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Reliability Centered Maintenance Optimization of Electric Distribution Systems

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1. Introduction

A basic component of the power quality generally and electricity supply in particular is the management of maintenance actions of electric transmission and distribution networks (EDS). Starting from this fact, the chapter develops a mathematical model of external interventions upon a system henceforth, called Renewal Processes. These are performed in order to establish system performance i.e. its availability, in technical and economic imposed constraints. At present, the application of preventive maintenance (PM) strategy for the electric distribution systems, in general and to overhead electric lines (OEL) in special, at fixed or variable time intervals, cannot be accepted without scientifically planning the analysis from a technical and economic the point of view. Thus, it is considered that these strategies PM should benefit from mathematical models which, at their turn, should be based, on the probabilistic interpretation of the actual state of transmission and distribution installations for electricity. The solutions to these mathematical models must lead to the establishment objective necessities, priorities, magnitude of preventive maintenance actions and to reduce the life cycle cost of the electrical installations (Anders et al., 2007).

1.1 General considerations and study assumptions

Based on the definition of IEC No: 60300-3-11 for RCM: „method to identify and select failure management policies to efficiently and effectively achieve the required safety, availability and economy of operation”, it actually represents a conception of translating feedback information from the past time of the operation installations to the future time of their maintenance, grounding this action on:

- statistical calculations and reliability calculations to the system operation;
- the basic components of preventive maintenance (PM), repair/renewal actions.

So, Reliability Based Maintenance (RCM) implies planning the future maintenance actions (T^+) based on the technical state of the system, the state being assessed on the basis of the estimated reliability indices of the system at the planning moment (T^0). At their turn, these reliability indices are mathematically estimated based on the *record of events*, that is, based on previously available information, related to the behaviour over period (T^-), i.e. to the (T^0) moment, concordant with Figure 1.

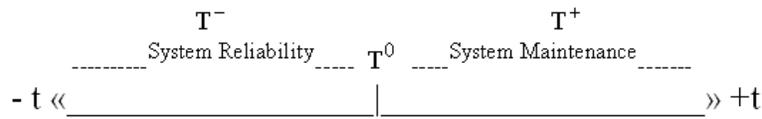


Fig. 1. Assessment and planning times of the RCM

Even if in case of the OEL, the two actions are apparently independent, as they take place at different times, they influence each other through the model adopted for each of them. Thus:

- the analytical expression of the reliability function adopted in while (T^-), depends directly by the basis of specific physical phenomena (such as wear, failure, renewal, etc.) of equipment during maintenance actions in time interval (T^+);
- in turn, the actions of the preventive maintenance in time interval (T^+), depend directly on the reliability parameters at the time (T^0) and by the time evolution of the *reliability function* of the system over this period of time. The interdependence of the two actions can be expressed mathematically given by the analytical expression by the *availability of system*, which is the most complex manifestation of the quality of the system's operation, because it includes both: the reliability of the system and its maintainability.

Accepting that the expression of the availability at a time t , the relationship given by the form (Baron et al., 1988):

$$A(t) = R(t) + [1 - R(t)] \cdot M(t') \quad (1)$$

where:

$A(t)$ - Availability;

$R(t)$ - Reliability;

$M(t')$ - Maintainability

It can be inferred that the availability of an element or of a system is determined by two probabilities:

- a. the probability that the product to be in operation without failure over a period of time (t); $R(t)$ - is called the *reliability function*;
- b. the probability that the element or the system, which fails over time interval (t), to be reinstated in operation in time interval (t'); $M(t')$ - is called the *Maintainability function*.

Thus, for components of EDS which are submissions by RCM actions, a distinctive study is required to model their availability under the aspect of modelling those two components:

1. The *reliability function* $R(t)$ of EDS, respectively of the studied component, in this case a OEL;
2. The *Maintainability function* $M(t')$, under the aspect of their specific constructive and operation conditions, maintenance.

