OPTIMISED ALLOCATION OF SECTIONALISING SWITCHES AND PROTECTION DEVICES IN DISTRIBUTION NETWORKS BY USING A REACTIVE TABU SEARCH ALGORITHM

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INTRODUCTION

Optimised allocation of sectionalising switches and protection devices in strategic points of the distribution circuits improves the quality of supplied power and the reliability indices of the system. Sectionalising switches and protection devices are allocated in the system during the planning stage. In some cases, due to consumers habits, vulnerability to faults in some regions of the system, type of consumers and load growth, it is necessary to re-allocate some switches and protection devices in order to improve the reliability and the operation network conditions. Switches are allocated in distribution networks to obtain an optimal or optimised operation strategy and make the power supply re-establishment in case of contingency. Allocation of protection devices in distribution systems is related with the reliability and continuity of the power supply, avoiding significant impacts that a fault could have in terms of consumers outage, reducing times for fault location and system re-establishment. Number and types of protection devices to be installed in a particular feeder will depend on the importance of the system, magnitude and type of load, circuit configuration and exposition to risks of different nature that can lead the system to permanent or temporary fault conditions. Alternatives that minimises the number of switches to be manoeuvred should be preferred since the greater the number of manoeuvres, the greater its execution time, and consequently, the greater the consumers interruption time. In general, impact of devices allocation on customers is related to the frequency and duration of an interruption. In this work, an integer mixed non-linear programming model (IMNLP) with real and binary variables for solving the sectionalising switches and protection devices allocation problem, is presented. Constraints considered for the problem reflect technical and economic limitations, such as series protection devices coordination, number of available equipments, importance of the analysed feeder, circuit topology, quality of power supply and physical limitations of the system, among others. For solving this problem it is proposed a dedicated Reactive Tabu Search Algorithm (RTS). Results and optimised strategies for allocating protection devices and switches considering a real-life network restoration, are presented.

MATHEMATICAL MODEL

Mathematical model for protection devices and switches allocation and re-allocation for system restoration, proposed in this work, is obtained by using the concept of non-supplied power and the historical database of permanent and temporary fault indices in the system [4-6]. Protection devices and switches optimised allocation problem, aimed at restoring distribution networks, is formulated in this work as follows:

Minimise \( \{ \text{Switches and Protection Devices Allocation/Re-allocation Fixed Costs} + \text{Non-supplied Power Cost due to the activation of Protection and Fault Isolation} + \text{Restoration Service Cost} \} \)

Subject to

- Kirchhoff's Current Law (Power Flow Equations);
- Flow Capacity in the feeders;
- Substations Capacity;
- Available number of each type of protection device – reclosers and fuses, for allocation;
- Maximum number of devices that can be allocated in series to obtain coordination and selectivity in the protection system;
- Sectors where should be allocated exclusively reclosers due to the importance of the load and/or subject to high indices of temporary faults;
- Sector of the network where loads cannot be subject of reclosing.

This is a combinatorial optimisation problem with a non-linear objective function, not differentiable, including real and integer variables and a set of linear and non-linear constraints.

Objective Function

Objective function of the problem considers the fixed costs due to the allocation and re-allocation of switches and protection devices, and the costs of non-supplied power due to the activation of protection devices and the cost of restoration after isolating a fault. The energy costs of the non supplied energy due to the protection devices activation, are related to the reliability costs of the system due to the protection equipment allocation. Considering the planning context, these costs can be minimised up to a value that justifies and makes adequate the cost benefit rate.

