Two-stage Control Strategy for UHVDC Voltage based on Bifurcation Trajectory Sensitivity

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Abstract. In order to solve the voltage bifurcation phenomenon caused by the continuous change of the load on the UHV grid receiving end system, this paper proposes a two-stage control strategy based on the bifurcation trajectory sensitivity. Firstly, the mechanism of bifurcation of UHV receiving part’s voltage is analyzed. Then the coordination correction model of voltage auxiliary decision and prediction control using bifurcation sensitivity is described. In order to verify the effect proposed, a typical accident of an ultra-high voltage receiving end is used for simulation. The simulation results show that the control effect can meet the stability requirements of the power grid. Two-stage Control Strategy could apply to solve the bifurcation problem.

1. Introduction

With the implementation of the “four revolutions, one cooperation” new energy security strategy, the new energy is connected to the grid on a large scale, the power supply structure is deeply adjusted, and the stable form of the power grid is more complicated[1]. China's power grid exhibits UHV AC-DC hybrid characteristics. The coupling of transmission and reception networks is becoming more and more tight, the integration characteristics of power grids are significant, and the dynamic interaction characteristics of multi-infeed DC groups are complex. At present, China's power grid is in the transition period of UHV grid construction, with large The capacity UHV DC is gradually put into operation, the characteristics of the power grid system change, and the system frequency and voltage stability problems are prominent[2-3]. In particular, it is very important to study the emergency control strategy under the voltage bifurcation fault of the UHV DC power receiving terminal.

Reference [4] firstly introduces the bifurcation phenomenon in the power system and the analysis method of static bifurcation and dynamic bifurcation instability, and then analyzes the load characteristics, adjustment of the on-load voltage regulator, and reactive power. The effect of compensation measures on voltage stability. On this basis, other literature deeply studies the limit-induced bifurcation problem of static voltage, and introduces the conditions and determination of the limit-induced bifurcation[5]. Reference [6], based on the characteristics of polynomial interpolation and power flow solution, an improved continuous power flow is proposed. In the prediction part of continuous power flow, a nonlinear prediction method is adopted. In the correction section of the continuous power flow, a hybrid correction method is employed. Further study shows through simulation that the voltage distribution of the distribution network system increases with the increase of the reactive capacity of the load device[7]. Reference [8] analyzes the maximum amount of power system load based on the bifurcation theory. Analysis of the above literature found that the existing literature has little research on the voltage stability of the UHV receiving end system, especially the emergency control when the terminal voltage is bifurcated.
2. Analysis of the mechanism of UHV receiving terminal voltage bifurcation

2.1. UHV network bifurcation theory basis

The nature of the power system is a dynamic nonlinear system. The change of the voltage stability form is essentially a process from stability to bifurcation. In the process of changing the state of the system with the change of parameters, the stability of the system will change, and the change is widely recognized by the theory of bifurcation\cite{9}. The bifurcation includes two aspects: time-sharing system status and parameter values. From the steady state to the instability bifurcation point, the range in which the parameters can be continuously changed is called the parameter space feasible region, and the bifurcation point constitutes the feasible domain boundary. The closer to the feasible domain boundary, the smaller the system state space attraction region (region of attraction), the worse the transient stability. The saddle knot bifurcation is directly related to the voltage collapse. At the saddle node bifurcation point, the system state monotonously diverges after the disturbance, which is consistent with the voltage collapse form. The limit-induced bifurcation is caused by the structural change of the system. For example, if the generator reaches the reactive upper limit, the PV is converted to the PQ node, and the reactive power compensation reaches the voltage limit input or exit. Before and after the structural change, the system may suddenly change from being in the upper half of the nose curve to being in the lower half, thus the voltage is unstable\cite{10}.

The 1100kV UHV DC system adopts a layered access network architecture and is connected to multiple AC systems through the DC inverter side, that is, the high voltage side of each pole on the inverter side is connected to the 1000kV AC system, and the low voltage side converter is connected to 500kV. The AC system uses a bipolar dual 12-pulse commutation scheme. Due to the layered access method, in terms of voltage stability control, compared with the traditional two-terminal DC transmission, it is necessary to coordinate and control multiple inverters, and the control system is more complicated\cite{11}. When the system parameters (for example, power generation and load) change slowly, it is necessary to analyze how the stability of the system equilibrium point changes. At this time, the bifurcation theory should be used to study the mechanism of the voltage stability of the UHV receiving terminal.

