Improved Correction Strategy for Power Flow Control Based on Multi-Machine Sensitivity Analysis

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ABSTRACT Sensitivity analysis is a conventional power grid analysis method that has been widely used in active power safety correction of power systems. This method relies on linearizing the power flow equation, assuming that the control variable change will continue to act on the power system until a new steady-state operating point is reached. However, this method ignores the quasi-steady-state physical response of power equipment to various control operations, which makes the method not suitable for real-time decision-making. Therefore, according to the improved equal and opposite quantity adjustment principle, this paper proposes a practical power flow correction control strategy, that can avoid repeated and inefficient adjustments of the system. In the proposed method, the single-machine sensitivity matrix under the AC power flow model is obtained based on the Taylor series expansion of the power flow equation. Subsequently, the multi-machine sensitivity with no dependence on the choice of the balancing machine is proposed considering the quasi-steady-state method. The study is verified on a practical system, showing that the proposed method has an error of less than 1% with a rapid computation speed. The proposed method satisfies the requirements of real-time analysis and online control strategies, which can provide a more practical approach for active power safety correction.

INDEX TERMS Real-time active power control strategy, multi-machine sensitivity, quasi-steady-state response, AC power flow model.

I. INTRODUCTION

Power system active power safety correction control is an important part of safety control and a means of ensuring safe and high-quality operation of power systems [1]. The main function of active power safety correction is to maintain the load rate of lines within normal ranges and to prevent transmission power from exceeding the limit of thermal stability. The adjustment mechanism is mainly to adjust the generator output, and the load can be removed if necessary. With a rapid increase of the electric load, the load rate of the transmission section becomes larger. The thermal stability problem of the transmission section has become one of the main factors that restrict the power transmission capacity and affect the safe and stable operation of the system.

If appropriate post-contingency corrective control (CC) actions are not taken in time to alleviate overload and maintain secure operations, consequences such as a cascading failure resulting in system blackout could occur [2].

Active power correction is a prominent research topic in power system analysis. In recent years, with the rise of new technologies such as high-voltage direct current (HVDC) and renewable energy, active power correction control is facing new challenges. Many scholars have gradually paid attention to this field and have achieved substantial results.

In terms of DC transmission, a study considered the risk of line overloads and cascading failures caused by either a DC blocking or a line outage [2]. For rapidly performing accurate CC actions, a second-order cone programming based CC optimization model for line overload alleviation in meshed AC/DC power systems was proposed. In [3], the problem of power flow control was addressed through the...
application of a power converter with a different connection configuration, namely, serial parallel dc power flow controller (SPDC-PFC). In terms of renewable energy, a flexible risk control strategy was proposed using an energy storage system [4]. It was used to assist in taking post-contingency remedial action for the removal of overload; however, stored energy often accounts for only a small proportion in the system. A new generation rescheduling algorithm was proposed that adjusted the generation output to mitigate variations in branch power flows, thereby reducing the probability of overload [5]. The algorithm helps prevent power congestion and balances renewable power generation and loads in power systems. In terms of security-constrained optimal power flow (SCOPF), an extended formula of the SCOPF problem was studied [6], with explicit consideration of the probability of emergency events and potential faults in CC operations after an emergency; however, details of the control strategy were not included. The optimal coordination problem of preventive control (PC) and CC was studied by means of a safety-constrained power flow prevention-correction optimization model [7]. The goal was to minimize the sum of PC and CC costs, while taking the probability of accidents into account.

The semi-analytical approach such as the holomorphic embedding method is a novel technique for solving power flow problems, helping us better calculate the power flow distribution in the network. When applied to the power flow control, the holomorphic embedding method can significantly improve the calculation accuracy of power flow and loading limit of each branch [8], [9]. The holomorphic embedding load-flow method (HELM) has been used in flexible AC transmission system (FACTS) devices modeling. The HELM models of Thyristor-based FACTS controllers and STATCOM were studied in [10] and [11], respectively. This method overcame the numerical problems faced by traditional iterative techniques. It has a broad development prospect in power flow solution, but further work is still needed to make it more suitable for line overload alleviation.

The current safety correction methods mainly include two categories—optimization methods and sensitivity methods. Optimization methods [12]–[15] establish the optimization model by setting the principle of operating point adjustment. The method includes an optimized objective function and operational safety constraints that need to be satisfied after adjustment. The corresponding adjustment measures can be obtained through mathematical methods. Such methods fully consider the various constraints in the system, usually with better safety and economy. However, it may lead to too much equipment involved in the adjustment, and some generators may have minimal adjustment. More importantly, the optimization model usually requires a long calculation time, which is not practical in grid emergency control. The sensitivity method first sorts generators according to the sensitivity of overload elimination, and then matches and adjusts the generator output according to this order until all overload branches fall within the limit. In contrast, the sensitivity method does not require iterations. Hence the algorithm is simple and calculation speed is faster. Moreover, it is easy to achieve the goal of minimum adjustment devices or minimum adjustment amounts, which is convenient for practical operation. Due to the above advantages of the sensitivity analysis method in safety correction, a few scholars have utilized the sensitivity analysis method in many fields.

FACTS technology is developing rapidly and playing an important role in enhancing power system stability and improving transmission capability. Sensitivity analysis methods are widely used in FACTS. In [16], the utilization of power flow controllers in multi-terminal–high-voltage DC grids based on the sensitivity analysis methods was studied to enhance static security. In order to solve the drawback of slow response of conventional power generation in CC, [17] adopted FACTS devices to control post-contingency power flow, and the study also investigated the effect of FACTS devices on the static security risk level of the power grid. The sensitivity analysis method was adopted to determine the optimal location of FACTS devices. In [18], the sensitivity coefficients between the power flow of lines with a series power flow controller (SPFC) and the overloaded line were obtained. These sensitivity coefficients were used to determine the required variation in power flow at the line with an SPFC to reduce the power flow of the overloaded line. The limitation of this method is that only certain lines can be adjusted to reduce overload.

