INDIRECT MONTE CARLO APPROACH TO EVALUATE RELIABILITY AND AVAILABILITY INDICES OF DISTRIBUTION NETWORKS

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ABSTRACT

The proposed work regards the reliability and availability assessment of repairable distribution systems by a Monte Carlo simulation approach. The main idea is to build a model to simulate the stochastic behaviour of an electric distribution system in which the components have both faulty and operational states. The possibility of restoration is also considered. The simulation is performed via an indirect Monte Carlo approach. From several simulations of the stochastic behaviour of the distribution system, the relevant performance indices regarding the system are estimated. The proposed simulation model is applied to some examples of distribution schemes.

1. INTRODUCTION

The reliability and availability evaluation of electric power systems has been subject of various publications [1, 2]. In this paper, a consolidated Monte Carlo method [2, 3, 4, 5] is adopted to estimate the reliability and availability indices of an electric distribution system. The main idea is to model the real stochastic behaviour of the electric system, considering components with both faulty and operational states, with the possibility of restoration after a fault and functional links. The estimated indices quantify the unavailability of the power supply to each load, thus providing the basis for evaluating necessary improvements to the reliability of the system, which can be achieved by modifying the components, or by introducing a new solution schemes.

2. THE MODEL

A graph structure is introduced to represent the topology of the electric system: every component whose stochastic behaviour is characterized by a failure and a repair rate is represented by a node: feeders, busses, circuit breakers, transformers and loads are nodes. (Note that the term load denotes the set of all components connected to a MV/LV transformer). Every node is described by its type, its connections with other nodes, its functional states and the corresponding transition rates, its initial functional state (before a stochastic transition) and its current functional state entered after a transition. For simplicity, but without loss of generality, the transition rates between the states of each node are assumed constant. The rated power of transformers and lines, along with the power needed by each load, is considered. Load busses are characterized by their class of importance. The set of the nodes of the graph is divided into two subsets according to the following rule: every node of a subset has the same functional states, even if it represents a different component. In particular, the subset named "LOG" groups the circuit breakers, the tie breakers and the disconnectors. These components may be in one of the following states:

- normal operating state (NOS), i.e. the component is closed and is able to open;
- faulty closed state (FCS), i.e. the component is closed and is not able to open;
- faulty operating state (FOS), i.e. the component is failed and has to be isolated from the system;
- standby state (SBS), i.e. the component is open and is able to close;
- faulty standby state (FSS), i.e. the component is open and is not able to close.

The subset named "ELE" is made by feeders, busses, transformers and loads: they are characterized by the following states:

- normal operating state (NOS), i.e. the component is working;
- faulty operating state (FOS), i.e. the component is faulted and has to be isolated from the system;
- standby state (SBS), i.e. the component is inactive but can be switched on if required.

For the sake of simplicity, only one faulty state is considered in this paper, even if there is the possibility to distinguish a one-phase faulty state from a three-phase faulty state for each component. A multi-phase fault is considered, as the problem of unwanted trips is more frequent for this case.

The theory of the "transport of the states of a system" [3, 4] is embraced to describe the stochastic life of an electric system. The system state at a given time *t* is represented by an integer variable *k*. Thus $\Omega \equiv (k, t)$ represents the system stochastic evolution in time as a random walk trajectory (figure 1).

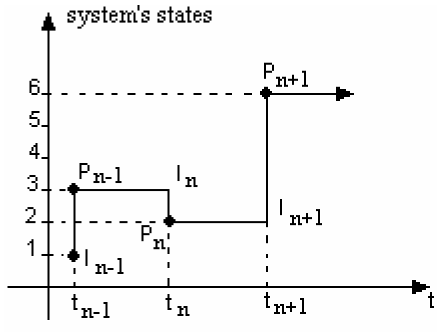

Figure 1 – Random walk trajectory

The realisation of a trajectory of the electric system is simulated through the indirect Monte Carlo approach. In general, one trial (history) of a Monte Carlo simulation based on the theory of the transport of the system states consists in generating a random walk which guides the system from one configuration to another, at different times. During a trial, starting from a given system configuration *k'* at *t'*, we need to determine when the next transition occurs and which is the new configuration reached by the system as a consequence of the transition. This can be done in two ways which give rise to the so-called "indirect" and "direct" Monte Carlo approaches [3, 4].