As the mathematical models of the two components $R(t)$ & $M(t')$ interdependent, we will continue by exposing some considerations regarding the establishment of $M(t')$, and section 3 will be devoted to developing the component $R(t)$ of the EDS.

1.2 EDS-Degradable systems subjected to wear processes

EDS in general and the OEL in particular, contain parts with mechanical and electrical character and their operation is directly influenced by different factors, being constantly subjected to the requirement of mechanical, electrical, thermal processes, etc. The literature shows the percentage of causes which determin interruptions of OEL, (Anders et al., 2007).

- Weather 55%; Damage from animals 5%; Human damage 3%; Trees 11%; Ageing 14%. Thus, one can say with certainty that these failures of systems are due to wear and can be defined as NBU type degradable systems (*New Better than Used*), whose operation status can improve through the preventive maintenance actions, called in the literature as *renewal actions*. As OEL maintainability is directly conditioned by the evolution in time of maintenance actions and it is imposed a defines mathematics, from the point of view of reliability and of the notions of: *wear, degradable system and renewal actions*.

1.3 Modelling of systems wear

In theory of reliability, the concept of the *wear* has a wider meaning than in ordinary language. In this context, the wear includes any alteration in time of characteristics of reliability, for the purposes of worsening or improving them (Catuneanu & Mihalache 1983). Considering the function of the reliability of equipment for a mission with a duration x , initialized at the t moment, of the type:

$$R(t, t+x) = \frac{R(t+x)}{R(t)} \quad (2)$$

- the equipment is characterized by the *positive wear* if the reliability function $R(t, t+x)$ is decreases in the range $t \in (0, \infty)$ for any value of $x \geq 0$, i.e. for any mission of the equipment, its reliability decreases with its age.
- the equipment is characterized by the *negative wear* if the reliability function $R(t, t+x)$ is increases in the range $t \in (0, \infty)$ for any value of $x \geq 0$, i.e. for any mission of the equipment, its reliability increases with its age.

From a the mathematical point of view, we can express the wear through *failure rate (FR)* of the equipment. From the relationship (2) and from the defining relationship of failure rate we obtain:

$$z(t) = \lim_{x \rightarrow 0} \frac{R(t) - R(t+x)}{x \cdot R(t)} = \lim_{x \rightarrow 0} \frac{R(t, t+x)}{x} \quad (3)$$

If the failure rate of the equipment with positive wear increases in time, then these systems will be called IFR type systems (Increasing Failure Rate) and if the failure rate of the equipment with negative wear decreases in time, these systems will be called DFR type systems (Decreasing Failure Rate).

An equipment is of *NBU degradable type* if the reliability function associated to a mission of the duration x , initialized at the t age of equipment, is less than the reliability function in interval $(0, t)$, regardless of the age and duration of x mission.

$$R(t, t+x) < R(t); \quad t, x \geq 0 \quad (4)$$

From the previous definition, results that a degradable equipment which was used is inferior that to a new equipment.

The notion of degradable equipment is less restrictive than that of equipment with positive wear, which supposed the decreasingd character of the function $R(t, t+x)$ with t age of equipment.

A particular problem consist of identifying the type of wear that characterizes an equipment/system, which can be obtained from reliability tests or from the analysis of the moments of failure in operation, which mathematically modelled, give the wear function, denoted by $T_s(F)$.

With:

- $F(t)$, *probability of failure function*, representing the probability that the equipment should enter the failure mode over time interval $(0, t)$ and is complementary to reliability function $R(t)$:

$$F(t) = 1 - R(t) \quad (5)$$

- $R(t)$ represent the *reliability function* of the equipment over time interval $(0, t)$.

According to system reliability $T_s = f(F(t))$, the graph function of the wear inscribed in a square with 1 side, can indicate the type of equipment wear by its form:

- concave for equipment with positive wear, of IFR type;
- convex for equipment with negative wear, of DFR type;
- first bisectrix for equipments characterized by lack of wear.

Thus, the literature allow for the study maintenance of OEL, the following assumptions:

- the OEL are degradable systems, by the of NBU type;
- the OEL are systems with positive wear, of IFR type;
- the OEL are repairable systems;
- the OEL allowed external interventions (the renewal actions), to restore the performances.

