Analysis and Suppression Strategy of Transient Frequency Deviation by Soft Guide Vane Control in Hydro Turbine

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Abstract. The hydro-dominant characteristic is notable after the asynchronous operation in Southwest China Power Grid which brings worse transient frequency deviation caused by water hammer effect. To prevent the possible cascading failure due to the worse transient frequency deviation in the secondary frequency regulation, the soft guide vane control law is proposed to suppress the water hammer effect in the transient regulation process based on the detailed turbine-penstock model. The discrete state space expression of the turbine-penstock model is built to simulate the regulation effect in the time domain and the PSO (Particle Swarm Optimization) algorithm is applied to optimize the soft guide vane control adjustment factor considering multi-object. Finally, the emergency AGC (Automatic Generation Control) adjustment in the single machine with load transmission system is conducted to verify the effect of transient frequency deviation suppression by optimized soft guide vane control.

1. Introduction
The asynchronous operation of Southwest China Power Grid (SCPG) has a notable feature of hydro-dominant in that the hydropower is more than 70% in Yunnan and up to 80% in Sichuan. Using back-to-back voltage source converter based high voltage direct current (HVDC) transmission from hydropower clusters in SCPG to the load center of eastern China benefits not only the transient power angle stability from sender to receiver but also the consumption of hydropower. However, the frequency stability gets fragile due to the limited power capacity dispatch via HVDC transmission system and the transient frequency deviation can be even worse results from the prominent water hammer effect in hydro-dominant power system [1-4]. Since the evolution of the grid architecture is irreversible and objectively favorable for renewable energy transition, it is necessary to consider the water hammer effect caused by flow inertia in diversion pipe of the hydro turbine so as to suppress the transient frequency deviation and ensure the safe and stable operation of hydro-dominant power system.

The researchers of hydro turbine governor and power system operation at home and abroad are mainly focused on the dynamic modeling and characteristic of hydro unit, harm for stability result from water hammer effect and its suppression strategies. Literature [5] analyzed the dynamic characteristic of the ideal lossless turbine compared with a detailed hydraulic turbine -penstock model and pointed out that the ideal lossless turbine is not adequate to depict the practical system dynamic affected by water hammer effect. Literature [6,7] analyzed the disservice to the transient frequency
deviation and ultra-low frequency oscillation in the power system brought by water hammer effect respectively, the strategy of delayed hydro turbine governor control is put forward to suppress the transient frequency deviation. Literature [8] investigated the large phase lag caused by water hammer effect in the hydro turbine governing system. Literature [9] proposed optimal guide vane control law for minimizing the reverse regulation of mechanical power based on Laplace analysis for ideal lossless turbine. Literature [10] adopted engineering method to suppress the water hammer effect by using ‘slow-fast-slow’ guide vane control law. Literature [11] analyzed the influence caused by water hammer effect to grid frequency considering unit’s spin spare capacity. Current researchers mostly concentrate on the impact of the water hammer effect on system stability aspect and rarely consider its influences on transient frequency deviation after the big disturbance in the hydro-dominant power system. For example, most of the hydro plants in Xinjiang, China were assessed by the grid authority in 2019 for their inability to response the power gap with large frequency deviation in 7-9 seconds. The survey result shows that the intensive water hammer effect brought by the structure of one tube multi-machine with long diversion pipe leads to the reverse regulation of active power in front of the large frequency deviation and make the transient frequency even worse. Most researchers quantitatively discuss the suppression of water hammer effect based on the ideal lossless turbine itself rather than the coordination measures between hydro unit and grid.

This paper analyzes the worse transient frequency deviation mechanism caused by water hammer effect and then introduces a more detailed turbine-penstock dynamic model applicable for water hammer effect analysis. The discrete state space expression of the hydro turbine model is set up for multi-objective optimization by PSO algorithm coordinated with the AGC instruction. Finally, the case study of emergency AGC adjustment in the single machine with load transmission system is built to verify the suppression of transient frequency by soft guide vane control.