The former is the one here adopted and consists in sampling first the time *t* of a system transition from the corresponding conditional probability density $T(t|t',k')$ of the system performing at time *t* one of its possible transitions out of *k'* entered at the previous transition at time *t'*. Then, the transition to the new configuration *k* actually occurring is sampled from the conditional probability $T(k|t,k')$ that the system enters the new state *k* given that a transition has occurred at *t* starting from the system in state *k'*. The procedure then repeats from *k* at time *t* to the next transition. The trial simulation then proceeds through the various transitions from one system configuration to another up to the mission time T_M. When the system enters a failed configuration, tallies are appropriately collected for the unreliability and instantaneous unavailability estimates (at the discrete times $t_j \in [0, T_M]$ in which the mission time has been subdivided), i.e:

- when the system at time τ fails for the first time in the trial, a one is added to the unreliability counter $C^R(t_j)$, $t_j \in [\tau, T_M]$;
- each time τ_{in} the system enters a failed configuration during the trial, a one is added to the unavailability counter $C^A(t_j)$, $t_j \in [\tau_{in}, \tau_{out}]$, τ_{in} and τ_{out} being the times at which the system enters and leaves the failed configuration, respectively.

After performing a large number of trials M, we can obtain estimates of the system unreliability and instantaneous unavailability by simply dividing by M and by the time interval Δt the accumulated contents of the respective counters $C^R(t_j)$ and $C^A(t_j)$, $t_j \in [0, T_M]$.

During the network operation, after a fault, it is important to re-configure the system by isolating the faulty component and restoring the power supply to each load, if possible. In the proposed simulation model, this is obtained by placing in the SBS particular nodes belonging to the LOG subsystem. If "I" is the set of these particular nodes, the state of nodes belonging to "I" will not be modified until the component will be restored. A possible strategy for the reconfiguration of the network is to maximize the amount of power supplied to the loads, while respecting the power limits of components.

When a node is restored (i.e. brought to a NOS), it is important to introduce a process that feeds again this node, modifying to NOS particular nodes of the set "I", if possible. All the operations associated to the network reconfiguration after a faulty event or after a restoration are expected to be completed within the sample time: if a transition occurs at time t_i, the network topology is changed and the new configuration is supposed to be fully operative at time $t_i + 1$.

During every iteration the counters of reliability and availability of power supply of each load are updated, based on the existence of a path between a feeder and load node at least.

Another important aspect related to some components belonging to the LOG group is selectivity, which improves the reliability and availability of the system. Total selectivity is considered as default condition of the relays equipping circuit breaker.

3. MODEL VALIDATION

The validation of the simulation procedure is performed by a comparison between estimates of reliability obtained by a Monte Carlo simulation and the results obtained by an analytical process (DBA) [6]. The system in figure 2 is considered. The transformer is the only component which can change state:

- rate of transition to FOS from NOS: $1.05 \cdot 10^{-4}$ [h^{-1}];
- rate of transition to NOS from FOS: $1.04 \cdot 10^{-2}$ [h^{-1}].

The mission time T_M is 10^4 hours, with resolution of an hour.

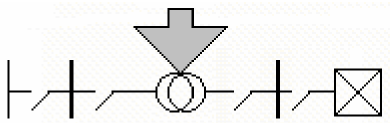

Figure 2 – System adopted for validation

The comparison between the availability calculated analytically (straight line) and the estimated one (dashed line) is presented in figure 3 and 4, with 10^3 and 10^5 Monte Carlo histories respectively.

The standard deviation for the estimated values with error-bar is also reported [3].

The figures clearly show that the Monte Carlo indirect method so far developed estimates the reliability of the load with a good approximation: in particular the more histories are considered, the more precise is the approximation.