Switches and Protection Devices Allocation and Re-allocation Fixed Costs

Fixed costs are related with the investment for the acquisition and installation of sectionalising switches and/or protection devices. In the case of re-allocation, involved fixed costs are basically due to the re-positioning of switches and/or protection devices. Mathematically, this fixed cost for each feeder \( i \) of the distribution system can be written as follows:
\[ FC_i = \sum_{j \in Q} FC_{P_{jk}} \cdot X_{jk} + \sum_{j \in CH} FC_{C_j} \cdot Y_{j} \] (2)

Where, \( FC_{P_{jk}} \), \( FCC_j \), are, respectively, installation fixed costs of protection device type \( k \) and sectionalising switch at point \( j \); \( Q \), \( CH \) are, respectively, set of points where it is allowed the allocation of protection devices and of sectionalising switches; \( X_{jk}, Y_j \) are, respectively, decision binary variables for allocation of protection devices type \( k \) and sectionalising switches at point \( j \).

Cost of Interruption Due to the Activation of Protection

Automatic reclosers and fuses are aimed at isolating distribution systems permanent faulted sections, and allowing transitory faults to be eliminated without disconnecting loads. To obtain the cost of non-supplied power (\( NSPC \)) function due to the activation of protection system, it is considered the total of connected loads due to temporary (\( \gamma \)) and permanent (\( \lambda \)) faults incidence in the analysed feeder, e.g. one year period.

Let us consider distribution feeder from Fig. 1, which has the possibility of allocating protection devices at any point (main section and laterals). Data referred to installed residential, commercial and industrial loads are available for each section defined by the points where the protection devices are allocated, as well as permanent and temporary fault indices.

\[ A_i = \sum_{j \in \gamma} \gamma_j \cdot X_{jk} \left( \sum_{l=1}^{\gamma} \left[ LR_j + LC_{j_l} + LI_j \right] \prod_{k=1}^{\gamma} \left( 1 - X_{jk} \right) \right) \] (3a)

\[ A'_{\gamma} = \sum_{j \in \lambda} \lambda_j \cdot X_{jk} \left( \sum_{l=1}^{\lambda} \left[ LR_j + LC_{j_l} + LI_j \right] \prod_{k=1}^{\lambda} \left( 1 - X_{jk} \right) \right) \] (3b)

\[ A_\lambda = \sum_{j \in \lambda} \lambda_j \cdot X_{jk} \left( \sum_{l=1}^{\lambda} \left[ LR_j + LC_{j_l} + LI_j \right] \prod_{k=1}^{\lambda} \left( 1 - X_{jk} \right) \right) \] (3c)

\[ A_\gamma = \sum_{j \in \gamma} \gamma_j \cdot X_{jk} \left( \sum_{l=1}^{\gamma} \left[ LR_j + LC_{j_l} + LI_j \right] \prod_{k=1}^{\gamma} \left( 1 - X_{jk} \right) \right) \] (3d)

Where, \( NSPC_i^p \) - non-supplied power cost of feeder \( i \) due to the activation of protection; \( \gamma_p \) number of points for possible allocation of protection devices in the main section; \( \lambda, \gamma \) are permanent and temporary fault rates for point \( i \) (fault/year); \( \lambda_{abc} \) defines the section, point at the section and the device type that can be installed; \( \gamma \) defines the section of the feeder (1 for main section and 2...n for laterals); \( b \) defines the point of section \( \alpha \); \( \epsilon \) defines the device type (1 for three-phase protection device and 2 for single-phase protection device); \( CE \) is the cost of interruption due to the activation of protection; \( NR(i) \) is the number of laterals downstream point \( i \); \( R(\beta) \) is the number of points for possible allocation of protection devices in lateral \( \nu \); \( LR(\nu), LC(\nu), LI(\nu) \) are, respectively, residential, commercial and industrial loads connected at section \( \nu \).

Restoration Service Cost

Considering feeder \( i \) from distribution system shown in Fig. 1, where restoration switches can be allocated at any bus (1, 2, ..., \( N \)), allocate switches at points 1, 2, ..., \( K \). These switches define sections 1, 2, ..., \( L \), that supply power to sets of residential, commercial and industrial loads.

Objective function of the problem consists in performing the switches allocation in order to minimise financial and social restoration costs when a contingency incidence at any section \( l \) occurs. Restoration costs include operational costs and those produced by the interruption of power supply due to network repairing and load re-managing into neighbour feeders [4-6].

