ANALYSIS OF DISTRIBUTIONS PROBABILITY OF SECONDARY POWER QUALITY INDICES ANALYSIS USING MONTE CARLO SIMULATIONS

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This paper aims to perform a simulation of the probability density (PDF) functions of a set of reliability and quality indices applied to electrical distribution systems, including the frequency and duration of interruption, power and energy not supplied. The quality indices are evaluated using analytical expressions for calculating average values, using the Monte Carlo method in order to obtain the PDFs.

Keywords: Power Quality, Monte Carlo, Electric Distribution, PDF, Relays

1. Introduction

The problems of power quality, important for the energy systems operation, have gained in recent years a special importance due to the user's sensitivity to disturbances [1-4]. This made the actual situation on market to be a permanent concern for power quality [5-7], planning, monitoring [8,9], standardization of the disruptive emissions and establishing the compatibility levels [10,11].

The research effort was directed on two main paths. In the first part we identified a real distribution single line diagram which was transposed into layers with the obtaining of the incidence matrices and the implementation in the Matlab program. In the second part we determined an operational algorithm for the test network, as close as possible to reality, in order to obtain by simulation a set of quality indices with comparison between modern relays (digital relays) and older generation of relays (analog relays).

2. Preliminary data

For the implementation of the single line diagram in Matlab and realization of the simulation algorithm we considered the following aspects:

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a. For a distribution system of k loads, the reliability analysis takes into account two types of indices:

- Local indices, are defined for each load point from 1 to k, and are calculated considering the frequency and duration of the states in which the k point is not supplied. The local indices taken into account was the frequency of interruptions, duration of interruptions, unsupplied power and unsupplied energy [12,13];
- Global indices, are defined for the entire electrical network, representing the reliability of the entire system. The global indices taken into account was SAIFI, SAIDI and CAIDI [14-17].

b. Consider the distribution system with k loads in the given time interval (0, T), we introduce a set Θ of defects that appear in the distribution system and the set $\mathbf{\Phi}_k$ of the defects appearance at the point k which represent the fact that point k is not powered, for all loads from 1 to k. A fault set f_Θ may require different phases of diagnosis and restart of the system, considering 3 types of faults:

- Faults at the power supply nodes, for the HV system with a single restart phase, due to the operations appeared in the HV system;
- Temporary faults in the distribution systems, with the action of the circuit breaker successful and restoration of normal operation, again with a single restart phase;
- Permanents faults, requiring three different phases of restart after action of circuit breaker:
  - Phase 1 (δ_{kf}^1), operation carried out from distance, from control center, to isolate the defect and put back into operation the part unaffected by the fault;
  - Phase 2 (δ_{kf}^2), additional manual operations, performed by the maintenance operation to isolate the defect and put back into operation the part unaffected by the fault;
  - Phase 3 (δ_{kf}^3), repairs are carried out at the fault site and completion of restart.

c. Consider that the faults are independent random events (RE) with a negligible probability of simultaneous appearance with a Poisson distribution:

$$\Pr\{\mathbf{n}_f = N_f\} = \frac{(\lambda_f T)^{N_f}}{N_f!} e^{-\lambda_f T} \quad (1)$$

where λ_f represents the failure intensity; T represents the length of the analysis period; N_f represents a deterministic number of the occurrences of the failure f.

d. Consider that the system multi-phase restart time for each phase is independent of the fault and the phase restart of the same fault. Is used RV + τ to represent the restart time;

e. Consider the following power quality indices, defined for the time interval [0, T]:

- Total duration of interruptions, represented by the random variable d_k at load *k* and *d* for the entire system
- Frequency of failures, f_k
- Not-supplied energy, represented by w_k at load *k* and *w* for the entire system
- Not-supplied power, PNS

f. For any possible fault, we consider the evaluation of the δ_{kf}^{m} as in Table 1, below, where *m* is the restoration phase, and $\delta_{kf}^{(m)}$ is a boolean variable, equal to zero is the load point is not fed by the faulted branch:

