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Published in:
IET Renewable Power Generation

Link to article, DOI:
10.1049/rpg2.12092

Publication date:
2021

Document Version
Publisher's PDF, also known as Version of record

Link back to DTU Orbit

Citation (APA):
Wang, P., Li, B., Jiang, Q., Chen, G., Han, X., Dragicevic, T., & Liu, T. (2021). The occurrence mechanism and damping method of ultra-low-frequency oscillations. IET Renewable Power Generation, 15(5), 1100-1115. https://doi.org/10.1049/rpg2.12092
The occurrence mechanism and damping method of ultra-low-frequency oscillations

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Abstract
The ultra-low-frequency oscillation (ULFO) problem has reappeared in China recently. Although the hydraulic generator is supposed to have a strong connection to this problem, the conditions for ULFO appearance and detailed reasons are not clear yet. In order to clarify the occurrence mechanism of ULFO, this paper studies each important part of hydraulic generator system, including the governor, exciter and power system stabiliser (PSS). The weak connection is confirmed to have an important impact on the occurrence of the ULFO. Nevertheless, by studying each device’s contribution to ULFO through the complex torque coefficient method, it is shown that the negative damping effect of the hydraulic governor will cause the instability in the ultra-low-frequency band, while the exciter and the PSS have little influence on ULFO. Additionally, the proportional–integral parameters of the hydraulic governor system are also studied to clarify their influence on ULFO based on the complex torque coefficient method. Based on the above analysis, two damping methods for ULFO suppression are finally proposed. To verify theory and damping methods, the simulations are implemented in PSCAD and PSASP software.

1 INTRODUCTION

In recent years, ultra-low-frequency oscillation (ULFO) has reappeared in the Chinese power system. Although the ULFO is not well known compared to classical low-frequency oscillation (LFO), it can be traced to as early as 1966, at which time a ULFO of 2.5–3.5 cycles per minute was first reported in the United States Northwest Pacific system [1]. Actually, ULFOs are the oscillations in power systems with frequencies below 0.1 Hz. Compared to the LFO problem, ULFO does not appear frequently. After the ULFO in the United States, only a few other ULFOs in Turkey and in Columbia have been observed, with the oscillation frequencies of 0.05 and 0.05–0.08 Hz, respectively [2,3]. As ULFO is such a special and typical problem, the detailed mechanism of it has not been clarified yet.

However, the ULFO reappears frequently in the Chinese power system in recent years. In islanding operation field test of Tianguang HVDC line and Jinsu HVDC line, oscillations with oscillation period of 10 and 14 s occurred, respectively. Meanwhile, the frequency fluctuated significantly and the amplitudes of fluctuations reached ±0.23 and ±0.26 Hz, respectively [4]. These two oscillations only occurred in the small HVDC island system, and the impact was relatively small. Nevertheless, a 0.05-Hz frequency oscillation occurred in the Yunnan power grid as the China Southern Power Grid conducted the field tests of asynchronous interconnection in March 2016, indicating that similar oscillations will also occur in a large power grid [5,6].

To make the theory of ULFO clear, a number of research studies have been performed on ULFO mechanism analysis and suppression methods in the last three years. Methods for analysing the ULFO mechanism mainly include complex torque coefficient method, eigenvalue method, Routh criterion and Nyquist criterion. Based on the complex torque coefficient method [7], it is found that the negative damping effect of the hydraulic governor will cause the instability in the ultra-low-frequency band, while the exciter and the PSS have little influence on ULFO. Additionally, the proportional–integral parameters of the hydraulic governor system are also studied to clarify their influence on ULFO based on the complex torque coefficient method. Based on the above analysis, two damping methods for ULFO suppression are finally proposed. To verify theory and damping methods, the simulations are implemented in PSCAD and PSASP software.
namely $T_{IN}$, would weaken the system stability [10]. Furthermore, the influence of different governor control modes and governor parameters on damping torque was analysed. It also indicated that the parameter $T_{IF}$ was a crucial factor affecting ULFO [11,12].

As for the eigenvalue method, it was concluded that the ULFO phenomenon was closely related to the hydraulic governor according to the hydraulic units’ state variables analysis obtained by the small-signal model [13-16]. Considering non-linear or coupled characteristics of the system, the conclusion that the primary frequency regulation of the hydraulic units was the source of ULFO was obtained. Besides, the influence of $T_{IN}$ on stability limit cycle was analysed based on the non-linear model of the system, and the increasing $T_{IF}$ would worsen the system stability [17,18]. Based on the Routh criterion, the system stability can also be judged by the signs of coefficients in the closed-loop characteristic equation and the first column of the Routh array. According to such method, the small ratio of the hydraulic governor proportion gain to the integral gain was regarded as the source of ULFO [19,20]. Simultaneously, the system stability can be judged according to the Nyquist curve of the system open-loop transfer function, and the high proportion of hydropower and the large phase lag of hydropower unit were also regarded as the reason for ULFO through the Nyquist criterion [21]. Furthermore, the positive energy provided by the hydropower unit was thought as the source of ULFO [22]. Especially, the compound mode may also produce ULFO under certain special factors [23].

On the other side, some research works propose the intelligent algorithm to optimise the governor parameters for ULFO suppression. According to [24] and [26], the performance of the hydraulic primary frequency regulation and the damping characteristics of the hydraulic units should be both taken into consideration for the parameter optimisation strategy. Actually, only the parameters of the generator with large correlation coefficient indexes considering the participating factors and inertia time are adjusted in a practical project [27]. There are also some online emergency control methods to suppress ULFO, such as the existing primary frequency regulation of some hydraulic generators chosen by the damping torque coefficient [28,29]. Quitting the step-response dead zone was also an effective way to suppress ULFO [30].