Sensitivity methods are also widely used in adjusting generator outputs and power flow control equipment, as well as for optimizing power flow. Due to the requirements of both speed and accuracy for online CC, a new linearized programming-based optimal power flow (OPF) algorithm for corrective FACTS control was proposed in [19]. Sensitivities can be updated during the OPF iterations to reduce the effect of errors caused by linearization. However, the problem of large errors in the linearized model has not been overcome. A sensitivity coefficient under a DC model has been used to mitigate line overload by corrective generation rescheduling and load shedding (LS) in [20]. The method ensures that the alleviation of existing violations does not create any new violations, but the sensitivity coefficient is still derived from the DC model. In [21], a robust security-constrained multiperiod OPF model was first constructed. The emergency measures with the least number of affected buses were identified and subsequently assessed by post-optimization sensitivity analysis. Theoretical results were obtained for overload relief by lines and series capacitor switching using the DC power flow calculation formula [22]. Since the proposed algorithm is based on the DC power flow model, it may lead to a large error if the outage of a line causes a considerable influence on the system operation.

Sensitivity analysis methods based on the linearized power flow model are also widely used in distribution networks and microgrids. Unbalanced structure, renewable distributed generation (DG) and energy storage system bring new difficulties in the analysis and computation. More accurate and efficient sensitivity analysis methods are required to
facilitate the following control and optimization strategies [23]. In [23], a sensitivity analysis method for three-phase distribution networks considering the network loss and unbalanced parameters was proposed. It can be applied to online power flow control requiring accurate real-time sensitivity results. In [24], a linear method for the steady-state analysis of radial distribution systems with distributed energy resources was proposed. The method directly provided the closed-form analytical expressions of the sensitivity coefficients. They are more accurate because they were derived from an analytical Jacobian-based model. In [25], the sensitivity analysis of the main convergence characteristics of multiphase power flow methods in unbalanced distribution systems was presented. In [26], a siting and sizing method of energy storage system based on sensitivity analysis of the power system was proposed. It can mitigate power and energy variation of the microgrid which utilizes many distributed renewable generators. In [27], the linear sensitivity analysis and interval technique were applied to load identification in the statistical energy analysis framework. The results showed that the measurement errors of damping loss factors and coupling loss factors had a large effect on identified loads.

The conventional sensitivity analysis methods [28]–[30] were derived from the DC power flow model, which has obvious advantages in terms of computational complexity, but has relatively low accuracy. Under the guidance of line overload adjustments, only one overload branch can be adjusted at a time. While correcting the multi-branch power flow, it is often difficult to balance all branches, and a seesaw problem may occur.

A few researchers have improved the conventional sensitivity analysis method from different perspectives. In [31], an important evaluation method for information flow based on cyber-physical sensitivity was introduced. The superiority of this model was validated by comparing its robustness and performance to that of conventional routing based on the shortest-path model; however, it relied too much on grid measurement systems. A coordinated optimization method was proposed to coordinate event-driven LS and corrective line switching (CLS), reducing the LS amount by linearized sensitivity analysis in [32]. In [33], the potential of lines was measured to simultaneously reduce overloads and prevent new ones, based on the power shift sensitivities of overloaded lines and the time required to complete the adjustment. Although the method considered the time taken for power adjustment, the linearized sensitivity coefficients used do not conform to the actual situation. In [34], a global sensitivity analysis (GSA) was proposed, which examined the sensitivity measure from the perspective of the entire range of each input variable. The GSA is preferable over the local sensitivity analysis (LSA), which gives an incomplete view of the sensitivities within a system.

In summary, most of the existing active power sensitivity analysis methods are based on the DC model, which is simple in calculation but low in accuracy. Because the sensitivity method based on the DC model cannot truly reflect the correction effect on active power flow, a few scholars have gradually adopted a sensitivity method based on the AC model.

AC sensitivity-based approaches were developed to find suitable locations of FACTS devices for active power flow control [35]–[37]. In [38], the influence of system parameter changes on the available transfer capability (ATC) was estimated with the AC sensitivity analysis. Based on the AC sensitivity of locational security impact factors (LSIFs), which represent the sensitivities of total risk in the system to the changes in active power output of generators [39], [40], a decomposed iterative algorithm suitable for the AC model was proposed in [41]. It solved the problem that existing methods relied on the DC approximation of the system model and did not completely capture the behavior of the system. For real-time alleviation of equipment overload and the increase of the system static load ability, the sensitivity of vulnerability index of generation units was proposed in [42]. It was accurately computed by an actual AC power flow incorporating the automatic generation control model. In [43], the influence of voltage-sourced converters (VSCs) on power flow in the system was studied using two sensitivity analysis methods based on the AC model. The results show that the proposed methods can redispatch the network flows effectively.

The sensitivity method based on the AC power flow model is relatively complicated. Although preliminary research results have been obtained, the research work in this area still needs to be expanded. In addition, due to the power-frequency characteristics of an actual system, it is necessary to consider the quasi-steady-state response process of power system equipment [44]–[46]. Equipment control needs to be based on systems in which response depends on the delay conditions, so that control measures can be more accurate and rapid [47], [48]. In [49], it was pointed out that conventional sensitivity analysis methods cannot truly simulate the physical response of actual power systems. The conventional sensitivity coefficient changes when the balancing machine changes at the same static operating point. In order to overcome this shortcoming, the quasi-steady-state sensitivity analysis method, which is a new systematic method, was proposed and its calculation formula was given. In [50], a practical active power sensitivity analysis optimization method was proposed that can meet the requirements of a real-time control strategy. The validity and correctness of the method have been proved through theoretical derivation and actual case studies.

