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An Algorithm for Reliability Assessment of Distribution Systems in Presence of Distributed Generators

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Abstract: Techniques able to assess distribution networks reliability have to be adapted to the Smart Grid paradigm that is going to be implemented in real scenarios in the next future. In this perspective, an algorithm for distribution systems reliability assessment in the presence of distributed generators, accounting for islanding operation too, is presented in this paper. The procedures of the algorithm are the core of an analytical method and random/sequential Monte Carlo simulation methods developed by the authors in previous works. These methods are based on two elements: the first one is a generalized systematic approach able to identify the fault effect on a network's node thanks to some topological rules (called "cases") applicable to any radial network; the second one is a technique to faster compute reliability indices by aggregating faulted branches (called "set of branches") and nodes (called "set of nodes"). The paper proposes two automatic and general procedures to identify the cases and the sets, which are useful for implementation of both analytical and Monte Carlo simulation methods.

Keywords: Analytical models, distributed power generation, distribution system reliability, Monte Carlo methods, smart grids.

1. Introduction

The distributed generators (DGs), especially based on renewable energies, are more and more present in distribution networks [1]-[11]. The increasing worldwide concern on environment-friendly and sustainable energy exploitation, and the consequent economical pressure posed by means of economical incentives are the main mechanisms that are driving towards a high penetration of renewable DGs (RDGs) [12]-[14]. Many issues arise from the introduction of DGs in the distribution network: power quality, power flow direction, non-intentional islanding, increased fault currents, protection discoordination, recloses operation, and so on [5]-[9], [13]-[22]. On the other hand, the RDGs will have a chance to support network planning, operation and dispatching [3], [5], [21]-[27] if the aforementioned technical issues are addressed. Furthermore, supplying the load of a distribution network by means of local power generation instead of the one delivered from the main grid during the rush hours could lower energy price [5],[27]-[29].

The possibility of operating in island mode some portions of the distribution network when a fault occurs could be a good opportunity to improve system reliability. In particular, these portions of network could operate disconnected from the main network until the fault is repaired, and the local load is supplied from local DGs. Each network portion could be regarded as an autonomous micro grid in a multi-micro grid distribution network [1], [6], [29]-[35]. In the following, the term “islanding” refers to the option to operate in "island mode" a portion of the distribution system and the term “island” refers to the related autonomous micro grid disconnected from the main distribution system. Obviously, it is necessary to overcome some technical issues to implement such an option such as protection setting, voltage and frequency regulation, resynchronization with the main network [3], [6], [29], [34]-[39]. Furthermore, a proper control and protection scheme has to be implemented [29], [31]-[34], [40]. This is one of the main challenges to be addressed for effective smart grid implementation [8], [29], [32], [41]-[43].

Usually, Monte Carlo simulation (MCS) or analytical methods are used to assess distribution system reliability [44]. MCS methods typically provide information, such as the probability distribution of reliability indices, the best and worst results in terms of reliability

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indices, the number of times a reliability index can exceed a target figure, the probability distribution of annual outages number and cumulative duration that are neglected by the analytical ones [45]. On the other hand, analytical methods are the best ones (from the view point of results precision and time consumption) when the expected values are required [46]. It is worth to note that, the expected values of reliability indices are very important when alternative planning solutions have to be found or operational decisions have to be taken [46]. Many research activities have devoted a great effort to adapt both methods to the new complex scenario described before in order to assess the reliability of smart grids.

In literature, calculation of annual outage rate and duration at the LPs of a network in which islanding is allowed is usually explained by means of practical examples only, derived from specific networks, so that the user must understand by induction the effect of a fault and, consequently, the underlying rules [47]-[57]. Indeed, some papers provide rules to be applied [58]-[63], but they are affected by one or more of the following limitations: the scenarios accounting for islanding and/or circuit breakers (CBs) and/or sectionalizes along the distribution network are neglected, islanding is permitted in some portions of the distribution network only, sufficient details to properly apply the method accounting for islanding are not given, the fluctuating behavior of the primary energy source (wind, sun) and, consequently, the variable power output from some RDGs is neglected, the validity of the method is not extended to all radial networks.