No matter what method was used to analyse the ULFO mechanism, the negative damping effect of the hydropower was regarded as the source of ULFO, which was an obvious difference from the LFO due to excitation system [31]. Actually, the ULFO risk is low in the practical system before the system is asynchronously connected. In the hydropower plants (HPPs), the power oscillations originating from a bulb turbine torque disturbance caused by an efficiency decrease of a single runner blade would occur [32,33]. And the system was also risky of local mode oscillation due to the increasing rapidity of frequency control in HPPs [34,35]. As the hydro-dominant South-west China Power Grid is planned to operate asynchronously, the ULFO risk in the Chinese Power Grid is much higher than ever before. In severe cases, the units may disconnect from the grid on a large scale, and the frequency may lose stability, which bring great risks to the grid safety. On the power source side, the governors in the whole power grid will operate frequently, which may damage the actuator or cause the units to trip due to the protection configurations. On the grid side, the cross section may exceed the limit because of the bulk power fluctuations. As for the load side, the enterprises, including precise instrument processing and manufacturing, may also suffer from the economic losses caused by the continuous frequency oscillation. Thus, considering the higher risk and negative effect of the ULFO, it is urgent to make clear the detailed mechanism of ULFO by looking at each important factor of the hydraulic generator system one by one.

From the above analysis, it can be seen that no matter what method is used to analyse the ULFO mechanism, the negative damping torque provided by the hydraulic governor was regarded as the source of ULFO. However, the research about ULFO mechanism did not point out why and how the ULFO suddenly occurred, as the hydraulic governor has been in operation for a long time. Therefore, the conclusion obtained by the past studies was not sufficient to explain the ULFO phenomenon that it often occurs in an asynchronously connected system. Furthermore, the influence of the exciter and the power system stabiliser (PSS) on ULFO was directly ignored in the past studies, which were only based on the phenomenon in the practical project and lacked theoretical support.

Therefore, this paper mainly analyses the oscillation characteristics of the system from two aspects of operating state of the system and the sending-end system itself, which is an improvement of ULFO. To reveal the mechanism of ULFO, this paper studies the hydraulic generator system in detail, including a synchronous machine, a governor, an exciter and the external reactance representing the system operating state. Based on the classical single-machine infinite-bus model, the state-space model of the hydraulic generator system is established. Through the eigenvalue analysis, the weak connection is regarded to have an important impact on the occurrence of the ULFO. Based on such conclusion, the damping characteristics of the governor, exciter and PSS are then obtained by the complex torque coefficient method to evaluate each part’s contribution to ULFO, where the inner cause aggravating ULFO is also confirmed as the governor from the perspective of the sending-end system itself. To give the suggestions for damping ULFO, the impacts of hydraulic governor parameters have been studied under weak connection between the system and the main power grid. Finally, two ULFO suppression methods are proposed based on two different mechanisms. In the above analysis, the eigenvalue method and the complex torque coefficient method validate each other, and the simulations in PSCAD and PSASP software also verify the theoretical part.

The organisation of this paper is as follows. Section 2 obtains the state-space equations of the generator, including detailed governor and exciter model. Section 3 researches ULFO based on the eigenvalue method to investigate the occurrence impact factors of ULFO. Section 4 studies the damping characteristic of generator’s different parts based on the complex torque coefficient and proposes the methods to damp ULFO. Section 5
verifies the theoretical analysis based on the simulations with three different systems. Finally, Section 6 concludes this paper.

2 STATE-SPACE MODEL WITH DETAILED EXCITER AND GOVERNOR

Most research works were based on the single-machine system to investigate LFO and ULFO mechanisms [7,12,17,36]. Furthermore, the speeds of all generators vary with the same phase and amplitude, and the frequencies oscillate together when ULFO occurs in the system. Therefore, the multi-machine system can be equivalent to a single-machine system with an equivalent acceleration time constant, and the effects of governors of different generators can be decoupled [21,25]. Meanwhile, the interactions among hydraulic power plant modes can be ignored. Consequently, the single-machine system is sufficient enough to analyse the occurrence mechanism of ULFO from the perspective of operating state and find each part’s contribution to ULFO.

To make a fair analysis and comparison, a classical single-machine infinite-bus system is chosen, as shown in Figure 1. The reactance $x_1$ represents the external reactance, namely, the reactance of transmission line. The infinite voltage is $U_t \angle \delta$ and the generator’s actual terminal voltage is $U \angle \theta$. For convenient analysis, the external reactance $x_1$ is considered as a part of generator’s leakage reactance; thus, the theoretical terminal voltage of the generator is $U_t \angle \delta$. Based on this single-machine infinite-bus model, the state-space model can be obtained by combining the equations of synchronous machine, governor and exciter.

