Research on Optimization of Single-phase Reclosing Sequence to Alleviate Voltage Sag of Sensitive Load Node

Li Ma1,a, Wei Zhang2,b*, Dingrong Tian3,c, Chao Zhang4,d and Shuping Gao5,e

1 School of Electrical and Control Engineering, Xi’an University of Science and Technology, Xi’an, Shaanxi, 710054, China
2 School of Electrical and Control Engineering, Xi’an University of Science and Technology, Xi’an, Shaanxi, 710054, China
3 School of Electrical and Control Engineering, Xi’an University of Science and Technology, Xi’an, Shaanxi, 710054, China
4 School of Electrical and Control Engineering, Xi’an University of Science and Technology, Xi’an, Shaanxi, 710054, China
5 School of Electrical and Control Engineering, Xi’an University of Science and Technology, Xi’an, Shaanxi, 710054, China

aemail:710849937@qq.com, cemail:20206029020@stu.xust.edu.cn, demail:957196121@qq.com, eemail:2398164784@qq.com

*Corresponding author:bemail:20206227097@stu.xust.edu.cn

Abstract. In order to reduce the voltage sag depth of the sensitive load node when the single-phase reclosing reclose fails, this paper proposes a single-phase reclosing sequence optimization method. When single-phase short-circuit to ground fault occurs on branch, the influence of reclosing sequence, including disconnecting and connecting, of circuit breakers at both branch sides on voltage sag of sensitive load node is analyzed. According to this, the reclosing sequence optimization scheme is put forward. Then, taking sensitive load node as the center, a branch stratification method and criterion of branch needing reclosing sequence optimization are proposed. The proposed method is verified in IEEE 30-bus system, the result shows the method is effective and feasible.

1.Introduction
In recent years, voltage sag has become a major threat to the normal operation of various sensitive equipment in modern society [1]. Short-circuit fault is an important cause of voltage sag [2]. At present, voltage sag is alleviated and controlled mainly by changing the power supply mode and installing compensation devices [3,4].

Most of the high-voltage line faults are single-phase ground faults, and single-phase reclosing is often used to try to restore line transmission after fault occurs [5]. Both single-phase short-circuit to ground fault of the line and reclosing operation may cause the voltage sag of the sensitive load node [6,7]. Literature [8] analyzes the impact of reclosing failure on the DC system, and proposes a single-phase reclosing sequence scheme to reduce the probability of commutation failure. The influence of single-phase reclosing sequence on sensitive load nodes is analyzed in [9], the author proposes a single-phase...
reclosing reclosing sequence scheme. However, the reclosing sequence here only comprises connecting operation, reclosing device disconnecting sequence is not considered.

This paper analyzes the influence of the reclosing sequence on the voltage sag of the sensitive load, and proposes a single-phase reclosing sequence scheme to reduce the depth of voltage sag at the sensitive load node according to the voltage of sensitive load node. In addition, the sensitive load node is taken as the center to stratify the power grid, and the branch which needs to optimize the reclosing sequence is determined. The simulation and calculation results show that the method in this paper can effectively reduce the voltage sag depth of the sensitive load node when the reclosing is disconnecting and reclosing on a permanent fault.

2. The influence of reclosing sequence on the voltage sag of sensitive load node

When a single-phase short-circuit fault occurs in the system, the sensitive load node voltage can be calculated through the three-phase unbalanced short-circuit fault analysis.

Figure 1 shows the power network structure. In the figure, P is the sensitive load node, F is the short-circuit fault point on any branch, d is the fault distance. Then the self-impedance of F and the mutual impedance between F and P are $Z_f^s$ and $Z_{ Pf}$ respectively, shown as follows:

$$Z_{ Pf}^s = (Z_{ Pf}^0 - Z_{ Pf}^+) d^2 + (2Z_{ Pf}^0 - 2Z_{ Pf}^+ + Z_{ Pf}^0) d + Z_{ Pf}^+$$

$$Z_{ Pf}^+ = (Z_{ Pf}^0 - Z_{ Pf}^+) d + Z_{ Pf}^0$$

In the formula, the superscript $s$ can be 1, 2 and 0, which represents positive sequence, negative sequence and zero sequence respectively; $Z_i^s$ and $Z_j^s$ are the self-impedances of nodes i and j respectively; $Z_{ij}^s$ is the impedance value of branch i-j.