The authors proposed in [64] a generalized systematic approach to evaluate distribution system reliability in Smart Grids where islanding improves network reliability, accounting for multi-micro grid network paradigm implementation. Its main benefits with respect to literature are to overcome the aforementioned limitations and to provide simple topological rules (called “Cases”) to identify fault effect on a LP, and such rules are applicable to any radial network. In [64] the analytical expressions related to each Case when islanding is permitted and not permitted have been also provided. Moreover, a Probability of Adequacy (PoA) of the island’s DGs has been defined and formulated. PoA is a measure of the ability of DGs to meet the local load and it is able to account for both annual and hourly models of LPs and DGs, and for both load curtailment and shedding policies [65]. In [66] a way to combine the random and sequential MCS (RMCS, SCMS) methods with the systematic approach, and a strategy to reduce the time consumption of both the overall methods (systematic approach plus RMCS or SCMS) have been proposed.

Finally, a way to faster compute reliability indices has been exploited by considering set of LPs, called "set of nodes" (SON, a node is a bus where LPs and/or DGs are connected), and "set of branches" (SOB, a branch is the electrical equipment’s connecting two nodes). Regardless the method (analytical, RMCS or SMCS) one wishes to apply in order to assess power system reliability, a procedure to determine the relative position among the PS, the SONs, the SOBs, the switches and the DGs in the network, and a procedure to aggregate each SON and SOB is necessary to make automatic reliability assessment. Therefore, the paper proposes two automatic and general procedures to identify the Cases and the sets, which are useful for implementation of both analytical and MCS methods. It is worth to note that, these procedures are fundamental for a factual application of the systematic approach in order to benefit from its advantages as well as from the related analytical formulation [64] and improved MCS methods [66].

2. Power System Reliability

A. Distribution reliability indices

Many reliability indices, such as System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), Customer Average Interruption Duration Index (CAIDI), Average Service Availability Index (ASAI) can be foreseen by means of the LPs' outage rate and duration [44].

$$SAIFI = \frac{\sum_{i=1}^{N_{LP}} N_{C,i}\ \lambda_i}{\sum_{i=1}^{N_{LP}} N_i} \tag{1}$$

$$SAIDI = \frac{\sum_{i=1}^{N_{LP}} N_{C,i}\ U_i}{\sum_{i=1}^{N_{LP}} N_i} \tag{2}$$

$$CAIDI = \frac{\sum_{i=1}^{N_{LP}} N_{C,i}\ U_i}{\sum_{i=1}^{N_{LP}} N_{C,i}\ \lambda_i} \tag{3}$$

$$\begin{aligned} ASAI &= 1 - \frac{SAIDI}{8760} \qquad non-leap\ year \\ ASAI &= 1 - \frac{SAIDI}{8784} \qquad leap\ year \end{aligned} \tag{4}$$

$$\lambda_i = \sum_{k=1}^{N_B} \lambda_{i,k} \tag{5}$$

$$U_i = \sum_{k=1}^{N_B} U_{i,k} \tag{6}$$

where:

i load point (LP) identification number (*id*), equal to the number of the node at which the load is connected

k branch identification number (*id*)

λ_i LP i annual outage rate (number of outages/year)

U_i LP i annual outage duration (sum of the outages time/year)

$\lambda_{i,k}$ LP i annual outage rate due to a fault in branch k

$U_{i,k}$LP i annual outage duration due to a fault in branch k

N_B number of branches in the network

N_{LP} number of LPs in the network

$N_{C,I}$ number of customers connected at the i-th LP.

Therefore, it is necessary to assess the parameters $\lambda_{i,k}$ and $U_{i,k}$ to foresee the aforementioned reliability indices. As said before, the systematic approach described in [64] is able to identify the effect on an LP due to a fault in a generic distribution network by means of simple topological rules, by knowing:

- The relative position among the primary substation (PS), the LP, the fault, the switches and the DGs in the network;
- The types of switches and DGs;
- The power demand and the capacity, respectively, of the LPs and DGs in the island which the LP belongs to.

In the following, radial networks are considered only. Moreover, if a point A (that is the location of a node or a branch or a switch) is located along the path between a point B and the PS, then A is said “upstream” from B and B is said “downstream” from A. Finally, the branches are numbered sequentially and each node takes the number of the upstream-connected branch.

