Postprint: Load Adjustment Strategy for Network Reconfiguration of De-energized Systems Based on Sensitivity Method

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Abstract

During power system restoration following a blackout, load restoration is required to balance the increase in generator output, but load energization may cause voltage violations at already restored nodes, affecting the security of the restoration process. This paper adjusts the load allocation scheme based on the sensitivity method to ensure that voltages at all nodes satisfy the requirements. First, sensitivity analysis is performed on the restored power grid. Based on power flow calculations, the sensitivity of voltage violation nodes to apparent power changes at all load nodes is computed. For the load node with the maximum sensitivity, the amount of load to be energized is calculated according to this maximum sensitivity, and power is evenly distributed among the load nodes. The above method is called iteratively until voltages at all nodes meet the requirements. Simulation on the IEEE 39-bus system verifies the effectiveness of the proposed method.

Full Text

Load Adjustment Strategy Based on Sensitivity Analysis During Network Reconfiguration of Blackout Systems

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Abstract

During power system restoration, load must be restored to balance the increasing generator output. However, load restoration may cause voltage limit violations at already-restored nodes, compromising the safety of the recovery process. This paper proposes a sensitivity-based approach to adjust load distribution schemes and ensure all node voltages remain within acceptable limits. First, sensitivity analysis is performed on the restored power grid. Based on power flow calculations, the sensitivity of voltage limit violation nodes to apparent power changes at all load nodes is computed. For the load node with maximum sensitivity, the required load adjustment is calculated based on this sensitivity value, and the power is then distributed equally among all load nodes. This process is iterated until all node voltages satisfy the requirements. Simulation results on the IEEE 39-bus system validate the effectiveness of the proposed method.

Keywords: blackout, sensitivity analysis, load adjustment, network reconfiguration

1 Introduction

As interconnected power grids continue to expand in scale, power system reliability has improved, yet factors affecting grid instability have also increased. Various uncertainties can still trigger large-scale blackout accidents with catastrophic societal impacts [1-2]. The restoration process for blackout systems can be divided into three stages: black start, network reconfiguration, and load restoration [3-4]. During the network reconfiguration stage, load restoration is necessary to balance increasing generator output, which is crucial for accelerating system recovery.

Extensive research has been conducted on load restoration optimization. Reference [5] optimizes distribution network load based on shortest path algorithms and genetic algorithms. Reference [6] utilizes rectangular coordinate optimal multiplier Newton power flow methods and sensitivity techniques to optimize load restoration quantities during the load recovery stage. Reference [7] employs genetic simulated annealing algorithms to determine maximum allowable load restoration amounts. Reference [8] proposes an intelligent optimization strategy for load restoration based on power grid partitioning. Reference [9] optimizes load restoration during network reconfiguration using analytic hierarchy processes and greedy algorithms to restore as much load as possible. Reference [10] proposes using real-time accurate data from wide-area measurement systems to maximize load restoration. Reference [11] considers cold load pickup characteristics during load restoration and uses particle swarm optimization to solve for maximum load restoration quantities. Reference [12] considers transient voltage and frequency variations during load restoration and employs adaptive genetic algorithms to determine load restoration amounts.

During the network reconfiguration stage, existing research primarily uses intelligent algorithms to obtain load distribution schemes that satisfy constraints. However, intelligent algorithms suffer from slow solution speeds, and since load allocation mainly coordinates with generator output, faster calculation of load distribution schemes is needed to accelerate network reconfiguration optimization.

Based on this need, this paper proposes a sensitivity-based method to adjust load distribution schemes and ensure all node voltages meet requirements. First, sensitivity analysis is performed on the restored power grid. Based on power flow calculations, the sensitivity of overvoltage nodes to apparent power changes at all load nodes is computed. For the load node with maximum sensitivity, the required load adjustment is calculated based on this maximum sensitivity value, and power is distributed equally among all load nodes. This method is called iteratively until all node voltages satisfy requirements. Finally, the proposed method is validated using the IEEE 39-bus system.

2 Sensitivity Analysis

Sensitivity analysis is one method for analyzing power network stability based on power flow equations. It expresses the degree of sensitivity between variables through differential relationships in the system, offering clear physical concepts and simple computation [13-14]. Based on linearization of network equations, sensitivity analysis examines relationships between state variables and control variables. When control variables undergo small changes, state variables also change accordingly.

2.1 Mathematical Model of Sensitivity Analysis

Sensitivity analysis is based on power flow equations. The fundamental power flow equations are the node power balance equations:

$$P_i = U_i \sum_{j \in i} U_j (G_{ij} \cos \delta_{ij} + B_{ij} \sin \delta_{ij})$$
$$Q_i = U_i \sum_{j \in i} U_j (G_{ij} \sin \delta_{ij} - B_{ij} \cos \delta_{ij})$$

where P_i and Q_i are the active and reactive power at node i; U_i and U_j are the voltages at nodes i and j; G_{ij} and B_{ij} are the real and imaginary parts of the node admittance matrix elements; and δ_{ij} is the voltage phase angle difference between the two nodes.

