OPTIMAL APPLICATION OF RECLOSERS AND SECTIONALISERS TO REDUCE NON-DISTRIBUTED ENERGY IN DISTRIBUTION NETWORKS

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ABSTRACT
This paper presents a method for optimal placement of reclosers and sectionalisers in overhead distribution networks to reduce Non-Distributed Energy (NDE) caused by permanent faults. The proposed algorithm uses an effective numbering method to determine the distribution network topology. This numbering method is very useful in the optimisation procedure and determination of savings achieved by reducing the non-distributed energy. Then a method is described for optimal placement of a recloser and sectionalisers in the network. Both voltage type and current type sectionalisers are considered at this stage. In the next stage, the optimal number of sectionalisers is determined based on economic considerations. Lastly, the validity of the presented method is evaluated by applying the algorithm on a typical Iranian 20 kV distribution feeder and the results are presented.

INTERDUCATION

Statistics show that over 70% of faults on the overhead distribution networks have transient nature, which can be cleared successfully by the reclosing operation. On the other hand, the permanent faults percentage is low, but their duration is high, compared to the transient faults. The affected region due to these faults can also be reduced by applying sectionalisers, since they split the network to some sections. Here a large portion of network is saved from energy cut-off, except the faulted section. As a result, electricity authorities consider seriously about the application of reclosers and sectionalisers in their network. In recent years, more attention has been given to the application of these devices to reduce NDE caused by permanent faults.

In the first step, the network topology should be defined properly for the optimisation procedure. Unlike the transmission systems, in distribution systems numbering the network branches and nodes is very important. This paper presents a numbering method for the distribution systems.

It has been a common practice to install reclosers in the sub-transmission substations. In this case, the feeder circuit-breaker can be controlled by a recloser relay. In the recent years, recloser packages are largely introduced into distribution networks. These are composed of a circuit-breaker and a recloser relay and can be installed anywhere on the distribution feeder.

Optimal number and placement of the sectionalisers can be determined regarding the saving obtained by installation of sectionalisers. Since sectionalisers can not break the fault current, their installation point greatly depends on the location of the recloser. This saving also depends on economic and technical factors. Technical factors are the network dimensions, the number of annual permanent fault occurrence on the network, the energy demand of the network, and the required maintenance time. Economic factors consist of period of study, load growth, interest and inflation rates, costs of NDE, and cost of reclosers and sectionalisers and their installation.

The installation point of the recloser affects the procedure of finding optimal number and locations of the sectionalisers. The presented method in this paper firstly determines the optimal position for a sectionaliser. The gained saving is determined with respect to the installation and maintenance costs of the sectionaliser. If the saving is positive, installation of the sectionaliser is economically feasible. Then the saving obtained by using two sectionalisers is calculated. In the installation of two sectionalisers, their type is important in their placement. The gained saving is compared with the saving of one sectionaliser. If the saving of one sectionaliser is more, the optimal number of sectionalisers is one. Otherwise, installation of more sectionalisers on the distribution feeder should be considered. This process continues until the saving obtained by installation of $k$ sectionalisers becomes less than the saving of $k-1$ sectionalisers. The optimal number of the sectionalisers would be equal to $k-1$.

NUMBERING NETWORK NODES AND BRANCHES

Network topology is an important aspect in the distribution systems studies. References [1-4] present methods for numbering the network components for solving the load-flow problem, which can be used in any other studies. In general, a numbering strategy is required in the studies of distribution networks.

This paper uses the numbering method in [6], which is somehow similar to the method presented by Goswami and Basu [2]. In this method, similar to the other methods, the numbering process starts from the source node, i.e. sub-transmission substation. The far end node of the connected branch to this node is numbered one. The number of each
branch is the number of its far end node. After first branch, the connected branch to its far end is then numbered. This process continues and if there is a lateral on the feeder, the branches of the lateral with fewer components are first numbered. Fig. 1 shows this numbering method for a typical network.