We mention that all models specific to these assumptions/behaviours of the OEL are dependent on the reliability function of the system in study and their effects model this function.

2. RCM – Evolutive process of renewal

In the analysis presented in section 1, aimed to observe the natural process of degradation of the system performance, without taking into account the capacity of external interventions, to oppose this degradation through the partial or total reconditioning system, in a word's through its renewal. Starting from these considerations, in this section we will try to present the specific models of external interventions, defined as a renewal strategy, performed to restore systems performance and to modelling the reliability function of systems in study, (Catuneanu & Mihalache, 1983).

2.1 Renewal process

We define the action of *renewal*, as: *the external intervention performed on a system that restores the system operating status and/or changes the level of its wear, respectively of the system reliability*. From the definition we can distinguish two types of renewal actions that can be performed on systems:

- *Failure Renewal (FR)*, is performed only at the appearance of some failures and its purpose is to restore the system operation. They are random events generated by the failure of the system;
- *Preventive renewals (PR)*, have the purpose of renewing the system before its failure. They can be random or deterministic events, according to the way in which they design

their strategies. Thus, the random or deterministic strategy of preventive renewals is added to a random process of failure renewals.

The classification of renewal actions can be performed on several criteria, of which we remind a few: the purpose, timing and costs of their occurrence, distribution and frequency and last but not least, the effects on the system safety, (Anders et al., 2007).

In this work, we analyze and study only preventive renewal processes, through their modelling influence on the system in the following cases:

- the system is known due to the reliability function and reliability indices, based on data received from operation;
- PR actions have the purpose of reducing the influence of the system wear and thus improve its reliability, which are considered preventive maintenance actions (PM) from this point of view;
- PR does not entirely change the characteristics of the system, and after the renewal action, the evolution of the system follows the same law of reliability until a new renewal;
- determining the PR frequency on the system will be based on technical criteria and/or economic ones;
- PR of system elements, will be performed considering the same assumptions of study as the system as a whole.

The evolution of an equipment will thus be represented by the succession of renewal moments t_1, t_2, \dots, t_n , and the intervals between them: x_1, x_2, \dots, x_n ... presented in the Figure 2.

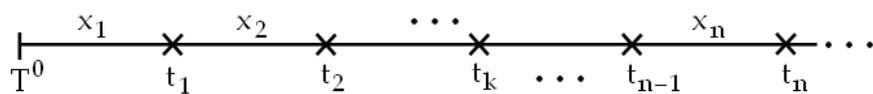


Fig. 2. The evolution of an equipment with renewal

If it is considered a certain time interval $(0, t)$, the number of PR denoted by N_t , performed during this time, is a discrete deterministic process, called preventive renewal process, as the basic component of preventive maintenance, which in turn determine planning, development and the effects of RCM on system. This, requires the development of PR strategies, enabling knowledge of behaviour of renewal equipment, used in the development of PM programs.

2.2 Renewal strategies

Studies classify and model the renewal strategies according to technical and economic parameters, which determine these strategies, in two distinct categories: non-periodic and periodic, (Catuneanu & Mihalache, 1983), (Andres et al., 2007).

- *Non-periodic renewal strategies*, are external interventions on one equipment of the system, which take place only when accidental failure of the equipment, in order to restore its performance and are performed in negligible time; are characteristic of the failure renewals.
- *Periodic renewal strategies*, are characteristic to the prophylactic renewals or preventive PR, providing the renewal of equipment before their failure and providing increased efficiency of equipments in operation. These types of strategies are characterized by a constant/variable and known duration between two consecutive preventive renewals,

based on a preventive maintenance program. In conclusion, that these strategies have a deterministic character.