Table 1

Evaluation of δ_{kf}^{m}

Fault type	φ_f	*m*	$\delta_{kf}^{(m)}$		Description
Supply	1	1	$\delta_{kf}^{(1)}$	1	Powered by the faulty line
				0	Otherwise
Temporary	1	1	$\delta_{kf}^{(1)}$	1	Powered by the faulty line
				0	Otherwise
Permanent	3	1	$\delta_{kf}^{(1)}$	1	k load is not supplied after breaker action
				0	Otherwise
		2	$\delta_{kf}^{(2)}$	1	k load is not supplied after the motor operation
				0	Otherwise
		3	$\delta_{kf}^{(3)}$	1	k load is not supplied after the manual operation
				0	Otherwise

3. Case study

To perform the simulation as close as possible to reality, we used as model to generate a radial electrical distribution network, the electric diagram of the Polytechnic University of Bucharest (Fig. 1), which includes all the existing elements from a general electric distribution network (circuit breakers, disconnectors, loads, protection relays, and lines)

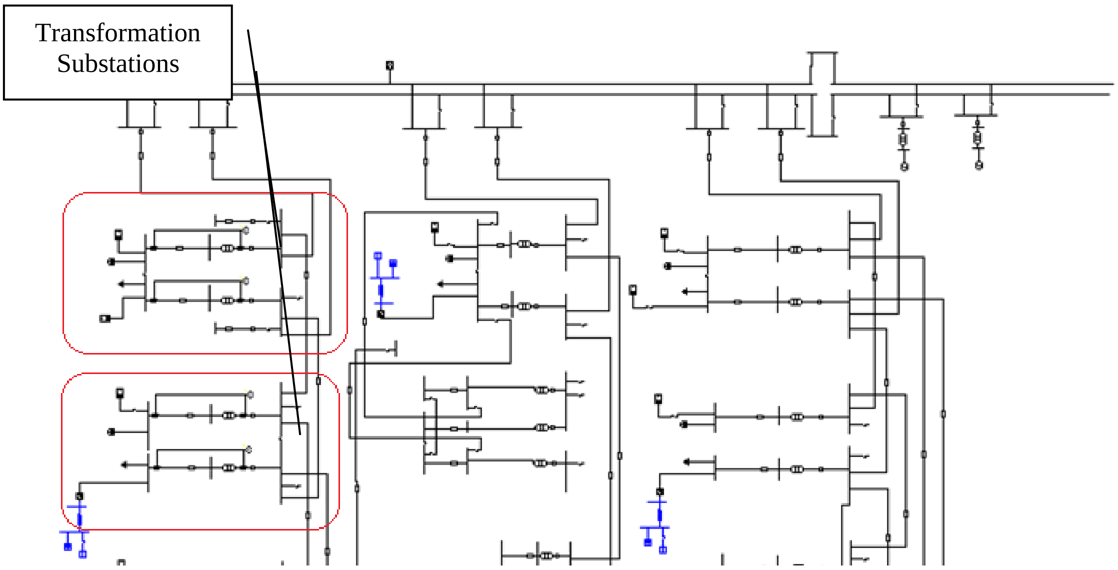

Fig. 1 – Electric diagram of Polytechnic University of Bucharest

The design of the network, including the protection relays, was structured in layers to simplify the calculation algorithm and to facilitate the application of various iterations. We can consider the test diagram of the studied system with 2 layered areas (named upper area and lower area of the network, as in Fig. 2)

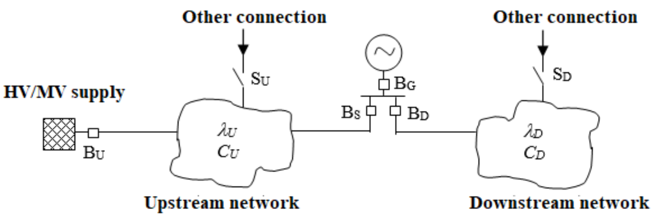

Fig. 2 – Design of the network with two areas aggregated with similar failure rate, and loads

For the SLD used (Fig. 1), we consider a radial network with n+1 nodes, supplied at constant voltage from the start note (node 0). For each note *i*, we define a path(*i*) as the ordered list of nodes encountered starting from the node 0 and going to node *i*. Each node belongs to a layer, which represents the position of the node in the network. For node *i*, layer(*i*)= size of path(*i*). The following criterion is assumed for counting lines and nodes:

— The nodes are counted sequentially, in ascending order, passing from layer to layer (Fig. 3), so any path from node 0 (CET), to a terminal node meets the numbers associated with the nodes in ascending order;

— Each feeder starts from the supply feeder and is identified by the feeder number (unique) at the end; the numbers in black represent the cross-feeding lines, and with red are represented the direct lines.

