A Control Method for Switching-Type Frequency Oscillations in Hydropower System Based on Adjusting Dead Zone Structure

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Abstract: For the switching-type ultra-low frequency oscillation (ST-ULFO) that cannot be suppressed by increasing damping, in the single-hydropower-generator power system (SHG-PS) with enhanced dead zone, a control method based on adjusting the non-smooth structure of the dead zone is proposed. First, the model of the SHG-PS with enhanced dead zone, corresponding to Filippov non-smooth system, and the ST-ULFO phenomenon are introduced. Second, a case of oscillation cannot be suppressed by increasing system damping, as the system equilibrium point disappeared under disturbance, is introduced. Next, a construction method to make the enhanced dead zone continuous is given. Then, the Hopf-like non-smooth bifurcation characteristics of the equilibrium point and the post fault dynamics of the SHG-PS before/after the enhanced dead zone continuity are compared. Finally, the effectiveness of control method is verified in the SHG-PS and the 2-area-4-generators system. The results show that, the oscillations which cannot be suppressed by increasing system damping, will be effectively suppressed by adjusting the enhanced dead zone structure.

1 INTRODUCTION

Ultra-low frequency oscillations (ULFOs) have occurred many times in the power grid with a high proportion of hydropower at home and abroad (Li et al., 2018). The ULFOs are quite different from the traditional low-frequency oscillations and threaten the safe operation of the power system Xue et al., 2021).

The ULFOs are mainly explained by the negative damping oscillation (Liu et al., 2016), the smooth forced oscillation (Ju et al., 2014), or the switching-type oscillation (non-smooth oscillation) Xue et al., 2021). The negative damping oscillation and the smooth forced oscillation correspond to the oscillations in smooth dynamical systems. While the switching-type oscillation correspond to the oscillations associated with the switches, such as dead zones, limits, or control switches in the non-smooth dynamical system (Xue and Wang, 2020)(Xue et al., 2021).

The negative damping oscillations and smooth forced oscillations can be suppressed or prevented by increasing the system damping. Due to the influence of water hammer effect, hydropower generators exhibit negative damping characteristics in the ultra-low frequency band. Thus, the control measures for ULFOs also adopt the way of improving system damping, such as optimizing the PID parameters of the governor (Zhou et al., 2017).

It is worth noting that, although the control measure of improving system damping has good universality, the switching-type oscillations reflect the large-scale dynamics of the system and have no clear correspondence with the local properties of the equilibrium point. For example, in a single-hydropower-generator power system (SHG-PS) with enhanced dead zone, the switching-type oscillations occur when the system with no equilibrium point or with a stable equilibrium point (SEP) (Xue et al., 2021).

On the other hand, in addition to increasing system damping, changing the size of dead zone can also suppress the switching-type oscillations. For example,

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literature (Xue et al., 2021) points out that increasing the size of dead zone of hydropower generators can keep the system from non-smooth bifurcation and avoid the switching-type oscillations. Although setting a large dead zone of governor is beneficial to the system stability, it also wastes part of frequency regulation capability at the same time.

In summary, for the control of switching-type frequency oscillations, increasing system damping may be ineffective and adjusting the dead zone size has the disadvantage of wasting the frequency regulation capability. In view of this, aiming at the switching-type oscillation cannot be suppressed by increasing system damping in the SHG-PS with enhanced dead zone, this paper proposes a control method based on adjusting the dead zone structure, and verifies the control effect in the SHG-PS and 2-area-4-generators systems.

2 SYSTEM MODEL AND OSCILLATION PHENOMENA

This section presents the system model of the simplified single-hydropower-generator power system (SHG-PS) with enhanced dead zone, together with its switching-type oscillation phenomena.