According to the mathematical model adopted in the calculation of specific parameters of renewals non-periodic or periodic renewal, we can distinguish the following types of strategies:

- *BRP (Block Replacement Policy)*,
It represents the simplest strategy of periodic renewal and consists of the renewal of the equipment either at the moment of its failure or at equal time intervals $\{k\Delta T, k = 1, 2, \dots\}$.
A first criterion used to implement this strategy, i.e. the calculation of period ΔT or the number of k renewals, over the imposed period T , consists of imposing a certain minimum level of the reliability function over the interval between two successive renewals, or at the end of a period T . The strategies by BRP type have the disadvantage of inflexible schedules of renewals, by the fact that preventive renewals are performed at predetermined moments of time, without taking into account the failure renewals imposed by the failures occurring in the system.
- *FRP (Failure Replacement Policy)*, define the situation for which T is not running the preventive renewals.
- *DRP (Delayed Replacement Policy)*, eliminates the disadvantages of BRP- type strategies by inserting deterministic preventive renewals between the Failure Renewal random type strategies.
- *ARP (Age Replacement Policy)*, represents the simplest strategy, in which preventive renewal is determined by the moment when the equipment reaches a certain age. In order to establish the age of the system at which the preventive renewal can be performed various technical criteria or economic criteria can be used.

These preventive strategies renewal operating at some predetermined time points and lead to total or partial elimination of accumulated wear, each time bringing equipment in operating condition characterized by lack of wear or with negligible wear. Establishing the renewal moment is made using the reliability model of equipment, based on the information referring to the behavior of the equipment in conditions of operating data, principles which are the foundation of the RCM design.

The option between the different RCM preventive renewal strategies must rely on uniform criteria leading to the best assessment. These criteria must be the result of technical and safety factors imposed to the system, as well as the result of economic considerations imposed to the preventive maintenance actions.

We mention only some of these criteria which are valid for EDS, these criteria developed in the following sections:

- imposing a certain minimum level of reliability function in the interval between two successive renewals or after a fixed period of time;
- imposing a maximum number of unplanned interruptions during a certain period;
- optimizing the operating costs and maintenance costs.

Different studies present additional evolutionary renewal strategies used in the renewal equipment, which are part of the *CRP type (Continuous Replacement Policy)* strategies.

Implementing the CRP type strategy by requires a continuous monitoring of equipment through measured quantities. Determining the moment of the next preventive renewal is made according to the evolution equipment parameters, established through diagnosis techniques.

This type of evolutionary strategy of renewal is underlying the maintenance actions planning by *CBM (Condition Based Maintenance) type*.

3. Electric Distribution Systems reliability assessment

In this section, we try to exemplify an algorithm for the RCM planning, through the optimizing the PM strategies for OEL 20kV, through his components, as a subsystem of the EDS.

3.1 Reliability assessment stages

Knowing the *availability* of EDS implies statistical processing of the database containing historical events, with the final purpose of determining the parameters and the analytical shape of the *reliability function* $R(t)$. This process is applied to each component of OEL, in accordance with corrective or preventive maintenance actions performed over time.

The analytical expression of the reliability function is a central issue of the reliability theory, in general and especially in RCM. The procedure for assessing the unknown parameters of a distribution function, is called an estimate and she performed in the selective treatment of data resulting from the analysis of reaction time in operation of the system with its components.

Estimating the reliability of OEL, based on statistical data processed during the operation, in this case from the $(0 \div T^0)$, presented in Figure 1 is based on modeling the subsystems' behavior with random processes.

Estimation modeling involves the following steps, for a OEL:

- a. the selection and processing of data resulting from the network operation until (T^0) , i.e. of random variables given by the behaviour of the system;
- b. establish the type of the theoretical distribution function which model the best random variables;
- c. calculation of distribution function parameters;
- d. verifying the correspondence between the adopted theoretical law and the database, with regard to the behavior of the system in operation. The regression method is given by the statistical information;
- e. reliability indices of OEL at the time T^0 ;
- f. availability estimation function of OEL.

To illustrate these steps, we study the case of OEL by 20 kV, has the following construction parameters:

- Transmission length $L = 90.589$ km;
- 1097 concrete pillars and 9 metal pillars;
- 1107 porcelain and glass insulators;
- Aluminium conductor steel reinforced (ACSR) by 35/50/95 mm².