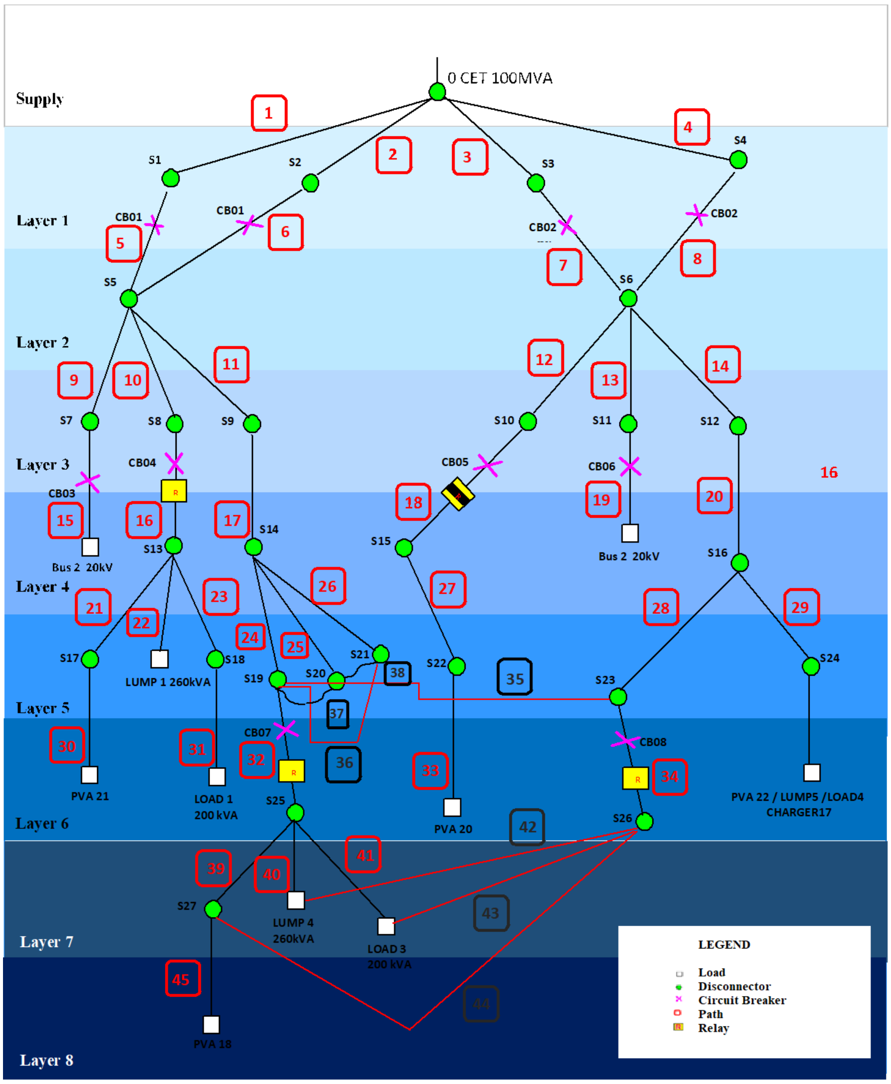

Fig. 3 - Layer-based representation of the tested SLD

The layered realization of the single-line diagram (SLD) leads to a convenient representation of the system from which we can extract the incident ($\mathbf{L} \in N^{n,n}$) and inverse matrices ($\mathbf{\Gamma} = \mathbf{L} \in N^{n,n}$), considering for each feeder a conventional value of +1 for transmitter bus and -1 for receiver bus, the generic components of the matrices can be visualized in Tables 2 and 3.