On the basis of previous research, this paper presents an innovative multi-machine sensitivity analysis method, which considers the quasi-steady-state physical response of power equipment to various control operations. It is more suitable for real-time analysis and horizontal comparison, despite the selection of a balancing machine. Moreover, a practical power flow correction control strategy is proposed. With abundant consideration of the safety restrictions of other lines, it can avoid introducing new overload and repeated adjustments.
Because this strategy involves the power-frequency characteristics of the power grid, more accurate calculation results can be obtained with a rapid computation speed. In general, the proposed method is more practical and efficient for the correction control of actual systems.

The remainder of this paper is organized as follows. Section II proposes a multi-machine sensitivity method considering the quasi-steady-state physical response. Section III describes the improved equal and opposite quantity adjustment principle and introduces a practical power flow control strategy. The proposed multi-machine sensitivity and control strategy are verified on a practical system in Section IV. Finally, some conclusions are drawn in Section V.

II. SENSITIVITY ANALYSIS METHOD
A. CONVENTIONAL SENSITIVITY ANALYSIS METHOD
The general equation for the power system model can be expressed as:

\[
f(x, u, p) = 0 \quad y = g(x, u, p)
\]

where \(x\) is the state variable, which includes the voltage and phase of the load nodes, and the phase of the generator nodes; \(u\) is the control variable, which includes the active power and voltage of the generator nodes, and the transformer ratio; \(p\) is the independent parameter variable, which includes constants such as \(G\) (conductance) and \(B\) (susceptance); \(y\) is the dependent variable, which includes the network loss and active power of the lines; \(f\) is a nonlinear power flow function reflecting the network topology.

When the network topology and the control variable \(u\) are given, the state variable \(x\) and the dependent variable \(y\) can be calculated from the power flow equation. When the condition changes, for example, the control variable \(u\) changes, we do not need to perform the power flow calculation again. Instead, we can quickly obtain the variation of the state variable \((\Delta x)\) and the dependent variable \((\Delta y)\) through the sensitivity coefficient. This is the idea of sensitivity analysis. Mathematically, the sensitivity coefficients can be divided into two types according to the intended goal. One is the sensitivity coefficient of the state variable \(x\) to the control variable \(u\), i.e., the state variable sensitivity. The other is the sensitivity coefficient of the dependent variable \(y\) to the control variable \(u\), i.e., the dependent variable sensitivity.

Linearizing the power flow equation yields the following:

\[
\begin{align*}
\Delta x &= S_{x-u} \Delta u \\
\Delta y &= S_{y-u} \Delta u
\end{align*}
\]

where \(S_{x-u}\) and \(S_{y-u}\) are the sensitivity matrix of the state variable \(x\) and the dependent variable \(y\) to the control variable \(u\), respectively. The calculation method is as follows:

\[
\begin{align*}
S_{x-u} &= - \left( \frac{\partial f}{\partial x^T} \right)^{-1} \left( \frac{\partial f}{\partial u^T} \right) \\
S_{y-u} &= \left( \frac{\partial y}{\partial u^T} \right)^T S_{x-u}
\end{align*}
\]

B. CONVENTIONAL SENSITIVITY ANALYSIS METHOD FOR ACTIVE POWER
In large power systems, the active power sensitivity coefficient describes the variation of the active branch power due to changes in the generator output. This method is based on the DC power flow model, such that when the generator output variation is \(\Delta P\):

\[
\Delta \theta = X \cdot \Delta P
\]

where \(\Delta \theta\) is the change in the voltage phase angle; and \(X\) is the busbar reactance matrix formed by the reactance of the series branch.

The active power variation of line \(l\) can be expressed as:

\[
\Delta P_l = \frac{M^T \Delta \theta}{X_l} = \frac{M^T (X \cdot \Delta P)}{X_l} \quad (5)
\]

where \(X_l\) is the primary branch reactance diagonal matrix; and \(M\) is the bus-branch incidence matrix. Eq. (5) can be expressed as:

\[
\begin{align*}
\Delta P_l &= S_l \Delta P \\
S_l &= \frac{X \cdot M_l}{X_l}
\end{align*}
\]

where \(S_l\) is the conventional active power sensitivity coefficient matrix.

C. ACTIVE POWER SENSITIVITY METHOD BASED ON AC POWER FLOW MODEL
Using polar coordinates, the basic power flow equation for a power system can be expressed as:

\[
\begin{align*}
P_i &= V_i \left( \sum_{j \in i} V_j (G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij}) \right) \\
Q_i &= V_i \left( \sum_{j \in i} V_j (G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij}) \right) \\
\quad i = 1, 2, \ldots, n
\end{align*}
\]

where \(P_i\) and \(Q_i\) are the active power and reactive power, respectively, injected by node \(i\); \(V_i\) and \(V_j\) represent the voltage amplitudes of node \(i\) and node \(j\), respectively; \(G_{ij}\) represents the conductance between node \(i\) and node \(j\); \(B_{ij}\) represents the susceptance between node \(i\) and node \(j\). \(j \in i\) indicates that node \(j\) in the system network is connected to the node \(i\) through the component (including the case of \(i = j\)), and \(\theta_{ij} - (\theta_{ij} - \theta_{ij})\) is the phase difference between the voltages of nodes \(i\) and \(j\).