In sensitivity analysis, all variables can be divided into three categories: control variables U, state variables X, and independent parameter variables α. Control variables include active and reactive power at load nodes and generator nodes; state variables include voltage magnitude and phase angle at load nodes; and independent parameter variables include line admittance and impedance. According to this classification, the power flow equations can be expressed as [15-18]:

$$f(X, U, \alpha) = 0$$

Linearizing the power flow equations at the operating point yields the expression for the sensitivity matrix between state variables and control variables:

$$\Delta X = -\left[\frac{\partial f}{\partial X}\right]^{-1}\left[\frac{\partial f}{\partial U}\right]\Delta U = S\Delta U$$

2.2 Sensitivity Indicators

This paper requires analysis of sensitivity indicators for node voltage variations with respect to load changes. Based on these sensitivity indicators, the required adjustments to active and reactive load for restoring voltage to within constraints can be determined. The significance of these two indicators is:

1. When active power at a PQ node increases, the node voltage decreases; conversely, when active power at a PQ node decreases, the node voltage increases.
2. When reactive power at a PQ node increases, the node voltage decreases; conversely, when reactive power at a PQ node decreases, the node voltage increases.

During the load restoration process, generator output increases gradually, and load restoration is also constrained by power increments. This paper employs sensitivity analysis to adjust load restoration and limit voltages within constraints.

3 Voltage Limit Violation Adjustment Strategy Based on Sensitivity Analysis

The basic strategy is to identify the node with the most severe voltage limit violation, use Equation (5) to calculate the sensitivity of this node’ s voltage to apparent power changes at all load nodes in the system, identify the load node with maximum sensitivity, and use Equation (6) to calculate the required load adjustment amount. If this adjustment amount exceeds the total load at the most sensitive node, the active load adjustment is set to that node’ s total load.

The sensitivity and load adjustment calculations are:

$$S_{gr} = (S_P + S_Q \tan\varphi_r)$$

$$\Delta P_L = \frac{(U - U_g)}{S_{gr}^{\max}}$$

After calculating the required load adjustment for voltage regulation, this power is distributed among the load nodes. The voltage regulation power is allocated equally to loads at each node, with reactive load adjusted proportionally to active load. Using equal distribution, voltages at all violation points decrease significantly with fewer adjustment iterations and minimal complexity. Based on this method, if voltage limit violations persist after adjustment, the process is repeated until voltage requirements are satisfied. The flowchart of the load restoration procedure during network reconfiguration is shown in the figure.

4 Case Study

To verify the effectiveness of the proposed algorithm, the IEEE 39-bus system is used for simulation analysis. Node 31 is assumed to be the black start power source and slack bus with an installed capacity of 580 MW. The total system restoration process is divided into nine time steps, with one generating unit started in each time step and partial important loads restored in the established network framework. The specific restoration sequence is shown in Table 1 .

The basic strategy is illustrated using the second time step as an example. In the first time step, all loads at node 31 are restored. In the second time step, generator output increases by 41.6 MW, which is distributed to nodes 4, 15, and 16. The power flow results after load distribution are shown in Table 2 .

As seen in Table 2, nodes 15, 16, and 19 experience voltage limit violations, with node 19 being the most severe. The sensitivity-based method is applied to adjust the voltage violations. First, the apparent power sensitivity between node 19 and all load nodes is calculated. The node with maximum sensitivity is identified, yielding a maximum sensitivity of -0.036, requiring a load increase of 225 MW at this node. This power is distributed equally among other load nodes, with reactive load increased proportionally to active load. The power flow results after load adjustment are shown in Table 3 .

The results demonstrate that all node voltages are brought within constraint limits, with both active and reactive loads increased while maintaining overall system power balance, confirming the effectiveness of the proposed load adjustment strategy. By calling this adjustment strategy repeatedly in each time step, rapid load adjustment during the restoration process can be achieved, providing support for network reconfiguration optimization.

5 Conclusion

Addressing the voltage limit violation problem caused by load restoration during network reconfiguration in blackout system recovery, this paper proposes a sensitivity-based load adjustment strategy. Power flow calculations are performed on the restored grid, the node with voltage limit violation is selected, and sensitivity analysis is used to calculate its sensitivity to all load nodes. The load node with maximum sensitivity is identified, the load adjustment amount is determined based on sensitivity techniques, and this adjustment is distributed to other load nodes. This process is iterated until all node voltages satisfy requirements.

IEEE 39-bus system simulation results demonstrate that the proposed method can effectively solve node voltage limit violation problems and improve grid security during the restoration process.

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Note: Figure translations are in progress. See original paper for figures.