The basic mathematical model of a UHV power network can be represented as a set of differential-algebraic equations (DAE):

\[
\begin{align*}
\dot{x} & = f(x, y, \mu) \\
0 & = g(x, y, \mu)
\end{align*}
\]

The state vector for the UHV AC-DC system is the node voltage amplitude and phase angle, which is the system parameter, which refers to the power load of the system receiving end.

The equations consist of differential equations for dynamic devices related to voltage stability and power flow equations that represent the power transfer relationship between nodes and are affected by the transmission network. The differential equation describes the dynamic behavior of UHV network equipment. The algebraic equation consists of the power system power flow equation and the equation describing the relationship between differential variables and algebraic variables. The equilibrium point of the UHV system is obtained by solving the following equations:

\[
\begin{align*}
0 &= f(x, y, \mu) \\
0 &= g(x, y, \mu)
\end{align*}
\]

After eliminating the variables, a differential equation of state describing the dynamics of the system is available:

\[
\Delta \dot{x} = (A - BD^{-1}C)\Delta x = A' \Delta x
\]

Where:
The voltage dynamic stability of the UHV system can be determined by the eigenvalues of the Jacobian matrix $\Lambda$, and then the position and type of the static and dynamic bifurcation points in the vector field $\mathbf{f}(x, \mu)$ are used to analyze the stability of the system receiving voltage.

2.2. Bifurcation model of UHV AC/DC system

The system is subjected to the bifurcation parameter of the end load factor to obtain the bifurcation model of the UHV AC/DC system:

$$\begin{aligned}
A &= \frac{\partial \mathbf{f}}{\partial x}(x_0, y_0, \mu_0), \\
B &= \frac{\partial \mathbf{f}}{\partial y}(x_0, y_0, \mu_0), \\
C &= \frac{\partial \mathbf{g}}{\partial x}(x_0, y_0, \mu_0), \\
D &= \frac{\partial \mathbf{g}}{\partial y}(x_0, y_0, \mu_0)
\end{aligned} \tag{4}$$

The variable with the lower corner a is the AC system variable, and the variable with the lower corner d is the DC variable.

3. Two-stage emergency control measures based on bifurcation trajectory sensitivity

3.1. Bifurcation trajectory sensitivity

For complex power systems, the trajectory sensitivity can clearly reflect the influence of system parameter changes on the system's bifurcation response, which can be used as the basis for voltage frequency control.

The initial value $x_\mu(t_0)$ of the trajectory sensitivity of the state variable relative to the parameter is 0, thereby calculating the initial value of $y_\mu(t_0)$ the trajectory sensitivity of the algebraic variable relative to the parameter $p$.

$$g_\gamma(t_0)y_\mu(t_0) = g_\mu(t_0) \tag{6}$$

The trajectory sensitivity can quantify the change in system response as the parameter changes. The state response and the change due to the change in parameter $p$ can be described as:

$$\Delta z(t) = \frac{\partial z(t)}{\partial \mu} \Delta \mu = z_{\mu}(t) \Delta \mu \tag{7}$$

Where:

$$z_{\mu}(t) := \begin{bmatrix} x_\mu(t)^T, y_\mu(t)^T \end{bmatrix}^T \tag{8}$$

The computational cost of obtaining the trajectory sensitivity is small, especially when the number of trajectories is required to be calculated.
3.2. Auxiliary decision making and Model Predictive Control (MPC) two-stage correction method
The basic idea of the two-stage correction method is: when the fork is forked, the first stage is put into the auxiliary decision. If the simulation predicts that the frequency or voltage cannot be restored to a stable operating level, the Model Predictive Control (MPC) correction is performed in the second phase until the frequency and voltage are restored by about 1 p.u. Event-driven auxiliary decision-making and data-driven MPC closed-loop correction can compensate for the lack of input of auxiliary decision-making control due to limited operation mode, and speed and voltage recovery. The two-stage calibration process is shown in Figure 1. In the off-line calculation of auxiliary decision, the trajectory sensitivity, low voltage set, sensitive control set and other information of each control pair frequency and voltage response curve can be calculated and stored at the same time. The MPC closed-loop control can use the stored corresponding information to establish an optimization model to calculate the control amount to improve the calculation efficiency.