When the system is in normal operation, with the change of network structure and network parameter \(Y_{ij}\) ignored, (7) can be expressed as:

\[
W = f(x)
\]

where \(W\) is the power vector of the node under normal conditions; and \(x\) is the state vector consisting of the node voltage and the phase angle under normal conditions.
If the system injection power is disturbed as \( \Delta W = (\Delta P, \Delta Q) \), the state vector will inevitably show a variation \( \Delta x \) and satisfy:

\[
W + \Delta W = f(x + \Delta x)
\] (9)

The right-hand-side term of (9) can be expanded in Taylor series as follows:

\[
W + \Delta W = f(x) + f'(x) \cdot \Delta x + \frac{1}{2} f''(x) \cdot (\Delta x)^2 + o(\Delta x)^2
\] (10)

When the disturbance and variation of state variables are not large, \( (\Delta x)^2 \) and the high-order terms can be ignored, so that (10) can be simplified as the following:

\[
W + \Delta W = f(x) + f'(x) \cdot \Delta x
\] (11)

Bringing (8) into (11) yields

\[
\Delta W = f'(x) \cdot \Delta x
\] (12)

That is, the relationship between the system state variable and the node power disturbance can be expressed as follows:

\[
\Delta x = [f'(x)]^{-1} \cdot \Delta W = [\frac{\partial f(x)}{\partial x}]^{-1} \cdot \Delta W = J^{-1} \cdot \Delta W = S \cdot \Delta W
\] (13)

where \( J \) is the Jacobian matrix in the power flow calculation iteration. Assuming that the system represented by (7) contains \( m \) \( PQ \) nodes, and using the Newton iteration algorithm to solve for the power flow, the Jacobian matrix can be expressed as (14), as shown at the bottom of this page, where the calculation of each sub-element is as follows:

\[
H_{ij} = \frac{\partial \Delta P_i}{\partial \theta_j}
\]

\[
= \begin{cases} 
-V_i V_j (G_{ij} \sin \theta_j - B_{ij} \cos \theta_j), & i \neq j \\
V_i^2 B_{ii} + V_i \sum_{j \in i} V_j (G_{ij} \sin \theta_j - B_{ij} \cos \theta_j), & i = j 
\end{cases}
\] (15)

\[
N_{ij} = \frac{\partial \Delta P_i}{\partial V_j}
\]

\[
= \begin{cases} 
-V_i V_j (G_{ij} \cos \theta_j + B_{ij} \sin \theta_j), & i \neq j \\
-V_i^2 G_{ii} - V_i \sum_{j \in i} V_j (G_{ij} \cos \theta_j + B_{ij} \sin \theta_j), & i = j 
\end{cases}
\] (16)

\[
M_{ij} = \frac{\partial \Delta Q_i}{\partial \theta_j}
\]

\[
= \begin{cases} 
V_i V_j (G_{ij} \cos \theta_j + B_{ij} \sin \theta_j), & i \neq j \\
V_i^2 G_{ii} - V_i \sum_{j \in i} V_j (G_{ij} \cos \theta_j + B_{ij} \sin \theta_j), & i = j 
\end{cases}
\] (17)

\[
L_{ij} = \frac{\partial \Delta Q_i}{\partial V_j}
\]

\[
= \begin{cases} 
-V_i V_j (G_{ij} \sin \theta_j - B_{ij} \cos \theta_j), & i \neq j \\
-V_i^2 B_{ii} - V_i \sum_{j \in i} V_j (G_{ij} \sin \theta_j - B_{ij} \cos \theta_j), & i = j 
\end{cases}
\] (18)

In (13), \( J^{-1} \) is the inverse of the Jacobian matrix; \( J^{-1} \) is also the sensitivity matrix \( S \) of the system state vector when the node power changes. According to the Jacobian matrix obtained by (13) and (14), when the node injection power changes, the variation of the state variable \( \Delta x \) under normal conditions can be obtained. After the node injection power change, the state variables are obtained as:

\[
\tilde{x} = x + \Delta x
\] (19)

After the state vector is known, the active power of any branch \( ij \) can be obtained as:

\[
P_{ij} = V_i V_j (G_{ij} \cos \theta_j + B_{ij} \sin \theta_j) - G_{ij} V_i^2
\] (20)

The AC sensitivity of node \( k \) to active power flow of branch \( ij \) is given by:

\[
S_{ij,k} = \frac{\partial P_{ij}}{\partial V_k} = \frac{\partial P_{ij}}{\partial V_i} \cdot \frac{\partial V_i}{\partial V_k} + \frac{\partial P_{ij}}{\partial V_j} \cdot \frac{\partial V_j}{\partial V_k} + \frac{\partial P_{ij}}{\partial \theta_i} \cdot \frac{\partial \theta_i}{\partial V_k} + \frac{\partial P_{ij}}{\partial \theta_j} \cdot \frac{\partial \theta_j}{\partial V_k}
\] (21)

In (21), \( \frac{\partial V_i}{\partial V_k}, \frac{\partial V_i}{\partial \theta_i}, \frac{\partial V_j}{\partial V_k}, \frac{\partial V_j}{\partial \theta_j}, \frac{\partial \theta_i}{\partial V_k}, \frac{\partial \theta_i}{\partial \theta_i} \), are functions of the node voltage or phase angle on both ends of the branch \( ij \), which can be obtained according to the power flow calculation result.
D. MULTI-MACHINE SENSITIVITY METHOD CONSIDERING THE QUASI-STeady-STATE RESPONSE

The conventional sensitivity analysis method assumes that changes in the control variables continue to act on the power system until the power system reaches a new stable operating point. However, an actual power system does not always operate in this manner. For example, the disturbance in the system may force the load or generator out of the system, resulting in the power mismatch between generation and load demands. The unbalanced power deviates the system frequency, which causes loads and generators to automatically adjust according to their respective power-frequency characteristics. Therefore, several control variables will change at the new stable operating point. The result calculated by the conventional sensitivity method differs from the actual adjustment of the generator outputs.

In this study, multi-machine sensitivity relying on quasi-steady-state theory is proposed. The method optimizes the AC sensitivity matrix using the correction coefficient, obtaining the actual active power sensitivities of the nodes. In power systems, one of the most common quasi-steady-state physical responses is the active power and frequency responses of generator, load, AGC regulation [49].

The conventional sensitivity method considers that the unbalanced power is only supported by the balancing machine. However, the system frequency will change due to the unbalance of the active power. In this case, some generators and loads will respond to the frequency change by automatically adjusting their active power, which balances the mismatch. How much the generators/loads respond to frequency changes can be found by their respective power-frequency characteristics.

