A METHOD BASED ON RECONFIGURATION FOR THE MINIMIZATION OF THE INTERRUPTIONS FREQUENCY IN POWER SUPPLY

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Abstract

The essential attributes of interruptions in the power supply of the consumers are the frequency and the duration. While the durations are predominantly influenced by the electrical network structure and the existent automations, the frequency is powerfully influenced by the functioning schema adopted. For electrical distribution networks working in a radial configuration, the frequency of interruptions may be minimised by the suitable choice of the loop opening points. The authors propose an original method for the minimization of the system average interruption frequency index (SAIFI) in power supply, which contains besides the technological restrictions also the restriction regarding the resistive power loss.

Keywords: reconfiguration, graph theory, minimization of the interruption frequency

1. INTRODUCTION

The reconfiguration of an electrical network consists in modifying the existing configuration by exchanging the functioning links between its elements in order to improve the performances. In general, electrical distribution networks (EDN) works in radial configurations. In this paper, a graph will be associated to an analyzed network: the bus-bars are taken for nodes (sources or consumers) of the graph, while the power lines are considered as branches. By realizing this model, for an EDN with one source, it should be obtained a *minimal tree*. In the same manner, in the case of EDN with more than one source, it should be obtained a *minimal forest* with a number of trees equal to that of source nodes [8].

On the other hand, the criteria used in the reconfiguration may be grouped in two main categories: (a) criteria which must fit in some limits called restrictions; (b) criteria which must be minimized/ maximized (resistive power losses, interruption number in power supply etc.). Therefore, the reconfiguration problem is one of *multi-criteria optimisation*, where the solution is chosen after the evaluation of a group of indexes, named *partial criteria*, which represent multiple purposes. Many solutions for onset the multi-criteria optimisation problems can be found in the literature; among them, a very used one is *the main criteria method* (frequently applied in the EDN reconfiguration problems): the main criterion is chosen, also indicating acceptable values for the other criteria, and they try to solve the problem [4].

The essential attributes of interruptions in the power supply of the consumers are *the frequency* and *the duration*. While *the durations* are predominantly influenced by the electrical network structure and the existent automations, *the frequency* is powerfully influenced by the adopted working scheme; they can be minimised by the suitable choice of the loop opening points [8].

A fault in an electrical distribution network with one source has a different impact upon the consumers depending on the place of the defect and on the existing type of switches:

a) If the electrical distribution network incorporates *switchgears* and/or *switch disconnectors*, any fault will lead to the interruption of the power supply for all the consumers, because the circuit breaker of the injection substation is switching off. Thus, for each consumer, the reliability block diagram will be series and will contain all the power lines of the adopted functioning schema.

b) If the electrical distribution network incorporates *circuit breakers*, the faults will have different consequences for every consumer, as it follows:
- A fault in a power line from the path between consumer and source: the power supply of the consumer will be interrupted, and the power lines of this path form a series reliability block diagram.
- A fault in whatever other power line: the consumer will be supplied (if the protections work properly).

c) If the electrical distribution network incorporates *mixed switches*, the reliability block diagram will be series, different for each consumer; it is composed by elements of the consumer - source path and other incidental elements with *switchgears* and/or *switch disconnectors*.

By associating a graph to the analysed network (with one source), where the branches are taken for *failure rate* of the power lines (λ), it can be confirmed that in case *a)*, in order to *minimize the number of interruptions* in the power supply for each consumer, it is compulsory to obtained a *minimal tree*. In case *b)*, it must be obtained a tree where all source - consumer paths are minimal. In case *c)*, the problem cannot be solved as in case *a)* or *b)*. Based on these comments and on the proper modelling of EDN with more than one source, the authors propose two original algorithms for the minimization of the interruptions in the power supply for electrical distribution networks; these algorithms refer to the cases *a)* and *b)*, and contain not only the technological restrictions, but also the restriction regarding the resistive power loss. These algorithms differ from other well-known reconfiguration methods (such as branch-exchange) and rely on mathematical concepts whose precision and promptitude are already demonstrated.

It must be also specified that the contingencies are simple and the EDN components are independent from the reliability point of view [8].

2. ELECTRICAL DISTRIBUTION NETWORKS WITH ONE SOURCE

In the proposed algorithms, in order to simplify the calculations, the reliability of the source (the reliability of injection substation) will not be taken into consideration because it manifests itself as a constant, no matter the adopted open-looped schema is; thus, the paper will be focussed on the customer network reliability [9].

