Three-phase Analytical Optimization Algorithm for Sectionalizing Switch Placement of a Medium Voltage Overhead Line

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ABSTRACT

In the paper, a new heuristic algorithm is proposed for the sectionalizing switch placement of medium voltage overhead lines whose switches are of the same type. The objective function includes the reliability indexes of system average interruption duration (SAIDI) and expected energy not supplied (EENS). The constraints involve the maximum available investment, user reliability requirement and maximum sectionalizing switch number, etc. A general maximum product criterion of benefitted load and isolated line length, is presented to locate a single switch, and a three-phase analytical optimization algorithm is proposed for the sectionalizing switch placement of a medium voltage overhead line. A case study shows the effectiveness and practicability of the proposed analytical model and algorithm.

INTRODUCTION

The installation of sectionalizing switches on feeders is one of the effective measures to improve the reliability of a distribution network. The research of distribution network switch placement optimization has become a research focus at home and abroad\textsuperscript{1-8}. In reference 1, a theorem is proposed regarding whether a sectionalizing switch should be set for each line segment. In references 2-4, genetic algorithm, ant colony algorithm and simulated annealing algorithm are used to optimize the switch placement. In reference 5, a general criterion is proposed based on the maximum product of benefitted load and isolated line length. In reference 6, based on a two-layer optimization algorithm, a dichotomy is proposed. In reference 7, a mathematical programming method is used. Reference 8 summarizes the research status of sectionalizing switch placement optimization at home and abroad.

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In this paper, a new heuristic optimization algorithm is presented for the placement of sectionalizing switches of the same type. The related multi-objective function combines the SAIDI and EENS. The constraints involve the reliability indexes’ requirement, the maximum sectionalizing switch number and/or the maximum available investment. A three-phase optimization algorithm is proposed with a case study.

BASIC CONCEPTS

Reliability indexes
Reliability indexes of a medium voltage distribution network fall into two categories, i.e., load point indexes and system indexes. In this paper, two important indexes of SAIDI and EENS are selected to simplify reliability evaluation.

Maximum sectionalizing switch number
Installing sectionalizing switches on feeders can improve their reliability. However, the effectiveness and economy will gradually decrease as the reliability improves. Therefore, in this paper the maximum sectionalizing switches number is defined as the number that results in an obvious reliability improvement (such as a change rate of at least 5% for some reliability index).

OPTIMIZATION MODEL OF LINE SECTIONALIZING

Objective function
To consider both of the outage time and energy not supplied for a distribution network, the following multi-objective function is adopted.

\[
\min R(M(n)) = W_1 \times \frac{SAIDI(M(n))}{SAIDI(M(0))} + W_2 \times \frac{EENS(M(n))}{EENS(M(0))}
\]
\[
= W'_1 \times SAIDI(M(n)) + W'_2 \times EENS(M(n))
\]

Where: \( n \) is the total added number of switches in an overhead line, and \( m \) is the total number of feeder segments; \( M(n)=[(m_1(1), m_2(1)),(m_1(2), m_2(2)),..., (m_1(m), m_2(m))] \), \( m_1(i) \) and \( m_2(i) \) is the state variables of sectionalizing switches at both ends of line segment \( i \) (1 stands for new installation, 0 stands for no new installation), \( n = \sum_{i=1}^{m} [m_1(i) + m_2(i)] \); \( W_1 \) and \( W_2 \) are weight factors, and \( W_1 + W_2 = 1 \); \( SAIDI(M(0)) \) and \( EENS(M(0)) \) stand for SAIDI and EENS in the initial state when there is no newly installed sectionalizing switches; \( SAIDI(M(n)) \) and \( EENS(M(n)) \) stand for SAIDI and EENS when the number of newly added sectionalizing switches is \( n \); \( W'_1 \) and \( W'_2 \) are equivalent weight factors, where \( W'_1 = \frac{W_1}{SAIDI(M(0))} \) and \( W'_2 = \frac{W_2}{EENS(M(0))} \).

Constraints
Constraints include some basic constraints of a distribution network, such as the nodal power balance equation, upper and lower limits of node voltage, equipment capacity limits, and some additional constraints related to the switch placement.
(1) Maximum sectionalizing switch number constraint
\[ \Delta R(M(n)) \geq \varepsilon \]  
Where: \( \Delta R(M(n)) = R(M(n-1)) - R(M(n)) \); for each newly added sectionalizing switch in an overhead line, \( \varepsilon \) is the minimum reduction rate of reliability index.