B. *Cases definition*

In the following $\rho_{A,x}$ stands for Probability of Adequacy (PoA) [64], [65] of the DGs in island x (x also indicates the switch whose opening gives rise to the island). It is be noticed that the greater the PoA of the DGs in an island, the lower the probability the local load is left unsupplied during islanding. It is assumed that a sectionalize is always installed where a CB is placed (in the following the set of CB and sectionalize, taken as a whole, is called CBS). The only switches placed in the network are CBSs and sectionalizes.

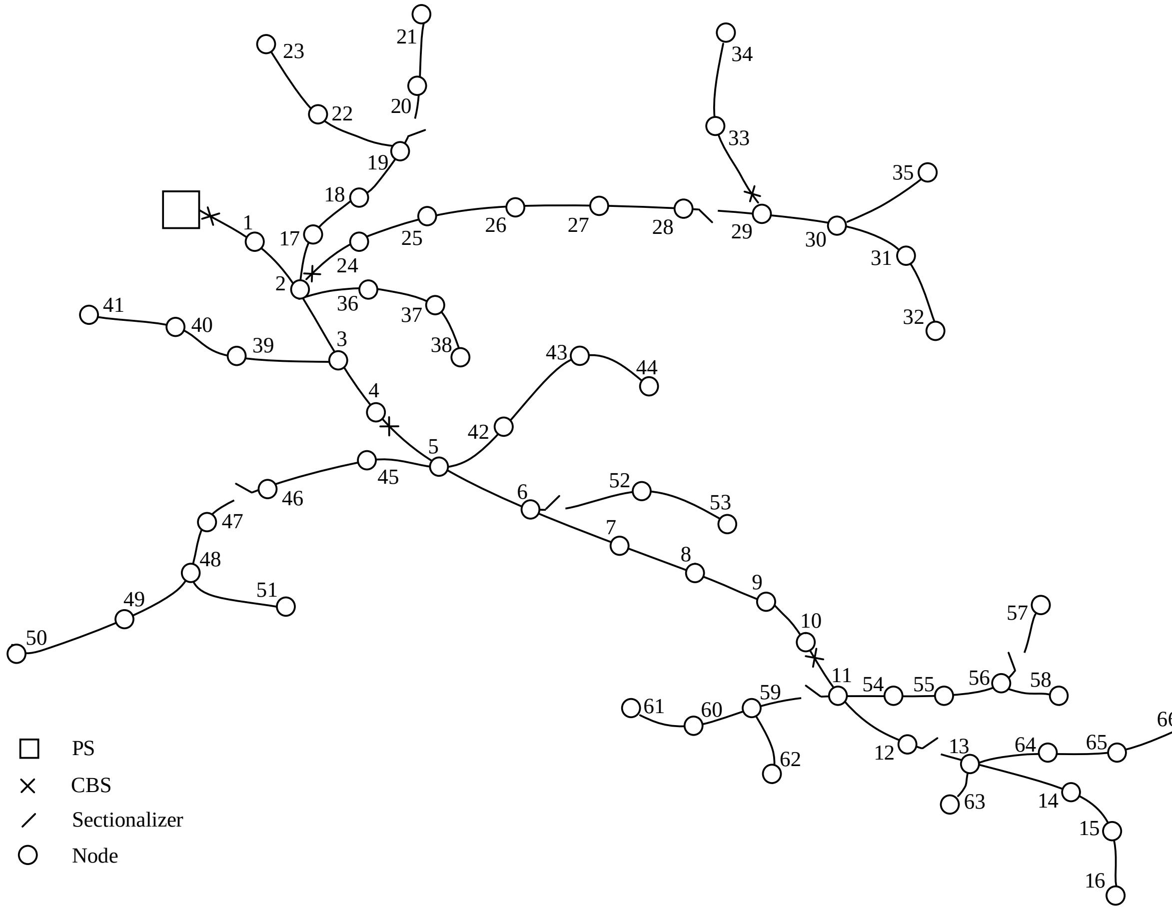

Figure 1. An example of radial distribution system

For the sake of completeness, in this section, the Cases described in [64] are briefly reported.