2. Mechanism Analysis of Worse Transient Frequency Deviation by Water Hammer Effect

Water hammer effect exists in the initial process of hydro turbine governing due to the reverse change of water pressure in penstock, as a result, the mechanical power of the turbine will experience the reverse regulation during the dynamic process [6,9,10]. The reverse regulated mechanical power does not affect the steady state of frequency for its attenuation characteristic but will deteriorate the transient frequency deviation further. Take the rotor motion equation of single unit equivalent model as consideration, $T_J$ is the inertia time constant of the equivalent unit, $\omega$ is the angular velocity, $\Delta P_m$ is the unbalanced mechanical power, $\Delta P_e$ is the unbalanced electromagnetic power, $D$ and $K_L$ is the generator equivalent damping coefficient and load frequency adjustment factor respectively, $\Delta P_{whe}$ is the reverse regulated mechanical power caused by water hammer effect in the initial regulating process [12].

$$T_J \frac{d\Delta \omega}{dt} = \Delta P_m + \Delta P_{whe} - \Delta P_e - (D + K_L)\Delta \omega$$ (1)

In the first period after the big disturbance in grid side, the changing $\Delta P_e$ leads to frequency deviation while $\Delta P_m$ retains unchanged because of the frequency dead zone setting and the governor execution delay. When the transient frequency crossing the frequency dead zone, the primary frequency control of the unit will be put into regulation, however, the $\Delta P_{whe}$ results from the guide vane fast regulation is in the same direction with changing $\Delta P_e$ which is like a ‘hammer’ to the transient frequency and makes it worse. Considering the single-phase ground fault in the single machine with load system, the simulation compared with the two kinds of the regulation methods in hydro turbine governor: 1) the conventional ramp guide vane regulation; 2) the guide vane remaining unregulated during the whole process. Fig 1 is the guide vane and mechanical power under two methods, the nominal power of the machine is 200MW with the 130MW load and the fault starts at 10s ends at 10.8s. Fig 2 is the frequency during the whole simulation process, the frequency deviation cannot recover in method 2) for its no regulation characteristic.
From the Fig.1 and Fig.2, the conclusion can be drawn in 2 points: 1) the reverse regulated mechanical power caused by water hammer effect works in the initial period during the fast regulation of the guide vane and brings a certain amount of phase lag which deteriorates the dynamic regulation characteristic; 2) the transient frequency deviation of conventional closed-loop adjustment gets worse due to the effect of water hammer compared with the guide vane remaining unregulated method which may trigger cascading failure after the after the big disturbance in grid side.

3. Transient Frequency Deviation Suppression Using Soft Guide Vane Control
The worse transient frequency deviation caused by water hammer effect after the big disturbance in grid side such as bipolar/unipolar blocking fault in HVDC or fault removal of the unit may expand the scope and extent of the fault further. Hence the optimized guide vane control law is necessary to make the transient guide vane regulation smooth, stable and rapid. Then the reverse mechanical power in the initial regulation process can be well suppressed.
The well-known classical ideal lossless penstock-turbine transfer function published by IEEE Working Group is not adequate to depict the practical system dynamic responses and performances when a turbine with long penstock is used [5], the more detailed turbine-penstock model derivated in literature [13] will be adopted in this paper, relating changes in mechanical power $P_m(s)$ produced by the turbine to changes in guide vane opening $\mu(s)$ is:

$$
G_m(s) = \frac{P_m(s)}{\mu(s)} = \frac{e_\mu \left[ 1 + \left( \frac{2sT_w}{\pi} \right)^2 \right] + \left( \frac{e_\mu}{2} - e_h \right) sT_w \left[ 1 + \left( \frac{sT_w}{\pi} \right)^2 \right]}{1 + \left( \frac{2sT_e}{\pi} \right)^2 + \frac{sT_w}{2} \left[ 1 + \left( \frac{sT_e}{\pi} \right)^2 \right]}
$$

(2)

Where $T_w$ is water hammer inertial time constant in seconds which can be get in field test, $T_e = 2L/v$ is the penstock elastic time constant in seconds and it depicts the strength of system elastic water hammer, $L$ is the length of the penstock, $v$ is the velocity of water pressure wave and its normal value is 1100~1200 m/s [14]; $e_\mu$ and $e_h$ are the coefficients depicting deviation relationship between mechanical power and guide vane opening, water head. $e_\mu$ and $e_h$ are usually set 1.0 and 1.5 respectively at rated speed and head.

Considering transient guide vane opening law is some function of time $\mu(t)$ with three elements: initial guide vane opening $\mu_0$ and end guide vane opening $\mu_t$ which are produced by AGC control instruction after big disturbance, the execution time of the guide vane $t_a$ determined by the opening step setting of turbine governor and pulse speed setting from AGC. The $\mu(t)$ can be seen as the ramp control law in reality during the transient process in that the guide vane actuator usually works at maximum velocity regardless of the guide vane control value as shown in Fig.1.