2.1 System Model

The system model studied in this paper is a simplified SHG-PS with enhanced dead zone. Its corresponding mathematical description is as follows (Xue et al., 2021):

$$\begin{cases} \dot{x}_1 = [F(x_4) + b_p(Y_{ref} - K_P F(x_4) - x_1)] \cdot K_I \\ \dot{x}_2 = (K_P F(x_4) + x_1 - x_2) \cdot K_{PI} / T_y \\ \dot{x}_3 = [x_2 - x_3 - K_{PI} T_W (K_P F(x_4) + x_1 - x_2) / T_y] \cdot 2 / T_W \\ \dot{x}_4 = [x_3 - K_L (x_4 - \omega_{ref}) - P_L] / T_J \end{cases} \tag{1}$$

Where x_4 represents the angular frequency ω, and the remaining parameters are given in the literature (Xue and Wang, 2020). The values of the relevant variables, if not otherwise specified, are the standardized values. $F(x_4)$ is the description of the enhanced dead zone, as shown in Figure 1.

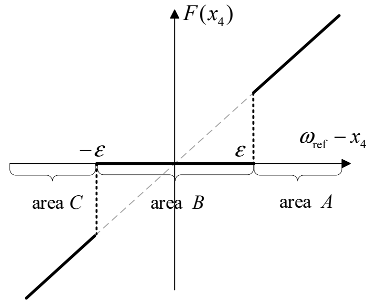

Figure 1: The model of enhanced dead zone.

The mathematical description is:

$$F(x_4) = \begin{cases} 0 & |\omega_{ref} - x_4| < \varepsilon \\ \omega_{ref} - x_4 & |\omega_{ref} - x_4| > \varepsilon \end{cases} \tag{2}$$

Figure 1 and equation (2) show that the SHG-PS is divided into three areas by the dead zone switching manifolds, i.e., $\Sigma_{b1}=\{x_4|x_4=\omega_{ref}-\varepsilon\}$ and $\Sigma_{b2}=\{x_4|x_4=\omega_{ref}+\varepsilon\}$. The area *A*/*C* corresponds to the regulation area and area *B* corresponds to the dead zone area. Due to the step control logic at the switching manifolds, the system vector field is discontinuous, thus, the SHG-PS with enhanced dead zone is a Filippov non-smooth system (Simpson, 2018).

2.2 Oscillation Phenomena

The SHG-PS with enhanced dead zone may occur ULFOs under sudden load perturbations (Xue et al., 2021).

For example, when the post-disturbance load P_L =1.02, the system has no equilibrium point and an ULFO of 0.084 Hz occurs, as shown in Figure 2.

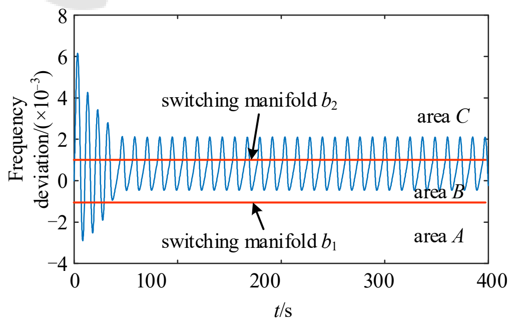

Figure 2: The frequency oscillation when P_L=1.02.

Figure 2 shows that the oscillation trajectory will cross the switching manifold Σ_{b2} and change in the area *B* and area *C*, corresponding to the switching-type non-smooth oscillation.

3 THE CASE OF OSCILLATION CANNOT BE SUPPRESSED BY INCREASING DAMPING

This section represents the case that increasing system damping cannot suppress the switching-type oscillation and analyzes the reasons.

Increasing system damping is generally considered as a method to suppress oscillation. For the SHG-PS of Section 2.1, the PI control parameters, i.e., K_P and K_I, can be adjusted to increase the mechanical damping coefficient D_m (Liu et al., 2016).

In the case of Section 2.2, the mechanical damping coefficient D_m under different parameter groups are shown in Table 1.

Table 1: The damping under different parameters.

	K_p	K_I	D_m
initial parameters	5	1	-2.97
parameter group 1	3	1	-2.81
parameter group 2	1	0.25	-0.78

Table 1 shows that, after adjusting PI parameters, the system damping is improved. Under the load disturbance of Section 2.2, the frequency changes of systems with different PI parameters are shown in Figure 3.