(2) Investment constraint
\[ nc \leq C_{\text{max}} \]  
Where: \( C \) is the unit price of a sectionalizing switch; \( C_{\text{max}} \) is the upper limit of the total investment for all the newly added sectionalizing switches.

(3) Reliability index constraint
\[ R(M(n)) \leq R_{\text{max}} \]  
Where: \( R_{\text{max}} \) is the maximum allowable value of \( R(M(n)) \).

CRITERION OF SINGLE-SWITCH PLACEMENT

A criterion of single-switch placement is used to determine the appropriate installation position of a switch in a line segment when the positions of all the other switches are fixed.

Benefitted load is defined as the outage load to be decreased or the load to endure less outage time due to a newly added sectionalizing switch (such as a circuit breaker or a disconnector).

When the types of all sectionalizing switches in an overhead line are the same, the product of benefitted load and isolated line length of a switch can be defined as the sensitivity of \( R(M(n)) \) to switch placement. To get the optimum placement of a sectionalizing switch, the smaller \( R(M(n)) \) is, the bigger the switch placement sensitivity is. Therefore, the maximum switch placement sensitivity is used as the criterion of switch placement.

For the line without a tie connection, the switch placement sensitivity \( \rho_i \) of switch \( K_i \) can be expressed as follows.
\[ \rho_i = X_{eq,i}L_{eq,i} \]  
Where: \( L_{eq,i} \) and \( X_{eq,i} \) are respectively the isolated line length and the equivalent benefitted load of switch \( K_i \). \( X_{eq,i} \) is given by
\[ X_{eq,i} = W_1\frac{N_{eq,i}}{N} + W_2P_{eq,i} \]  
Where: \( N \) is the total number of customers, \( N_{eq,i} \) and \( P_{eq,i} \) are the customer number and load corresponding to the line segment \( X_{eq,i} \), respectively.

For the line with a tie connection, the switch placement sensitivity of switch \( K_i \) can be defined as follows.
\[ \rho_i' = X_{eq,i}'L_{eq,i} + X_{eq,i}L_{eq,i} \]  
Where: \( L_{eq,i} \) and \( X_{eq,i} \) are respectively the isolated line length and the equivalent benefitted load of switch \( K_i \) with the tie connection being regarded as the power source. \( X_{eq,i}' \) is given by
\[ X_{eq,i}' = W_1\frac{N_{eq,i}'}{N} + W_2P_{eq,i}' \]  
Where: \( N_{eq,i}' \) and \( P_{eq,i}' \) are the number of customers and load corresponding to \( X_{eq,i}' \), respectively.
THREE-PHASE ANALYTICAL OPTIMIZATION ALGORITHM

Based on the criterion of single-switch placement, a three-phase analytical optimization algorithm for sectionalizing switch placement of a medium voltage overhead line is proposed in this paper. Firstly, in the first-phase optimization, the reasonable candidate switch placement locations are identified; then, in the second-phase optimization, a heuristic method is applied to determine the optimum number of switches and their initial placement; finally, in the third-phase optimization, an iterative method is used to further optimize and adjust the switch placement.

First-phase

The first-phase optimization identifies the candidate locations of sectionalizing switches. For radial line segments, we know from Equation (9) that the candidate switch placement should be the power source ends (starting ends) of line segments as the black dots show in Figure 1 (a). According to Equation (9) and (11), the candidate sectionalizing switch locations of line segments with a tie connection should be at both ends of each line segment, as shown in Figure 1(b).

Second-phase

Based on the criterion of single-switch placement, a heuristic method is used in the second phase of optimization to determine the optimal number of switches and their initial locations. The steps are listed as follows.

1. Let \( j = 0 \); identify the benefitted load and isolated line length of each candidate switch respectively.
2. Let \( j = j + 1 \); calculate the \( \rho_i / \rho_i' \) for every candidate switch; find \( \max \rho_i / \rho_i' \) and install a sectionalizing switch in the corresponding position.
3. Considering the influence of installed switches, recalculate the benefitted load and isolated line length of other candidate switches, repeat step 2 until the constraints are satisfied.

Third-phase

Considering the local optimum problem of a heuristic optimization algorithm, we can improve the solution by adjusting the placement of each switch one by one.