2.1 The synchronous machine model

Since ULFO has a low oscillation frequency and a long oscillation period, the full dynamics of fast phenomenon can be neglected under such time scale [21]. By neglecting fast dynamics that have reached equilibrium during the ULFO, the widely used three-order synchronous machine model is suitable for ULFO theoretical analysis [36], which is presented as follows:

$$
\frac{d}{dt} \Delta E_q' = \frac{1}{T_{d0}} (\Delta E_{fd} - \Delta E_q) \tag{1}
$$

$$
\frac{d}{dt} \Delta \omega = \frac{1}{T_J} (\Delta M_m - \Delta M_e) - \frac{1}{T_J} D \Delta \omega \tag{2}
$$

$$
\frac{d}{dt} \Delta \delta = \omega_0 \Delta \omega. \tag{3}
$$

In the above equations, $\omega$ is the per unit rotor speed, $\omega_0$ is the rated rotor speed, which is 314 rad/s, $T_J$ and $D$ are the acceleration time constant and damping coefficient of the rotor, respectively, $M_m$ and $M_e$ are the input mechanical power and the output electromagnetic power, respectively, $E_{fd}$ is the field winding $d$-axis voltage, $E_q'$ is the $q$-axis voltage, $E_q'$ is the $q$-axis transient electromotive voltage, and $T_{d0}$ is the $d$-axis transient time constant. $\Delta$ is the linearisation symbol.

As for the detailed variables’ relationship in the synchronous machine, it can be described in the classical Phillips–Heffron model, as shown in Figure 2 [37,38].

Coefficients $K_1$–$K_6$ can be found in [38], and they can also be found in a supplementary document. $\Delta U_{\text{pss}}$ is the output of the PSS. The detailed governor and exciter models in the diagram are not given, as they are going to be discussed in the following part.

2.2 The exciter model

Regarding the excitation system, it is mainly to analyse whether the changes of excitation parameters will cause the system to have the risk of ULFO. Therefore, the non-linear characteristics of the excitation system can be ignored. The type of DC1A excitation system is chosen [39] since it can make the terminal voltage at rated value under different operating points. For theoretical analysis, a simplified exciter model is obtained by setting some parameters of the DC1A excitation system at special value, as shown in Figure 3.

In Figure 3, $U_{\text{ref}}$ is the input reference voltage, $K_A$ and $T_A$ are the gain and time constant of the voltage regulator, respectively, $K_F$ and $T_F$ are the gain and time constant of the exciter, respectively, and $K_{E'}$ and $T_{E'}$ are the gain and time constant of the excitation control system stabiliser, respectively. By choosing the output $U_R$ of the voltage regulator, the output $U_F$ of
the excitation control system stabiliser, and the output $E_{jd}$ of the exciter as the state variables, the model of the exciter can be written as follows:

$$\frac{d}{dt} \Delta U_R = -\frac{1}{T_A} \Delta U_R - \frac{K_A}{T_A} \Delta U_t - \frac{K_A}{T_A} \Delta U_F$$

$$\frac{d}{dt} \Delta E_{jd} = \frac{1}{E_I} \Delta U_R - \frac{K_E}{E_I} \Delta E_{jd}$$

$$\frac{d}{dt} \Delta U_F = \frac{K_E}{E_I} \frac{1}{T_J} \Delta U_R - \frac{K_E}{E_I} \frac{1}{T_J} \Delta E_{jd} - \frac{1}{E_I} \Delta U_F.$$  

(4)  

(5)  

(6)

2.3 The hydraulic governor model

The hydraulic governor and actuator model is presented in Figure 4, where $K_p$, $K_D$, and $K_I$ are the gains of the proportional–integral–derivative (PID) regulator. $B_p$ is the compensation coefficient, $T_e$ is the integral time constant of servo system, and $\omega_{ref}$ is the reference rotor speed, which is 1 p.u. as it is in per unit. The deadband of the hydraulic governor only influences the stability of the system, which has been already in the ULFO mode according to the describing function method [41]. Therefore, the value of deadband is set to 0 p.u. in this paper since this paper aims to clarify the occurrence mechanism of ULFO.

In addition to the PID governor system and the hydraulic servo system, the hydraulic prime mover and the water diversion pipe also should be contained in the speed control system of the hydraulic generator. The model of water diversion pipe includes the rigid water hammer model and the elastic water hammer model. Actually, the elastic water hammer model can reflect the dynamic characteristics of the hydraulic turbine in wide bandwidth. However, the theoretical analysis about the dynamic characteristics of this model is complicated since the model has strong non-linearity. Since the phase–frequency characteristics of the two different diversion pipeline models are very close in the frequency range where the oscillation frequency is not greater than 0.1 Hz, the linear rigid water hammer model can satisfy the oscillation problem analysis [40]. The prime mover model corresponding to the rigid water hammer model can be represented by (7), and the corresponding transfer function block diagram is shown in Figure 5.

$$G_1(s) = \frac{e_j - (e_{gb} + e_{gb}e_y)T_w s}{1 + e_{gb}T_w s} = \frac{K_w(1 - aT_w s)}{1 + bT_w s}.$$  

(7)

In (7), $a$ is equal to $e_{gb}T_d/(e_{gb} - e_{gb}a)$, $b$ and $K_w$ are equal to $e_{gb}$ and $e_{gb}$ respectively. $e_j$ is the transfer function of turbine torque to the guide vane opening and $e_{gb}$ is the transfer function of turbine torque to the water head. $T_w$ is the water starting time constant, namely the hydraulic turbine parameters. When the values of $e_j$, $e_{gb}$, $e_{gb}$, $e_{gb}$, and $e_{gb}$ are set to 1, 1.5, 1, 0.5 and 0, respectively, the classical rigid water hammer model can be obtained, where the values of $a$ and $b$ are 1 and 0.5, respectively.