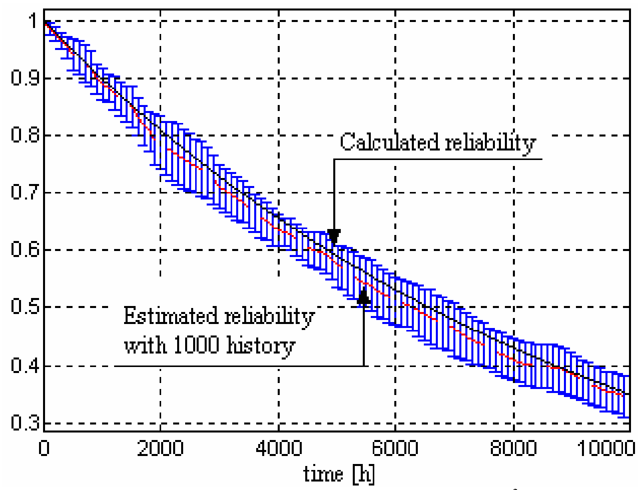

Figure 3 – Estimated and calculated reliability with 10^3 histories

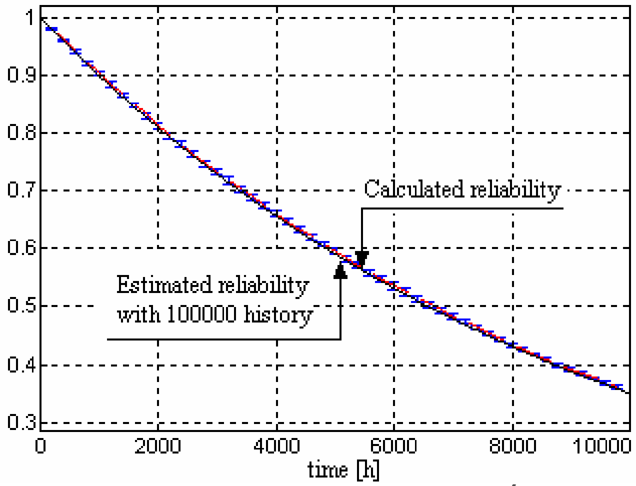

Figure 4 – Estimated and calculated reliability with 10^5 histories

4. TESTS AND RESULTS

The proposed model is applied in order to analyze the performance of different distribution schemes.
In section 4.1 and 4.2 a simple radial distribution scheme is considered: in particular the ideal configuration where every line is protected with a circuit breaker is analyzed in section 4.1, while in section 4.2 different solutions using only 2 circuit breakers on the feeder are presented. In 4.3 a radial distribution scheme with possibility of back-feed is taken into account.

4.1 Ideal scheme with circuit breakers

The adopted scheme is presented in figure 5: all the switchers (11, 16, 21, 26) are supposed to be circuit breakers.

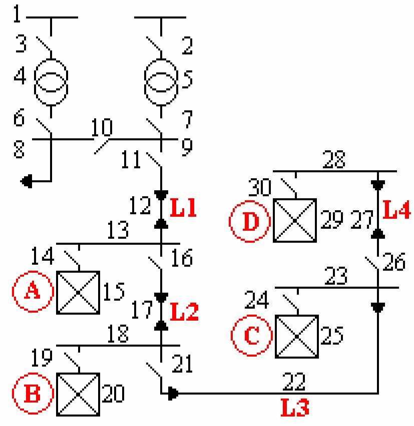

Figure 5 – Radial distribution scheme

Table 1 contains the relevant data for all the components.

TABLE 1 – Relevant data for case 1

Component	A [MVA]
Feeder	40
Transformer	60
Load A	2
Load B	3
Load C	7
Load D	4

Line	length (km)
L1	2
L2	5
L3	10
L4	6

The rates of transition of the components adopted in this simulation are reported in table 2 [7, 8, 9]. The HV systems are assumed absolutely reliable for simplicity (no fault is simulated in bus 1). The distribution feeder is connected to a substation bus. This bus is connected (in normal condition) to the transformer 5, but can be connected to the transformer 4 through the tie breaker 10 (its initial functional state is SBS) in case of failure of the transformer 5
The tie breaker is moved to NOS only if the circuit breaker 6 or 7 is in SBS or FSS; this is an example of functional links between components of the system.

TABLE 2 – Transition rates

From	to	c.b. MV[h^{-1}]	Trans.[h^{-1}]	Line [km/h^{1}]	Discon.
NOS	FCS	3.6e-8	x	x	3.6e-9
NOS	FOS	4.9e-7	3.00e-6	2.3e-5	4.9e-8
FCS	NOS	0.23	x	x	0.023
FCS	FOS	4.9e-7	x	x	4.9e-8
FOS	NOS	0.23	0.23	0.46	0.023
SBS	FSS	3.6e-8	x	x	3.6e-9
FSS	NOS	0.23	x	x	0.023

Figure 6 reports the reliability of the loads A and D evaluated using $8 \cdot 10^3$ Monte Carlo histories and T_M of $2 \cdot 10^4$ hours with resolution of an hour (sample time).