Suppose that the system has \( n \) power-adjustable nodes, the unbalanced power is shared by \( n \) nodes according to a proportional distribution factor. The function of the balancing node is shared by multiple nodes. The nodes that actually play the balancing role are regarded as multi-machine balancing nodes.

If the distribution factor of node \( i \) is assumed to be \( r_i \), then the distribution factor of the system nodes can be expressed as follows:

\[
    r = [r_1, r_2, \ldots, r_n]^T
\]

Furthermore,

\[
    \sum_{i=1}^{n} r_i = 1
\]

The unbalanced power after disturbance is assumed as \( \Delta P_{\text{sum}} \). When the quasi-steady-state response is not considered, the adjustment amount of active power injection is set as follows:

\[
    \Delta P = [\Delta P_1^0, \Delta P_2^0, \ldots, \Delta P_n^0]^T
\]

According to the conventional sensitivity method, only the power of the balancing machine changes, whereas the power change of the other nodes is zero. Considering the power-frequency characteristics, the power of the remaining generators and loads will also change in accordance with the system frequency. The actual power adjustment can be expressed as follows:

\[
    \Delta P = \Delta P^0 - r \cdot \Delta P_{\text{sum}}
\]

where, \( \Delta P_{\text{sum}} = \sum_{i=1}^{n} \Delta P_i^0 \). Eq. (25) can be expressed in the following manner:

\[
    \Delta P = \Delta P^0 - r \cdot 1_{1 \times n} \cdot \Delta P^0
\]

where \( 1_{1 \times n} \) is a row vector with all its elements equal to 1. \( F \in R^{n \times n} \) is a correction matrix between the multi-machine balancing system and the single-machine balancing system. There must be:

\[
    F = I_{n \times n} - r \cdot 1_{1 \times n}
\]

\[
    \Delta P = F \cdot \Delta P^0
\]

where \( I_{n \times n} \) is a unit matrix of dimension \( n \times n \).

Assuming that the reactive power of the system is balanced in place and only the change of the active power is considered, namely, \( \Delta W = \Delta P \). Eq. (28) is then substituted into (13). The relationship between the state variable and the node power disturbances in the multi-machine balancing system can be expressed as follows:

\[
    \Delta x = S \cdot F \cdot \Delta P^0 = S' \cdot \Delta P^0
\]

Note that \( S \) becomes new \( S' \) after considering the quasi-steady-state response. In this paper, \( S \) is defined as the single-machine sensitivity matrix, whereas \( S' \) is defined as the multi-machine sensitivity matrix, satisfying the following equation:

\[
    S' = S \cdot F = S \cdot (I_{n \times n} - r \cdot 1_{1 \times n})
\]
III. ACTIVE POWER SAFETY CONTROL STRATEGY BASED ON IMPROVED EQUAL AND OPPOSITE QUANTITY ADJUSTMENT PRINCIPLE

A. MULTI-MACHINE SENSITIVITY OF ADJUSTING NODE PAIRS

The conventional active power safety control method only adjusts for the overload branches, which disables the consideration of safety constraints of other branches. During the correction process, the branches that are not overloaded initially, but have a lower safety margin, may be overloaded. It is often difficult to deal with the multi-branch overload problem, resulting in relatively inefficient control methods. Based on the principle of equal and opposite quantity adjustment [51], this paper introduces the power constraints of normal branches to ensure that the overloaded are eliminated without causing new ones.

In [51], the principle of equal and opposite quantity adjustment means that a generator with reduced output is paired with a generator with increased output, and vice versa. The reduced and increased output of each pairing generators are equal. They are a pair of adjusting nodes. This principle can ensure that the output of the balancing machine does not change much. However, it may introduce repeated adjustment problems using this strategy to deal with multi-branch overloads. To solve the problem, we firstly propose the concept of the multi-machine sensitivity of adjusting node pairs. Then, the improved control strategy is presented in the next part.

According to the calculation method presented in Section II, the multi-machine sensitivity matrix $S'$ of the power-adjustable nodes can be calculated. Assuming the multi-machine sensitivity of node $i$ to line $l$ is $S'_{il}$, $S'$ can be expressed as follows:

$$ S' = \begin{bmatrix} S'_{11} & S'_{12} & \cdots & S'_{1n} \\ S'_{21} & S'_{22} & \cdots & S'_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ S'_{l1} & S'_{l2} & \cdots & S'_{ln} \end{bmatrix} \quad (31) $$

Each pair of adjusting nodes will show the overall adjusting characteristics. Assuming that node $i$ is a node with increased output, and node $j$ is a node with reduced output. Their power adjustment amounts are both $\Delta P_i$ ($\Delta P_j$). Their sensitivities to line $l$ can be expressed as follows:

$$ \Delta P_i = \Delta P_i S'_{li} - \Delta P_i S'_{lj} = \Delta P_i (S'_{li} - S'_{lj}) \quad (32) $$

Here, $\Delta P_i$ is the power adjustment of line $l$. The multi-machine sensitivity of this pair of adjusting nodes to line $l$ is the following:

$$ S'_{l-i} = S'_{li} - S'_{lj} \quad (33) $$

Here, $S'_{l-i} < 0$ indicates that adjusting node pairs can reduce the load rate of line $l$, whereas $S'_{l-i} > 0$ indicates that adjusting node pairs can increase the load rate of line $l$. When $S'_{l-i} < 0$, the greater the absolute value of $S'_{l-i}$, the stronger the ability of the adjusting node pairs to reduce the line load rate.

B. IMPROVED EQUAL AND OPPOSITE QUANTITY ADJUSTMENT PRINCIPLE

To solve the problem of multi-branch overload, the branches should be adjusted in accordance with the overload order of severity. During the process, the adjusted nodes are no longer adjusted in the reverse direction to avoid repeated adjustment. Assume that there are $m$ overload branches in a system. Taking the overload line $l$ as an example, the adjusting process is as follows.