Case 1

No switch is installed between faulted branch k and LP i.

E.g. i=42 and k=8 in Figure1.

Fault effect both when islanding is permitted and not

The LP is left unsupplied until the fault is repaired.

Case 2

- At least one CBS j is installed between faulted branch k and LP i.
- CBS j is not placed between the PS and i.

E.g. i=42, k=55, j=11 in Figure1.

Fault effect both when islanding is permitted and not

The fault does not affect the LP.

Case 3

- One or more CBSs are installed between faulted branch *k* and LP *i*, (the CBS closest to *k* among them is called *j*);
- each of them is placed between the PS and *i*.
- No sectionalize is installed between *j* and *k*.

E.g. *i*=42, *k*=40, *j*=5 in Figure1.

Fault effect when islanding is not permitted

The LP is left unsupplied until the fault is repaired.

Fault effect when islanding is permitted

A mean portion of the LP, proportional to 1-$\rho_{A,j}$, is left unsupplied until the fault is repaired, while the remaining portion is not affected by the fault.

Case 3.1

- One or more CBSs are installed between faulted branch *k* and LP *i*, (the CBS closest to *k* among them is called *j*);
- each of them is placed between the PS and *i*.
- One or more sectionalizes are installed between *j* and *k*, (the sectionalize closest to *k* among them is called *sc*);
- each of them is placed between *j* and the PS.

E.g. *i*=34, *k*=26, *j*=33, *sc*=29 in Figure1.

Fault effect when islanding is not permitted

The LP is left unsupplied until the fault is repaired.

Fault effect when islanding is permitted

The effect is similar to Case 3. The difference is that the mean portion of the LP left unsupplied depends firstly on the PoA of the island due to CBS *j* opening, then on the island due to sectionalize *sc* opening.

Case 3.2

- One or more CBSs are installed between faulted branch *k* and LP *i*, (the CBS closest to *k* among them is called *j*);
- each of them is placed between the PS and *i*.
- At least one sectionalize *sc* is installed between *j* and *k*.
- Sectionalize *sc* is not placed between *j* and the PS.

E.g. *i*=42, *k*=21, *j*=5 and *sc*=20 in Figure1.

Fault effect when islanding is not permitted

The LP is left unsupplied until the fault is isolated (that is sectionalize *sc* switching time).

Fauteffect when islanding is permitted

A mean portion of the LP, proportional to 1-$\rho_{A,j}$, is left unsupplied until the fault is isolated (that is sectionalize *sc* switching time), while the remaining portion is not affected by the fault.

Case 4

- No CBS is installed between faulted branch *k* and LP *i*.
- At least one sectionalize *j* is installed between *k* and *i*.
- Sectionalize *j* is not placed between the PS and *i*.

E.g. *i*=42, *k*=53, *j*=52 in Figure1.

Fault effect both when islanding is permitted and not

The LP is left unsupplied until the fault is isolated (that is sectionalizer *j* switching time).

Case 5

- No CBS is installed between faulted branch *k* and LP *i*.
- One or more sectionalizes are installed between *k* and *i* (the sectionalize closest to *k* among them is called *j*);
- each of them is placed between the PS and *i*.

E.g. *i*=31, *k*=26, *j*=29 in Figure1.

Fault effect when islanding is not permitted

The LP is left unsupplied until the fault is repaired.

Fault effect when islanding is permitted

A mean portion of the LP, proportional to 1-$\rho_{A,j}$, is left unsupplied until the fault is repaired, whereas the remaining portion is left unsupplied until the fault is isolated (that is sectionalize *sc* switching time) and the local DGs is available again ($t_{AV,j}$).

C. Analytical Formulation

Table 1 reports the equations to be applied to compute $\lambda_{i,k}$ and $U_{i,k}$ when islanding is permitted and not permitted [64]. A PoA equal to zero is equivalent to "islanding not permitted"; in fact the equations in column two and three in the table are equal to each other when PoA is zero. In Table 1:

j is the switch installation branch (j also indicates the island created after opening the switch in j); where both j and sc appear, the former identifies a CBS, the latter a sectionalize;

f_k branch k failure rate (number of faults/year, which looks like to a failure frequency [66]);

$t_{S,j}$ switching time of sectionalized installed in j;

$t_{R,k}$ branch k repair time.