In the third phase of optimization, the optimization range of a newly added sectionalizing switch is the involved lines of benefitted load and isolated line when all the other switches are fixed.

Let \( j = 1 \) and the steps of third-phase optimization are listed as follows.

1. Determine the third-phase optimization range of switch \( K_j \). 

(a) For aerial feeders without a tie connection  
(b) For aerial feeders with a tie connection

Figure 1. Candidate locations of sectionalizing switches.
Assuming that switch \( K_j \) is not installed, calculate the switch placement sensitivity of all the candidate switches in their optimization range. Place switch \( K_j \) where the switch placement sensitivity is maximum.

Let \( j = j + 1 \), jump to step ① until all the switches go through step ③.

If there are any change of switch placement from step ① to ③, let \( j = 1 \), jump to step ①; otherwise, output the results.

CASE STUDY AND ANALYSIS

An actual feeder in reference 6 is chosen. The data of feeders and loads are listed in reference 6. The average failure rate of lines is 0.1 fl/(km·a); the average repair time of lines is 4h; the switching time for sectionalizing switches is 20min, the switching time for tie switches is 30min. For feeders without a tie connection, \( \varepsilon \) in Equation (2) is taken as 0.05; \( W_1 = W_2 = 0.5 \); for feeders with a tie connection, in order to install the same number of switches as that in reference 6, \( \varepsilon \) in Equation (2) is taken as 0.015.

The candidate switch positions for the actual feeder with and without a tie connection are shown in Figure 2. The final results of switch placement for the actual feeder with and without a tie connection are listed in Figure 3.

For the actual feeder without a tie connection, the number of line segments is 4, and 3 sectionalizing switches are added, located in the starting ends of line 4~6, 10~14 and 19~21. The system reliability index EENS is 4.883MWh/yr.

For the actual feeder with a tie connection, the comparison of optimization results for the sectionalizing switch placement using different approaches is listed in Table 1. We can see that, among all the 6 situations of different switch numbers, compared to reference 6, a smaller EENS can be obtained by the proposed method, and a maximum decreased percentage (19.85%) of EENS is obtained when 8 sectionalizing switches are added.
Table 1. Optimization Result Comparison Using Different Approaches.

<table>
<thead>
<tr>
<th>Number of switches</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Switch position</td>
<td>Starting end of 6-10, 14-17</td>
<td>Starting end of 6-10, 14-17</td>
<td>Starting end of 6-10, 14-17</td>
<td>Starting end of 6-10, 14-17</td>
<td>Starting end of 6-10, 14-17</td>
<td>Starting end of 2-4, 10-14, 14-17, 17-19, 21-23</td>
</tr>
<tr>
<td>EENS (MWh)</td>
<td>3.7223</td>
<td>2.5884</td>
<td>2.1556</td>
<td>1.8457</td>
<td>1.6076</td>
<td>1.3786</td>
</tr>
<tr>
<td>Switch position</td>
<td>End end of 4-6; Starting end of 14-17</td>
<td>End end of 4-6, 17-19; Starting end of 14-17</td>
<td>End end of 4-6, 14-17; Starting end of 14-17</td>
<td>End end of 4-6, 14-17; Starting end of 14-17</td>
<td>End ends of 2-4, 10-14, 17-19, 21-23; Starting end of 14-17</td>
<td>End ends of 4-6, 10-14, 14-17, 17-19, 21-23</td>
</tr>
<tr>
<td>EENS (MWh)</td>
<td>3.624</td>
<td>2.482</td>
<td>1.944</td>
<td>1.590</td>
<td>1.449</td>
<td>1.105</td>
</tr>
<tr>
<td>Decreased percentage of EENS (%)</td>
<td>2.64</td>
<td>4.11</td>
<td>9.82</td>
<td>13.85</td>
<td>9.87</td>
<td>19.85</td>
</tr>
</tbody>
</table>

**CONCLUSION AND DISCUSSION**

1. For a medium voltage overhead line with the same type of sectionalizing switches, a simple and intuitive criterion of maximum product of benefitted load and isolated line length is defined to determine the placement of a single switch.
2. It is intuitively presented that any source end of a line segment is a candidate switch location.
3. The proposed algorithm of three-phase analytical optimization is simple, intuitive, reasonable and practical, and provides reasonable and fewer candidate switch locations.
4. The case study shows the rationality and practicability of the proposed method.

**REFERENCES**