Firstly, the load rates of the lines are obtained using PSD-BPA [52] or other power flow calculation software. The adjusting node pairs satisfying $S'_{l-i} < 0$ are arranged in descending order of the absolute value of $S'_{l-i}$. Then, the adjustment amount of the adjusting node pairs is calculated. The adjustment amounts $\Delta P_i$ and $\Delta P_j$ should satisfy the following principles.

1. The adjusting node pairs should not exceed the output limits, namely, $\Delta P_i \leq \Delta P_i^{\text{max}}$ and $\Delta P_j \leq \Delta P_j^{\text{max}}$. $\Delta P_i^{\text{max}}$ and $\Delta P_j^{\text{max}}$ are the maximum additive output quantity of node $i$ and the maximum deductible output quantity of node $j$, respectively.

2. Eliminate as much overload as possible. To eliminate the overload $\Delta P_l$, the adjustment should be $\Delta P_{ad} = -\Delta P_l/S_{l-i}$. When multiple overload branches in the system exist, the adjustment should be the maximum value, i.e., $\Delta P_{ad} = \max\{\Delta P_{ad1}, \Delta P_{ad2}, \ldots, \Delta P_{adm}\}$.

3. Ensure that all normal branches are below their limits. It is assumed that the redundancy of a normal branch $k$ is $\Delta P_k$. When $S'_{k-i} < 0$, the limit violation is avoided. When $S'_{k-i} > 0$, it means that adjusting the active power of the nodes will cause the power flow to increase, or even to exceed the upper limit. The adjustment needs to be constrained, and the constraint amount is $\Delta P_{con} = \Delta P_k/S'_{k-i}$. To ensure that all normal branches do not exceed the limits, the constraint amount should be the minimum value, i.e., $\Delta P_{con} = \min\{\Delta P_{con1}, \Delta P_{con2}, \ldots, \Delta P_{con}\}$, where $t$ is the total number of normal branches.

4. The direction of power flow should not change. Considering that substantial adjustment will cause a decrease of power flow to zero and then an increase in the opposite direction, which may cause a major change in the power flow operation, introducing new problems. Therefore, it is necessary to introduce a constrain amount for preventing the power flow from increasing in the reverse direction. Assume that the current active power of the line $l$ is $P_0$. To ensure that its power flow does not increase in the opposite direction, the maximum reduction amount is $P_0$ and the maximum adjustable amount of the nodes is $P_{rel} = -P_0/S'_{l-i}$. To ensure that all power flows will not increase in the opposite direction, the minimum adjustment amount needs to be found, i.e., $P_{re} = \min\{P_{re1}, P_{re2}, \ldots, P_{res}\}$, where $s$ is the total number of branches in the system.

In summary, the adjustment amount of the adjusting node pairs should be:

$$ \Delta P_i = \Delta P_j = \min\{\Delta P_i^{\text{max}}, \Delta P_j^{\text{max}}, \Delta P_{ad}, \Delta P_{con}, P_{re}\} \quad (34) $$
\( \Delta P_i(\Delta P_j) \) in (34) is the maximum adjustment amount of the nodes. If the adjustment amount of the adjusting node pairs exceeds the value \( \Delta P_i(\Delta P_j) \) in (34), at least one adjustment principle cannot be satisfied. Because \( \Delta P_i(\Delta P_j) \) meets the above safety limits, it can ensure that the original overload is eliminated and new overloads will not appear. The maximum overload elimination amount of the node pairs is also a parameter that is the focus of attention in practical applications. It is defined as the adjustable ability of the node pairs, namely, \( P_{abl} \). It indicates the ability of the node pairs to reduce the overload under safety margins. According to the definition, the adjustable ability of the node pair \( i, j \) to the overload line \( l \) can be expressed as:

\[
P_{abl,ij} = \Delta P_i \times S_{ij}^{f-ij} \tag{35}
\]

\( P_{abl,ij} < 0 \) indicates that adjusting the active power of node pair \( i, j \) can reduce the load rate of line \( l \), whereas \( P_{abl,ij} > 0 \) indicates that adjusting the active power of node pair \( i, j \) can increase the load rate of line \( l \). When multi-machine sensitivity is the same, to reduce the number of devices participating in the adjustment process, the node pairs with a large adjustable ability should first be selected for adjustment.

After one pairing adjustment, the adjustable amount of the nodes and the active power flow of line \( l \) are refreshed. If line \( l \) is still overload, one of the adjusting nodes must reach the limit and cannot be adjusted again. Assume that node \( j \) reaches the lower limit and cannot be reduced. However, node \( i \) still can be increased. In the output reduction operation sequence, select the next output reduction point \( j = j + 1 \) and repeat the pairing adjustment until the overload is zero.

The above method eliminates the overload branches in the system one by one and also guarantees that the normal branches do not exceed the limits. During the adjusting process, the output of generator nodes are preferentially adjusted, and the load nodes are adjusted when the generator nodes cannot be adjusted anymore.

The online active power flow control strategy based on the multi-machine sensitivity analysis method is shown in Fig. 1. This control strategy eliminates the overload on each line, while fully considering the safety restrictions of other lines. Therefore, it can reduce the whole adjustment amount and improve the adjustment efficiency.

### IV. CASE STUDIES

#### A. MULTI-MACHINE SENSITIVITY VERIFICATION

Taking a power grid in a certain region of China as an example, the grid includes approximately 2380 buses and 2410 branches. PSD-BPA and MATLAB (MathWorks, US) are used as simulation tools, and the raw data are real-time measurement data of the grid.