Tabel 1. Contribution of faulted branch *k* on LP *i*'s annual outage rate and duration, when islanding is permitted and not permitted.

Case	Islanding not permitted	Islanding permitted
1	$\lambda_{i,k} = f_k$ $U_{i,k} = f_k\, t_{R,k}$	$\lambda_{i,k} = f_k$ $U_{i,k} = f_k\, t_{R,k}$
2	$\lambda_{i,k} = 0$ $U_{i,k} = 0$	$\lambda_{i,k} = 0$ $U_{i,k} = 0$
3	$\lambda_{i,k} = f_k$ $U_{i,k} = f_k\, t_{R,k}$	$\lambda_{i,k} = f_k\left(1-\rho_{A,j}\right)$ $U_{i,k} = f_k\left(1-\rho_{A,j}\right)t_{R,k}$
3.1	$\lambda_{i,k} = f_k$ $U_{i,k} = f_k\, t_{R,k}$	$\lambda_{i,k} = f_k\left[\left(1-\rho_{A,j}\right)+\rho_{A,j}\left(1-\rho_{A,sc}\right)\right]$ $U_{i,k} = f_k\begin{bmatrix}\left(1-\rho_{A,j}\right)\left(t_{S,sc}+t_{AV,sc}\right)+\\ \left(1-\rho_{A,sc}\right)\left(t_{R,k}-t_{S,sc}-t_{AV,sc}\right)\end{bmatrix}$
3.2	$\lambda_{i,k} = f_k$ $U_{i,k} = f_k\, t_{S,sc}$	$\lambda_{i,k} = f_k\left(1-\rho_{A,j}\right)$ $U_{i,k} = f_k\left(1-\rho_{A,j}\right)t_{S,sc}$
4	$\lambda_{i,k} = f_k$ $U_{i,k} = f_k\, t_{S,j}$	$\lambda_{i,k} = f_k$ $U_{i,k} = f_k\, t_{S,j}$
5	$\lambda_{i,k} = f_k$ $U_{i,k} = f_k\, t_{R,k}$	$\lambda_{i,k} = f_k$ $U_{i,k} = f_k\begin{bmatrix}t_{S,j}+t_{AV,j}+\\ \left(1-\rho_{A,j}\right)\left(t_{R,k}-t_{S,j}-t_{AV,j}\right)\end{bmatrix}$

D. MCS

RMCS and SMCS can be applied to evaluate $\lambda_{i,k}$ and $U_{i,k}$ by appropriately using random numbers and the cases described before. RMCS is applied to the distribution system reliability analysis by considering a fault probability (ρ_{AF}) for each branch [66].

Then, a random number $x\in[0;1]$ is generated and:

$$\begin{array}{lcl} 0 \le x < \rho_{AF,k} & \Rightarrow & branch\,k\,is\ faulted \\ \rho_{AF,k} \le x \le 1 & \Rightarrow & branch\,k\,is\,not\ faulted \end{array} \qquad (7)$$

In the first case (the random number is less than the fault probability), it is assumed that the fault occurs and the switches closest to the fault open. A time to repair (*ttr*$_k$), a time to switch (*tts*), and a time to be available (*tta*) are, respectively, computed for branch *k*, for each opened sectionalized, for the DGs of the islands created by some of such opened sectionalizes. Furthermore, a random number in the interval [0;1] is computed for each island, in order to compare this value with the PoA of the island DGs. When the random number lower than the PoA, the LP is considered as "not supplied". Afterwards, the systematic approach enables to identify the fault effect on each LP and consequently to update the LP reliability indices. This procedure is repeated N_{RMCS} times for each branch, and finally the indices average value is calculated [66].

SMCS works on a simulation period of size T. Firstly, a time counter is set to 0. Thereafter, at each simulation step, the same quantities considered for RMCS and a time to fault (ttf_k) for branch *k* are computed, then the systematic approach is applied to each LP to correctly identify the effect the fault has on it. The time counter is updated at the end of the simulation step by summing the time to fault and the time to repair of the faulted branch. When the time counter exceeds T, the average values of $\lambda_{i,k}$ and $U_{i,k}$ are computed for each LP. This procedure is performed for each branch so as to obtain the average values λ_i and U_i related to each LP. It is worth to note that this procedure enables to take into account the effect of adding various kinds of switches at any time while the simulation runs, thanks to the systematic approach used for case's identification.