Table 2

Incidence matrix L

Noduri	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45
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Table 3

Inverse matrix Γ

Noduri	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45
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39	-1	-1	-1	-1	-1	-1	-1	-1			-1			-1			-1			-1				-1	-1	-1		-1				-1		-1	-1	-1			-1					
40	-1	-1	-1	-1	-1	-1	-1	-1			-1			-1			-1			-1				-1	-1	-1		-1				-1		-1	-1	-1				-1				
41	-1	-1	-1	-1	-1	-1	-1	-1			-1			-1			-1			-1				-1	-1	-1		-1				-1		-1	-1	-1					-1			
42	-1	-1	-1	-1	-1	-1	-1	-1			-1			-1			-1			-1				-1	-1	-1		-1				-1		-1	-1	-1				-1		-1		
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45	-1	-1	-1	-1	-1	-1	-1	-1			-1			-1			-1			-1				-1	-1	-1		-1				-1		-1	-1	-1			-1	-1		-1		-1	-1

The current simulation technology mostly uses the power of the Matlab software. A program has been developed, with a calculation algorithm that includes the probabilistic Monte Carlo method, which provides a complete view of the test network and the mutual coupling between the feeders from L matrix with identification of the matrix **Γ** and calculation, in various situations of possible defects, the proposed power quality indices.

For the simulation, we considered that the best distribution for our random numbers is Poisson distribution, due to the fact that its field of definition covers “the probability of rare events”, and in our case (analysis of quality indices), events (interruptions) are rare. The main purpose of the study was to make a comprehensive comparison of older generation of relays (analog relays) in relation to modern, digital relays, using the same test network. In this scope, the following scenarios were taken into account in Matlab simulation:

Scenario 1

The studied test network consists of new generation digital protection relays, so we can consider the following constants (dates compared with operation manuals for different type of relays and compared with ETAP database):

- Circuit breaker selectivity in both areas (upper and lower areas): 95%
- Successful action of the circuit breakers in both areas: 90%

Scenario 2

The studied test network consists of analog protection relays (old generation) for which we considered a coefficient of 5% at the end of 10 years operation for the deterioration of the internal parameters, so that we can consider for 40 years of usage the following constants:

- Circuit breaker selectivity in both areas (upper and lower areas): 75%
- Successful action of the circuit breakers in both areas: 70%

For the input data presented for both scenarios, the simulations were performed in several variants, modifying the MC parameters for 10 and 40 years with iterations of 1000 and 10000 cycles. All scenarios are presented in Table 4.

Table 4

Scenarios for input data

	Scenario	**Years**	**Iterations**	**Probability of circuit breaker selectivity (upper and lower areas)**	**Successful action of the circuit breakers (upper and lower areas)**
Digital relays	**1-A**	10	1000	95%	90%
	1-B	10	10000	95%	90%
	1-C	40	1000	95%	90%
	1-D	40	10000	95%	90%
Analog relays	**2-A**	10	1000	75%	70%
	2-B	10	10000	75%	70%
	2-C	40	1000	75%	70%
	2-D	40	10000	75%	70%

4. Results of the study

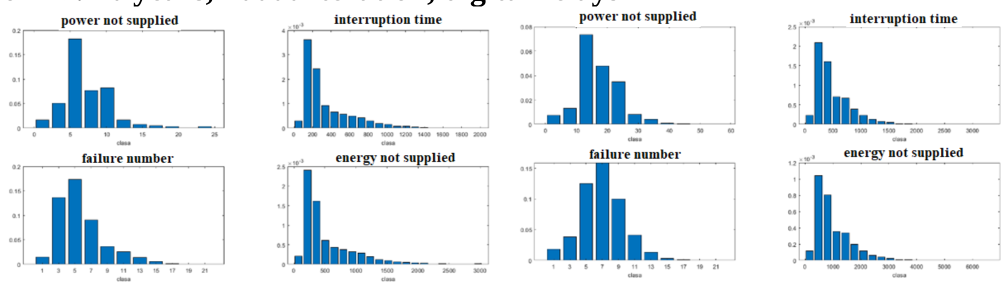
The results of the simulations are presented in the figures below:

Scenario 1-A: 10 years, 1000 iteration, digital relays

(a) (b)

Fig. 4 – (a) Lower areas of the network , (b) Upper areas of the network

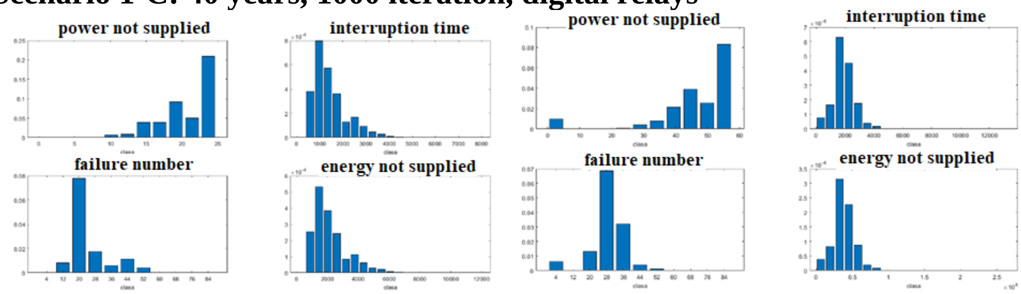
Scenario 1-B: 10 years, 10000 iteration, digital relays



(a) (b)

Fig. 5 – (a) Lower areas of the network , (b) Upper areas of the network

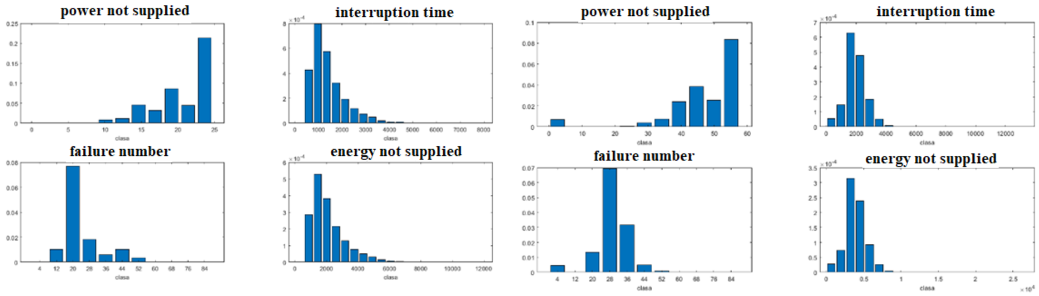
Scenario 1-C: 40 years, 1000 iteration, digital relays



(a) (b)

Fig. 6 – (a) Lower areas of the network , (b) Upper areas of the network

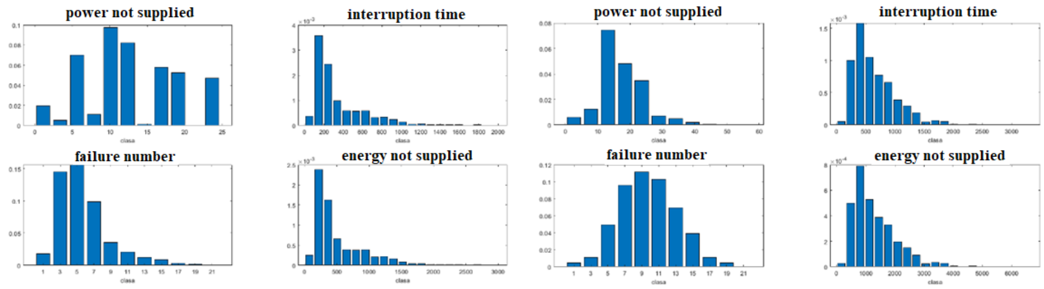
Scenario 1-D: 40 years, 10000 iteration, digital relays



(a) (b)