![Power network structure](image)

Figure 1. Power network structure

When a single-phase short-circuit to ground fault occurs at the fault point F (take A phase as an example), the fault phase voltage at the sensitive load node P is

$$u_{P,A} = u_{P,A}^{ref} - \frac{Z_{Pr}^0 + Z_{Pr}^+ + Z_{Pr}^2}{Z_{Pr}^0 + Z_{Pr}^+ + Z_{Pr}^2} u_{P,A}^{ref}$$

In the formula, $u_{P,A}^{ref}$ is the phase A voltage at point P before the fault, and $u_{P,A}^{ref}$ is the voltage at point F before the fault.

According to formula (3), when the line fails, the fault phase voltage of the sensitive load node is mainly determined by the impedance between the fault point and the sensitive load node. When circuit breaker of i side and circuit breaker of j side operate, the impedance between the fault point and the sensitive load node changes, causing the sensitive load node voltage to change. That is, reclosing sequence, including disconnecting and connecting, of circuit breakers at both sides of branch i-j will affect the voltage sag amplitude of the sensitive load node.

In the following part, PSASP software is used to simulate IEEE 30-bus system. Detailed influence of reclosing sequence on voltage sag of sensitive load node (Bus 15) is analyzed as follows.
2.1. The influence of the reclosing disconnecting sequence on the voltage sag of the sensitive load

Take the permanent single-phase short-circuit to ground fault of branch 18-19 as an example, as shown in Fig. 2, when the branch fails at \( t_0 \), the circuit breaker on one side of the branch is disconnected at \( t_1 \), and then the circuit breaker on the other side is disconnected at \( t_2 \).

In Fig. 2, when the branch fault occurs, the node voltage of sensitive load drops to 0.3875 p.u.. When the circuit breaker on node 18 side of the branch is disconnected first, the voltage restores to 0.773 p.u.; When the circuit breaker on node 19 side of the branch is disconnected first, the voltage only restores to 0.4606 p.u.. It can be seen that the disconnecting sequence of the circuit breakers on both sides of the branch affects the depth of voltage sag on sensitive load node.

![Figure 2. Voltage of sensitive load node during reclosing action](image1)

![Figure 3. Voltage of sensitive load node during reclosing action](image2)

2.2. The influence of the reclosing connecting sequence on the voltage sag of the sensitive load

As shown in Fig. 2, at \( t_3 \), the circuit breaker on one side of the branch is connected first, at \( t_4 \), the circuit breaker on the other side of the branch is connected. At \( t_5 \), the circuit breaker of the first connected side is disconnected again, and at \( t_6 \), the circuit breaker of the second connected side is disconnected, and the system returns to normal.

In Fig. 2, if the automatic recloser on node 18 side recloses the circuit breaker after a preset time, the node voltage of the sensitive load drops to 0.4606 p.u.; When the automatic reclosing device on node 19 side recloses the circuit breaker after a preset time, the voltage of the sensitive load node drops to 0.773 p.u.. It can be seen that the connecting sequence of circuit breakers on both branch sides affects the depth of voltage sag on the sensitive load node.

In the same way, simulation results (shown in Figure 3) show that the reclosing sequence of branch 29-30 has little effect on voltage sag of sensitive load node.

3. Determine the reclosing sequence optimization scheme

3.1. Optimization scheme of reclosing disconnecting sequence

Assuming a single-phase grounding short-circuit occurs on branch i-j, \( u_{iA}^\text{std} \) means the standard unit phase A voltage of sensitive load node P when i-side circuit breaker is first disconnected, \( u_{jA}^\text{std} \) means the standard unit phase A voltage of sensitive load node P when j-side circuit breaker is first disconnected. According to equations (1) ~ (3), \( u_{iA}^\text{std} \) and \( u_{jA}^\text{std} \) can be calculated.