Fig. 1- Numbering method on a typical network

SAVING GAINED BY UTILISING A DISCONNECTOR

The main purpose of utilising automation equipment is to restore the upstream loads when a fault occurs on the network, or in other word, reducing the cost of NDE. This is done by disconnecting the downstream faulted section. This cost must be balanced to the equipment installation cost. For a single disconnector, its optimal location can be found as [5]:

$$C_i = K P_i f_i l_i c_n - C_d$$  \hspace{1cm} \text{(1)}$$

where:
- \(C_i\): Amount of savings gained by installing a disconnector
- \(K\): Coefficient for converting the first year costs to the whole review period
- \(P_i\): Upstream demand of node \(i\)
- \(f_i\): Annual failure rate per line length
- \(l_i\): Line length downstream of node \(i\)
- \(t\): Difference between repair time and switching time
- \(c_n\): Outage-cost parameter of NDE
- \(C_d\): Cost of a disconnector (including maintenance) over the whole review period

It should be noted that the equation is derived on the following assumptions:
- Risk of failure is proportional to the length of line
- Costs of outage are proportional to the NDE
- Growth of load is equal at every load point
- Average values are used

Equation (2) is the modified form of (1) to cover the case of installation of automation equipment in a network based on the three latter assumptions.

$$C_i = k_i P_i \rho_i - C_d$$  \hspace{1cm} \text{(2)}$$

where \(C_i\), \(C_d\) and \(P_i\) are similar to (1), \(\rho_i\) is the fault distribution density function along the feeder, with a magnitude between 0 and 1, and \(k_i\) is a coefficient defined as follows:

$$k_i = K F_i l_i c_n$$  \hspace{1cm} \text{(3)}$$

where \(K\), \(c_n\) and \(t\) are similar to (1) and \(F_i\) is the annual number of the permanent fault occurrence on the feeder.

\(\rho_i\) can be computed as below:

$$\rho_i = \frac{\sum_{j=1}^{n} p_j l_j}{\sum_{j=1}^{n} p_j}$$  \hspace{1cm} \text{(4)}$$

where:
- \(p_j\): Relative probability of fault occurrence on the line section \(j\)
- \(l_j\): Length of the line section \(j\)
- \(n\): Number of the nodes in the network
- \(D\): Set of nodes which are located at the downstream of the node \(j\)

THE ALGORITHM

Reclosers can be installed on the supplying point or along the feeder. It has been a common practice to install reclosers in the sub-transmission substations or the feeder circuit breaker can be controlled by recloser relay. In the recent years, recloser packages are largely introduced in the distribution networks, and they can be installed anywhere on a distribution feeder. The installation point of the recloser affects the procedure of finding the optimal number and location of the sectionalisers.

Recloser Installed at the Sub-Transmission Substation

When the recloser is located at the sub-transmission substation, sectionalisers can be installed anywhere on the feeder.

Savings gained by utilising one sectionaliser. Equation (2) can be used to determine the savings gained by utilising a sectionaliser. This equation can be rewritten as:

$$C_i = k_i P_i \rho_i - C_d$$  \hspace{1cm} \text{(5)}$$

where:
- \(C_i\): Amount of savings gained by installing a sectionaliser
- \(C_d\): Cost of a sectionaliser

The optimal position can be readily determined by calculation of \(C_i\) for all the nodes. If the value of \(C_i\) is negative for all the nodes, it means that the use of a sectionaliser on the feeder
is not economical. On the other hand, for positive values of \( C_s \), the use of sectionaliser is economical and the node with the highest value of \( C_s \) is the optimal position for its installation.

The value of \( C_s \) is normally negative at twigs. Therefore the twigs can be omitted from optimal placement process, without losing the global optimum. Reference [6] recommends ignoring the branches with downstream load of less than 5% of the total load. According to the (5), \( C_s \) depends on the upstream load as well as the probability fault occurrence on the downstream network. If the downstream load is low and the downstream fault occurrence is high, the gained saving would increase. When the downstream load is only considered, the branches with the high fault rate might be omitted. Therefore, the omission criterion should be composed of the upstream load and the downstream fault rate. Here, it is suggested that their product is considered as the omission criterion. In order to determine the criterion, it is useful to apply the per-unit values of the downstream loads, in the base of the total load. When this criterion is less than 0.05, the node can be omitted from the placement procedure. Therefore, a set defined as Voltage Sectionaliser Location Set (VSLS); consisting of the nodes with the criterion of higher than 0.05. In this case, VSLS can be used for both voltage and current type sectionalisers.

**Savings gained by utilising two sectionalisers.** If the gained saving is positive in the case of one sectionaliser, it cab be concluded that the application of the sectionaliser is economical for the network. However, the higher saving would be gained by utilising more sectionalisers. Therefore, the case of using two sectionalisers should be considered. In this case, (5) should be modified as:

\[
C_{(s_1, s_2)} = k_s (P_{s_1} \rho_{s_1} + P_{s_2} \rho_{s_2}) - 2C_s
\]

(6)

In (6) \( s_1 \) and \( s_2 \) are the installation location of the sectionalisers, and \( s_1 < s_2 \).