Mathematically, the \( NSPC \) for feeder \( i \) of a generic distribution system, shown in Fig. 1, can be formulated as follows:

\[ NSPC_i^{L} = \sum_{I=1}^{L} CAN_I \] (4)

The term \( CAN_I \) for each feeder section \( I \), is composed by the costs of non-supplied power to the consumers of the faulted section \( (CP_I) \), consumers upstream the fault section \( (CM_I) \) and consumers downstream the faulted section \( (CL_I) \), modelled as follows:
Constraints for the switches allocation problem, i.e. feeders capacity limitations, Kirchhoff’s current law, power flow through the lines and voltage profile, are considered through a fast and efficient distribution networks power flow algorithm [1]. Constraints that should be incorporated into the optimised protection devices allocation problem are of technical and economic nature. Constraints of technical nature are related with the protection devices coordination and the system topology (number of devices of the same category in series). Constraints of economical nature are related with the installation and operation costs of devices, type and load importance.

**SOLUTION TECHNIQUE**

Mathematical model (1) is a MINLP problem and for its solution it is proposed a specialised Reactive Tabu Search (RTS) [2]. Particularities of this algorithm are detailed as follows:

**Codification**

Each feeder has \( N \) points for allocating switches and protection devices, and the equipment (for manoeuvring and/or protecting switches) allocated on the feeder is represented by value 1 and non allocated by value 0 (binary representation). Changing the current configuration for the neighbour one, it is necessary to redefine the index of the terms for calculating the objective function.

**Initial Configuration**

For allocating protection and control devices, it is considered a fixed quantity of equipment, which is a function of the installed load, number of consumers, reliability indices studies and socio-economic factors related to the consumers. Equipment is randomly allocated at each section \( j \), for each one of \( i \) feeders of the system (\( i \in 1, I \) is the set of feeders of the system). Candidate points for protection allocation are determined by following some rules based on technicians and engineers’ knowledge from utilities operation and planning areas, such as:

- Recloser or fuse allocation at the beginning of long sections, where the minimum level of short circuit is not enough to sensitive the back protection device.
- Recloser or fuse allocation, for important loads and for whose service continuity must be high, and in case the circuit length downstream these loads is long.
- Recloser allocation at the beginning of lateral that feed loads classified as special or of great importance.
- Recloser allocation at the beginning of laterals that supply power to important loads located in areas subject to high incidence of temporary faults.
Fitness Function

It is used a penalty function for treating the configuration unfeasibility problems.

Neighbourhood Structure and Tabu List

The neighbourhood structure, i.e. the transition of one configuration to another is effectuated by a feeder, maintaining unchanged the quantity of the equipment on the following way:
(a) The first equipment allocated on the current configuration will change the position, the others remain unchanged;
(b) The transition of these equipment is effectuated for the first position of the current configuration that has no equipment allocated, which defines the first neighbourhood of \( N(x) \).
The next transition is effectuated for the second position of the current configuration and thus successively, where every device, one by one, changes for every position of the current configuration that has no equipment allocated. At the end of these transitions it is obtained the set of the neighbour configuration of the current configuration \( N(x) \).

The tabu list preserves the attributes used for generating the visited solutions on a recent past, i.e. on the last transitions to avoid returning to the configurations already visited (cycling phenomenon). For representing the structure of this list, it is used a matrix arrangement, which is updated in each iteration of the tabu search. For analysing the next neighbour configuration it is necessary to verify if this configuration has no forbidden attributes on the list. The attribute adopted in this work is the position of the switch and protection device on the feeder that can be changed simultaneously. The configuration visited during the search and the corresponding numbers of repetition are stored in the memory, in such way that it is possible to verify if there are repetitions of configurations after the last movement be effectuated, and calculate the interval between two visits. The reactive mechanism increases quickly the size of the list when the configurations are being repeated. On the other side, there is a slow mechanism that reduces the size of the list if there are no configuration repetitions after a predefined number of iterations.