In the actual operation of power system, it is difficult for the circuit breakers on both branch sides to operate synchronously when the branch fails. Considering from reducing influence of voltage sag on sensitive load node, if \( u_{iA}^\text{std} > u_{jA}^\text{std} \), disconnect the i-side circuit breaker first; if \( u_{iA}^\text{std} < u_{jA}^\text{std} \), disconnect the j-side circuit breaker first.
3.2. Optimization scheme of reclosing connecting sequence

Assuming a single-phase grounding short-circuit occurs on branch i-j, \( u^{i}_A \) means the standard unit phase A voltage of sensitive load node P when i-side circuit breaker is first connected, \( u^{j}_A \) means the standard unit phase A voltage of sensitive load node P when j-side circuit breaker is first connected. In the same way, \( u^{ic}_A \) and \( u^{jc}_A \) can be calculated.

Considering from reducing influence of voltage sag on sensitive load node, if \( u^{ic}_A > u^{jc}_A \), disconnect the i-side circuit breaker first; if \( u^{ic}_A < u^{jc}_A \), disconnect the j-side circuit breaker first.

4. Determination of the branch needing reclosing sequence optimization

According to the simulation analysis in Section 2, reclosing sequence of some branches has significant influence on voltage sag of sensitive load node, while for some branches, the influence is not worth mentioning. Therefore, to alleviate the voltage sag of sensitive load node, determination of the branch which needs reclosing sequence optimization is a problem that must be solved.

4.1. Stratification of the grid

Taking sensitive load node P as the center and searching out along the grid network, this paper proposes a branch stratification method according to the distance from branch to the sensitive load node. The steps of this method are as follows:

- Step 1. divide all the branches directly connected with sensitive load node P into the first layer branch set;
- Step 2. \( G = 2, 3, 4,... \), divide all the branches directly connected with the \((G-1)\)'th layer into the G'th layer branch set;
- Step 3. \( G = G + 1 \). Repeat step 2 until all branches are divided.

4.2. Criterion of branch needing reclosing sequence optimization

After the stratification of the grid is completed, taking i-side circuit breaker as the first disconnecting side and the first connecting one, \( u^{ic}_A \) and \( u^{ic}_A \) can be obtained; taking j-side circuit breaker as the first disconnecting side and first connecting one, \( u^{jc}_A \) and \( u^{jc}_A \) can be obtained. Obviously, \( u^{ic}_A \) equals to \( u^{ic}_A \) and \( u^{ic}_A \) equals to \( u^{ic}_A \).

\[ r = |u^{ic}_{P,A} - u^{ic}_{P,A}| = |u^{ic}_{P,A} - u^{ic}_{P,A}| \]  (4)

Set threshold \( \varepsilon \), if \( r \leq \varepsilon \), it means that the reclosing sequence does not need to be optimized when a single-phase ground fault occurs in branch i-j; if \( r > \varepsilon \), it means that the reclosure sequence needs to be optimized when a single-phase ground fault occurs in branch i-j.

5. Example analysis

Taking IEEE30-bus power grid (shown in Figure 4) as an example, all branches are stratified according to the proposed stratification method in section 4, in which bus 15 is the sensitive load node.

Figure 4. IEEE30-bus system diagram
After stratifying the grid branches, the search for branch that needs reclosing sequence optimization starts from the first-layer branch set, in which the branches are searched in the order of branch i-side number from small to large. The fault point is set at the middle of branch i-j, that is, d=0.5. Sensitive load is connected to bus 15. Calculate $u_{P_i}^o, u_{P_i}^e, u_{P_j}^o$ and $u_{P_j}^e$. When the search in the first layer branch set is completed, using the same way to search in the second layer branch set and calculate the four voltages. After the search in the second layer branch set is completed, using the same method to search in the remaining branch sets in turn and calculate relative voltages until all branches are searched. Taking $\varepsilon$ as 0.1, the calculation results and optimization scheme are shown in Table 1.

