(s)} = -T_W s,
\]

(5)

where \( T_W \) is the time constant of the water conduit.

Overall, the transfer function of a hydroturbine can be written as:

\[
G_i(s) = e_y \frac{1 - eT_W s}{1 + e_qh T_W s},
\]

(6)

where \( e = e_y \times e_qh / e_y - e_h \).

(3) The generator

As shown in Figure 1, the generator model in the Phillips–Heffron model is written as:

\[
\begin{align*}
T_a \frac{d\omega}{dt} &= \Delta T_M - \Delta T_e - D\Delta\omega \\
\Delta\omega &= \frac{1}{\delta_0} \frac{d\Delta s}{dt} \\
\Delta T_e &= K\Delta\delta
\end{align*}
\]

(7)

2.2. Damping Characteristic in ORM

From Figure 1 and the equations in Section 2.1, the increase in hydroturbine output torque in ORM is obtained by:

\[
\Delta T_M = -\Delta\omega \frac{G_{pl}}{1 + b_p G_{pl}} G_{servo} G_t = -\Delta\omega G_{ym}
\]

(8)

\[
G_{ym}(s) = \frac{K_{ps} + K_i}{(1 + b_p K_p) s + b_p K_i T_y s + T_y s + T_y e_qh T_W s}
\]

(9)

When \( s = j\omega \),

\[
G_{ym}(j\omega) = K_Y (\text{Re}_Y + \text{Im}_Y j),
\]

(10)

where

\[
\begin{align*}
K_Y &= \frac{e_y}{[b_p K_p^2(1 + b_p K_p)^2 + 1 + e_qh T_W^2 \omega^2]} > 0 \\
\text{Re}_Y &= A_Y \omega^4 + B_Y \omega^2 + C_Y \\
A_Y &= -e_qh T_W^2 \left[ K_p (1 + b_p K_p)^2 - T_y K_j \right] + T_y K_p (1 + b_p K_p)^2 \left( e + e_qh \right) \\
B_Y &= K_p (1 + b_p K_p)^2 - T_y K_j - \left( e + e_qh \right) T_W T_y (1 + b_p K_i T_y) \\
C_Y &= b_p K_i^2 > 0
\end{align*}
\]

(11)

The damping torque \( \Delta T_D \) is:

\[
\Delta T_D = K_Y \times \text{Re}_Y \times (-\Delta\omega).
\]

(12)
The direction of $\Delta T_D$ is determined by the signs of $K_Y$ and $Re_Y$. When $K_Y$ and $Re_Y > 0$, $\Delta T_D$ is in the same direction as $-\Delta \omega$. The governor provides positive damping.

According to Equation (11), $K_Y > 0$ and $C_Y > 0$.

The value of $A_Y$ is related to the values of the parameters, while the sign of $A_Y$ is identifiable. According to the normal standards of power system, $b_p = 0.04$ in most cases.

$$A_Y < -e_{qh} T_W^2 \left[ K_P \left( 1 + b_P K_P \right)^2 - T_Y K_I \right] < -e_{qh} T_W^2 \left( K_P - 0.2 K_I \right),$$  

(13)

The values of $K_P$ and $K_I$ are often tuned based on the values of $T_W$ and $T_a$. There is no widely accepted or accurate tuning method. In engineering, the difference in $K_P$ and $K_I$ is often not very big, which means $K_P/K_I < 5$. Thus, $A_Y$ is negative.

Setting $Re_Y = 0$, the critical frequency $\omega_1$ is obtained by:

$$\omega_1 = \sqrt{\frac{B_Y + \sqrt{B_Y^2 - 4 A_Y C_Y}}{-2 A_Y}} = \sqrt{\frac{2}{-2 A_Y}} \omega_0,$$

(14)

When $\omega < \omega_1$, $Re_Y > 0$, $\Delta T_D$ is in the same direction as $-\Delta \omega$; when $\omega < \omega_1$, $Re_Y < 0$, $\Delta T_D$ is in the opposite direction as $-\Delta \omega$. In Equation (14), $X$ is the first-order function of $T_W$ and $A_Y$ is the second-order function of $T_W$. $\omega_1$ varies inversely with $T_W^{0.5}$, meaning that $\omega_1$ decreases as $T_W$ increases.

The direction of $\Delta T_M$ in the $\Delta \delta - \Delta \omega$ coordinates system is shown in Figure 2.

![Figure 2](image_url)  

Figure 2. Location of the change in hydroturbine torque ($\Delta T_M$) in opening regulation mode (ORM).