The values of \( s_1 \) and \( s_2 \) depend on the type of sectionalisers. There is no limit for the voltage type sectionalisers, whereas current type sectionalisers cannot be placed in series with each other. In other words, current type sectionalisers need an extra consideration in choosing \( s_1 \) and \( s_2 \).

In the case of voltage sectionalisers, \( s_1 \) and \( s_2 \) can take a value between \( I \) and \( n \). In this case, \( C_{(s_1, s_2)} \), \( k_s \), \( P_{s_1} \), \( P_{s_2} \), \( \rho_{s_1} \), and \( \rho_{s_2} \) and \( C_s \) are similar to (5), but the value for \( \rho_{s_1} \) differs. Here, \( \rho_{s_1} \) is the probability of fault occurrence in the network section protected by the sectionaliser installed at the \( s_1 \) and it is not necessarily equal to the probability of fault occurrence downstream node \( s_1 \).

For current type sectionalisers, \( C_{(s_1, s_2)} \), \( k_s \), \( P_{s_1} \), \( P_{s_2} \), \( \rho_{s_1} \), \( \rho_{s_2} \) and \( C_s \) are similar to (5), but there are some limits on choosing \( s_1 \) and \( s_2 \). Here, \( \rho_{s_1} \) is always equal to the fault occurrence density function at node \( s_1 \). At first, \( s_1 \) is selected on a lateral, and then \( s_2 \) can be chosen from the downstream network of this lateral.

The \( C_{(s_1, s_2)} \) value is calculated for all the nodes. \( s_1 \) and \( s_2 \) corresponding to the highest value of \( C_{(s_1, s_2)} \) are the optimal installation locations of two sectionalisers.

If \( s_1 \) and \( s_2 \) corresponding to the twigs or when they are very close to each other, usually \( C_{(s_1, s_2)} \) is low or negative. Therefore, in this case twigs can also be omitted from the calculations. The defined VSLS set at previous section can be used. Here another set is required for current type sectionalisers. This set is defined as a set of nodes, which are located on the laterals, and the mentioned criterion is higher than a specified value, e.g. 0.04. This set is defined as Current Sectionaliser Location Set (CSLS).

In installation of two sectionalisers, if they are voltage type, \( s_1 \) and \( s_2 \) are chosen from the VSLS set. In the case of current type sectionalisers \( s_1 \) is chosen from CSLS, and \( s_2 \) is selected from VSLS set, corresponding to the downstream network of the lateral of \( s_1 \).

When the maximum value of \( C_{(s_1, s_2)} \) is computed, it should be compared with highest value of \( C_s \) which was calculated at the previous stage. If \( C_s \) is higher than \( C_{(s_1, s_2)} \), the optimal number of sectionalisers is equal to one and its location is at node or line section \( s \). In this case, cost of installing the second sectionaliser is more than the gained saving. On the other hand, if \( C_{(s_1, s_2)} \) is higher, the installation of two sectionalisers is more economical. However, the cases of using more sectionalisers should still be considered at this point, in search for the optimal number.

**Savings gained by utilising multiple sectionalisers.** When \( n \) sectionalisers are installed in a distribution network, (5) can be modified as below:

\[
C_{(s_1, \ldots, s_n)} = k_s \sum_{i=1}^{n} (P_{s_i} \rho_{s_i}) - nC_s
\]

(7)

where:

\( s_1, \ldots, s_n \) : Installation locations of \( n \) sectionalisers in order, i.e. \( s_1 < \cdots < s_n \).

\( P_{s_i} \) : Upstream load of node \( s_i \).

\( \rho_{s_i} \) : Fault occurrence probability at the section related to the sectionaliser installed at the node \( s_i \).

In this case similar to the installation of two sectionalisers, the values that variables \( s_1, s_2, \ldots, s_n \) can take, depending on the sectionalisers type. In the case of the voltage type sectionalisers, the evaluation of \( \rho_{s_i} \) is important, whereas for the current type sectionalisers the values which variables \( s_1, s_2, \ldots, s_n \) can take, is a question.

In the case of current type sectionalisers, similar to the case of using two sectionalisers, the reference sets of the variables are different. Locations \( s_1, s_2, \ldots, s_{n-1} \) should only be selected
on laterals, in such a way that they do not placed in series with each other. Reference set for positions \( s_1, s_2, \ldots, s_{n-1} \) is similar to CSLS defined for position \( s_1 \) and the reference set for \( s_n \) is similar to \( s_2 \) as described in using two sectionalisers. In the case of voltage sectionalisers, when \( P_0 \) is determined, the gained saving can be computed.