Fig. 7 – (a) Lower areas of the network , (b) Upper areas of the network

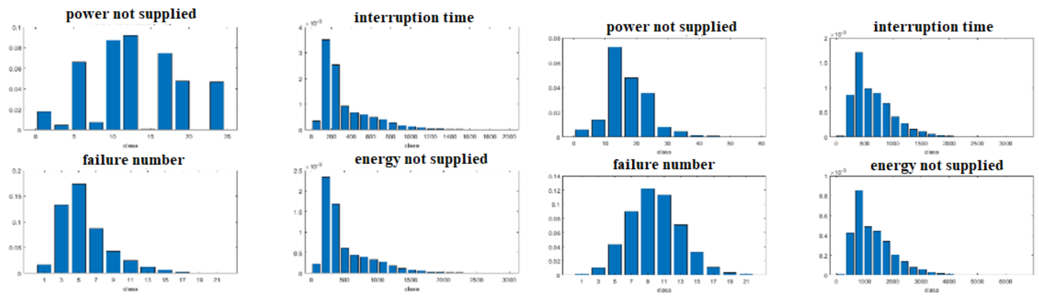
Scenario 2-A: 10 years, 1000 iterations, analog relays



(a) (b)

Fig. 8 – (a) Lower areas of the network , (b) Upper areas of the network

Scenario 2-B: 10 years, 10000 iterations, analog relays



(a) (b)

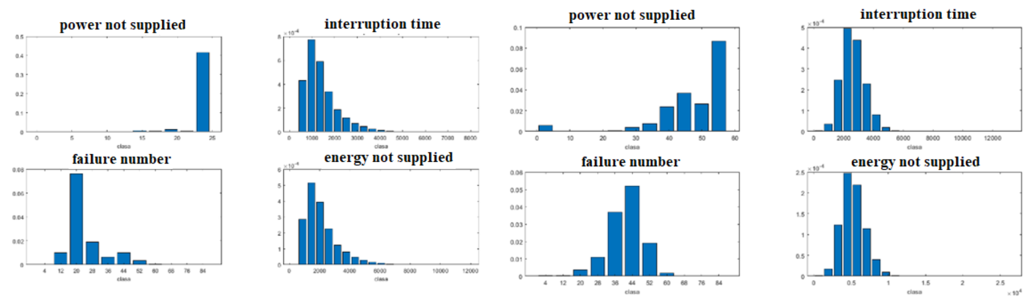
Fig. 9 – (a) Lower areas of the network , (b) Upper areas of the network

Scenario 2-C: 40 years, 1000 iterations, analog relays

(a) (b)

Fig. 10 – (a) Lower areas of the network , (b) Upper areas of the network

Scenario 2-D: 40 years, 10000 iterations, analog relays



(a) (b)

Fig. 11 – (a) Lower areas of the network , (b) Upper areas of the network

4. Conclusions of the study

As a result of the study and the simulations performed on the test network using the Monte Carlo method, we can observe and conclude the following aspects:

— A sequential MCM has been implemented to address the issue of power quality indices. The MCM method is efficient because it provides not only the mean value and variance, but also the entire PDF of the various reliability indices (probability density function).

— The results obtained on a test network were compared with the analytical values of the power quality indices, an approach that highlighted the fact that the Monte Carlo method applied to the data falls within the 95% confidence interval compared to the data obtained from the physical system.

— There are major differences in the power supply quality between the two scenarios studied in relation to the situation of protection relays in the system, concluding the periodic need to modernize the protection and electrical equipment components of networks.
— The continuous increase of the level of disturbances in the form of harmonics determined by the modern technologies of the consumers as well as the increased requirements of the consumers regarding the quality of the voltage on the supply bars, impose the existence of a large number of specialized monitoring equipments. current, the level of electricity quality in the nodes of the electricity network.
— The quality of electricity supplied to consumers, on a competitive energy market, will be one of the important criteria of the consumer in choosing the supplier, but also in the acceptance by the supplier of the connection of disruptive consumers. Monitoring the level of electricity quality provided by the supplier but also the level of electromagnetic disturbances caused by the consumer is a basic element in achieving a fair contractual relationship between supplier and consumer.

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