### Table 1. Voltages of bus 15 and optimization scheme when different sides of the branch are used as the first disconnecting side and the first connecting side

| Branch set       | Branch i-j | Voltages of Sensitive load node 15,p.u. | Optimization or not | Optimization scheme |
|------------------|------------|----------------------------------------|---------------------|---------------------|
| First layer      | 12-15      | $0.162$ | 0.4698 | 0.3078 | Yes | 15 | 12 |
| branch set       | 14-15      | $0.2806$ | 0.6404 | 0.3658 | Yes | 15 | 14 |
|                  | 15-18      | $0.8353$ | 0.2475 | 0.5878 | Yes | 15 | 18 |
|                  | 15-23      | $0.8557$ | 0.2235 | 0.6322 | Yes | 15 | 23 |
| Second layer     | 12-13      | $0.9451$ | 0.2949 | 0.6502 | Yes | 12 | 13 |
| branch set       | 12-14      | $0.5555$ | 0.4331 | 0.1224 | Yes | 12 | 14 |
|                  | 12-15      | $0.7859$ | 0.3439 | 0.442 | Yes | 12 | 16 |
|                  | 15-18      | $0.7730$ | 0.4606 | 0.3124 | Yes | 18 | 19 |
|                  | 23-24      | $0.7677$ | 0.4909 | 0.2768 | Yes | 23 | 24 |
| Third layer      | 2-4        | $0.8855$ | 0.9564 | 0.0709 | No |     |     |
| branch set       | 3-4        | $0.7946$ | 0.9757 | 0.1811 | Yes | 4  | 3  |
|                  | 4-6        | $0.8701$ | 0.8247 | 0.0454 | No |     |     |
|                  | 16-17      | $0.6610$ | 0.5366 | 0.1244 | Yes | 16 | 17 |
|                  | 19-20      | $0.7055$ | 0.5383 | 0.1672 | Yes | 19 | 20 |
|                  | 22-24      | $0.6529$ | 0.6390 | 0.0139 | No |     |     |
|                  | 24-25      | $0.9785$ | 0.5878 | 0.3907 | Yes | 24 | 25 |
| Fourth layer     | 1-2        | $0.9227$ | 0.9656 | 0.0429 | No |     |     |
| branch set       | 1-3        | $0.9104$ | 0.9672 | 0.0568 | No |     |     |
|                  | 2-5        | $0.9727$ | 0.9477 | 0.025 | No |     |     |
|                  | 2-6        | $0.8966$ | 0.956 | 0.0594 | No |     |     |
|                  | 6-7        | $0.9848$ | 0.8428 | 0.142 | Yes | 6  | 7  |
|                  | 6-8        | $0.966$ | 0.7991 | 0.1669 | Yes | 6  | 8  |
|                  | 6-28       | $0.9435$ | 0.8384 | 0.1051 | Yes | 6  | 28 |
|                  | 10-17      | $0.6242$ | 0.4371 | 0.1871 | Yes | 10 | 17 |
|                  | 10-20      | $0.6135$ | 0.5532 | 0.0603 | No |     |     |
|                  | 10-22      | $0.5534$ | 0.4696 | 0.0838 | No |     |     |
|                  | 21-22      | $0.4717$ | 0.5015 | 0.0298 | No |     |     |
|                  | 25-26      | $0.9947$ | 0.8271 | 0.1676 | Yes | 25 | 26 |
|                  | 25-27      | $0.9627$ | 0.731 | 0.2317 | Yes | 25 | 27 |
|                  | 5-7        | $0.9274$ | 0.9792 | 0.0518 | No |     |     |
|                  | 8-28       | $0.964$ | 0.9661 | 0.0021 | No |     |     |
|                  | 9-10       | $0.4297$ | 0.9773 | 0.5476 | Yes | 10 | 9  |
|                  | 9-11       | $0.9863$ | 0.6332 | 0.3531 | Yes | 9  | 11 |
|                  | 10-21      | $0.5626$ | 0.3686 | 0.194 | Yes | 10 | 21 |
|                  | 27-29      | $0.9683$ | 0.8939 | 0.0744 | No |     |     |
|                  | 27-30      | $0.9666$ | 0.913 | 0.0536 | No |     |     |
| Sixth layer      | 29-30      | $0.9563$ | 0.9464 | 0.0099 | No |     |     |