Therefore, the gained saving, \( C_{(s_1, \ldots, s_n)} \), for \( n \) sectionalisers can be computed for different positions. For each value of \( n \), the optimal case is obviously the one with maximum value of the \( C_{(s_1, \ldots, s_n)} \).

**Optimal number of the Sectionalisers.** In order to determine the optimal number of sectionalisers, \( C_{(s_1, s_2, s_2)} \) is computed and compared with \( C_{(s_1, s_2, s_1)} \). If \( C_{(s_1, s_2, s_1)} \) is lower, it can be concluded that the installation of two sectionalisers is the most optimal case. Otherwise, installation of three sectionalisers would be a better option. In order to find whether this case is the optimum one, the value of \( C_{(s_2, \ldots, s_n)} \) should be computed. This procedure continues for the higher number of sectionalisers, until in the case of \( n = k \) where the maximum value of \( C_{(s_1, \ldots, s_n)} \) becomes less than the maximum value of \( C_{(s_1, \ldots, s_{n-1})} \). Therefore, the optimal number of sectionalisers is equal to \( k-1 \) and the optimal locations are \( s_1, s_2, \ldots, s_{n-1} \).

**Recloser Installed on the Feeder**

When the sub-transmission circuit breaker does not have the reclosing feature or the recloser relay is not installed, the recloser packages can be utilised. These are composed of a reclosing feature or the recloser relay is not installed, the gained saving can be evaluated in order to compute the gained saving, (5) can be modified as follow:

\[
C_s = k_s (P_s, P_r) - C_R
\]

where: 
- \( C_s \): Gained saving by a recloser installation
- \( C_R \): Cost of a recloser

Sectionalisers should be installed on the downstream network of the recloser location. Therefore, the recloser should be installed on the main feeder and there is no need to check all of the nodes. A reference set can be defined as Recloser Location Set (RLS), which is composed of the main feeder nodes.

**Savings gained by utilising one sectionalis.** When one sectionalis is installed, the gained saving can be evaluated as below:

\[
C_{s,s} = k_s (P_s, P_r, + P_s, P_r) - C_R - C_S
\]

Taking in mind that the sectionaliser must be installed on the downstream network of the recloser, therefore \( r \) must be lower than \( s \). The reference set for \( r \) is RLS and \( s \) is chosen from VSLS in a way that it locates on the downstream network of the recloser installation position.

**Savings gained by utilising multiple sectionalisers.** When there is a multiple use of the sectionalisers on a network (9) should be modified as:

\[
C_{s,s(s_1, \ldots, s_n)} = k_s (P_s, \sum_{i=1}^{s} P_s, P_n) - C_R - n C_S
\]

Here also \( r \) should be lower than \( s \). Reference set for the recloser location is RLS. Similar to the previous case, selection of \( s_1, s_2, \ldots, s_n \) depends on the type of sectionalisers and they are chosen from VSLS and CSLS.

**Optimal number of the Sectionalisers.** The optimum case can be determine by computing the gained saving by installation of a recloser. If it is positive, installation of the sectionalisers should be studied as mentioned before.

**CASE STUDY**

The proposed algorithm has been tested on the test network of [6]. This network topology is normally used in Iranian distribution networks. The network data, including line parameters, line sections length, fault occurrence relative probability and peak loads are presented in [6]. The other parameters are similar to [6]. The cost of non-distributed energy, \( c_s \), is equal to \( 2 \times 10^{-4} \) currency unit. The value of \( k_s \) is therefore equal to 0.125. The cost of a sectionaliser is taken to be $15, and the cost of a recloser is $25.

At first, installation of one sectionalis, or a recloser, on the feeder is considered. When the savings gained by installation of a sectionalis on each node are studied, it can be seen that the saving is negative for most of the nodes, which are mainly related to the twigs. On the other hand, in the case of the nodes belong to VSLS; it can be observed that, in spite of 80% reduction in the computational burden, the result does not change. In both cases optimal installation position is at the line section 119.