![Figure 1. Two-Stage calibration process](image)

3.2.1 Auxiliary decision optimization method
Since the auxiliary decision is based on the offline typical mode, the transient safety stability margin may be unqualified when applied to the system online operation. Therefore, the auxiliary decision and the model predictive control method should be used together.

3.2.1.1 Objective function of assistant decision-making optimization model
For the voltage bifurcation caused by the load increase, it is usually necessary to adopt a load shedding method to solve. For regional power grids with load shedding measures, the cost of maintaining system stability should be as small as possible to avoid excessive accident penalties. Therefore, aiming at the minimum cost of control measures, the objective function is established as follows:

\[ C = \sum_{i=1}^{n} w_i p_{li} P_{li,0} \]  \hspace{1cm} (9)

In the formula, \( C \) is the total control measure cost; \( i \) is the number of the load shedding place; \( w_i \) is the cost of the unit load shedding at the load shedding point, including the economic loss and accident penalty caused by the load shedding; \( p_{li} \) is the load shedding rate; \( P_{li,0} \) is the initial load of the node Quantity; \( n \) is the total number of load points.

3.2.1.2 Restrictions
3.2.1.2.1 Restriction of load cut

\[ \sum_{i=1}^{n} L_i = \sum_{i=1}^{n} L_i \]
All busbars that provide load shedding form the control space. The actual load-cutting node (busbar) forms a load-shedding control vector. The maximum value of the load-cuttable load of each load-cut node forms the maximum load-shedding vector. The load-shedding constraint can be described as:

\[
\theta \leq P \leq P_{\text{max}}
\]

\[
P = [p_{l1}, p_{l2}, \ldots, p_{ln}]^T
\]

\[
P_{\text{max}} = [p_{l1,\text{max}}, p_{l2,\text{max}}, \ldots, p_{ln,\text{max}}]^T
\]

Where, \( p_{lj} \) is the actual load shedding for the node; \( p_{l,j,\text{max}} \) is the maximum load shedding for the node.

3.2.1.2.2 Load point selection
In order to maximize control benefits and reduce the amount of optimization calculation, several nodes with the highest sensitivity can be selected for control. There is a dominant instability mode in the system instability. Taking the transient voltage stability as an example, the same load-cutting measure has different effects on the transient voltage stability of different observation nodes. To reduce the calculation amount, it can be taken as the retraction point load to the system transient. The influence of voltage stability is measured, and then the largest number of nodes are taken as load control nodes to optimize the control scheme.

In summary, the mathematical model of emergency load shedding is obtained as follows:

\[
\min \quad C = \sum_{i=1}^{n} w_i p_{l,i} P_{l,i,0}
\]

s.t. \( \eta \geq \varepsilon \)

\( \theta \leq P \leq P_{\text{max}} \)

(12)

3.2.2 Model predictive control (MPC) coordination correction model
In the case of voltage bifurcation, select a few of the most sensitive controls, only to find the control that should be invested at the current moment. Voltage instability often manifests as a drop in local node voltage, so it is necessary to first find low voltage nodes and then filter the sensitive control set based on these voltages relative to the controlled trajectory sensitivity. The inertial center frequency is used to represent the whole network frequency, and the sensitive control set is screened according to the frequency relative to the controlled trajectory sensitivity.

Define a low voltage set at the end of the prediction time interval \([t_k, t_{end}]\):

\[
U = \{ U_{\text{end},j} : U_{\text{end},j} \leq U_{\text{lim}} \}
\]

(13)

Where, \( U_{\text{end},j} \) is the voltage amplitude of the node \( i \) at the time of the \( t_{end} \), and \( U_{\text{lim}} \) is the set value. Defining the sensitive control set as following:

\[
S = \left\{ \begin{array}{l} u_{k,j} \quad \left| \frac{\partial U_{\text{end},j}}{\partial u_{k,j}} \right| \geq S_{\text{lim}1} \quad \text{or} \quad \left| \frac{\partial F_{\text{end}}}{\partial u_{k,j}} \right| \geq S_{\text{lim}2}, U_{\text{end},j} \in U \end{array} \right\}
\]

(14)

Where \( u_{k,j} \) denotes the \( j \)th control at \( t_k \) time; \( F_{\text{end}} \) is the inertia center frequency at the time of \( t_{end} \); \( \frac{\partial U_{\text{end},j}}{\partial u_{k,j}} \) and \( \frac{\partial U_{\text{end},j}}{\partial u_{k,j}} \) are the trajectory sensitivity of the low voltage amplitude and the inertial center...
frequency with respect to the \( t_k \) time control \( j \) respectively at the time of the \( t_{end} \); \( S^{lim1} \) and \( S^{lim2} \) are set value.