3. Set of Branches and Nodes

A. Definition and assessment

A set of branches (SOB) affecting in the same way the reliability of a given LP can be considered as an equivalent branch. In detail, the N_{Bj} branches located between switch *j* and the switches placed downstream from *j* belong to SOB *j* (see Figure2). An equivalent branch failure rate (f_{SOBj}) and repair time ($t_{R,SOBj}$) for SOB *j* is obtained by summing, respectively, the branch failure rate and the normalized repair time of its branches. The normalized repair time of a branch belonging to SOB *j* is computed by multiplying the failure rate by the repair time of the branch, and, then, by dividing the result by the equivalent branch failure rate of *j*. Therefore:

$$f_{SOBj} = \sum_{k=1}^{N_{Bj}} f_k \tag{8}$$

$$t_{R,SOBj} = \frac{\sum_{k=1}^{N_{Bj}} f_k \, t_{R,k}}{f_{SOBj}} \tag{9}$$

Similarly, the set of N_{Nj} nodes, located between switch *j* and the switches placed downstream from it, is defined as set of nodes (SON) *j* (see Figure2). An equivalent number of customers for SON *j* ($N_{C,SONj}$) is obtained by summing the number of customers of its nodes (a node without customers is considered as a LP with $N_{C,i}$ equal to zero).

$$N_{C,SONj} = \sum_{i=1}^{N_{Nj}} N_{C,i} \tag{10}$$

A SOB affects each LP belonging to a SON in the same way, that is all LPs within the same reliability zone have the same annual outage rate and duration [62].

Obviously, the use of SONs and SOBs instead of LPs and branches, does not change the value of the system reliability indices, but it drastically reduces their computation time. Therefore, a procedure able to identify them is very important.

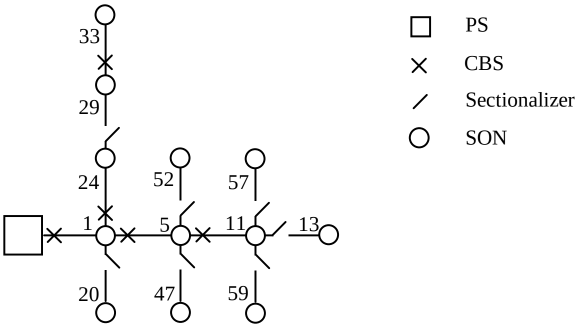

Figure 2. Network equivalent to the one depicted in Figure1 considering SOBs and SONs instead of branches and nodes to reduce the computational time.

B. Identification procedure

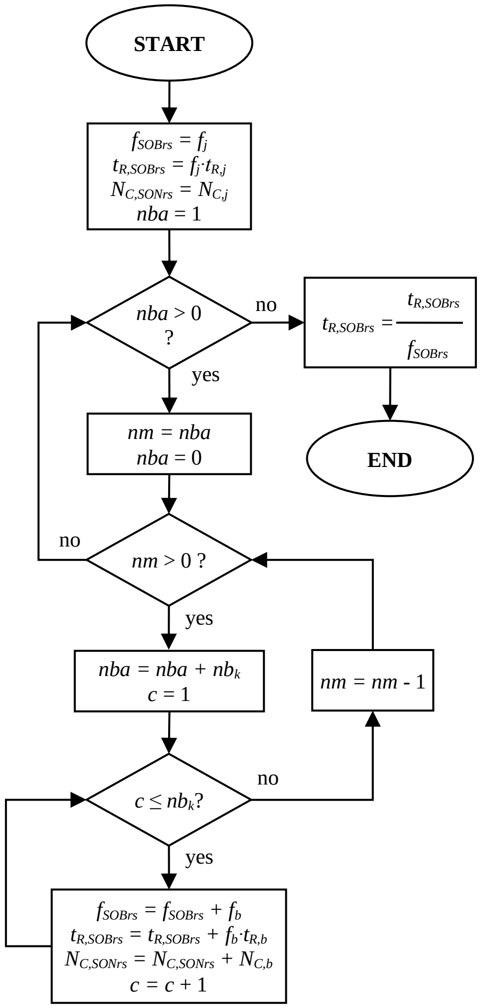

Figure 3. An example of block diagram to identify the SOBs.