The water hammer effect is prominent under the guide vane ramp control because of the rapid change of water pressure during initial regulation process. To optimize the guide vane ramp control law, the soft guide vane control based on index law is proposed which is:

$$
\mu(t) = k(e^{nt} - 1) + \mu_0, \quad 0 \leq t \leq t_a
$$

(3)

$k$ and $n$ is the control parameter need to be identified, considering the continuity at $t = t_a$ which is $\mu(t_a) = \mu_t$, the relationship between $k$ and $n$ can be determined:

$$
k = \frac{\mu_t - \mu_0}{e^{nt} - 1}
$$

(4)

So $n$ which is called soft guide vane control adjustment factor in (3) and (4) needs to be identified. Since the complexity of the turbine-penstock model shown in (2) is beyond Laplace analysis, the engineering concept should be adopted to solve the engineering problem. Fig 3 depicts the degree of soft regulation with different $n$ from 0.2~2 under AGC control instruction settings of $\mu_0 = 0.4, \mu_t = 0.6, t_a = 10$. 
it can be concluded that the degree of soft regulation is positively related to the value of \( n \) which means the initial transient regulation of guide vane will be smoother and softer the larger \( n \) is set. It seems that the reverse mechanical power caused by water hammer effect can be well suppressed if \( n \) is large enough, however, the real guide vane executing law is limited by the hydraulic condition and hydro turbine governing system. When \( n \) is set too large, the tail velocity of guide vane may exceed the maximum guide vane execution velocity \( v_{\text{max}} \), so one constraint of \( n \) is:

\[
\mu \left( t_{\text{r}} \right) = \left( \mu_t - \mu_0 \right) ne^{nt} < v_{\text{max}}
\]

(5)

On the other hand, different hydraulic conditions call for different \( n \) settings. When the \( T_w \) and \( T_e \) are small, the dynamic characteristic of hydro turbine is relatively good then the \( n \) setting with small value is suitable. On the contrary, the complicated hydro dynamic characteristic with large \( T_w \) and \( T_e \) needs a large \( n \) setting considering the real execution of guide vane.

Here the continuous state space expression of \( G_{\text{ht}}(s) \) is built for the following discrete analysis in the program. One of the state space expression of \( G_{\text{ht}}(s) \) is:

\[
\begin{cases}
X = AX + BU \\ Y = CX + DU
\end{cases}
\]

(6)

Where \( X \) is state vector with \( l \) dimensions; \( U \) is the input vector with \( r \) dimensions; \( Y \) is the output vector with \( m \) dimensions; \( A \) is the \( l \times l \) state matrix; \( B \) is the \( l \times r \) input matrix; \( C \) is the \( m \times l \) output matrix; \( D \) is the \( m \times r \) feedforward matrix. The corresponding matrix of \( G_{\text{ht}}(s) \) is:

\[
A = \begin{bmatrix}
-8/T_w & -\pi^2/T_e^2 & -2\pi^2/(T_e^2 T_w) \\
1 & 0 & 0 \\
0 & 1 & 0
\end{bmatrix}, \quad B = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}
\]

(7)

\[
C = \begin{bmatrix}
24/T_w & 0 & 6\pi^2/(T_e^2 T_w)
\end{bmatrix}, \quad D = [-2]
\]

The continuous state space expression needs to be discretized when analyzed in microcomputer, \( \Delta t \) is the control cycle set in program, the discrete state space expression is:
Where $E$ is the $l \times l$ identity matrix then the mechanical power under different $n$ setting in (3) can be simulated by (7) and (8) for optimization purpose in the program. PSO algorithm can be used here for $n$ setting optimization, the constraints can be listed in (9), $v_{c_{\text{max}}}$ and $v_{o_{\text{max}}}$ are the maximum guide vane execution velocity for close and open, here $v_{c_{\text{max}}} = -0.1$ p.u./s and $v_{o_{\text{max}}} = 0.1$ p.u./s based on the static adjustment test of hydro turbine governor. The second constraint in (9) is set to reduce the average rate of guide vane execution velocity. $\Delta \mu_{\text{max}}$ is the maximum guide vane execution amount every time to protect the penstock and turbine of the hydro plant, it is set to 0.3 p.u. Here. $T_{w_{\text{max}}}$ and $T_{e_{\text{max}}}$ are the maximum water hammer inertial time constant and maximum penstock elastic time constant, they are set to 3.5s and 4s respectively according to the real extreme hydraulic condition [13]. $n_{\text{max}}$ is the maximum soft guide vane control adjustment factor and is set to 2 with the consideration of guide vane execution velocity limit under different regulation conditions.

The minimizing of maximum reverse mechanical power $\Delta p_{1_{\text{max}}}$ and maximum overshoot mechanical power $\Delta p_{2_{\text{max}}}$ during the transient process are mainly involved in the optimization purpose as well as the moment $t_c$ when mechanical power crossing the $\mu_0$ line which indicates the rapidity of hydropower unit output. The three indexes are illustrated in Fig.4.