In a low-frequency region, $\Delta T_D$ is in the same direction as $-\Delta \omega$. The regulation of the governor provides negative damping and worsens system stability. In a high frequency region, $\Delta T_D$ is in the same direction as $-\Delta \omega$. The regulation of a governor provides negative damping and worsens system stability. With increasing $T_W$, the critical frequency $\omega_1$ decreases and system stability deteriorates.

To validate the conclusion, a real hydropower unit was chosen as an example. The hydroturbine was linearized in a certain operating point, where $c_y = 1.6$, $e = 1.02$, and $e_{qh} = 0.48$. $K_P$ was 5 and $K_I$ was 8. When $T_W$ was 0.2, 1.2, 2.2, and 3.2, the values of $K_P$ and $K_I$ and the corresponding response time were as listed in Table 1. The power response times in different conditions are almost the same and meet the standards.
Table 1. The parameters in ORM.

| $T_W$ | $K_P$ | $K_I$ | Power Response Time (s) | Critical Frequency (rad/s) |
|-------|-------|-------|--------------------------|---------------------------|
| 0.2   | 4     | 6.1   | 14                       | 2.68                      |
| 1.2   | 4     | 6.8   | 14                       | 0.40                      |
| 2.2   | 4     | 7.5   | 14.1                     | 0.28                      |
| 3.2   | 4     | 8.7   | 14.1                     | 0.23                      |

The Bode graph of $G_{Ym}(s)$ is shown in Figure 3. In Figure 3, in the low-frequency region, the phase angle is between $270^\circ$ and $360^\circ$; in the high-frequency region, the phase angle is between $90^\circ$ and $270^\circ$. ORM provides positive damping in the low-frequency region and provides negative damping in the high-frequency region. The critical frequency decreases with increasing $T_W$. The stability deteriorates with increasing $T_W$.

2.3. Damping Characteristics in PRM

From Figure 1 and the equations in Section 2.1, the increase in hydroturbine output torque in PRM is obtained by:

$$\Delta T_M = -(\Delta \omega + K_P \Delta \delta) G_{P1} G_{servo} G_t = -\Delta \omega G_{Pm},$$  \hspace{1cm} (15)
\[ G_{Y_m}(s) = \left(1 + K e_p \frac{\omega_0}{s} \right) \frac{K p s + K_i}{s} \frac{1}{1 + \frac{1}{e_y} \frac{1 - e T_{WS}}{1 + e q h T_{WS}}}. \]  

(16)

When \( s = j \omega \),

\[ G_{p_m}(j \omega) = K_p (R e_p + I m_j), \]

(17)

where

\[
\begin{align*}
K_Y &= \omega^2(1+2 e^2)/(1+e^2 T_w^2) > 0 \\
R e_p &= A_p \omega^4 + B_p \omega^2 + C_p \\
A_p &= -e e_q h T_w^2 [K_p - T_y K_i - K e_p \omega_0 T_y K_p] - T_y K_p T_w (e + e_q h) \\
B_y &= K_p - K_i T_w (e + e_q h) - K e_p \omega_0 [e e_q h T_w^2 K_i + (e + e_q h) (T_y K_i T_w - K_p T_w) - K_p T_y] \\
C_y &= -K e_p \omega_0 K_i > 0
\end{align*}
\]

(18)

The damping torque \( \Delta T_D \) is:

\[ \Delta T_D = K_p \times R e_p \times (-\Delta \omega), \]

(19)

The direction of \( \Delta T_D \) is determined by the signs of \( K_p \) and \( R e_p \). When \( K_p \) and \( R e_p > 0 \), \( \Delta T_D \) is in the same direction as \( -\Delta \omega \). The governor provides positive damping. According to Equation (18), \( K_p > 0 \) and \( C_p < 0 \). When \( \omega \) is very low, \( R e_p < 0 \). The governor provides negative damping in low-frequency regions. The sign of \( A_p \) is related to the parameters. In engineering, \( \omega_0 = 314, e_p = 0.04, 0.1 < T_y < 0.2, \) and \( K \) is related to the operating condition. In normal operating conditions, \( 0.8 < K < 1.2 \), and the coefficient of \( T_w^2 \) is positive.

\[-K_p + K_i T_y + K e_p \omega_0 K_p T_y > 0.0048 K_p + 0.1 K_i > 0\]  

(20)