In a radial network, the number of SONs is equal to the number of SOBs. Moreover, SON *j* and SOB *j* are strictly related to each other, because when a node belongs to SON *j*, the branch connected upstream from the node belongs to SOB *j* (in the following such node and branch are, respectively, referred to as "related node" and "related branch"). Then, identifying the nodes belonging to a SON implies identifying the branches belonging to a SOB and vice versa. In the following, a procedure to identify a SOB and to evaluate its equivalent branch failure rate and duration is described. Starting from the identified SOB, the equivalent number of customers of the related SON is evaluated by summing the number of customers connected to the ending node of each branch belonging to the SOB.

The number of SOBs in a radial network is equal to the number of switches, and a SOB is associated to each switch (in the following referred to as "related switch"). Therefore, the following criteria can be applied to find the branches which belong to a specific SOB *rs*, where *rs* is the related switch, and *j* is the identification number of the branch in which it is installed. The procedure starts (step 0) by assigning branch *j* and node *j* to SOB *rs* and SON *rs*, respectively. Then the following steps are recursively repeated:

1) For each branch *k* added to the SOB at the previous step the related node *k* is "marked";
2) For each "marked" node *k*, each branch *b* ($\neq k$) connected to node *k* is assigned to SOB *rs*, provided that no switch is installed in *b*, and the related node is assigned to SON *rs*.

The procedure stops when no additional branch is assigned to the SOB at step 2 for all marked nodes. Figure3 shows an example of block diagram based on the proposed procedure, which is useful to identify SOB and SON, in order to calculate the equivalent branch failure rate and repair time for a SOB as well as the equivalent number of customers for a SON.

In figure 3:
nba number of branches added at the previous step;
nm number of marked nodes whose branches are not assigned yet;
k identifier of the *nm*-th marked node whose branches have been added to the SOB at the previous step;
nb_k number of branches, connected to node *k*, without any switch installed, minus one (that is branch *k*);
b identifier of the *c*-th branch among the nb_k branches.

4. Fast method to identify the cases

The use of SONs and SOBs instead of LPs and branches entails that a switch is installed in each branch of the equivalent reduced network (Figure2). Moreover, in a radial network, considering a SOB *k* and a SON *i* ($i\neq k$), the SOB can be located:

A. Downstream from the SON;
B. Upstream from the SON;
C. Elsewhere.

Two cases have to be considered in configuration A: case 2 and 4. Case 2 occurs when one or more CBSs are installed between the SON and the SOB (e.g., *i*=5, *k*=11 and CBS=11 in Figure2), otherwise, when no CBS is installed in that position, but one or more sectionalizes are installed between the SON and the SOB (e.g., *i*=5, *k*=52 and sectionalize=52 in Figure2), case 4 occurs.

Three cases have to be considered in configuration B: case 3, 3.1 and 5. Case 3 occurs when one or more CBSs are installed between the SON and the SOB, and no sectionalize is installed between the SOB and the CBS closest to it (e.g., *i*=5, *k*=1 and CBS=5 in Figure2). Case 3.1 occurs when one or more sectionalizes are installed between the SOB and the CBS (e.g., *i*=33, *k*=24, CBS=33 and sectionalize 29 in Figure2). Finally, case 5 occurs when between the SON and the SOB one or more sectionalizes only are installed (e.g., *i*=47, *k*=5 and sectionalize=47 in figure 2).

When the SOB is not located downstream or upstream from the SON (configuration C), three cases have to be considered: case 2, 4 and 3.2. Considering a SON *i*, a SON *k*, and the paths from the PS to them, the last common node (starting from the PS) belonging to both paths is called "fork node" of *i* and *k*, and it is referred to as $FN_{i,k}$. Case 2 occurs when at least one CBS is installed between SOB *k* and the $FN_{i,k}$ (e.g., *i*=13, *k*=29, CBS=24 and $FN_{13,29}$=1 in

Figure 2). By construction of the equivalent reduced network, if no CBS is installed in that position, than there is at least one sectionalize.

