CIEM 2009 Conference, Bucharest, November 12-14, 2009

IMPACT OF THE FUEL CELLS INTEGRATION INTO ELECTRIC DISTRIBUTION NETWORKS FOR END-USE CONSUMERS

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This work is aimed at making a comprehensive evaluation of the probability density functions (PDFs) of a set of reliability indices applied to electricity distribution systems with distributed generation (fuel cells) – including frequency and duration of interruptions, power and energy not supplied. By considering the number of occurrences and duration of the interruptions as random variables (RVs), the indices become RVs and are evaluated through analytical expressions for computing their expected values and variances and with the Monte Carlo method in order to obtain the PDFs.

Keywords: electric networks, distributed generation, fuel cell, Monte Carlo

1. Introduction

The modular power generation systems are becoming more and more some real profitable solutions for customers growing demands on power in a decentralized way. The mitigation of increased pollution levels from classical generation systems, the increasing number of software and technical solutions available on the market and, especially, an one way attitude towards strong incentives for using renewable sources are the main reasons for the success of the so-called distributed power generation. The well-known properties of the well established distribution systems (undirectionality of power flows; decreasing voltage profiles along the feeders), are no longer fully available when a certain amount of distributed generation is present.

Although the heart of a fuel cell is simple, a fuel cell system for use in combined heat and power applications is complex. There are two main reasons:

- First, until the hydrogen economy becomes a reality, the hydrogen delivered to the fuel cell needs to be extracted from a fossil fuel, typically natural gas or propane. A fuel processor is required for this purpose.
- Secondly, as with other CHP(Combined Heat and Power) devices the system needs to be designed to make use of the surplus heat generated from the reformer and from the fuel cell itself. A PEM (Polymer Electrolyte Membrane) fuel cell operates around 80ºC while the reformer generates 120ºC. Typically the electrical efficiency of the fuel cell system is around 35%. In other words, for every kilowatt of electricity generated there are around two kilowatts of heat.

A summary of benefits and limitations of fuel cells is shown in **Table 1**. It points out the existing types of fuel cells, and their main features.

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Table 1:

Benefits and limitations of fuel cells technology

Benefits	**Limitations**
• increases energy efficiency	• substantial initial investment
• reduces energy costs	• financial returns vary according to price of electricity and fuels
• reduces green house gas emissions	
• stabilizes energy costs	

The aspects which are discussed in the paper include solutions and strategies adopted for performing an efficient voltage control, the integration of local generation in the distribution systems, a reliable evaluation of distribution system losses and the choice of adequate techniques for their reduction, and the role of distributed generation to provide reserve services or perform wheeling in competitive electricity markets.

For a distribution system with K load points, the reliability analysis takes into account two types of indices (*local* and *global*)[1]:

The aim of this section is to introduce methods for calculating the analytical expressions of expected value and variance of the reliability indices, their PDFs and Cumulative Distribution Functions (CDFs).

For a better understanding of the purpose of the system analysis, we consider several parameters some of which are constant and deterministic (load power), or constant but associated to an exponential distribution (failure rate) or probabilistic, as RVs, as shown in Table 2

Table 2

Nature of the distribution system variables

	Constant	Probabilistic
Load power (P)	**X**	
Failure Rate (λ)	**X**	
Restoration Time ($\boldsymbol{\tau}$)		**X**
Number of Occurrences of Fault (**n**)		**X**

Also, we consider the distribution system with K load points during a given time interval $[0,T]$. We introduce a set Θ of the faults occurring in the distribution system and the sets Φ_k of the faults for which load point k is not supplied, for $k = 1,\ldots,K$. A fault $f \in \Theta$ may require different phases of fault diagnosis and system restoration. Three types of faults are considered:

1. faults at the *supply nodes*, concerning the high voltage (HV) system, with a single restoration phase, due to the operations occurring on the HV system;
2. *temporary* faults in the distribution system, with trip of the circuit breaker, successful re-closure and final normal operation, again with single restoration phase;
3. *permanent* faults, requiring three different restoration phases after the trip of the circuit breaker:
    a) remote –controlled operations, driven from the control center, to isolate the fault and restore the operation in the non-faulted part of the system;

b) additional manual operations, performed by the maintenance operators to isolate the fault and restore the operation in the non-faulted part of the system;
c) on-site repair of the fault and final service restoration.

We assume that faults are independent random events, with negligible probability of simultaneous faults.

2. Reliability indices

For calculating the reliability indices, it is essential to know the PDF of $\boldsymbol{\tau}$, because we must utilize the convolution without constraints. This boundary restrains the freedom of choosing PDFs, in particularly at Normal (Gaussian) and Gamma (only if they have the same scale factor).