![Fig.4 Illustration of the three indexes in the optimization purpose](image-url)
The linear combination of the three standardized indexes is adopted as the optimization purpose of PSO algorithm which is (10), the $P_{mr}$ is the rated capacity of hydropower unit.

$$J_{PSO,n} = k_1 \frac{\Delta P_{m1\max}}{P_{mR} \mu_0} + k_2 \frac{\Delta P_{m2\max}}{P_{mR} H_0} + k_3 \frac{t_c}{t_a}$$  \hspace{1cm} (10)

$k_1 \sim k_3$ are the weight of corresponding optimization part and the first part with coefficient $k_1$ is highly related to the water hammer effect while the second and third part with $k_2$ and $k_3$ mainly reveal the rapidity and smoothness of the regulation process. According to the main optimization purpose to suppress the transient frequency deviation, coefficient $k_1$ should be set larger than the other two coefficients. After the several times of optimization coefficients adjustments, $k_1 \sim k_3$ are set to 1, 0.1 and 0.2 respectively can achieve a relatively good optimization effect. The outcome of soft guide vane control by PSO is shown in (11) when $T_w = 3s$, $T_s = 2s$, $\mu_0 = 0.4$, $\mu_1 = 0.6$, $t_a = 10s$, $\Delta t = 0.001s$.

$$\begin{align*}
    n &= 0.2101 \\
    \frac{\Delta P_{m1\max}}{P_{mR}} &= 0.0092 \\
    \frac{\Delta P_{m2\max}}{P_{mR}} &= 0.0211 \\
    t_c &= 5.9070s \\
    J_{PSO,n} &= 0.0926
\end{align*}$$  \hspace{1cm} (11)

The mechanical power simulation of the optimized soft guide vane control with PSO above compared with conventional ramp control is shown in Fig.5, the optimized soft guide vane control can suppress 77.4% the reverse mechanical power fluctuation compared with the conventional ramp guide vane control. By this way, the transient frequency deviation caused by water hammer effect can be well suppressed. Meanwhile, the rapidity and the overshoot of the mechanical power regulation are well controlled which benefits from multi-objective optimization by PSO algorithm.
4. Case Study

The structure of the AGC emergency adjustment in the single machine with load transmission system is shown in Fig. 6. The HTG block represents hydro turbine and governor, \( T_w = 3s, T_e = 2s \) and the rated capacity of the unit is 200MW; \( P_L = 70\text{MW} \) is the equal load of the machine; the simulated AGC emergency adjustment instruction is set to verify the suppression of transient frequency deviation by soft guide vane control and the AGC instruction is \( \mu_0 = 0.35\text{p.u.}, \mu_1 = 0.5\text{p.u.}, t_a = 10s \). The instruction starts at 50s and ends at 60s during which the frequency under optimized soft guide vane control law is compared with ramp control law. To regulate the frequency in the system after the simulated AGC instruction, the hydroelectric governor PID closed-loop adjustment is put in at 60s.

![Fig.6 Single machine with load AGC controlled transmission system](image)

The soft guide vane control adjustment factor \( n = 0.2506 \) according to the multi-objective optimization by PSO algorithm. Fig. 7 illustrates the mechanical power controlled by conventional ramp control and optimized soft guide vane control in the detailed turbine-penstock model. Fig. 8 compares the transient frequency deviation in the transmission system controlled by two laws during 50–60s. The transient frequency can achieve about 0.15Hz reduction by the optimized soft guide vane control in the certain scene.

![Fig.7 Mechanical power by soft and ramp guide vane control](image)
5. Conclusions
Through the mechanism analysis of worse transient frequency deviation caused by water hammer effect in the hydro-dominate power system, the suppression strategy which optimizes the hydro guide vane transient control law called soft guide vane control is proposed. Based on the detailed penstock-turbine model, the discrete state space expression for time domain simulation is built. To optimize the soft guide vane control adjustment factor $n$, the multi-objective optimization by PSO algorithm is conducted and the typical model simulation result reveals that 77.4% reverse mechanical power fluctuation can be well suppressed by optimized soft guide vane control. At last, the case study of the AGC emergency adjustment in single machine with load transmission system is simulated, comparing with the conventional ramp control method, the optimized soft guide vane control really has a significant suppression effect on transient frequency deviation. The soft guide vane control law is necessary to regulate the output power of the hydro unit coordinated with AGC instructions or the stability control device quick adjustment instructions under unfavorable hydraulic conditions.

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