As a consequence, case 3.2 occurs when at least one CBS is installed between SON *i* and the $FN_{i,k}$ (e.g., *i*=13, *k*=47, CBS=11, sectionalize=47 and $FN_{13,47}$=5 in Figure2); otherwise, case 4 occurs (e.g., *i*=13, *k*=59, sectionalize=59 and $FN_{13,59}$=11 in Figure2).

It is worth to note that:

- FN ≡ node *i* ⇔ configuration A;
- FN ≡ node *k* ⇔ configuration B.

On account of these remarks the block diagram of case identification is constructed and shown in Figure4, where “a-b-c ?” stands for “Is b placed between a and c ?”, and "S" indicates a sectionalize.

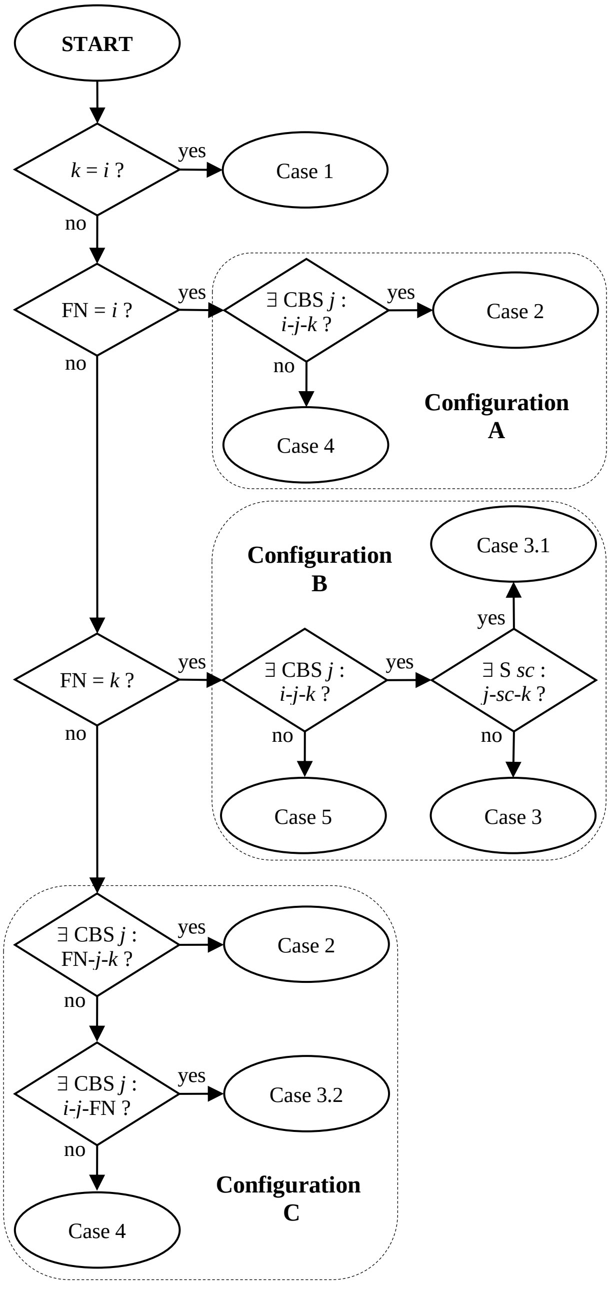

Figure 4. An example of block diagram to cases identification.

5. Conclusion and Future Work

This paper has described two automatic and general procedures that are the core of the considered analytical and MCS methods able to assess distribution networks reliability, also accounting for islanding. The main benefits of these procedures are to provide a fast way to compute reliability and to lay the foundations for a future software implementation. In this perspective the way of representing the network, as well as the data structure applied to store network's information, will be very important for the implementation of an automated computer-based reliability assessment tool. Therefore, in a future work an efficient network representation and data structure will be investigated to lead up to an effective implementation of the proposed procedures in order to develop a free code for expediting the reliability analysis carried out by means of analytical and MCS methods.

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