2.1 Definition of the reliability indices

In this work, we consider the following reliability indices, defined for the time interval $[0,T]$[3]:

- The ***total duration of the interruptions***, represented by the RVs $\mathbf{d}_k$ at load point k and $\mathbf{d}$ for the whole system;
- The ***total energy not supplied***, represented by the RVs $\mathbf{w}_k$ at load point k and $\mathbf{w}$ for the whole system;
- ***The Frequency of fault occurrence*** f_k;
- ***The Power not supplied*** (P^{NS}).

We also assume that the power delivered to load point k to be P_k during normal operation. For $k = 1,\ldots,K$, the classical reliability indices are then expressed in terms of the expected values of the RVs $\mathbf{d}_k$ and $\mathbf{w}_k$. For the *local indices*, we consider the expected value $E\{\mathbf{d}_k\}$ of the duration of the interruptions and the expected value $E\{\mathbf{w}_k\}=C_k\, E\{\mathbf{d}_k\}$ of the energy not supplied to load point k. The probability of the event "load point k is not supplied at a generic instant" is given by $E\{\mathbf{d}_k\}/T$. G*lobal indices*, which depend on the whole network can be build by computing a weighted average of the load point indices, using as weights the numbers of customers or the power supplied to the load points in normal conditions.

2.2 Expected value of the interruption duration at load point k

The occurrence of a fault leads to a sequence of mutually exclusive fault states. Each fault state corresponds to a restoration phase, with remote-controlled or manual operations performed for restoring the service. By neglecting the simultaneous faults, it is possible to compute the duration of the service interruption during the restoration phases for any load point. We assume the service restoration after a fault $f\in\Theta$ to include a number φ_f of independent restoration phases.

The expected value $E\{\mathbf{d}_k\}$ of the duration of the service interruption during the restoration phases at load point k is computed by considering all the restoration phases in which load point k is not supplied. We introduce the binary variable $\delta_{kf}^{(m)}=1$ if load point k is not supplied in the phase m of service restoration after the fault $f\in\Theta$, otherwise $\delta_{kf}^{(m)}=0$ [3]. Assuming a negligible probability of simultaneous faults, in the restoration phase m =

$1,\dots,\varphi_f$ after fault $f \in \Theta$ with failure rate λ_f, corresponding to the restoration time $\boldsymbol{\tau}_f^{(m)}$, the expected value of the duration of the interruption is

$$E\{\mathbf{d}_\mathrm{k}\} = \sum_{f\in\Theta}\sum_{m=1}^{\varphi_f} \lambda_f \, E\{\,\tau_f^{(m)}\,\}\,\delta_{kf}^{(m)}$$

In the presence of permanent faults with multi-phase restoration, it is convenient to evaluate, for each fault $f \in \Theta$ and for all the load points $k = 1,\dots,K$, the binary variable $\delta_{kf}^{(m)}$ introduced by the fault, for m=1,…, φ_f. For each fault at a supply node, with a single restoration phase (φ_f =1), the variable $\delta_{kf}^{(1)}$ is equal to unity for the load points fed by the faulted supply node, zero otherwise. For each *temporary fault*, the trip of the circuit breaker isolates all the load points fed by the faulted branch, there is again a single restoration phase (φ_f =1) and the variable $\delta_{kf}^{(1)}$ is equal to unity for the load point fed by the faulted branch, zero otherwise. For each permanent fault, with three restoration phases (m = 1,2,3), the value of $\delta_{kf}^{(m)}$ depends on the restoration phase:

- in the first phase, $\delta_{kf}^{(1)}$=1 if load point k is not supplied after the trip of the circuit breaker, otherwise $\delta_{kf}^{(1)}$=0;
- in the second phase, $\delta_{kf}^{(2)}$=1 if load point k is not supplied after the remote-controlled operations, otherwise $\delta_{kf}^{(2)}$=0;
- in the third phase, $\delta_{kf}^{(3)}$=1 if load point k is not supplied after the manual operations, otherwise $\delta_{kf}^{(3)}$=0.

For any permanent fault, the evaluation of $\delta_{kf}^{(m)}$ for m = 2,3 requires the detailed simulation of the operators performed to isolate the fault and to restore service. For this reason, we choose the backward/forward sweep analysis method (which will be presented in the next chapter).