Order \( A_p > 0 \), then

\[ T_w > \frac{e e_q h (-K_p + K_i T_y + K e_p \omega_0 K_p T_y)}{(e + e_q h) K_p T_y}, \]

(21)

When Equation (21) is tenable, the sign of \( A_p \) is positive. Setting \( R e_p = 0 \), the critical frequency \( \omega_1 \) is obtained by:

\[ \omega_1 = \sqrt{-B_p + \frac{B_p^2 - 4 A_p C_p}{2 A_p}} = \sqrt{\frac{Y}{2 A_p}}. \]

(22)

When \( \omega < \omega_1 \) and \( R e_p < 0 \), \( \Delta T_D \) is in the same direction as \( -\Delta \omega \); when \( \omega < \omega_1 \) and \( R e_p > 0 \), \( \Delta T_D \) is in the opposite direction as \( -\Delta \omega \). In Equation (2), \( \omega_1 \) decreases as \( T_w \) increases. Generally, when Equation (21) is false, \( \Delta T_D \) is in the opposite direction as \( -\Delta \omega \) in almost all frequency regions. The regulation of a governor provides negative damping and worsens system stability. When Equation (21) is tenable, the direction of damping torque depends on frequency \( \omega \). In low-frequency regions, \( \Delta T_D \) is in the same direction as \( -\Delta \omega \). The regulation of the governor provides negative damping. In high-frequency regions, \( \Delta T_D \) is in the same direction as \( -\Delta \omega \). The regulation of the governor provides positive damping. With the increase in \( T_w \), the critical frequency \( \omega_1 \) decreases and system stability improves.

The same as with ORM, the same hydropower unit was chosen as an example. The values of \( K_p \) and \( K_i \) and corresponding response times are listed in Table 2. The power response times in different conditions are almost the same and meet the standards.
Table 2. The parameters in power regulation mode (PRM).

| \( T_W \) | \( K_P \) | \( K_I \) | Power Response Time (s) | Critical Frequency (rad/s) |
|---------|--------|--------|------------------------|---------------------------|
| 0.2     | 2      | 3.4    | 14.1                   | -                         |
| 1.2     | 2      | 2.8    | 14.1                   | 4.77                      |
| 2.2     | 2      | 2.3    | 14.2                   | 2.1                       |
| 3.2     | 1.8    | 1.9    | 14.1                   | 0.98                      |

The Bode graph of \( G_{Pm}(s) \) is shown in Figure 4. In Figure 4, the phase characteristic when \( T_W = 0.2 \) is different compared with the others. In this condition, Equation (21) is false. The phase angle is between 90° and 225° in all frequency region. The governor always provides negative damping. When \( T_W = 1.2, 2.2, \) and 3.2, the phase angle is between 0° and 90° in high-frequency regions. The governor provides positive damping. The critical frequency \( \omega_1 \) is 4.77, 201, and 0.98, illustrating that PRM worsens the stability in low-frequency regions and improves the stability in high-frequency regions when Equation (21) is tenable. The stability is strengthened with increasing \( T_W \).

Figure 4. Bode graphs of \( G_{Pm}(s) \) with different \( T_W \): (a) \( T_W = 0.2 \); (b) \( T_W = 1.2 \); (c) \( T_W = 2.2 \); (d) \( T_W = 3.2 \).
3. Stability Analysis of Different Modes

In this section, the stability of power angles with disturbance of electromagnetic torque is studied through eigenvalue analysis. From Figure 1, the block diagrams of ORM and PRM are obtained thorough transformation.

3.1. Transfer Function of ORM

The block diagram of ORM is shown in Figure 5.

\[
G_{Ym}' = \frac{G_g}{1 + KG_{Ym}} \frac{\omega_0}{s} = \frac{a_Y's^3 + b_Y's^2 + c_Y's + d_Y'}{A_Y's^5 + B_Y's^4 + C_Y's^3 + D_Y's^2 + E_Y's + F_Y'}
\] (23)

3.2. Transfer Function of PRM

The block diagram of PRM is shown in Figure 6.

The transfer function is:

\[
G_{Prm}' = \frac{(1 + e_pG_{gov})G_g}{1 + K(1 + e_pG_{gov})} \frac{\omega_0}{s} = \frac{a_p's^3 + b_p's^2 + c_p's + d_p'}{A_p's^5 + B_p's^4 + C_p's^3 + D_p's^2 + E_p's + F_p'}
\] (24)

3.3. Eigenvalue Analysis of ORM and PRM

To conduct further analysis, the PI coefficients in Tables 1 and 2 were adopted. Under these parameters, the power response times were almost the same. Then 8 functions of different $T_W$ and regulation modes were obtained.