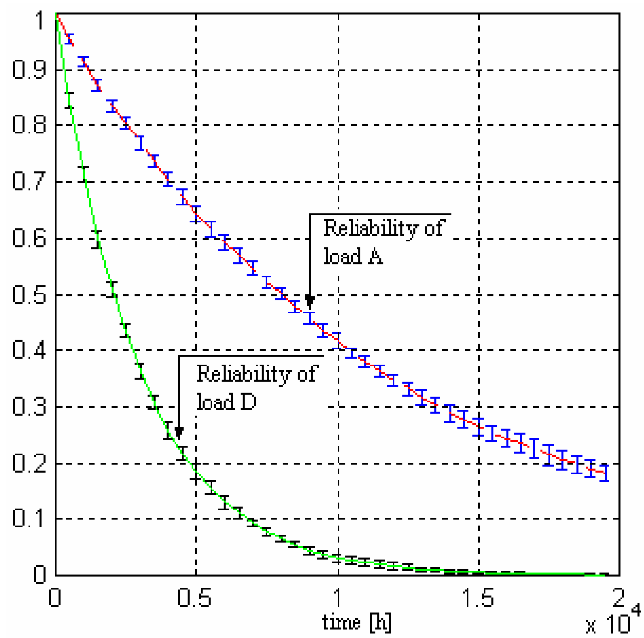

Figure 6 – Reliability for load A and load D in case 1

The reliability of power supply of load D is less than the one of load A. The resulting values, that can be easily confirmed by using an analytical approach, are valid under the hypothesis of complete selectivity of circuit breakers.
In table 3 the average availability of power supply of each load in case of complete selectivity of circuit breakers and time of transition to NOS of tie breaker 10 less than an hour is presented.

TABLE 3 – Average availability for case 1

Load	Rated pwr [kVA]	Available pwr [kVA]	Available pwr [%]
A	2000	1999.6	99.98
B	3000	2998.9	99.96
C	7000	6996.3	99.94
D	4000	3997.2	99.92

In particular the average number of times in which the tie breaker is moved to NOS to improve the availability of power supply of the distribution feeder is 0,0575 times for history. Table 4 reports the number of hours in which power supply is on nominal path and the number of hours in which the tie breaker is in NOS.

TABLE 4 – Supply paths for case 1

Load	Pwr supplied on nominal path [h]	Pwr supplied with tie breaker NOS [h]	Power not supplied [h]
A	19998,70	0,16	1,14
B	19995,30	0,16	4,54
C	19991,80	0,16	8,4
D	19988,30	0,16	11,54

It is important to remark that selective relaying of circuit breakers in a MV system for multi-phase faults is not straightforward; this is due to the relatively small impedance of MV lines (especially for MV cables of large cross section used in urban distribution).
In such cases, the short circuit currents do not vary significantly from the beginning to the end of the feeder, making very tricky the selection of the faulted section based on the fault current value.
If, for example, the circuit breaker 11 is not selective for the 30 percent of trips of the circuit breaker 16, the number of instantaneous interruption of power to the load 15 increases; on the contrary its average availability is not influenced by the lack of selectivity: in fact, the circuit breaker 11 is expected to be reclosed within an hour, thus the load 15 is normally fed within the sample time.

4.2 Real configurations with at least 2 circuit breakers

Generally the distribution system is characterized by only one circuit breaker on the beginning of the feeder: the relevant relay is aimed at protecting the whole feeder. Using the distribution scheme in figure 5 for the analysis, only the switcher 11 is a circuit breaker while 16, 21 and 26 are disconnectors. The average availability of power supply to each load is presented in table 5, column 2 (case 1a): the power supply of all loads is influenced by a fault on the feeder because of the trip of circuit breaker 11.
The optimal placement of a second circuit breaker, along with the relevant improvement of average availability, is evaluated by using the developed Monte Carlo model. In table 5, column 3 (case 1b), the average availability of power supply if the second circuit breaker is placed in 16 is presented. Column 4 (case 1c) is related to the placement of the second circuit breaker in 21; column 5 (case 1d) shows the average availability if 11 and 26 are circuit breakers.

TABLE 5 – Average availability with two circuit breakers

Load	Available power [kVA]			
	case 1a	case 1b	case 1c	case 1d
A	1996.6	1996.8	1996.8	1996.7
B	2995.0	2995.0	2995.1	2995.1
C	6988.7	6988.7	6988.7	6989.0
D	3993.7	3993.7	3993.7	3993.7
total	15974.0	15974.2	15974.3	15974.5

4.3 Back feed configuration

The distribution feeder in figure 7 is also considered. In this scheme there is the same radial distribution feeder of figure 5, with the possibility of back-feed using tie breakers connected to a nearby radial distribution feeder. It is the case of normally open ring, a solution that is commonly used to improve the availability of power supply.
This scheme usually occurs in urban areas, where the high density of load gives the possibility of putting in place "cross links" (line 54) between distribution feeders connected to different HV/MV stations The number of components of each distribution feeder is higher than those of the previous example. The case in which 23 and 24 are circuit breakers is presented (this case can be easily compared with the case 1a presented in section 4.2).