2.1 Electrical distribution network with switchgears and/or switch disconnectors

If the electrical distribution network incorporates *switchgears* and/or *switch disconnectors* (a common case for Romanian MV and LV networks), any fault will lead to the interruption of the power supply for all the consumers, because the circuit breaker of injection substation is switching off. Thus, for each consumer, the reliability block diagram will be a series one and will contain all the power lines from the adopted working diagram. Figure 1 presents both a typical electrical network (where the adopted loop opening point is between nodes *7* and *8*) and the corresponding reliability block diagram (characterized by the breakdown intensities).

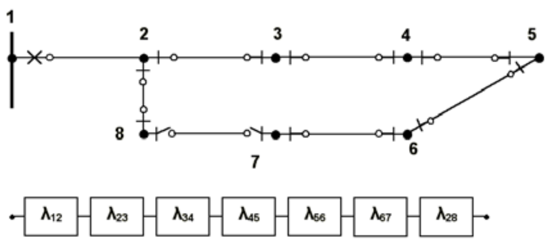

Figure 1. EDN with switchgears and/or switch disconnectors and its coresponding reliability block diagram

The average number of interruptions (faults) in the power supply is provided by [7]:

$$M[v(T)] = (1-Q)\cdot\lambda_e\cdot T \approx \lambda_e\cdot T \qquad (1)$$

where:

Q is the breakdown probability, which in the case of EDN is *0.0009 – 0.0000009*, and therefore can be ignored;

T – the reference period [*year*];

λ_e – the failure rate of the equivalent element to the attached reliability block diagram [$year^{-1}$].

Having in view the fact that *T* is a constant (for example, *1* year) and that the equivalent failure rate is obtained by the algebraic sum of the failure rate of each element belonging to the reliability block diagram, it can be formulated the objective function (OF) as follows:

$$\sum_{(i,j)\in BranchesSet}\lambda_{(i,j)} = MIN \qquad (2)$$

When formulating the problem in this way, we can identify it as a specific one belonging to the graphs theory, namely the determination of a *minimal tree*. To solve this problem, some specific algorithms belonging to the graph theory are well known; among them, Prim, Kruskal and Sollin algorithms [5].

Based on the Prim algorithm, the authors propose an original algorithm (*SIGRECO/1*) for the minimization of the interruptions in the power supply; the suggested algorithm contains not only the technological restrictions but also the restriction regarding the resistive power loss.

***SIGRECO/1* algorithm**

It is given G = (X, U) and the values of its branches:

ΔP = Initial Value; // It represent the accepted resistive power losses, where the Initial Value is initialised with 4%

(a) k=1;

T=∅ ; // the branches set tree

Choose x_k from X; // at the first step, it is chosen the node 1

$S_k = \{x_k\}$; // the nodes set of searched tree

Abandon(i, j) = 0; // the function which contains the information regarding the fulfilled of restrictions by the branch (i, j)

// 0: the restrictions are fulfilled;

// 1: the restrictions are not fulfilled;

// it is initialised with zero for all the graph's branches

(b) **for** *k:=1,n* ***executes***

(b1) **for** *i:=1, k-1* ***executes***

select y_i from X- S_k the adjacent node of x_i so that the branch (x_i, y_i) is minimal from $\omega(X-S_k)\cap\omega(x_i)$ and Abandon(x_i, y_i) = 0;

end_for

If it does not exist, ΔP = ΔP + step { step=1% } and go to (a);

- *chooses among selected branches, branch (x_i, y_i) minimal,*
  $l(x_l, y_l) = \min\{l(x_i, y_i)| i:=1, k-1\}$;
- *for this branch it is calculated the continuous rating;*
- *Are the restrictions fulfilled? If yes, go to step (b2). If not, then Abandon(x_i, y_i) = 1 and go to step (b1)*

(b2) $x_k := y_l$; $S_k := S_k \cup \{x_k\}$; $T := T \cup \{(x_l, y_l)\}$;

end_for.

As at any fault all customers are disconnected (there is only one circuit breaker in the injection substation), the *system average interruption frequency index* (sustained interruptions) can be estimated as [6]:

$$SAIFI = \frac{\text{Total number of customer interruptions (longer than 3 minutes)}}{\text{Total number of customers served}} \quad (3)$$

that is, in our case:

$$SAIFI \approx \frac{(\sum_{i=1}^{n} \lambda_i) \cdot T \cdot k \cdot N}{N} = (\sum_{i=1}^{n} \lambda_i) \cdot T \cdot k, \quad (4)$$

where:

λ_i is the failure rate of power line *i* [*year*$^{-1}$];

n – the number of working power lines of the system;

N - total number of supplied customers;

T – the reference period [*year*];

k – an approximation coefficient (*k ≈ 0.95 for underground lines* and *0.2 for overhead lines*): it estimates the number of sustained interruptions.