3.2 Random variables

The OEL operation time was selected as random variable form the database of the beneficiary of the 20 kV power line, which includes the sheets of incidents and interventions over a period of about five years. The OEL operation time is expressed according to:

- moments of time t_i (expressed in days), when the OEL stopped functioning. Only those failures/interruptions in electricity supply were considered, which were followed by corrective actions in installation to bring the facility into operation of OEL;

- the period of corrective actions, tr_i (expressed in minutes), to restore in operation OEL, the values are presented in Table 1.

Nr	1	2	3	4	5	6	7	8	9	10	11	12	13	14
t_i	62	68	80	200	210	212	254	290	407	418	483	497	510	539
t_{ri}	213	118	352	209	339	640	165	305	229	215	154	1970	204	303

...	45	46	47	48	49	50	51	52	53	54
...	1272	1370	1399	1483	1578	1596	1597	1608	1638	1712
...	482	1350	270	150	343	270	200	403	178	841

Table 1. Incidents database

3.3 Distribution function

Establishing a law distribution used in reliability implies good knowledge of the physical bases of the phenomenon of wear, of the specific ways in which these phenomena manifest themselves and of the type of wear to which each OEL component and the entire system has been subjected. Considered as an EDS component, the OEL contains, at its turn, components of a mechanical character, whose operations are directly influenced by mechanical actions, electrical ones (e.g. overvoltages, over currents), temperature, environmental pollution, etc. We can say with certainty that the OEL failures are due to wear and slow aging and, from the standpoint of their reliability, they are treated as IFR and NBU type, with an increasing failure rate.

Given these findings, *the law of Weibull distribution* is adopted as *theoretical law* for modelling such survival processes. This law is specific for positive wear systems, being also characteristic for overhead electrical lines.

In the case of an OEL in operation whose components are characterized by the absence of hidden defects, but show a striking phenomenon of aging in time while the intensity of failures increases monotonically, *the law of Weibull distribution* is adopted as theoretical law, which is specific for positive wear systems, being also characteristic for overhead electrical lines.

Of all the known forms of the Weibull distribution law (two and three parameters, normalized) let us accept the form with two parameters for modeling the reliability of the electrical line in study. This form has the mathematical expression (Baron et al., 1988), (IEC 61649, 2008):

$$R(t, \alpha, \beta) = e^{-\alpha \cdot t^\beta} \quad (6)$$

Where:

$\alpha > 0$ - is a scale parameter;

$\beta > 0$ - is a shape parameter, $\beta > 1$ for components of IFR type;

$t (0, +\infty)$ - time variable.

The relationship (6) expresses the probability that the event will occur in time interval $(0, t)$ or as they say in the theory of reliability is the probability of the OEL functioning without fault until t moment.

3.4 The parameters of Weibull distribution function

There are several studies which present a lot of techniques and methods to evaluate the Weibull function parameters, depending on: the number of function parameters chosen, the scope of the application, the available statistical data, etc.

In (Dickey, 1991), (IEC 61649, 2008), are mentions statistical methods for assessing the parameters for Weibull distribution of failures type and constant repair time. The Statistics Toolbox MATLAB programming environment allows the evaluation of parameters of the Weibull function, with the instructions, (Blaga, 2002):

```
[parmhat,parmci]=wblfit (t)
    parmhat (1); parmhat (2);
```

A synthesis of the calculation methods and accuracy of the Weibull parameters is presented in (IEC 61649, 2008).

In the paper (Baron et al.,1988), the authors presents a practical mathematical method of setting the a and β parameters with two parameters of Weibull law by the form of relationship (6), based on statistical data obtained from the analysis of operating arrangements of the OEL, as well as in the following assumptions:

- there are significant records concerning the concerning to the number of defects and the operating times between them;
- the average recovery times are negligible compared with the operating times.