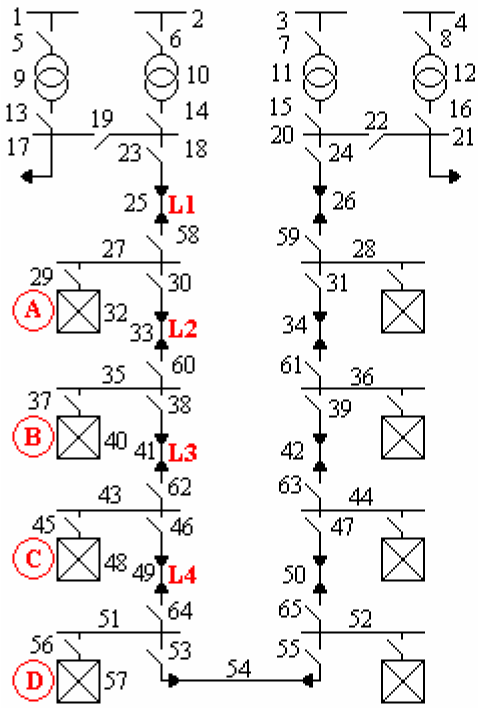

Figure 7 – Normally open ring scheme

The values of reliability and availability of power supply are estimated using $8 \cdot 10^3$ Monte Carlo histories and T_M of $2 \cdot 10^4$ hours. The estimated reliability functions are different from case 1a because of the presence of more disconnectors. The values of available power to each load are bigger than case 1a radial distribution feeder because of the presence of tie breakers at the end of each radial feeder. Table 6 presents the available power supply to each load under the hypothesis of time of switching to NOS of tie breakers less than an hour. The average power for each load does not vary between the first and the last nodes of each feeder: this is the main difference from the previous distribution scheme. The results give a quantitative indication about the real improvement of availability and availability .

TABLE 6 – Average availability with back feed

Load	Rated A [kVA]	Available A [kVA]	Available A [%]
A	2000	1998.9	99.94
B	3000	2998.4	99.95
C	7000	6996.1	99.94
D	4000	3996.4	99.92

In table 7 the number of times in which the tie breakers 36 and 38 go to NOS because of a fault of a component is presented. This information allows to consider a further penalty given by a switching time more than an hour.
The numbers of hour of unavailability of power supply are presented in table 8.

TABLE 7 – No. of switching

Tie breaker	Number of switching for history
36	6.93
38	6.93

TABLE 8 – unavailability

Load	Unavailability [h]
A	2.86
B	2.93
C	2.95
D	3.02

The quantification of unavailability of power supply is traduced in term of a cost. In particular considering the cost of new solutions and the cost in Euro/MWh of power not supplied it is possible to compare the presented solutions by a technical/economical point of view.

CONCLUSIONS & FUTURE WORK

Quantitative information related to the reliability and availability of power supply to each load of a network system, is the base for technical-economical comparisons between different distribution schemes.
An analytical approach to the problem is not exhaustive in many real cases:

- if the number of components of the system in study is high;
- if there are functional links between components;
- if the real behaviour of components has to be accounted for (e.g., if the selectivity of relaying is considered, which in turn depends on the type and severity of fault);
- if the switching time of the breakers is to be taken into account.

On the contrary, the Monte Carlo method allows to consider in a simple way components with multiple states, and allows to introduce time-dependent rates of transition and to manage functional links and restoration events.
In this paper a methodology for the quantification of the reliability and availability of power supply of loads is presented. A simulation is performed via an indirect Monte Carlo approach: random state changes are generated at random times and specific algorithms are used to update correspondingly the configuration of the system after fault or restoration events according to the power rating of transformers and circuit breakers.
The mean number of hours in which a load is powered by the preferred path is estimated, along with the mean number of state modifications for each component following each event on the system (typically, fault events) and the mean percent availability of electric power to loads. Using the proposed simulation model, a comparison of different distribution schemes is performed, and a quantitative evaluation of the availability improvement (mean and referred to each load) is given.
The future work will regard the study of the reliability and availability of existing electric distribution systems, comparing the Monte Carlo technique and analytical methods. The aim is to propose different solutions that improve the reliability and availability of the system under analysis, considering, performing a complete technical/economical analysis.
The future work will be also aimed at defining indicators to consider real times of operation of tie breakers and circuit breakers.

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