### 3.2.2.1 Reference track adjustment control set reduction

When the system pressure is too far from the operating state, trying to restore the two to a steady state value by one control may make the optimization problem have no solution, and may cause a large fluctuation of the electric quantity, thereby adversely affecting the stability. Therefore, the reference trajectory is adjusted at each optimization. It is desirable to \( t_{end} \) at the end of the prediction time interval, and each control reduces the difference between the voltage average of the voltage set \( U_{end} \) (or \( F_{end} \)) and 1 p.u. by \( a\% \) (and \( b\% \)). But when they are close to running, the control should restore it directly to 1p.u., that is:

\[
U_{end}^{min} = \begin{cases} 
U_{end} + (1-U_{end}) \cdot a\%, & 1-U_{end} > 0.02 \\
1, & 1-U_{end} \leq 0.02 
\end{cases}
\quad (15)
\]

\[
F_{end}^{min} = \begin{cases} 
F_{end} + (1-F_{end}) \cdot b\%, & 1-F_{end} > 0.001 \\
1, & 1-F_{end} \leq 0.001 
\end{cases}
\quad (16)
\]

Where, \( U_{end}^{min} \) and \( F_{end}^{min} \) are the voltage and frequency reference trajectories at the time of the tend.

The state of the power system at \( t_k \) is taken as the initial state, and the response of the system in the predicted time interval \([t_k, t_{end}]\) under the fault is predicted by the simulation model. At the same time, the trajectory sensitivity is calculated using the numerical method and the direct method. Based on the trajectory sensitivity, a rolling coordination optimization model is established, which is solved to obtain the control quantity that minimizes the cost and satisfies the constraint. Taking into account the time required for the calculation, the control implementation time is postponed to the next sampling instant \( t_k + T \). Finally, let \( k = k + T \), repeat the above process until the predicted frequency and voltage return to the steady state operating level. The process is shown in figure 2.

In MPC-based closed-loop control, each response prediction, trajectory sensitivity calculation, and coordinated optimization are based on new sampling time data, and the control amount is fed back to the grid.
Figure 2. MPC-based coordinated optimization closed-loop control

3.2.2.2 Model predictive control voltage correction model
When establishing a model prediction optimization model for voltage correction, only a few of the most sensitive load-cut points are selected as the control set to establish the objective function:

\[
J = \min \left\{ \Delta u_k^T R \Delta u_k \right\}
\]

(17)

The desired trajectory is adjusted with the rolling optimization process, and each control is specified in the constraint to reduce the difference between the low voltage average and 1 p.u. by a\%.

\[
\bar{U}_{L}^{min} = \bar{U}_{L} + \left(1 - \bar{U}_{L}\right) \cdot a\%
\]

(18)

In the constraint, only the steady-state low-voltage bus average of the fault is constrained and the control step is constrained:

\[
\begin{cases}
    m\bar{U}_{L}^{min} - (U_{L1}^{L} + \cdots + U_{Ln}^{L}) \leq \left( \frac{\partial U_{L1}}{\partial u} + \cdots + \frac{\partial U_{Ln}}{\partial u} \right) \Delta u_k \\
    \Delta u_k^{min} \leq \Delta u_k \leq \Delta u_k^{max}
\end{cases}
\]

(19)

4. Case analysis
The summertime operation mode of East China Power Grid is used as a simulation example to verify the effectiveness of the proposed method. As the system is continuously increased by the end load, the receiving terminal voltage is abnormal, as shown in figure 3. In order to restore the terminal voltage as soon as possible, the frequency and voltage are coordinated and corrected by the emergency measures mentioned in this paper.