It can be seen from Table 1 that when circuit breakers of different branch sides are first disconnected or first connected during a permanent fault, the voltage sag depth of the sensitive load node is different.
For only a few branches, the influence of reclosing sequence on sensitive load node is not obvious. For branches 12-15, 14-15, 15-18, 12-16, reclosing sequence has a significant impact on the depth of the voltage sag of the sensitive load node. By optimizing the reclosing sequence of these branches, voltage sag of bus 15 can be effectively alleviated. While for branches 8-28, 21-22, 27-29, 29-30, the influence of reclosing sequence on voltage sag can be ignored. Whether to optimize the reclosing sequence of these branches is not that important.

In addition, most of the branches with obvious difference of bus 15 voltage when different branch side is taken as the first operation side are concentrated in the first and the second layer branch sets; and the branches with the insignificant difference are mostly concentrated in the third, fourth, fifth, and the sixth layer sets. As the layer number increases, such difference will become less obvious, and the number of branches that need reclosing sequence optimization will also decrease.

6. Conclusion
This paper proposes a single-phase reclosing sequence optimization method, and determines the branch that needs to optimize the reclosing sequence, which can effectively alleviate the voltage sag of the sensitive load nodes when permanent short-circuit fault occurs in the grid.

(1) When single-phase short-circuit to ground fault occurs on branch, the influence of reclosing sequence, including disconnecting and connecting, of circuit breakers at both branch sides on voltage sag of sensitive load node is analyzed. Using simulation calculations, an optimization scheme of disconnecting and connecting sequence for circuit breakers at both fault branch sides is proposed.

(2) Taking sensitive load node as the center, a branch stratification method is proposed based on the structure relationship between branch and sensitive load node. The difference between threshold value and the absolute value of voltage difference is taken as the criterion, where voltage difference is the difference between two sensitive load node voltages when i-side and j-side of branch i-j are taken as the first disconnecting side or the first connecting side.

(3) The calculation results show that the proposed method can alleviate the voltage sag of sensitive load node without increasing investment.

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References
[1] LIU, P., OU, Y.S. (2019) Optimization of Power Quality Monitoring Network Considering Severity of Substation Voltage Sags and Difference of Monitors. Automation of Electric Power Systems, 41(3):161-167.
[2] Cheng, H.Z. (2012) Power quality detection and analysis. Science Press, Beijing.
[3] Chen, Z.L., Xu, W.S. (2015) Reason and Prevention of Voltage Interruption and Voltage Sag. Transactions of China Electrotechnical Society, 30 (S1): 518-520.
[4] Luo, A., Xu, Q., Ma, F., et al. (2016) Overview of power quality analysis and control technology for the smart grid. Journal of Modern Power Systems & Clean Energy, 4(1):1-9.
[5] Lu, J.D. Research on single phase to ground fault diagnosis of EHV transmission lines. Xi’an University of science and technology.
[6] Liang, Z.F., Suonan, J.L., Song, G.B., Kang, X.N. (2013) Research review of adaptive reclosing in transmission lines. Power System Protection and Control, 41 (06): 140-147.
[7] Shen, J., Shu, Z.H., Chen, J., Lu, J.F., Zhao, Q.C., Zhu, X.T. (2018) Application of Adaptive Auto-reclosing in Power System. Automation of Electric Power Systems, 42 (06): 152-156.
[8] Shu, H.C., Sun, S.Y., Liu, K.Z., Dai, Y.T. (2012) Study on Reclosing Sequence of AC Transmission Lines Near Converter Stations. Proceedings of the CSEE, 32 (07): 114-123+199.
[9] Liang, Z.F., Zhang, Q., Song, G.B., Fan, Z.F., Li, B.W. (2019) Single-phase Reclosing Sequence for Reducing Voltage Sag Depth and Duration. Automation of Electric Power Systems, 43 (09): 165-170.