By choosing the regulator’s integral block’s output $X_1$, servo system’s output $X_2$ and the final output $M_m$ as the state variables, the model of hydraulic governor can be written as follows:

$$\frac{d}{dt} \Delta X_1 = -K_f \Delta \omega - K_f B_f \Delta X_1$$

$$\frac{d}{dt} \Delta X_2 = \frac{T_f K_D K_I B_F + DK_D - T_f K_D}{T_f T_f} \Delta \omega - \frac{1}{T_f} \Delta X_2$$

$$+ \frac{1 - K_f B_f + K_D K_f^2}{T_f} \Delta X_1 - \frac{K_f}{T_f} \left[ (\Delta M_m - \Delta M_l) \right]$$

$$\frac{d}{dt} \Delta M_m = \frac{2 \left(T_f K_D - T_f K_D K_I B_F - DK_D\right)}{T_f T_f} \Delta \omega$$

$$+ 2 \left(K_f B_f - 1 - K_f K_f^2\right) \frac{T_f}{T_f} \Delta X_1 - \frac{2K_D}{T_f} \Delta M_l$$

$$+ 2 \frac{T_f + T_g}{T_f T_f} \Delta X_2 + 2 \frac{T_g K_D - T_g T_f}{T_f T_f} \Delta M_m.$$  

(8)  

(9)  

(10)
TABLE 1 The value of different parameters

| Parameter      | Symbol | Value          |
|----------------|--------|----------------|
| Synchronous machine | x_d   | 1.1 p.u.       |
|                 | x_d'  | 0.3 p.u.       |
|                 | x_q   | 0.7 p.u.       |
|                 | x_1   | 0.15 p.u.      |
|                 | T_j   | 10 s           |
|                 | t_{base} | 2400 MVA     |
|                 | t_{d0} | 8 s            |
| Exciter        | K_A   | 46             |
|                 | T_A   | 0.06           |
|                 | K_E   | 0.8            |
|                 | T_E   | 0.85           |
|                 | K_F   | 0.1            |
|                 | T_F   | 1              |
| Governor       | K_P   | 2              |
|                 | K_I   | 1              |
|                 | K_D   | 0              |
|                 | B_P   | 0.04           |
|                 | T_L   | 0.2            |
|                 | T_S   | 0.25           |

The non-state variables in the above equations can be represented by state variables with the help of Figure 2. Thus, the state-space model of the hydraulic generator system with the detailed governor and exciter model can be obtained as represented by (11). The detailed expressions of state variable \( \Delta x \) and state matrix \( A \) can be found in the Appendix.

\[
\Delta x = A \Delta x. \tag{11}
\]

3 | ANALYSIS OF KEY FACTORS LEADING TO ULFO BASED ON THE EIGENVALUE METHOD

As the state-space model has been obtained, this section finds out the key factors leading to the ULFO problem. To study the specific role that each parameter plays in the ULFO process, the pole changing situations of the whole model need to be obtained. Since the characteristics roots corresponding to matrix \( A \) can reflect the system stability, the important parameters of governor, exciter and synchronous machine are discussed, respectively, based on the eigenvalue method. The reference voltages on the high-voltage side and low-voltage side are 230 and 20 kV, respectively. The base capacity is 2432.4 MVA.

The initial values of different parameters in the system are given in Table 1. The maximum and minimum values of the parameters are set to abnormal values to contain all the situations in the practical project, so that the conclusions in this paper are also applicable in the practical project. It should be noted that the diagrams of poles are plotted in its suitable scale, such that some poles far away from the imaginary axis are not plotted for a better investigation.

3.1 | The exciter parameter analysis

The most important parameters of the exciter are \( K_A \) and \( T_A \). The pole changing situations are given in Figures 6–8 when \( K_A \) and \( T_A \) are increasing, where Figure 7 shows the details near imaginary axis in Figure 6.
It can be seen that the exciter parameters have little relationship with ULFO, as the dominant poles near imaginary axis basically stay at $-0.2089 \pm 4.3959i$, which is 0.6996 Hz. Even if $T_\psi$ increases to 10, which is a usual big value and produces the poles of $-0.2159 \pm 0.3697i$, they are still far away from the imaginary axis and have much higher damping ratio compared to the dominant poles of $-0.2089 \pm 4.3959i$. Thus, we can conclude that the exciter's parameters mainly influence non-dominant poles and will not cause ULFO problem.

### 3.2 The governor parameter analysis

Similarly, the pole changing situations with different governor's PID parameters and water starting time constant $T_w$ are analysed as shown in Figures 9–12.

From the PID parameter analysis above, it can be seen that the governor's PID parameters can lead to the LFO problem, as they can produce positive poles in the low-frequency band. But they still cannot produce ULFOs.

As for the water starting time constant $T_w$, the pole changing situation is shown in Figure 12, which indicates that no ULFO modes can be produced even if $T_w$ reaches to 50. Thus, we can conclude that the hydraulic governor will not lead to ULFO in normal condition.

### 3.3 The synchronous machine parameter $x_1$ analysis

As the external reactance $x_1$ is considered as the leakage reactance of the generator in theoretical analysis, it is taken as a parameter of the synchronous machine. The other synchronous machine parameters are basically fixed and cannot change, so $x_1$ is studied here, as shown in Figure 13.

![Figure 13](image-url)
According to the results of Figure 13, it can be clearly seen that the original dominant poles of \(-0.2089 \pm 4.3959i\) move to ultra-low frequency area when \(x_1\) increases. It indicates that the big \(x_1\) or weak connection will cause the ULFO problem. To further investigate the key state variables influencing ULFO, the participating factors of all state variables shown in (11) are obtained for analysis.