In order to cope with the voltage bifurcation phenomenon, a certain proportion of the load is started to be removed when the strategy shown above is t=1.7 seconds. In the first control, at the sampling time tk, the controllable node and the regional load whose absolute value of the steady-state voltage trajectory sensitivity is greater than 0.01 p.u. are selected into the sensitive control set. The track...
sensitivity is shown in table 1. The voltage and frequency recovery coefficients in equations (15) and (16) are $a = b = 70$. The closed-loop control is stopped under the condition that the steady-state frequency of the prediction system is in the interval $[1.0005, 0.9995]$ and the voltage is in the interval $[1.005, 0.995]$.

After the third stage of load shedding correction in the second stage, the voltage and frequency are coordinated to return to a stable operation level, as shown in figureure. The sensitive control set and the control quantities of each stage are shown in table 2.

### TABLE 1. Voltage trace sensitivity

| Sensitive Control Set                  | $U_{MengXi}_{230}$ | $U_{Wan-GangXi}_{230}$ | $U_{Wan-HuoLONG}_{230}$ |
|---------------------------------------|--------------------|------------------------|--------------------------|
| Wan-RuiFeng __230.kV                 | -0.0989            | -0.0649                | -0.0592                  |
| Wan-MengXi __230. kV                  | -0.0449            | -0.0289                | -0.0264                  |
| Wan-PuQing __230. kV                  | -0.0203            | -0.0171                | -0.0158                  |
| Wan-ShiZhuan __230. kV                | -0.0800            | -0.0506                | -0.0461                  |
| WanJiuJiang __230. kV                 | -0.0569            | -0.0540                | -0.0490                  |
| Wan-GangXi __230. kV                  | -0.0469            | -0.0469                | -0.0425                  |
| Wan-HuoLONG __230. kV                | -0.0302            | -0.0294                | -0.0308                  |
| J6 Partition                          | -0.0025            | -0.0027                | -0.0027                  |
| J7 Partition                          | -0.0019            | -0.0022                | -0.0023                  |
| J8 Partition                          | -0.0024            | -0.0025                | -0.0025                  |
| J9 Partition                          | -0.0024            | -0.0027                | -0.0027                  |

### TABLE 2. Sensitive control set and control amount under two-stage calibration

| Trajectory sensitivity control set   | Auxiliary decision cutting load /% | MPC first cut off load /% | MPC second cut off load /% | MPC third cut off load /% |
|--------------------------------------|-----------------------------------|---------------------------|---------------------------|---------------------------|
| Wan-RuiFeng __230.kV                 | -                                 | 54.2                      | 22.5                      | 10.7                      |
| Wan-MengXi __230. kV                 | -                                 | 24.1                      | 22.8                      | 16.4                      |
| Wan-PuQing __230. kV                 | -                                 | 12.5                      | 15.4                      | 41.4                      |
| Wan-ShiZhuan __230. kV               | -                                 | 43.3                      | 26.0                      | 17.6                      |
| WanJiuJiang __230. kV                | -                                 | 36.5                      | 28.0                      | 19.7                      |
| Wan-GangXi __230. kV                 | -                                 | 30.4                      | 27.5                      | 20.4                      |
| Wan-HuoLONG __230. kV               | -                                 | 19.8                      | 23.5                      | 0.0                       |
| J6 Partition                         | 55.0                              | 3.4                       | 0.8                       | 1.1                       |
| J7 Partition                         | 60.0                              | 4.3                       | 0.5                       | 2.0                       |
| J8 Partition                         | 45.0                              | 3.5                       | 1.2                       | 2.1                       |
| J9 Partition                         | 60.0                              | 2.9                       | 0.8                       | 1.1                       |
Observation figure 4 shows that after the two-stage correction strategy is applied, the voltage at the receiving end gradually recovers, and the basic recovery is stable after 3.5 seconds. The control effect is ideal and can meet the system stability requirements.

5. Conclusions
In this paper, the bifurcation mechanism of UHV receiving voltage bifurcation problem is studied, and a two-stage frequency and voltage coordination correction method is proposed. In the first stage, event-driven auxiliary decision-making is put in, and the frequency or voltage recovery is not ideal. In the case, the MPC-based coordination correction is invested in the second stage. The simulation results show that the method accelerates the recovery speed by the quick input of the auxiliary decision-making, and the closed-loop control effectively increases the control amount, coordinates the correction frequency and voltage, and makes the receiving terminal voltage reach the stable operation level.

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