To verify the practicability of the method, this study obtains a 24-hour data file on a certain day and calculates the sensitivity coefficient by two methods—single-machine sensitivity (conventional AC sensitivity) and multi-machine sensitivity. When calculating the multi-machine sensitivity, it is assumed that the power-frequency characteristics of each generator are equal, i.e., the distribution factors are the same. Twenty main nodes in the system are considered. Thus, the distribution factors of each generator are all 0.05. The data in this study are taken from the same static operating point; however, the balancing machine changes with time. The practical balancing machines at different times of the day are shown in Table 1.

| Time  | Balancing machine | Time  | Balancing machine |
|-------|-------------------|-------|-------------------|
| 1:00  | A                 | 13:00 | C                 |
| 2:00  | A                 | 14:00 | B                 |
| 3:00  | A                 | 15:00 | B                 |
| 4:00  | A                 | 16:00 | B                 |
| 5:00  | A                 | 17:00 | B                 |
| 6:00  | A                 | 18:00 | A3                |
| 7:00  | A                 | 19:00 | D                 |
| 8:00  | A                 | 20:00 | A3                |
| 9:00  | A3                | 21:00 | C                 |
| 10:00 | A3                | 22:00 | C                 |
| 11:00 | B                 | 23:00 | C                 |
| 12:00 | B                 | 24:00 | C                 |

A partial schematic diagram of the power grid topology is shown in Fig. 2, which mainly shows the lines related to this study.

The sensitivity coefficient of node C3 to line AB1 at each moment is obtained by the two analytical methods of single-machine sensitivity and multi-machine sensitivity, as shown in Fig. 3. In this figure, the two sensitivity coefficients are both less than zero, indicating that active power injection of the generators increases within the safety margin, which can reduce the load rate of the branch.

From this case, it can be seen that the sensitivity coefficient obtained according to the single-machine sensitivity method has a large variation at the same static operating point. This is because different balancing machines are chosen with time in an actual power grid. This result is consistent with the conclusions obtained in [49] using a DC model. Therefore, the single-machine sensitivity method cannot be applied to actual grid real-time active power safety analysis. When the multi-machine sensitivity method is adopted,
the multi-machine sensitivity coefficient does not change greatly with time. In this way, the multi-machine sensitivity coefficient can be applied to the real-time horizontal comparison analysis of active power safety control in the grid. The multi-machine sensitivity coefficient is basically the same as that in the case of the multi-machine balancing system, indicating a high calculation accuracy.

**B. ANALYSIS OF ACTIVE POWER SAFETY CORRECTION CASES**

The raw data are taken from the measurement data of the above-mentioned power grid at 11 am. The active power safety correction strategy adopts the online power flow control strategy introduced in Section III. Firstly, the load rates of 467 transmission lines of 500-kV voltage grade under normal operating conditions are calculated, as shown in Fig. 4.

It can be seen from Fig. 4 that the lines with load rates below 60% under normal operating conditions account for more than 99% of the total number of lines. It is not necessary to consider active power correction under normal operating conditions. To simulate the system equipment out of operation after a failure, an “N – 1” breaking simulation is performed on the system. It is found that some lines are overloaded.

Taking the system shown in Fig. 2 as an example, the validity of the proposed method is illustrated by an overloaded line elimination process. The upper transmission limit of line AB₁ is 3291.8 MW. After line AB₂ exits operation, the active power flow of line AB₁ is 3367.5 MW, and the load rate is 102.3%.

According to the multi-machine sensitivity method proposed in this study, the sensitivity coefficients of power-adjustable nodes to line AB₁ are obtained. Subsequently, it calculates the multi-machine sensitivity of each node pair to line AB₁. The absolute value of multi-machine sensitivity and adjustable ability of the top few nodes corresponding to line AB₁ are shown in Table 2. When correcting the overload on other lines, these power-adjustable nodes may have different sensitivity coefficients and adjustable abilities. The node pairs with multi-machine sensitivity less than zero are arranged in descending order of the multi-machine sensitivity absolute value. When the multi-machine sensitivity is the same, node pairs are sorted according to the adjustable ability. The ones with large sensitivity but zero adjustable ability are not listed.

**TABLE 2. Top few node pairs corresponding to line AB₁.**

| Adjusting node pairs | Multi-machine sensitivity | Adjustable ability (MW) | Adjusting node pairs | Multi-machine sensitivity | Adjustable ability (MW) |
|----------------------|---------------------------|-------------------------|----------------------|---------------------------|-------------------------|
| A4-A2                | 0.77183                   | 17.44                   | D4-A1                | 0.43277                   | 36.44                   |
| A4-C3                | 0.68917                   | 117.84                  | B3-A1                | 0.40486                   | 213.89                  |
| A4-A1                | 0.43277                   | 100.79                  | B3-B1                | 0.40486                   | 68.30                   |
| D3-A1                | 0.43277                   | 40.42                   | B3-C4                | 0.36749                   | 83.86                   |

The top adjusting node pairs in the system are represented in Fig. 5, which shows the multi-machine sensitivity coefficient and the adjustable ability of each adjusting node pair. Note that the adjustable ability is not positively correlated with sensitivity coefficients. This is because the adjustable ability is not only related to the sensitivity coefficient, but also related to the current generators operating state. When formulating the strategy, the generator with a high sensitivity
The “N − 1” safety limit is set to 90% of the line active power flow upper limit. For line AB1 with a load rate of 102.3%, according to the adjustment principle proposed in Section III, the correction scheme is shown in Table 3. Each reduced output node is paired with an increased output node.

| TABLE 3. Correction scheme for the overload on line AB1. |
|--------------------------------------------------------|
| Reduce output (MW) | Increase output (MW) | Load rate of line AB1 (%) |
| Step 1 | A4 reduces 232.9 | A2 increases 22.6 | 97.6% |
| | C3 increases 171 | A1 increases 39.3 | |
| Step 2 | D3 reduces 93.4 | A1 increases 93.4 | 96.4% |
| | A1 increases 84.2 | End | |
| Step 3 | D4 reduces 84.2 | End | 95.3% |
| | A1 increases 84.2 | End | |
| Step 4 | B3 reduces 43 | A1 increases 311.4 | 90.0% |
| | B1 increases 119.6 | End | |