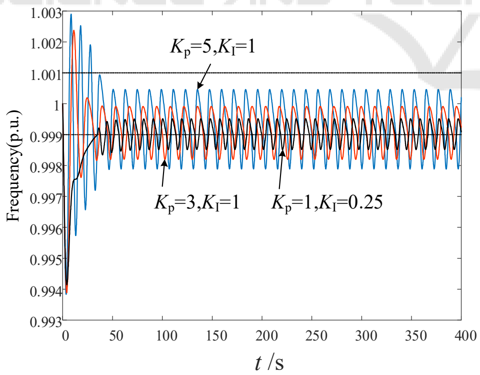

Figure 3: The frequency changes under different PI.

Figure 3 shows that after increasing the damping, the system still occur the switching-type frequency oscillation, that is, the switching-type oscillation of SHG-PS with enhanced dead zone cannot be effectively suppressed by increasing damping.

It is worth noting that, although the system damping is improved, the step characteristic at the switching manifold of SHG-PS has not changed. Under a certain load disturbance, the system still has no equilibrium point, and the switching-type oscillation will still occur. Therefore, the switching-type oscillation of SHG-PS with enhanced dead zone (Filippov non-smooth system) may not be suppressed by increasing damping.

4 CONTINUOUS ENHANCED DEAD ZONE

This section introduces a construction method to make the enhanced dead zone continuous at the switching manifold, so that the system has a SEP under certain load disturbances.

To make the system always has an equilibrium point, the dead zone characteristic should be continuous. On the other hand, to make the governor adjust quickly, the step characteristic shall be retained at the switching manifold. The continuous function $f(x)$ simulating step characteristics, as shown in equation (3), can meet these requirements.

$$f(x)=\frac{k}{1+e^{-\frac{(x-a)c}{b}}} \quad (3)$$

where a, b, c, and k are the constants, determining the interval and degree of the step.

With the function $f(x)$, the enhanced dead zone can be continuous, as shown in Figure 4.

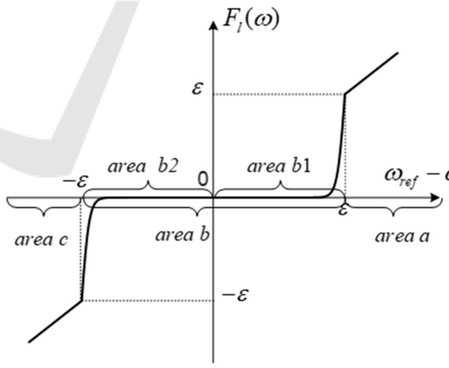

Figure 4: The continuous enhanced dead zone.

The mathematical description is：

$$F_l(\omega)=\begin{cases} \dfrac{k}{1+e^{\frac{(\omega_{ref}-\omega-\varepsilon)c}{b}}} & 0<\omega_{ref}-\omega<\varepsilon \\ -\dfrac{k}{1+e^{\frac{(\omega-\omega_{ref}-\varepsilon)c}{b}}} & -\varepsilon<\omega_{ref}-\omega<0 \\ \omega_{ref}-\omega & |\omega_{ref}-\omega|>\varepsilon \end{cases} \tag{4}$$

The SHG-PS with continuous enhanced dead zone is no longer a Filippov non-smooth system with discontinuous vector fields, but a piecewise-smooth continuous system (a type of the non-smooth system) (Simpson, 2018). That is, the type of non-smooth systems is changed. The continuous system includes area *a*, area *b*1, area *b*2 and area *c*.

5 SYSTEM BIFURCATION CHARACTERISTICS BEFORE AND AFTER CONTINUITY

This section presents the non-smooth bifurcation characteristics of the equilibrium point and the post fault dynamics of the SHG-PS before/after the enhanced dead zone continued.

Considering typical system parameters, the pre-fault system load is rated 1 and the system operates at the SEP, i.e., $(x_1, x_2, x_3, x_4) = (1, 1, 1, 1)$. Considering the sudden load change (i.e., the load parameter P_L takes different values after the perturbation), the non-smooth bifurcation characteristics of the equilibrium point and the post fault dynamics of the SHG-PS before the enhanced dead zone continued can be obtained, as shown in Figure 5 (Xue et al., 2021).