Table 3**:**

Evaluation of possible fault types and corresponding load point indices

Type of Fault	φ_f	m	$\delta_{kf}^{(m)}$		Explanation
Supply point	1	1	$\delta_{kf}^{(1)}$	1	Fed by the faulted branch
				0	Otherwise
Temporary	1	1	$\delta_{kf}^{(1)}$	1	Fed by the faulted branch
				0	Otherwise
Permanent	3	1	$\delta_{kf}^{(1)}$	1	Load point k is not supplied after the trip of the circuit breaker
				0	Otherwise
		2	$\delta_{kf}^{(2)}$	1	Load point k is not supplied after the remote-controlled operations
				0	Otherwise
		3	$\delta_{kf}^{(3)}$	1	Load point k is not supplied after the manual operations
				0	Otherwise

3. Distribution system structure and analysis

For performing calculations as close as possible to the reality, we thought to generate a radial electrical distribution network which includes all the elements existing in a real electrical distribution network:

- Circuit breakers;
- Disconnects:
  - Remotely commanded;
  - Manually commanded
- Loads
- Branches (lines or transformers)

3.1 Network structure and definitions

The following criterion is assumed for node and line numbering:

- The nodes are numbered sequentially in ascending order proceeding from layer to layer (**Figure 1**), in such a way that any path from the root node to a terminal node encounters node numbers in ascending order;
- Each branch starts from the sending bus (at the root side) and is identified by the number of its (unique) ending bus.

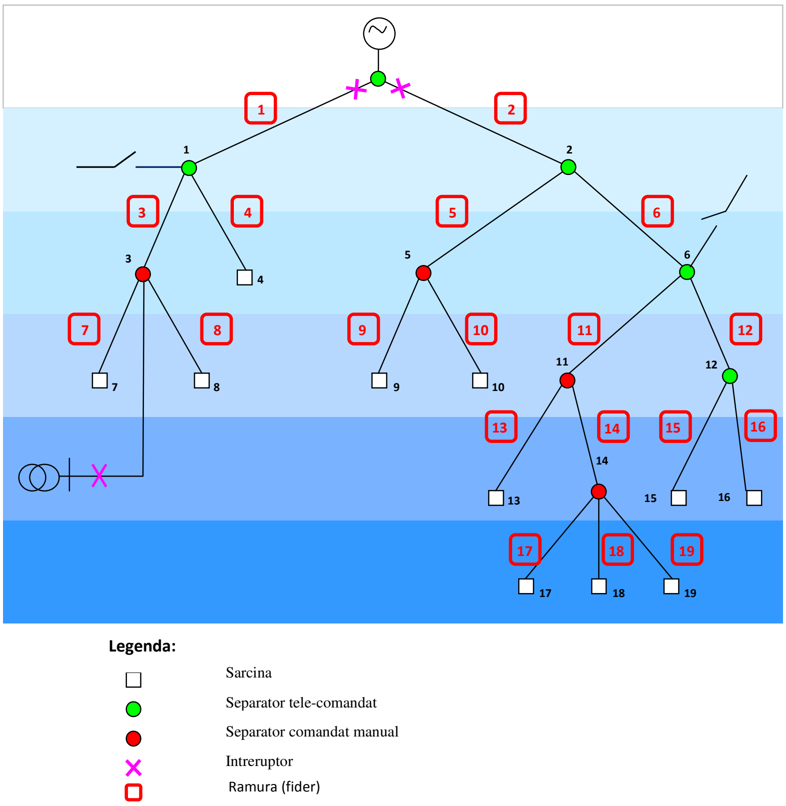

Figure 1: Layer-based representation of the tested electrical network

So, it was implemented an algorithm which identifies a network and its mutually coupling between branches (**L** matrix) and further on, identifies the **Γ** matrix [4]. Its next attribute is to compute the power not supplied for temporary faults at each branch by varying m from $\delta_{kf}^{(m)}$ (**Table 3**).

4. Application of the Monte Carlo Method

4.2 The sequential Monte Carlo method

The sequential MCM [7] has been used to address the reliability indices computation. Typically, the number of faults involving a single load point is not very high, so that the load points indices exhibit unusual forms with possible multi-modal shapes. In these cases, the MCM is particularly used. Therefore, some load point indices have been computed. Global indices are less interesting for the MCM method application, since the presence at several load points make these indices very close to the Normal form.

In order to achieve this goal, a Matlab program has been implemented.

The program is structured to run in steps, facilitating the interventions required for any modifications, also providing a better level of understanding of the algorithm.

Step 1: Read data of the electrical network matrix, composed of sending nodes, receiving nodes, type of each node (0-rigid; 1-circuit breaker; 2-remote controlled disconnect; 3-manual controlled disconnect), failure rate (λ) for each node for temporary faults, λ for each node for permanent faults, restoration time ($\boldsymbol{\tau}$) for temporary faults and $\boldsymbol{\tau}$ for permanent faults; also the restoration times for Gamma-distributed temporary and permanent faults (min/year) (shape factor and scale factor) are established; the step concludes with the initialization of the indices (as permanent failure rate and temporary failure rate), and the number of years for the analysis (in our case, 10 years).