The indexes of these functions are listed in Tables 3 and 4.
Figure 6. Block diagram of PRM.

Table 3. The parameters in ORM.

| $T_W$ | Zero         | Pole          | Damping Ratio | Natural Frequency (rad/s) |
|-------|--------------|---------------|---------------|--------------------------|
| 0.2   | -0.0939 +    | -0.2345       | 0.0183        | 5.1199                   |
|       | 5.1190i      |               | 0.2246        | 1.000                    |
|       | -6.6667      |               | 1.000         | 5.3849                   |
|       | -0.2586      | 5.1190i       | 0.0183        | 5.1199                   |
|       | -0.2418      | -1.6709       | 1.6709        | -6.6667                  |
|       | -0.2345      | -1.6667       | 5.1199        | 7.4845                   |
|       | -6.6667      | -0.2345       | 5.1190i       | 7.4845                   |
|       | 5.0221i      | 5.0221i       | 5.0238        | 5.0238                   |
|       | -0.1311 -    | 5.0221i       | 7.3419        | 0.9885                   |
|       | -0.1311 +    | 5.0221i       | 7.3419        | 0.2664                   |
|       | -0.1311 -    | -0.1311 +     | 0.2664        | 0.7375                   |
| 3.2   | -0.6250      | 4.9705i       | 7.2708        | 9.730                    |
|       | 4.9705i      | -0.2586       | 7.2708        | 4.9730                   |
|       | -0.3000      | 4.9705i       | 4.9730        | 4.9730                   |
|       | -0.1585 -    | 4.9705i       | 4.9730        | 4.9730                   |
Table 4. The parameters in PRM.

| $T_W$ | Zero | Pole | Damping Ratio | Natural Frequency (rad/s) |
|-------|------|------|---------------|--------------------------|
| 0.2   | $-7.3752 +$ | $-0.1018 +$ | 1.0000        | 0.2071                  |
|       | $3.8488i$ | $5.2020i$ | 0.0196        | 5.2030                  |
| 1.2   | $-7.3752 -$ | $-0.1018 -$ | 0.0196        | 5.2030                  |
|       | $3.8488i$ | $5.2020i$ | 1.0000        | 7.4804                  |
|       | $-0.2096$ | $-7.4804$ | 1.0000        | 9.7755                  |
|       | $-9.7755$ |          |               |                         |
|       | $-0.2255$ |          |               | 0.2255                  |
|       | $-4.4456$ | $-0.5081 +$ | 1.0000        | 1.8498                  |
| 2.2   | $-1.9516$ | $4.6213i$ | 0.1093        | 4.6492                  |
|       | $-0.2295$ | $-0.5081 -$ | 0.1093        | 4.6492                  |
|       | $4.6213i$ |          | 1.0000        | 6.2418                  |
|       | $-6.2418$ |          |               |                         |
|       | $-0.2537$ |          |               | 0.2537                  |
|       | $-0.7184$ |          | 1.0000        | 0.7184                  |
|       | $-4.9143$ | $-0.6449 +$ | 1.0000        |                         |
|       | $-0.6927$ | $4.6364i$ | 0.1378        | 4.6811                  |
| 3.2   | $-0.2621$ | $-0.6449 -$ | 0.1378        | 4.6811                  |
|       | $4.6364i$ |          | 1.0000        | 6.3139                  |
|       | $-6.3139$ |          |               |                         |
|       | $-0.2882 +$ |          | 0.1248i       |                         |
|       | $0.1248i$ |          | 0.9177        | 0.3141                  |
|       | $-5.1917$ | $-0.2882 -$ | 0.9177        | 0.3141                  |
|       | $-0.2820 +$ |          | 0.9177        | 0.3141                  |
| 3.2   | $0.1345i$ | $-0.6713 +$ | 0.1407        | 4.7725                  |
|       | $-0.2820 -$ |          | 0.1407        | 4.7725                  |
|       | $0.1345i$ | $-0.6713 -$ | 1.0000        | 6.3726                  |
|       | $4.7250i$ |          | 1.0000        |                         |
|       | $-6.3726$ |          |               |                         |

The dynamic performance of systems in ORM is determined by two conjugate poles. When $T_W$ increases to 1.2 from 0.2, the real part of the dominant poles decreases significantly from 0.271 to 0.0129. The stability deteriorates greatly. From 1.2 to 3.2, the stability margin increases a little from 0.0129 to 0.0712, while the damping ratios are only about 0.01, resulting in poor stability.