For each eigenvalue, namely \(\lambda_i\), it satisfies (12) and (13), where \(\Phi_i\) is the right eigenvector of matrix \(A\) corresponding to the eigenvalue \(\lambda_i\). And \(\Phi_i\) is the column vector not equal to zero. \(\Psi_i\) is the left eigenvector of matrix \(A\) corresponding to the eigenvalue \(\lambda_i\). \(\Psi_i\) is the row vector not equal to zero.

\[
A\Phi_i = \lambda_i \Phi_i \quad (12)
\]
\[
\Psi_i A = \lambda_i \Psi_i \quad (13)
\]

Based on the above two equations, the participating factors can be obtained from (14), where \(\Phi_{ki}\) and \(\Psi_{ik}\) are the \(k\)th term of \(\Phi_i\) and \(\Psi_i\) respectively. The element \(p_{ki}\) reflects the participation of the \(k\)th state variable in the \(i\)th mode.

\[
p_{ki} = \Phi_{ki} \Psi_{ik} \quad (14)
\]

As \(\Phi_{ki}\) measures the activity of \(x_k\) in the \(i\)th mode and \(\Psi_{ik}\) represents the weight of this activity to the mode, \(p_{ki}\) can be used to measure the sum participation level.

The participating factors of different variables are shown in Figure 15, where the participating factors in the two connection situations are given.

It can be found that the participating factors of the variables \(\Delta \omega\) and \(\Delta \delta\) are much bigger compared to the ones of
other state variables from Figure 15. The difference of the participating factors between the exciter and the hydraulic governor is not so obvious when \( x_1 \) is 0.15 p.u. However, when \( x_1 \) is 290 p.u., that is, the system is in the ULFO mode, the exciter hardly participates in ULFO since the participating factors of exciter’s state variables can be approximated as zero. On the contrary, the hydraulic governor will deeply participate in ULFO. It can be concluded that as \( x_1 \) increases (the oscillation mode changes from LFO to ULFO), the participating factors of the exciter’s state variables and hydraulic governor’s state variables will decrease and increase, respectively. Furthermore, the participating factors of the exciter’s state variables will even be reduced to zero as \( x_1 \) increases to a certain value.

4 | GENERATOR’S INNER CAUSES TO ULFO AND DAMPING METHODS

After the external key factor has been confirmed, it is important to find out generator’s inner parameters’ relationship with ULFO when the value of \( x_1 \) is big. To clearly reveal the relationship between different devices of generator system, the complex torque coefficient method is used to shed light on each part’s specific contributions to ULFO in this section. Based on the complex torque coefficient method, the damping methods of ULFO are finally given.

4.1 | The complex torque coefficient theory

The complex torque coefficient method is well known and useful for generator’s dynamic stability analysis [38]. It can be described in three steps. First, determine the transfer function between the torque increment \( \Delta M \) and load angle increment \( \Delta \delta \). Second, let \( s = j \omega \) in the transfer functions. Finally, the coefficients of \( \Delta \delta \) and \( j \Delta \delta \) can be calculated. Here, the coefficient of \( j \Delta \delta \) decides the damping characteristic of generator; it is called damping torque coefficient, which is mainly used for oscillations study.

According to the transfer function of the exciter, PSS, and governor, the damping coefficients of each device can be calculated out with the help of Figure 2, where the model of PSS is given in Figure 16, in which \( T_{i_s}, K_{PSS}, T_1, T_2, T_3 \) and \( T_4 \) are 5.5, 150, 4.9619, 0.0064, 4.9619 and 0.0064, respectively. And the damping coefficients of the exciter, PSS, and governor are calculated by (15)–(17). The detailed expressions of the three damping coefficients can be found in the Appendix, where \( \omega_d \) is the frequency to be calculated.

\[
\Delta M_{D}^{\text{new}} = \frac{K_{\text{Num}}}{K_{\text{Den}}} = \frac{K_{\text{Num2}}}{K_{\text{Den1}}} + \omega_d^2 \frac{K_{\text{Den2}}}{K_{\text{Den1}}} \quad (15)
\]

\[
\Delta M_{D, \text{PSS}} = \frac{K_{\text{PSS1}}K_{\text{PSS2}}}{K_{\text{PSS1}}} + \omega_d^2 \frac{K_{\text{PSS2}}}{K_{\text{PSS1}}} \quad (16)
\]

\[
\Delta M_{D, \text{governor}} = \frac{K_{\text{g1}}K_{\text{g2}}}{K_{\text{g1}}} + \omega_d^2 \frac{K_{\text{g2}}}{K_{\text{g1}}} \quad (17)
\]

4.2 | Damping characteristic analysis in ultra-low-frequency band through the complex torque coefficient method

The damping torques (or damping torque coefficients) are calculated and plotted based on (15)–(17). According to last section’s conclusion, the external reactance \( x_1 \) is of great importance to ULFO. Thus, two different damping torques situations are presented when external reactance \( x_1 \) is small and big, as shown in Figures 17 and 18. The total damping torque in figures is the sum of the damping torque provided by the exciter,
PSS, and governor, which reflects the whole dynamic stability of the generator system.

From the two figures, it can be found that in the ultra-low-frequency band, namely frequency below 0.1 Hz, the total damping torque is basically decided by the governor. That is because the damping torque provided by the PSS mainly concentrates on classical low-frequency band above 0.1 Hz, while the exciter contributes little damping torque in the whole frequency band, which also validates the previous participating factors analysis. Therefore, the PSS cannot suppress ULFO, which is quite different from the situation in LFO. Actually, the big external reactance would further decrease PSS’s damping torque according to Figure 18. Thus, we can just analyse the governor’s parameter when the system has big external reactance rather than investigating every coefficient one by one, because the operating point (or the dominant pole) has now moved to ultra-low-frequency band from low-frequency band according to Figure 13.