By analysing the relationship (4), it can be observed that *T*, *k*, *n* are constants; the minimisation of *SAIFI* is concentrated to the minimisation of $(\sum_{i=1}^{n} \lambda_i)$.

2.2 Electrical distribution network with circuit breakers

If the electrical distribution network integrates *circuit breakers*, the faults will have different consequences for any customer, as it follows:

- A fault in a power line from the path between consumer and source: the power supply of the customer will be interrupted and the power lines of this path form a series reliability block diagram.
- A fault in whatever other power line: the consumer will be supplied (if the protections work precisely).

Figure *2* presents a typical HV (110 kV) Romanian distribution network (with two circuit breakers for each branch) and its associated reliability block diagrams for peripheral customers (the loop opening point is between nodes 6 and 7).

By attaching a graph to the analysed network, a tree where all source – consumer paths are minimal must be obtained. The authors propose (based on a heuristic search method – *best first*) an original algorithm (*SIGRECO/2*) for the minimization of the interruptions in the power supply; the method incorporates, in addition to the technological restrictions, the restriction regarding the resistive power loss [10].

The heuristic method *best first* is recommended for two essential attributes [3]:

- it does not explore the entire solutions space;
- it can not lead to the blockages.

At every step in the exploring process, by using the objective function for all generated nodes, the most promising node is selected; the specific rules are applied for the expansion of the chosen node and the generation of its successors. All these nodes are added to the generated nodes group. Again, the most promising node is selected and the process continues. The strength of this method consists in the way of how the objective function, which gives information concerning the "merits" of each generated node, is defined. Consequently, in the proposed algorithm, the objective function will include the whole path state between the evaluated candidate node and the source node; at each step, the node is added to the corresponding path in such a way that the entire state of the existing network becomes the best.

***SIGRECO/2* algorithm**

a. *it selects the source node (at first, the tree is composed of only a source node);*
b. *it finds all the adjacent nodes to the selected nodes (which already belong to the tree) – the candidate nodes;*
c. *for each candidate node, it determines all the paths to the source node (which contain nodes and branches already included in the tree);*

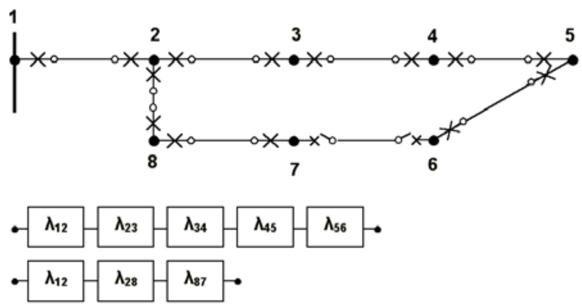

Figure 2. EDN with circuit breakers and and its coresponding reliability block diagrams for peripheral customers (*6* and *7*)

d. *for each path, it verifies that the restrictions are fulfilled;*
e. *if the restrictions are fulfilled by at least one candidate node, it pass on to pint* f*, otherwise, it return to point* b*, where it eliminates, of all the candidate nodes, the last chosen node;*
f. *for each path (that fulfils the restrictions) it estimates its value (the objective function is evaluated);*
g. *it chooses the candidate node and the optimum path (with* λ *minimum equivalent) and introduce it in the tree;*
h. *If there are nodes that are not included in the tree, passes to point* b*, otherwise the algorithm is over.*

The proposed algorithm assures a non-prohibitive performance time (it does not explore the entire solutions space) and it can not lead to blockages (it will always generate a good solution). The result is obtained at the end of a series of optimum decisions; at each step, it is chosen the node and the branch for which, on the entire path (chosen node – source node), the objective function attaints an extreme.

Once the optimal tree was obtained (all source – consumer paths are minimal), the *average number of interruptions in power supply* (relationship *1*) can be calculated for each customer; in the mentioned relationship, λ_e represents the algebraic sum of the failure rate of all branches corresponding to the source – customer path. In this case, the *system average interruption frequency index* is calculated by:

$$SAIFI \approx \frac{\sum_{x=1}^{n} \sum_{i=1}^{PathComponentNumberCustomerX} \lambda_i \cdot T \cdot k}{n} \qquad (5)$$

By analysing the equation (5), we can notice that *T*, *k*, *n* are constants; as a result, the minimisation of *SAIFI* is reduced to minimisation of λ_e for each customer.

3. ELECTRICAL DISTRIBUTION NETWORKS WITH MORE THAN ONE SOURCE

In the case of EDN with more than one source, it should be obtained an *optimal forest* with a number of trees equal to that of source nodes. By proper modelling, the problem can be reduced to obtaining an *optimal tree*.