In PRM, the stability also deteriorates considerably from $T_W = 0.2$ to $T_W = 1.2$. The stability is improved from $T_W = 1.2$ to $T_W = 3.2$. When $T_W = 3.2$, the damping ratio is 0.2058, which much larger than that of ORM, indicating that PRM has better stability than ORM.

4. Numerical Simulation and Validation

The analysis above is based on a linear model. While the linear mode is unable to study the most common disturbances in a power system, to further validate the conclusion above, a nonlinear model that is able to describe the real characteristic of hydropower unit and electromagnetic transient process was established. The simulation under two faults was conducted to study the performance of ORM and PRM further.

4.1. System Model

The structure of a system model is shown in Figure 7. The model was built based on the operating data of a real hydropower unit.
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Figure 7. Block diagram of the simulation system.

The PI controller servosystem was well-described in Section 2. The model of a hydroturbine is described by the matrixes of six coefficients in Equation (4) in various gate positions and unit speeds [28]. The model can accurately reflect the nonlinear characteristic of hydroturbine. The 7-order normal model of the salient-pole synchronous generator model was adopted [29]. The excitation system was the static excitation system with a power system stabilizer [29]. The power grid was assumed to be an infinite system.

Two typical disturbances are simulated in the system:

1. **Disturbance 1:** Three-phase short circuit. In 1 s, the three-phase short circuit occurs in the head of a line; the breaker trips in 1.15 s and closes in 1.75 s.
2. **Disturbance 2:** Voltage fluctuation. A sine wave is added on the system voltage in 5 s and disappears in 20 s. Its frequency is 0.16 Hz and the amplitude is 2% of the rated value.

Simulations using different $TW$ of ORM and PRM were conducted. The parameters of the six simulation cases are listed in Table 5.

| Simulation Case | Regulation Mode | $TW$ |
|-----------------|-----------------|------|
| Case 1          | ORM             | 0    |
| Case 2          | ORM             | 1.3  |
| Case 3          | ORM             | 2.7  |
| Case 4          | PRM             | 0    |
| Case 5          | PRM             | 1.3  |
| Case 6          | PRM             | 2.7  |

#### 4.2. Responses under Three-Phase Short Circuit

To accurately illustrate the performance in detail, the responses of hydroturbine output torque $m_t$, power angle $\delta$, and rotor speed deviation $x$ are given in the Figures 8–10 below.

1. **Response of hydroturbine output torque $m_t$**
   - The order of the stability of hydroturbine output torque $m_t$ responses in 6 cases was found to be: Case 3 > Case 2 > Case 1 > Case 6 > Case 5 > Case 4.

2. **Response of power angle $\delta$**
   - The order of the stability of the power angle $\delta$ responses in the 6 cases was found to be: Case 6 > Case 5 > Case 1 > Case 3 > Case 2 > Case 4.

3. **Response of rotor speed deviation $x$**
   - The order of the stability of rotor speed deviation $x$ responses in the 6 cases was: Case 6 > Case 5 > Case 2 > Case 3 > Case 1 > Case 4.

#### 4.3. Responses under Voltage Fluctuation

The responses of hydroturbine output torque $m_t$, power angle $\delta$, rotor speed deviation $x$ and output power $P$ are given in Figures 11–14 below.
Figure 6. Block diagram of PRM.

Figure 7. Block diagram of the simulation system.

Figure 8. Response of hydroturbine output torque $m_t$ under three-phase short circuit.

Figure 9. Response of power angle $\delta$ under three-phase short circuit.

Figure 10. Response of rotor speed deviation $x$ under a three-phase short circuit.
Figure 9. Response of power angle $\delta$ under three-phase short circuit.

Figure 10. Response of rotor speed deviation $x$ under a three-phase short circuit.

Figure 11. Response of hydroturbine output torque $m_t$ under voltage fluctuation.
Figure 11. Response of hydroturbine output torque $m_t$ under voltage fluctuation.

Figure 12. Response of power angle $\delta$ under voltage fluctuation.

Figure 13. Response of rotor speed deviation $x$ under voltage fluctuation.
Figure 13. Response of rotor speed deviation \( x \) under voltage fluctuation.

Figure 14. Response of output power \( P \) under voltage fluctuation.