4.3 Governor parameter’s impact to ULFO in weak connection situation

Now, it is clear that the weak connection or big external reactance $x_1$ causes the high risk of the ULFO, and the governor mainly decides the whole damping characteristic of the generator system. This part will discuss governor parameter’s impact on ULFO in weak connection situation ($x_1 = 144$ p.u.), where the $T_w$ parameter is reset to 1 for a better observation. Based on (17), the damping torque changing situations with different PID governor parameters and water starting time constant $T_w$ can be obtained as shown in Figures 19–22. The pentagrams in figures are the operating points based on theoretical dominant pole calculations.

From Figure 19, it can be concluded that the damping torques would first be increased and then decreased with increasing $K_P$. This is because the big value of $K_P$ will increase the oscillation frequency simultaneously and finally lead to smaller damping torques. Figure 20 indicates that bigger $K_I$ will decrease damping torque as the operating points are also shifted to lower frequency area and make damping torque smaller. Figure 21 shows that the damping torque can be slightly enhanced with suitable big value of $K_D$, while the dominant poles would be changed to a new unstable LFO mode if $K_D$ is too big.

As for the water starting time constant $T_w$, the damping torque would be decreased when $T_w$ increases according to Figure 22, and the dominant poles are influenced slightly.

4.4 The damping methods of ULFO

From the above analysis, it can be seen that to solve the ULFO problem, the key step is to increase the damping torque in the ultra-low-frequency band. There are two ways to realise it.

The first method is parameter adjustment. As the damping torque in the ultra-low-frequency band is mainly decided by the governor, we can adjust the PID parameters of the governor. That is by changing $K_I$ to a smaller value and $K_D$ to a suitable bigger value. As for the parameter $K_P$, it should be carefully tested in practical application because of existence of inflection point.
In order to make the ULFO suppression more effectively, some intelligent algorithms are generally used to optimise the hydraulic governor’s PI parameters, such as particle swarm optimisation and optimal PID parameter optimisation. The essence of this method is to adjust the PI parameters to weaken the primary frequency regulation performance of the hydraulic governor providing negative damping torque. It can be concluded that although the ULFO can be suppressed effectively, it sacrifices the primary frequency regulation performance of the hydraulic governor.

The second method is designing governor PSS (GPSS), which is similar to classical PSS designing. As the transfer function of the governor system is a lag system, the GPSS can be designed as a lead controller so that the positive $\Delta M$ can be outputted by the GPSS to enhance the damping torques. The structure of the GPSS is shown in Figure 23, and the output of the GPSS is added before governor PID block. The detailed design steps of GPSS parameters can be found in the supplementary document. Since the GPSS only suppresses ULFO by providing a phase compensation, this method will not weaken the primary frequency regulation performance of the hydraulic governor.

To compare the effects of these two suppression methods, the optimal PID parameter optimisation method is adopted, which is described in detail in [42]. The suppression effect of these two methods on ULFO will be compared later.

5 | SIMULATION VERIFICATION

Based on the above theoretical analysis, this section will implement the validations through simulation. The simulation model is established in PSCAD software according to the single-machine infinite-bus system in Figure 1, where the output of the generator is zero to eliminate operation level’s impact. Furthermore, the benchmark wscc9 system is also established in PSASP software to verify the applicability of the theory in any realistic condition. Since all units have the same rotor speed in the process of ULFO, the wscc9 system can reflect the interconnected system when analysing the ULFO problem. In order to verify the theory that the weak connection influences ULFO greatly, a simulation is carried out based on the four-machine two-area test system, which is a typical AC/DC hybrid interconnected system. In these three simulation models, the fifth-order model of the synchronous machine is adopted since the electromagnetic transients of the field winding and $D–Q$-axis damping windings are taken into consideration. Meanwhile, the fifth-order model can also represent the electromechanical transient of the rotor motion. Therefore, the fifth-order model is suitable for the transient stability analysis of the power system with high accuracy requirements.

5.1 | The simulation results in a single-machine infinite-bus system

Due to the limitation of pages, the ULFO key factor analysis part only presents the simulations of different external reactance $x_1$ (the other parameters’ simulations can be found in the supplementary document).

The detailed value of oscillation frequency in Figure 24 is shown in Table 3. It can be clearly seen that the oscillation period will become longer as the external reactance increases. In other words, the oscillation frequency decreases monotonically with the increase in the external reactance, as shown in Table 3. The bigger external reactance produces ULFO, while smaller $x_1$ leads to LFO. Once the external reactance increases to a certain value, the oscillation mode will change from LFO to ULFO. In
TABLE 3  The oscillation frequency of different $x_1$

| $x_1$ (in p.u.) | Frequency (in Hz) |
|-----------------|-------------------|
| 1.59            | 0.4325            |
| 29              | 0.1250            |
| 72              | 0.0840            |
| 144             | 0.0613            |

FIGURE 25  Simulations with different $K_P$ when $x_1 = 144$ p.u.

In other words, the system is risky of ULFO when the system is weakly connected to the main power grid, which is consistent with the theoretical analysis in the frequency domain, as shown in Figure 14. The system is unstable under the LFO because $T_{W}$ has been reset to 1 for better observation.