Step 2: Initialization of the parameters required for Monte Carlo (MC) simulations. There are the boundary values which delimit the acceptable values of MC simulation. Also there are the range of the classes utilized to realize MC histograms, whose limits are also determined in function of Power Not Supplied (PNS), for which two a priori values for each level were chosen and the number of classes inside the range min-max

Step 3: For a single load point a series of routines are executed to calculate:

- The Power Not Supplied (PNS),
- The Outage Time,
- Number of Interruptions,
- The Energy Not Supplied (ENS)
-

Step 4: Extraction of the incidence matrix Gamma out of the test-network

Step5: An external cycle for MC calculation is generated, composed of the following subroutines:

- Creation of the random temporary fault profile;
- Creation of the random permanent fault profile;
- Another cycle is initialized for computing the reliability indices:
    - Location of the temporary faults;
    - Computation of PNS TotalInterrTime, NumberInterr, ENS for temporary faults at each branch;
    - Location of the permanent faults;
    - Computation of the PNS, TotalInterrTime, NumberInterr, ENS for permanent faults at each branch,
    - Computation of MC histograms for PNS, TotalInterrTime, NumberInterr and ENS.

The data used in the program was structured, for more convenience, into a two-dimension array, having number of rows equal with number of nodes of the test-network and number of columns equal with the number of indices needed for our iterations. In our case, the columns were formed by: *ending nodes* (of the test-network), *receiving nodes*, *type of receiving node* (**0**-rigid; **1**-circuit breaker; **2**-remote controlled disconnect; **3**-manual controlled disconnect), *load* (in p.u.), *failure rate for each node for temporary faults* and *failure rate for each node for permanent faults.*

In order to further clarify the program output, a table containing principal indices of the network has been realized (Tables 4-6). It shows the variables (PNS, Interrupted Time, Number of Interruptions and ENS), differentiated upon the left (***L***) and right (***R***) part of the test-network. It is obvious that the step number is the same for all (25 steps), but appears a difference between minimum values (PNS and ENS) from left side and the right side of the test-network.

Table 4

Values for program variables, depending on the positioning on the network (L = Left; R = Right)

Variable	**Network side**	**Min**	**Step**	**N° of steps**
PNS	**L**	10	1.6	25
	R	50	2	25
Interruption Time	***L***	100	130.2	25
	R	100	130.2	25
Number of Interruptions	**L**	0	4.18	25
	R	0	4.18	25
ENS	***L***	0	110	25
	R	0	220	25

Table 5

Results of Monte Carlo simulation of the test-network with Matlab program

Variable	Side of test-network	**50000 Iterations**			**25000 Iterations**		
		Expected Value	Variance	Standard deviation	Expected Value	Variance	Standard deviation
Number of Interruptions	***L***	27.7	630	25.1	23.3	437	20.9
	R	77.1	4941	70.3	72.8	4563	67.5
Interruption Time [min]	***L***	664.9	664910	815.4	741.9	769965	877.4
	R	1136.1	1389866	1178.9	1131.5	1312599	1145.6
PNS [p.u.$_{MW}$]	***L***	25.6	629	25.1	27.1	712	26.7
	R	71.1	4770	69.1	126.8	4268	65.3
ENS [p.u.$_{MW}$ h]	***L***	575.1	472067	687.1	569.5	7916910	2813.7
	R	1169.3	1525242	1235.1	1316.7	2480102	1574.8

Table 6

Analytical values and comparison with the MCM results

Variable		**LEFT**			**RIGHT**		
Type of computation		Analytical	MCM		Analytical	MCM	
			25000 [iterations]	50000 [iterations]		25000 [iterations]	50000 [iterations]
Number of Interruptions		27.5	23.3	27.7	77	72.8	77.1
PNS[p.u.$_{MW}$]		27.5	27.1	25.6	77	126.8	71.1
Interruption Time[hours]	*Permanent*	25			70		
	Temporary	4.2	12.4	11.1	11.7		
	TOTAL	29.2			81.7	18.9	18.9
ENS[p.u.$_{MW}$ h]	*Permanent*	25			70		
	Temporary	4.2	9.5	9.6	11.7		
	TOTAL	**29.2**			**81.7**	21.9	19.48

6. Conclusions

- A sequential MCM has been implemented to deal with the calculation of the reliability indices. The MCM method is effective to give not only the expected value and variance, but the whole PDF of different reliability indices.
- permanent faults have a very long restoration time, failure rate and relatively long restoration time, so that the values obtained by the MCM method vary according to the number of permanent faults occurred in the time period under study. This causes the discrepancies between analytical and simulated mean values.
- The interest for the PDF is due to the possibility of computing particular information such as the tail probability, that could be useful for defining additional indicators such as the probability of exceeding a given value, important for the regulation of competitive electricity markets.
- Results obtained on a test distribution system have been successfully compared to the analytical values of the reliability indices.

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