Scape Mechanism

This mechanism is implemented by a random proceeding, i.e. when occurring several repeated solutions it is effectuated an allotment among the points of the solutions of the problem under study, trying to change them and therefore to increase the distance between the current solution and the local optimum points that cause the cycling phenomenon.

Stop Criterion

The stop criterion adopted is the maximum number of iterations allowed.

TESTS AND RESULTS

Results are referred to a simulation of a real-life circuit containing 134 buses, as illustrated on Fig. 2. Table I shows the supplying capacity for every feeder used for effectuating the tests and obtaining the results presented. Table II shows the costs of interrupting the electric energy – repair and switching, for each category of consumer [3]. Table III shows the fixed costs of the manoeuvring switches and the protection and control devices. The tests were effectuated in two steps: 1) Protection devices are allocated attending the imposed constraints for each feeder; 2) Protection devices obtained by the optimization algorithm are fixed, and the problem of optimized allocated switches is solved. Reclosers have double objective: to protect and manoeuvre. On the points where are allocated fuses it is not allowed the allocation of manoeuvring switch.

Table I Power Supply Capacity and Installed Load

<table>
<thead>
<tr>
<th>Substation</th>
<th>Power Supply Capacity (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SE</td>
<td>7,000</td>
</tr>
<tr>
<td>SE1</td>
<td>3,000</td>
</tr>
<tr>
<td>SE2</td>
<td>3,000</td>
</tr>
<tr>
<td>SE3</td>
<td>3,000</td>
</tr>
</tbody>
</table>

Table II Repairing (CR) and Switching (CC) Costs, by Category of Consumers

<table>
<thead>
<tr>
<th>Category</th>
<th>CR (4 hours)</th>
<th>CC (1.5 hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
<td>6 (US$/kW)</td>
<td>0.4 (US$/kW)</td>
</tr>
<tr>
<td>Commercial</td>
<td>120 (US$/kW)</td>
<td>60 (US$/kW)</td>
</tr>
<tr>
<td>Industrial</td>
<td>18,544</td>
<td>9.62 (US$/kW)</td>
</tr>
</tbody>
</table>

Table III Control and Protection Equipment Fixed Cost

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Cost in US$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recloser</td>
<td>15,000.00</td>
</tr>
<tr>
<td>Fuse</td>
<td>500.00</td>
</tr>
<tr>
<td>Sectionalising Switch</td>
<td>180.00</td>
</tr>
</tbody>
</table>

The energy supplying interruption cost due to the protection devices performance is 1 US$/kW.

Considered constraints for this feeder are: There are only two available reclosers; Fuses cannot be installed in the main section of the feeder; There is one circuit breaker between buses 1 and 2; Maximum number of series fuses is equal to three; Fuses cannot be allocated upstream the reclosers; Flow capacity of the feeders and reserve capacity of substations should not be violated.
Table IV Best Configurations: Sectionalising switches and Protection Devices Allocation

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Selected Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reclosers</td>
<td>35-36</td>
</tr>
<tr>
<td></td>
<td>47-48</td>
</tr>
<tr>
<td>Manoeuvring</td>
<td>22-23, 35-36, 47-48, 48-61, 78-89, 79-80, 102-103</td>
</tr>
<tr>
<td>Switches</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>CENS (US$/year)</td>
<td>497,324.32</td>
</tr>
</tbody>
</table>

Best configuration found for this circuit, i.e. with the smallest NSPC was in Table IV. Also, it should be observed that in all results a recloser and a sectionalising switch allocation was performed between buses 35-36 and 47-48. In this case, only the recloser is allocated, which has also the protection and switching functions, consequently only is considered the recloser fixed cost.

CONCLUSIONS

In this work, a formulation that considers control and protection devices influence for the improvement of both, quality of power supply service and system reliability indices, was proposed. In the performed tests with the analysed feeder, proposed methodology found good quality solutions that fulfill the imposed constraints.

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