(1) Response of hydroturbine output torque \( m_t \)
The order of the stability of hydroturbine output torque \( m_t \) responses in the 6 cases was: Case 1 > Case 2 > Case 3 > Case 6 > Case 5 > Case 4.

(2) Response of power angle \( \delta \)
The order of the stability of the power angle \( \delta \) responses in the 6 cases was: Case 6 > Case 5 > Case 2 > Case 3 > Case 1 > Case 4.

(3) Response of rotor speed deviation \( x \)
The order of the stability of the rotor speed deviation \( x \) responses in the 6 cases was: Case 6 > Case 5 > Case 3 > Case 2 > Case 1 > Case 4.

(4) Response of output power \( P \)
The order of the stability of the output power \( P \) responses in the 6 cases was: Case 6 > Case 5 > Case 3 ≈ Case 2 ≈ Case 1 > Case 4.

5. Discussion

The damping characteristics of ORM and PRM are relative to the frequency of oscillations and operating parameters. The tendency of the damping characteristics of ORM are irrelevant to the operating parameters. ORM provides positive damping in low-frequency regions and provides negative damping in high-frequency regions. The critical frequency is determined by the operating parameters. For PRM, both the tendency of damping characteristics and critical frequency are influenced by the operating parameters. When

\[
T_W > \frac{e_{gh}(-K_p + K_I \omega_0 K_p T_y)/(e_{gh} K_p T_y)}{e + e_{gh}},
\]

PRM provides negative damping in low-frequency regions and positive damping in high-frequency regions. Otherwise, PRM always provides negative damping. To validate the analysis, a linear model of a real hydroturbine unit was studied. When \( T_W \geq 1.2 \), the critical frequency of ORM is less than 0.6 rad/s. When \( T_W = 0.2, 1.2, 2.2, \) and 3.2, the critical frequency of PRM \( \omega_1 \) is infinite, 4.77, 2.01, and 0.98, respectively. The frequency range of normal frequency oscillations in power systems is 0.6–15.7 rad/s. ORM provides negative damping in normal oscillations when \( T_W \geq 1.2 \). The critical frequency of PRM is inside the range. PRM provides positive...
damping in the majority of frequency ranges. When $T_W \geq 3.2$, PRM provides positive damping in normal oscillations.

Eigenvalue analysis illustrated that the damping ratio and stability margin of PRM are bigger than that of ORM when $T_W$ is large. When $T_W$ is very small, ORM is more stable than PRM. The finding contradicts that in reference [23] because we used different research objects. In reference [23], the frequency stability of the hydropower unit in an isolated power system was analyzed, neglecting the electromagnetic transient process and variable operating parameters, whereas we studied a large-scale power system and analyzed the power angle stability. The performance of ORM and PRM is relative to the operating parameters.

A numerical simulation of two typical disturbances was conducted to further study the stability of ORM and PRM. Some results were obtained from these responses:

1. The hydroturbine output torque $m_t$ is more stable in ORM than in PRM.
2. When $T_W = 0$, the power angle $\delta$, rotor speed $x$, and output power $P$ in ORM are more stable than in PRM; when $T_W \geq 1.3$, the stability of power angle $\delta$, rotor speed $x$, and output power $P$ in PRM is better than in ORM.
3. The stability in ORM changes a little when $T_W$ increases; the stability in ORM is improved obviously when $T_W$ increases.

For the important parameters such as rotor speed, power angle, and active power, PRM shows better stability than ORM when $T_W$ is large.

6. Conclusions

In this study, the damping characteristic analysis, eigenvalue analysis, and numerical simulation were conducted to examine the stability of ORM and PRM. The stability of ORM and PRM is relative to the value of $T_W$. Thus, some points were concluded from the analysis:

1. The governor in ORM provides positive damping in low-frequency regions and provides negative damping in high-frequency regions when $T_W$ is considerable. The stability decreases with increasing $T_W$.
2. When operating parameters meet some conditions, a governor in PRM provides negative damping in low-frequency regions and positive damping in high-frequency regions. The stability increases with increasing $T_W$.
3. The stability margin and damping ratio of transfer function in PRM are larger than in ORM.
4. The time domain simulation results of a three-phase short-circuit and voltage fluctuation supported the theoretical analysis.

For real hydropower units, $T_W$ is often larger than one. Hydropower units in PRM have better stability than hydropower units in ORM. Especially for hydropower-domain systems or systems with many inherent instable factors, PRM is the first choice for hydropower units. In addition, the limitation of parameters for PRM to provide positive damping would be helpful in the tuning of PI coefficients.

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