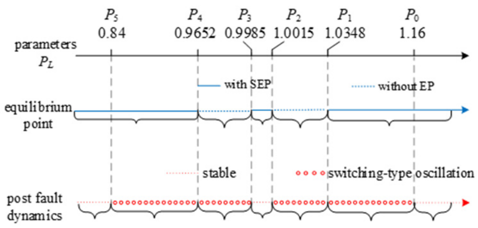

Figure 5:The non-smooth bifurcation characteristics before continuity.

Figure 5 shows that with the change of the load parameters, the system undergoes a Hopf-like non-smooth bifurcation, manifesting that the equilibrium point disappears and switching-type oscillation occurs at the same time. Furthermore, P_2 and P_3 are the bifurcation points (P_1 and P_4 correspond to another type of bifurcation (Xue et al., 2021), which is not considered in this paper).

Considering the continuous enhanced dead zone parameters taken as: b=0.01, c=70, k=2, and ε=0.002, respectively, and under the same simulation conditions, the Hopf-like non-smooth bifurcation characteristics of the SHG-PS after the enhanced dead zone continued can be obtained, as shown in Figure 6.

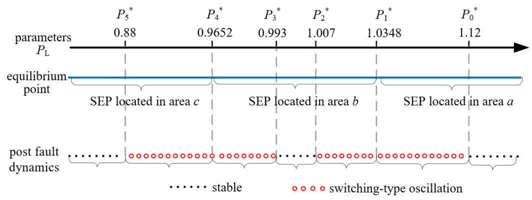

Figure 6:The non-smooth bifurcation characteristics after continuity.

Compared with Figure 5, Figure 6 shows that：

1) The range of disturbance load parameters that may induce switching-type oscillation is decreased after the enhanced dead zone is continuous, which is beneficial to the system stability. For example, the range $1.0015 \le P_L \le 1.16$ can be reduced to $1.007 \le P_L \le 1.12$, specifically.

2) After the enhanced dead zone is continuous, the SHG-PS always has a SEP, and the switching-type oscillation is no longer related to the system without equilibrium point. That is, the Hopf-like non-smooth bifurcation with the equilibrium point disappearing does not occur, thus avoiding the switching-type oscillations.

6 CONTROLLER VERIFICATION

This section verifies the control effect of continuous enhanced dead zone in SHG-PS and 2-area-4-generators system, respectively.

6.1 Effect in SHG-PS

After the enhanced dead zone continuity, there is always a SEP. In addition, optimizing PI control parameters to increase damping can further increase the global stability of system.

Taking the load perturbation parameter P_L=1.02 as an example, the dynamic characteristics of the SHG-PS with enhanced dead zone and with continuous enhanced dead zone under different PI parameters can be obtained, as shown in Figure 7.

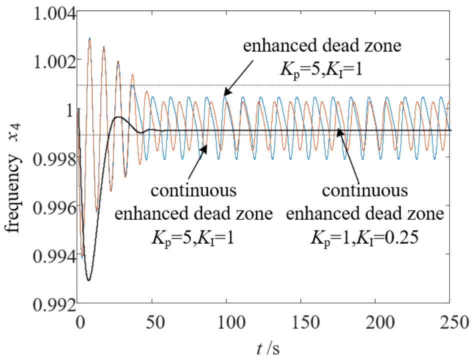

Figure 7: Control effect in SHG-PS.

Figure 7 shows that:

1) With the initial parameters, i.e., K_P=5 and K_I=1, the oscillation amplitude will be somewhat reduced after the enhanced dead zone continuity. The possible reason is that after the enhanced dead zone continuity, the governor has begun to participate in the regulation when the frequency deviation gradually approaches the set value of dead zone.

2) With the optimized parameters, i.e., K_P=1 and K_I=0.25, the frequency of the SHG-PS with continuous enhanced dead zone, will return to stability. While the SHG-PS with enhanced dead zone still occur frequency oscillation, as shown in Figure 3. The switching-type frequency oscillation of the SHG-PS is effectively suppressed by adjusting dead zone structure and optimizing PI control parameters.

6.2 Effect in 2-area-4-generators System

In this subsection, a 2-area-4-generators system, as shown in Figure 8, is used to verify the control effect.