The value of the parameters ' α ' and ' β ' is derived from the relationship (6), which by logarithm application, results as:

$$\lg R_N(t_{fi}) = -\alpha \cdot t_{fi}^{\beta} \cdot \lg e \text{ or: } \lg[1 / R_N(t_{fi})] = \alpha \cdot t_{fi}^{\beta} \cdot \lg e \quad (7)$$

repeating the operation of logarithms, result:

$$\lg\{\lg[1 / R_N(t_{fi})]\} = \lg(\lg e) + \lg \alpha + \beta \lg t_{fi} \quad (8)$$

$$\text{with notations: } R_N(t_{fi}) = 1 - t_{fi} / t_{fi}^{\max}; a = \lg(\lg e) + \lg \alpha; b_i = \lg\{\lg[1 / R_N(t_{fi})]\} \quad (9)$$

$$\text{is obtained from (8) equation of a straight line: } b_i = a + \beta \lg t_{fi} \quad (10)$$

for which using the method of least squares system is obtained the following equations system is obtained:

$$\begin{aligned} \sum_{i=1}^n b_i &= n \cdot a + \beta \cdot \sum_{i=1}^n \lg t_{fi} \\ \sum_{i=1}^n b_i \lg t_{fi} &= a \sum_{i=1}^n \lg t_{fi} + \beta \sum_{i=1}^n (\lg t_{fi})^2 \end{aligned} \quad (11)$$

$$\text{or :} \quad \begin{aligned} A &= n \cdot a + \beta \cdot B \\ C &= B \cdot a + \beta \cdot D \end{aligned} \quad (12)$$

which solved in relation with a and β unknown, result:

$$a = \frac{C \cdot B - A \cdot D}{B^2 - n \cdot D} ; \beta = \frac{n \cdot C - A \cdot B}{n \cdot D - B^2} \quad \text{and} \quad \alpha = 10^{[a - \lg(\lg e)]} \quad (13)$$

For the OEL 20 KV in study, by replacing the parameters from Table 3.1 in the previous relations, the following values of parameters of the Weibull function distribution result:

$$\alpha = 1.2669 \cdot 10^{(-4)} \quad \text{and} \quad \beta = 1.2939 \quad (14)$$

which allows modeling the reliability function $R(t)$ of OEL the through the relationship:

$$R(t) = e^{-1.2669 \cdot 10^{(-4)} \cdot t^{1.2939}} \quad (15)$$

and the nonreliability function $F(t)$, through the relationship: $F(t) = 1 - R(t)$ (16)

and the graph presented in Figure 3.

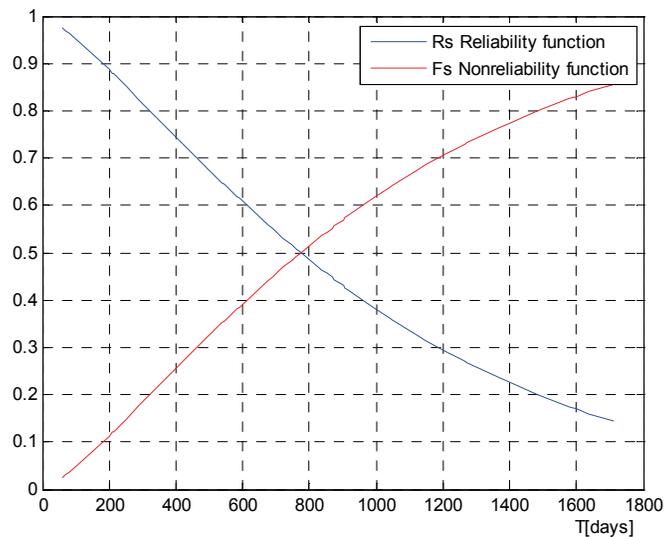


Fig. 3. Variation of reliability functions and failure probability

3.5 Concordance test

The fundamental criterion in adopting the distribution law is the concordance between the theoretical law, which in our case is Weibull distribution and experimental data, which in this case is the recorded database.