Therefore, the final control scheme for eliminating the safety hazard of line AB1 is as follows: the output of node A4 is reduced from 532.9 MW to 300 MW; the output of node D3 is reduced from 513.4 MW to 420 MW; the output of node D4 is reduced from 324.2 MW to 240 MW; the output of node B3 is reduced from 612.5 MW to 181.5 MW; the output of node A2 is increased from 677.4 MW to 700 MW; the output of node C3 is increased from 2109 MW to 2280 MW; the output of node A1 is increased from 761.7 MW to 1290 MW; the output of node B1 is increased from 1001.3 MW to 1120.9 MW. The output of each generator during the adjustment process is shown in Fig. 6. In the figure, the generator outputs are expressed as percentages. The upper limit of the output is 100%, and the lower limit of the output is 0%.

The advantages of the proposed control strategy are illustrated by comparing it with the equal and opposite quantity adjustment control strategy. Both control strategies are based on the multi-machine sensitivity proposed in the fourth part of Section II. In addition, the optimization method presented in [12] is also taken into comparison. The comparison results of the three methods are shown in Table 4 and Table 5.

| TABLE 4. Adjustment amounts of the three methods. |
|--------------------------------------------------|
| Adjusting nodes | Optimization Method (MW) | Sensitivity method (MW) |
| A | -32.8 | -78.2 | 528.3 |
| A1 | 414.8 | 478.3 | |
| A2 | -28.2 | 38.6 | 22.6 |
| A3 | 20.8 | | |
| A4 | -228.1 | -286.1 | -232.9 |
| B | -2.8 | -29.2 | |
| B1 | 108.2 | 291.4 | 119.6 |
| B2 | -9.2 | | |
| B3 | -335.2 | -472.2 | -431.0 |
| C | 23.7 | | |
| C1 | -38.2 | 40.8 | |
| C2 | 34.9 | | |
| C3 | 168.0 | 182.4 | 171 |
| C4 | 22.8 | | |
| D | 4.5 | | |
| D1 | 33.8 | 37.2 | |
| D2 | 8.2 | | |
| D3 | -92.2 | -134.9 | -93.4 |
| D4 | -38.1 | -68.1 | -84.2 |
| D5 | -34.9 | | |

| TABLE 5. Comparison results of the three methods. |
|--------------------------------------------------|
| Optimization Method (MW) | Sensitivity method (MW) |
| Total adjustment amount (MW) | Previous strategy | Proposed strategy |
| 1679.4 | 2137.4 | 1683 |
| Number of adjusting devices | 20 | 12 | 8 |

When the equal and opposite quantity adjustment method is adopted, a new overload will appear on line AA1, resulting in an increase in the total adjustment amount and the number of adjusting devices. As can be seen from Table 5, compared to the equal and opposite quantity adjustment
method, the control strategy proposed in this paper can ensure the prevention of overload on other lines and avoid repeated adjustment problems. The method can also make the adjustment amount lesser and the number of devices involved in the adjustment smaller. It can correct the power flow more efficiently, which is convenient for practical application. In addition, although the total adjustment amount of the proposed control strategy is slightly larger than the optimization method, the optimization method adjustment strategy involves all nodes, and the adjustment amounts of some nodes are minimal, such as node B and node D, which is not practical.

According to the power flow correction control strategy proposed in this paper, the load rates and the nodal voltages before and after adjusting are shown in Fig. 7 and Fig. 8, respectively. The lines with the load rate ranking in the top ten are shown in Fig. 7. Other lines are far away from the safety limits, so they have been omitted. The subscript number indicates the serial number of the double-circuit lines. Fig. 8 demonstrates that all nodal voltages are within the allowable range after correction control.

In order to demonstrate the distribution of power flow more clearly, the line load rates before and after correction control are marked on the schematic diagram of the power grid topology, as shown in Fig. 9. After the control scheme is implemented on the system, the load rate of line AB1 is 89.88%. There are no other lines overload at this time. As shown in Table 3, the load rate of line AB1 is 90% using the correction control strategy proposed in this paper. Compared with the theoretical calculation results, the numerical error is only 0.12%, which indicates that the method has high precision and satisfies the actual demand.

The calculation program in this paper is developed based on Matlab. The PC configuration is: Intel Core i7-4710 CPU / 8.00GB RAM. The single calculation process takes less than 0.3s, which has favorable timeliness.

V. CONCLUSION

This paper proposes an improved correction strategy for power flow control based on multi-machine sensitivity analysis. The main contributions are as follows:

1) In this study, the Taylor series expansion of the power flow equation is used to obtain the single-machine sensitivity matrix under the AC power flow model. In addition, the multi-machine sensitivity matrix was obtained by the quasi-steady-state method. The results show that the proposed method is suitable for real-time analysis and horizontal comparison.

2) Based on the improved equal and opposite quantity adjustment principle, a practical active power flow correction control strategy is proposed. The case studies indicate that the proposed control strategy can effectively reduce the adjustment amount and the number of adjusting devices, compared with the equal and opposite quantity adjustment principle.

3) In the proposed method, the introduced correction coefficient accurately reflects the power-frequency characteristics of the power grid. Therefore, the results are more accurate, with a calculation error of less than 1%. Moreover, less than 0.3 s is required for the single computing process of the control strategy. The case studies on an actual grid verify that the method satisfies the requirements of real-time analysis and online control strategies.

There are still some limitations in model derivation and scenario analysis. More practical case studies are required to verify and improve the model. The holomorphic embedding
method is considered to be introduced in the future work. Besides, ways to explore the relationship of sensitivity coefficients between different static operating points are also the future research direction.

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