The proposed modelling is based on "fictive source method" [2] which consists on introducing a fictive source node (FS) linked by real source nodes (S1, S2, S3 – figure3.a) via fictive branches with zero failure rate. For reducing the problem at the case of EDN with one source, authors propose the replacement of FS and real source nodes group (FS, S1, S2, S3 – figure 3.b) by a single *compact fictive source* (CFS). It is important to specify that, in this case, the real source node reliability will be encapsulated in its incidental branch reliability.

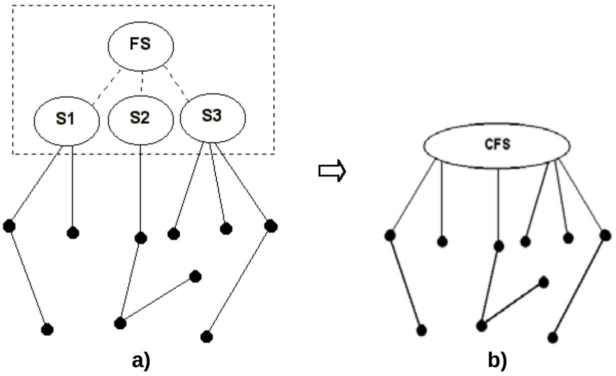

Figure 3. A tree with: a) fictive source (FS); b) compact fictive source (CFS)

By means of this model, the problem is solved in a similar way as the case of EDN with one source. A single exception appears: in the case of EDN with *switchgears* and/or *switch disconnectors*, the number of reliability block diagram is equal to the number of supply feeders (incidental branches). In this case, the algorithm SIGRECO/1 will provide a feasible radial configuration with low SAIFI; the obtained scheme will not necessarily be the best possible solution.

4. APPLICATION

The two algorithms have been implemented in the visual environment programming language *C++ Builder* that, thanks to its graphic interface, ensures an extreme lightness in the use [1]. This software is applied to an electrical distribution network presented in two cases: equipped with *switchgears* (Figure *1*) and equipped with *circuit breakers* (Figure *3*). The load flow is solved with *ascendant – descendant* method [8].

Table 1. Branches' length

Branch	i	j	Length [km]
1	1	2	0
2	2	3	1
3	2	8	1
4	3	4	1
5	4	5	1
6	5	6	1
7	6	7	2
8	7	8	3

The branch lengths are presented in Table 1 and the customers' charges, in Table 2. The longitudinal parameters of electrical lines are considered as follows:

– the specific resistance: *0.751* [*Ω/km*];
– the specific reactance: *0.38* [*Ω/km*];
– the specific failure rate: *0.087* [an^{-1}/km].

Table 2. Customers' charges

i	P [kW]	Q [kVAr]
2	110	92
3	35	5
4	41	12
5	38	15
6	120	7
7	87	20
8	64	10

In the case of EDN with switchgears, the optimal schema of Figure *1* is obtained; the numerical values are:

$M[v(T)] = 0.78$ [interruptions];
$SAIFI = 0.78 \cdot 0.2 = 0.157$;
$\Delta P = 28.7$ [kW] < 6 %.

In the case of EDN with circuit breakers, we obtaine the optimal schema indicated in Figure *3*, where:

$M_2[v(T)] = 0.174$ [interruptions];
$M_3[v(T)] = 0.261$ [interruptions];
$M_4[v(T)] = 0.348$ [interruptions];
$M_5[v(T)] = 0.435$ [interruptions];
$M_6[v(T)] = 0.522$ [interruptions];
$M_7[v(T)] = 0.522$ [interruptions];
$M_8[v(T)] = 0.261$ [interruptions];
$SAIFI = 0.36 \cdot 0.2 = 0.072$;
$\Delta P = 29.4$ [kW] < 6 %.

5. CONCLUSIONS

This paper presents two original algorithms aiming to determine the optimal open-looped points of electrical distribution networks working in radial configurations.

The first algorithm presents the particular case of the EDN with switchgears and/or switch disconnectors. Based on the Prim algorithm, it will always obtain the best solution for EDN with one source; for EDN with multiple sources, the algorithm will provide a feasible radial configuration with low SAIFI, but the obtained scheme will not necessarily be the best possible solution.

The second algorithm is solves the particular case of the EDN with circuit breakers; because the minimal paths between any costumer and source node will be always obtained, the algorithm guarantees a minimal number of interruptions in the power supply for each node of the network.

The algorithms presented in this paper may be combined in order to obtain a general valid method for the optimisation of radial configuration of an EDN with mixed switches.

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