Under the condition that the external reactance $x_1$ is 144 p.u., that is, the system is in weak connection with the main power grid, the simulations about the influence of hydraulic governor parameters on oscillation characteristics can be obtained, as shown in Figures 25–28.

When $K_P$ increases from 1 to 10, the rotor speed of the generator will change from a divergent state to a convergent state from Figure 25. Once $K_P$ continues to increase to a certain value, the rotor speed of the generator will change from a convergent state to a divergent state. In other words, the damping torque provided by the hydraulic governor first increases and then decreases as $K_P$ increases, which is consistent with the theoretical analysis in the frequency domain, as shown in Figure 19. As is shown in Figure 26, the larger the $K_I$, the more serious of the divergence of the rotor speed, which indicates that the system is prone to instability with larger $K_I$. Increasing $K_D$ properly can effectively suppress the ULFO, but the system may be out of stability as $K_D$ increases to a certain value, as shown in Figure 27. As $T_W$ increases, the rotor speed of the generator will change from the divergent state to the convergent state, as shown in Figure 28, that is, the system is risky of instability with larger $T_W$. Actually, the simulations in the time domain validate the theoretical analysis in the frequency domain in Section 4 and also validate that parameter adjustment is effective to improve the damping characteristic of ULFO.

It can be clearly seen that the rotor speed of the generator converges quickly with the GPSS, as shown in Figure 29. It proves that the GPSS can significantly suppress ULFO, where the parameters of the GPSS in Figure 23 are $K_g = 2$, $T_{g1} = 1$, $T_{g2} = 2$, $T_{g3} = 1$, and $T_{g4} = 2$. 
5.2 The simulation results in the wscc9 system

The simulation results in the wscc9 system are shown in Figure 31, where there is a three-phase short-circuit fault at the STNC-230 bus at 2 s. The simulation results reflecting the influence of the exciter and hydraulic governor parameters on oscillation characteristics when the system is in strong connection are presented in the supplementary document. Besides, the simulation results under three-phase open-circuit fault and reference voltage disturbance are also given in the supplementary document. It can be clearly seen that the system is risky of ULFO only when $x_1$ increases to a big value from Figure 31. Actually, the big external reactance can be regarded as the asynchronous interconnection with the main power grid. Therefore, the phenomenon that ULFO almost occurred in an asynchronously connected system can be explained based on the theoretical analysis in the frequency domain and simulation results in the time domain.

When the system is in weak connection, the simulations regarding to the influence of hydraulic governor parameters on ULFO can be obtained. Since $K_P$ and $K_D$ have similar effects on ULFO, there only gives the simulation results with different $K_P$, as shown in Figure 32, due to the page limitations. The simulation results with different $K_I$ and $T_W$ are shown in Figures 33 and 34, respectively.

The influence of the hydraulic governor parameters on ULFO is the same in the above two different systems, and the system may be unstable due to the unreasonable settings of the hydraulic governor parameters. In particular, an excessively large $T_W$ will increase the negative damping effect of the hydraulic governor, which will lead to instability in the system, as shown in Figure 34. The simulations also validate the theoretical
analysis in the frequency domain in Section 4, which is based on the complex torque coefficient method.

For clear observation of the effectiveness of the GPSS, it is only validated in two realistic conditions. The first case is to add an impulse load to the STNC-230 load at 2 s, and the second case is to add a step to the reference voltage of generator 1 at 2 s. Besides, the effectiveness of the GPSS in the condition that a small disturbance is added to the STNC-230 load is also validated, which is presented in the supplementary document.

The simulations representing the suppression effects of the two methods mentioned in Section 4.4 are shown in Figures 35 and 36. From Figure 35, it can be seen that both of the two methods can suppress ULFO effectively. Furthermore, the suppression effect is the most effective when the PI parameters of the two hydraulic governors are optimised at the same time. The comparison of the damping torque provided by the two hydraulic governors under different situations is shown in Table 4, where the damping torque after the parameter optimisation of the second governor is the largest. The damping torque analysis and the simulation results validate each other.

Though the ULFO can be effectively suppressed by optimising PI parameters, the lowest point of frequency will decrease, as shown in the sub-graph in Figure 35. On the contrary, the GPSS effectively suppresses ULFO while increasing the lowest point of the frequency. This phenomenon is more obvious, as shown in Figure 36. Therefore, the damping torque and primary frequency regulation performance should be considered comprehensively when suppressing ULFO.

5.3 The simulation results in the four-machine two-area system

The structure of the four-machine two-area system is shown in Figure 37, where the typical parameter of the transmission line is 0.488 Ω/km. The simulation results with different distance are given in Figure 38.

When the distance is small, the generators are in strong interconnection with the main power grid. In this condition, the system is not risky of ULFO even if the system is with 100% hydropower, as shown in Figure 38. However, when the distance is large, the generators and the main power grid are interconnected only through the HVDC transmission line, and the system is in weak connection with the main power grid. In this case, the system is prone to ULFO, as shown by the red and...
green curves in Figure 38. The simulation results strongly prove that the weak connection is the source of ULFO.

In weak connection situation, the simulations reflecting the effect of hydraulic governor parameters on ULFO are shown in Figures 39–41.

It can be clearly seen that the influence of $K_p$ on the damping ratio is not monotonous, as shown in Figure 38. Appropriate increase of $K_p$ can effectively suppress ULFO, but increasing $K_p$ to a certain value will cause the system instability. On the contrary, decreasing $K_f$ and $T_p$ is an effective way to suppress ULFO since the damping ratio increases monotonously with the decrease of $K_f$ and $T_p$, as shown in Figures 39 and 40.