Firstly, the case of installation of the recloser in the sub-transmission substation is studied. The optimal locations and the gained savings are presented for up to 8 sectionalisers. Table 1 presents the results for installation of 1 to 8 voltage type sectionalisers. Regarding this table, the highest saving of $233.32 is gained by installation of 6 sectionalisers.
TABLE I- Optimal locations and gained saving of voltage sectionalisers

<table>
<thead>
<tr>
<th>Number of sectionalisers</th>
<th>Optimal installation locations of sectionalisers</th>
<th>Gained saving</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>119</td>
<td>109.41</td>
</tr>
<tr>
<td>2</td>
<td>51 119</td>
<td>176.32</td>
</tr>
<tr>
<td>3</td>
<td>14 51 119</td>
<td>202.22</td>
</tr>
<tr>
<td>4</td>
<td>14 35 51 119</td>
<td>216.88</td>
</tr>
<tr>
<td>5</td>
<td>14 35 51 100 162</td>
<td>229.84</td>
</tr>
<tr>
<td>6</td>
<td>14 35 51 100 135 162</td>
<td>233.32</td>
</tr>
<tr>
<td>7</td>
<td>14 35 51 100 120 135 162</td>
<td>232.55</td>
</tr>
<tr>
<td>8</td>
<td>14 35 52 64 100 120 135 162</td>
<td>224.26</td>
</tr>
</tbody>
</table>

Table II shows the optimal positions and gained savings of installation of 1 to 8 current type sectionalisers. Here, the optimum number of sectionalisers is 7 with a gained saving of $224.54.

TABLE II- Optimal locations and gained saving of current sectionalisers

<table>
<thead>
<tr>
<th>Number of sectionalisers</th>
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</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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</tr>
<tr>
<td>4</td>
<td>14 35 51 119</td>
<td>216.88</td>
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<td>14 35 51 101 119</td>
<td>218.86</td>
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<tr>
<td>6</td>
<td>14 35 51 120 135 162</td>
<td>222.57</td>
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<tr>
<td>7</td>
<td>14 35 51 101 120 135 162</td>
<td>224.54</td>
</tr>
<tr>
<td>8</td>
<td>14 35 52 64 101 120 135 162</td>
<td>216.25</td>
</tr>
</tbody>
</table>

In the case of utilising a recloser package on the feeder, the optimal locations and the gained savings are presented for one recloser and 0 to 7 sectionalisers. Table III presents the results. Here, the highest saving of $209.24 is gained by installing one recloser and 6 sectionalisers.

TABLE III- Optimal locations and gained saving of a recloser and voltage sectionalisers

<table>
<thead>
<tr>
<th>Number of sectionalisers</th>
<th>RIL</th>
<th>Optimal installation locations of sectionalisers</th>
<th>Gained saving</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td>119</td>
<td>224.54</td>
</tr>
<tr>
<td>1</td>
<td>50 119</td>
<td>119</td>
<td>117.17</td>
</tr>
<tr>
<td>2</td>
<td>34 51 119</td>
<td>119</td>
<td>161.79</td>
</tr>
<tr>
<td>3</td>
<td>13 14 51 119</td>
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<td>6</td>
<td>13 14 35 51 100 120 131</td>
<td>119</td>
<td>201.46</td>
</tr>
<tr>
<td>7</td>
<td>13 14 35 51 100 120 135 162</td>
<td>119</td>
<td>193.35</td>
</tr>
</tbody>
</table>

Table IV shows the optimal positions and gained savings of installation of a recloser and up to 7 current type sectionalisers. Here, the optimum number of sectionalisers is 6 with a saving of $201.46.

TABLE III- Optimal locations and gained saving of a recloser and current sectionalisers

<table>
<thead>
<tr>
<th>Number of sectionalisers</th>
<th>RIL</th>
<th>Optimal installation locations of sectionalisers</th>
<th>Gained saving</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td>119</td>
<td>224.54</td>
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<td>1</td>
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<td>13 14 51 119</td>
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<td>13 14 35 51 119</td>
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<tr>
<td>6</td>
<td>13 14 35 51 100 120 131</td>
<td>119</td>
<td>201.46</td>
</tr>
<tr>
<td>7</td>
<td>13 14 35 51 100 120 135 162</td>
<td>119</td>
<td>193.35</td>
</tr>
</tbody>
</table>

The installation location of the recloser would be a question, i.e., where should it be installed, in the sub-transmission substation or along the feeder. This question cannot be answered only by considering NDE. Some other factors should be considered, such as power quality indexes, the imposed stress to the network equipment especially to the power transformer, and the characteristic of the supplied loads via the recloser against the reclosing shuts. Therefore, deciding about where the recloser should be installed cannot be done only by considering non-distributed energy.

CONCLUSION

This paper presents a method for optimum use and location of a recloser and sectionalisers on a distribution feeder. This is done by balancing the non-distributed energy cost against the installation costs of the recloser and sectionalisers. A suitable numbering methodology, which well defines the network topology, is used. Different routines have been developed for voltage type and current type sectionalisers considering installation location of the recloser. The proposed algorithm has been tested on a typical Iranian feeder and the results are presented.

REFERENCES