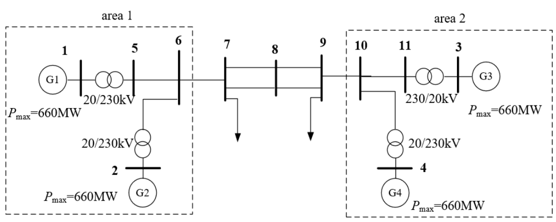

Figure 8: The 2-area-4-generators system.

The 2-area-4-generators system is set as follows: four generators are all hydropower units, where the dead zone of G1 governor is enhanced or continuous enhanced dead zone, and the dead zones of remaining three generators are traditional dead zone.

The main system parameters are set as follows: dead zone $\varepsilon = 0.05$Hz ; water hammer effect coefficient T_w=0.3; PI parameters K_p=5 and K_I=2.5.

Two fault conditions are set as follows:

1) Small disturbance: 5MW load is reduced at bus 7.

2) Large disturbance: 100MW output is reduced in generator G1.

Under large/small disturbances, the frequency characteristics of the system with enhanced dead zone or continuous enhanced dead zone, are shown in Figure 9 and Figure 10, respectively.

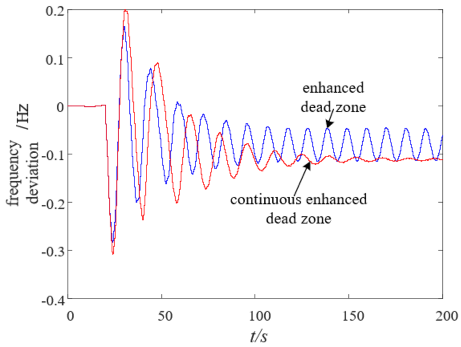

Figure 9: The system frequency under small disturbance.

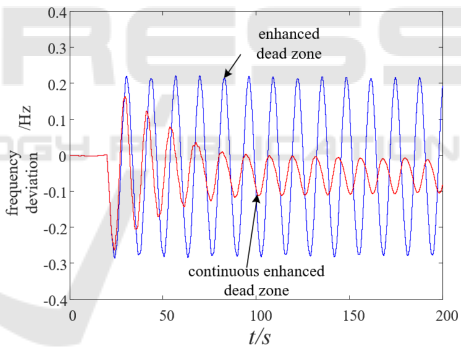

Figure 10: The system frequency under large disturbance.

Figure 9 and Figure 10 show that:

1) When the dead zone of G1 governor is enhanced dead zone, the system will occur the oscillation with oscillation frequency of 0.09Hz under small disturbance. While the dead zone is replaced with a continuous enhanced dead zone, the system frequency gradually stabilizes and the oscillation disappears.

2) Under the large disturbance, the 2-area-4-generators system will occur ULFO, no matter the enhanced dead zone is discontinuous or continuous. However, the system with continuous enhanced dead zone has smaller oscillation amplitude, which may reduce the degree of harm to the system.

Therefore, under large/small disturbances, the governor with continuous enhanced dead zone can effectively suppress the oscillation, and the system stability is better.

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7 CONCLUSIONS

Aiming at the ST-ULFO in hydropower systems with enhanced dead zone, this paper provides a control method based on adjusting the non-smooth structure of the enhanced dead zone and verifies its effectiveness. The conclusions are as follows:

a) SHG-PS with enhanced dead zone is a Filippov non-smooth system. It may have no equilibrium point and occur the switching-type oscillation under certain load disturbance. Only increasing the system damping cannot suppress the switching-type oscillation.

b) The continuous function simulating step characteristics can make the enhanced dead zone continuous. The corresponding continuous system maintains the rapidity of governor action, and there is no longer a Hopf-like non-smooth bifurcation with the equilibrium point disappearing.

c) The continuous enhanced dead zone can effectively suppress frequency oscillation, that is, adjusting the dead zone non-smooth structure can suppress the switching-type oscillation.

It is worth noting that, the continuous enhanced dead zone is an ideal model that has not yet been put into use in real systems. To be practical, its structural parameters still need to be optimized and analyzed.

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