6 | CONCLUSION

Based on the analysis above, the following conclusions can be obtained.

(1) The weak connection influences the occurrence of ULFO a lot. The big external reactance $x_1$ will let system's dominant poles move to the ultra-low-frequency band.
(2) In the ultra-low-frequency band, the damping torque of the generator system is decided by the governor, while the PSS mainly influences the classical low-frequency band above 0.1 Hz.
(3) When the connection of the generator is weak and the system operates in an ultra-low-frequency area, small $K_f$ and suitable big $K_p$ of the governor system are beneficial to increase ULFO's damping ratio. And the big water starting time constant $T_w$ would decrease system's damping ratio. As for the parameter $K_p$'s impact, it is decided by operating point's relative position to inflection point.
(4) To suppress ULFO, besides the governor parameter adjustment method, designing GPSS similar to classical PSS is another effective way.

ACKNOWLEDGEMENTS

This work was supported by the Science and Technology Project of State Grid Corporation of China under Grant 521999180003.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.
APPENDIX

The state variable $\Delta x$ and state matrix $A$ in (11) can be expressed as follows.

$$
\Delta x = \begin{bmatrix}
\Delta \delta \\
\Delta \omega \\
\Delta E_{\omega J} \\
\Delta U_{\omega J} \\
\Delta X_1 \\
\Delta X_2 \\
\Delta M_a
\end{bmatrix}
$$

$$
A = 
\begin{bmatrix}
A_{ij} & A_{ie} & A_{eg} \\
A_{eg} & A_{ee} & A_{eg} \\
A_{eg} & A_{eg} & A_{gg}
\end{bmatrix}
$$

$$
A_{ij} = 
\begin{bmatrix}
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 1 / T_J \\
0 & 0 & 0
\end{bmatrix}
$$

$$
A_{ie} = 
\begin{bmatrix}
0 & 0 & 0 \\
0 & 0 & 0 \\
-1 / T_J & 0 & -1 / T_J
\end{bmatrix}
$$

$$
A_{eg} = 
\begin{bmatrix}
-1 / T_J \\
1 / T_J \\
0 & 0 & 1 / T_J \\
-1 / T_J & 0 & -1 / T_J
\end{bmatrix}
$$

$$
A_{gg} = 
\begin{bmatrix}
-B_p K_f & 0 & 0 \\
-B_p K_f / T_g & 1 / T_g & -K_p / T_g \\
2K_p / T_g & -2K_p / T_g & -2K_p / T_g
\end{bmatrix}
$$

The parameters in (7) are as follows:

$$
\begin{align*}
K_{\text{Num}1} &= K_2 K_4 K_6 / T_E - K_2 K_3 K_6 \omega_d^2 - K_2 K_3 K_6 \omega_d^2 \\
K_{\text{Num}2} &= K_2 K_4 K_6 / T_E \omega_d^2 - K_2 K_3 K_6 \omega_d^2 \\
K_{\text{Den}1} &= K_2 K_4 K_6 / T_E - T_p \omega_d^2 - T_p \omega_d^2 \\
K_{\text{Den}2} &= 1 + T_p \omega_d^2 + T_p \omega_d^2 \\
K_{\text{PSS}1} &= K_2 K_4 K_6 / T_E - T_p \omega_d^2 - T_p \omega_d^2 \\
K_{\text{PSS}5} &= 1 + T_p \omega_d^2 + T_p \omega_d^2
\end{align*}
$$

The parameters in (8) are as follows:

$$
\begin{align*}
K_{\text{PSS}7} &= K_{\text{PSS}1} K_{\text{PSS}3} K_{\text{PSS}5} - K_{\text{PSS}2} K_{\text{PSS}4} K_{\text{PSS}5} \omega_d^2 \\
K_{\text{PSS}6} &= (K_{\text{PSS}1} K_{\text{PSS}3} + K_{\text{PSS}2} K_{\text{PSS}4}) \omega_d^2 \\
K_{\text{PSS}8} &= K_{\text{PSS}1} K_{\text{PSS}3} K_{\text{PSS}5} + K_{\text{PSS}4} K_{\text{PSS}5} \omega_d^2 \\
K_{\text{PSS}9} &= K_{\text{PSS}1} K_{\text{PSS}3} K_{\text{PSS}5} + K_{\text{PSS}2} K_{\text{PSS}4} K_{\text{PSS}5} \omega_d^2 \\
K_{\text{PSS}11} &= K_{\text{PSS}1} K_{\text{PSS}3} K_{\text{PSS}5} + K_{\text{PSS}2} K_{\text{PSS}4} K_{\text{PSS}5} \omega_d^2 \\
K_{\text{PSS}12} &= K_{\text{PSS}1} K_{\text{PSS}3} K_{\text{PSS}5} + K_{\text{PSS}2} K_{\text{PSS}4} K_{\text{PSS}5} \omega_d^2
\end{align*}
$$

The parameters in (9) are as follows:

$$
\begin{align*}
K_{S1} &= -(0.5 T_w + T_s + 0.5 K_p K_s T_w T_g) \omega_d^2 + B_p K_f \\
K_{S4} &= (K_p - K_f T_w) \omega_d^2 + K_f T_w \omega_d^2 \\
K_{S5} &= -(K_D - K_f T_w) \omega_d^2 + K_f \\
K_{S2} &= (1 + 0.5 T_w + B_p K_f + T_s B_p K_f) \omega_d - 0.5 T_w T_g \omega_d^2
\end{align*}
$$