For this study, the validation of the chosen distribution law it is imposed by concordance study between: Weibull distribution by the form (15), with two parameters α , β , calculated with formulae (13), with experimental data presented in Table 1.

This can be achieved using the chi square concordance test which, in MATLAB, Statistics Toolbox is achieved with the procedure, (Blaga, 2002) :

$$[h,p] = \text{chi2gof}(t,@cdfweib_OEL)$$

where: - t is line matrix of experimental data, and

- $@cdfweib_OEL$ is the cumulative density function $F(t)=1-R(t)$.

The following values resulted are $h=0$, $p=0.935$. This means the acceptance of the null hypothesis of concordance between the observed data and the theoretical Weibull distribution of the parameters α , β , with the level of significance of 6.5%.

3.6 Reliability indices

Determining the reliability indices of an OEL facilitates the knowledge of the safety level in the operation of the OEL analyzed and the whole assembly which composes the OEL. The OEL 20 KV is studied as a repairable simple element, which regains its operating ability after failure, through repair, and then it can continue operation until the next failure. The evolution in time of such an element is a sequence of t_{fi} operating times with tr_i and repair times, for which, the following indices of reliability can be defined and calculated (Dub, 2008):

- MTBF, Mean Time Between Failures, given by the relationship:

$$MTBF = \frac{\sum_{i=1}^n t_{fi}}{n} \text{ [day]} \quad \text{with } t_{fi} = t_i - t_{i-1}; \quad MTBF = 31.7037 \text{ [day]} \quad (17)$$

- λ , failure rate, $\lambda = \frac{1}{MTBF} \text{ [day}^{-1}\text{]}; \quad \lambda = 0.031542 \text{ [day}^{-1}\text{]} \quad (18)$

- MTTR, Mean Time Repair, $MTTR = \frac{\sum_{i=1}^n tr_i}{n-1} \text{ [day]}; \quad MTTR = 0.2506 \text{ [day]} \quad (19)$

- μ , repair rate, $\mu = \frac{1}{MTTR} \text{ [day}^{-1}\text{]}; \quad \mu = 3.9897 \text{ [day}^{-1}\text{]} \quad (20)$

For the case of steady state, indices P and Q are defined. In our case, which chose the Weibull model for shaping the reliability function, and considering that ($\beta = 1.2939$), $\beta \cong 1$, we used the relationships of availability associated with the exponential distribution with operating times and repair times.

- P, success probability, $P = \frac{\mu}{\lambda + \mu}; \quad P = 0.9922 \quad (21)$

- Q, failure probability, $Q = \frac{\lambda}{\lambda + \mu} \quad \text{or} \quad Q = 1 - P \quad (22)$

- $M(\alpha(t))$, Total average duration of operation of the OEL for a time interval (0,T)

$$M(\alpha(t)) = P \cdot T \quad (23)$$

- $M(\beta(t))$, Total average duration of failure of the OEL for a time interval (0,T)

$$M(\beta(t)) = Q \cdot T = (1 - P) \cdot T \quad (24)$$

- $M(\gamma(t))$, the average probably number of interruptions in operation of the OEL for a time interval $(0,T)$

$$M(\gamma(t)) = \lambda \cdot P \cdot T = \mu \cdot Q \cdot T \quad (25)$$

3.7 The availability function

In the case of an exponential variation of *reliability function* $R(t)$, the following indices are specified, (Dub, 2008):

- $A(t)$, operating probability at a time t , called *availability*, which corresponds to the relation (1)

$$A(t) = \frac{\mu}{\lambda + \mu} + \frac{\lambda}{\lambda + \mu} \exp[-(\lambda + \mu)t] \quad (26)$$

- $\bar{A}(t)$, probability to be in course of repairing at a time t , called *unavailability*

$$\bar{A}(t) = \frac{\lambda}{\lambda + \mu} \cdot [1 - \exp[-(\lambda + \mu) \cdot t]] \quad (27)$$

For the OEL in study, based on the known indices λ and μ and on relations (26) and (27), Figure 4 presents a variation of the availability/unavailability function of the OEL.

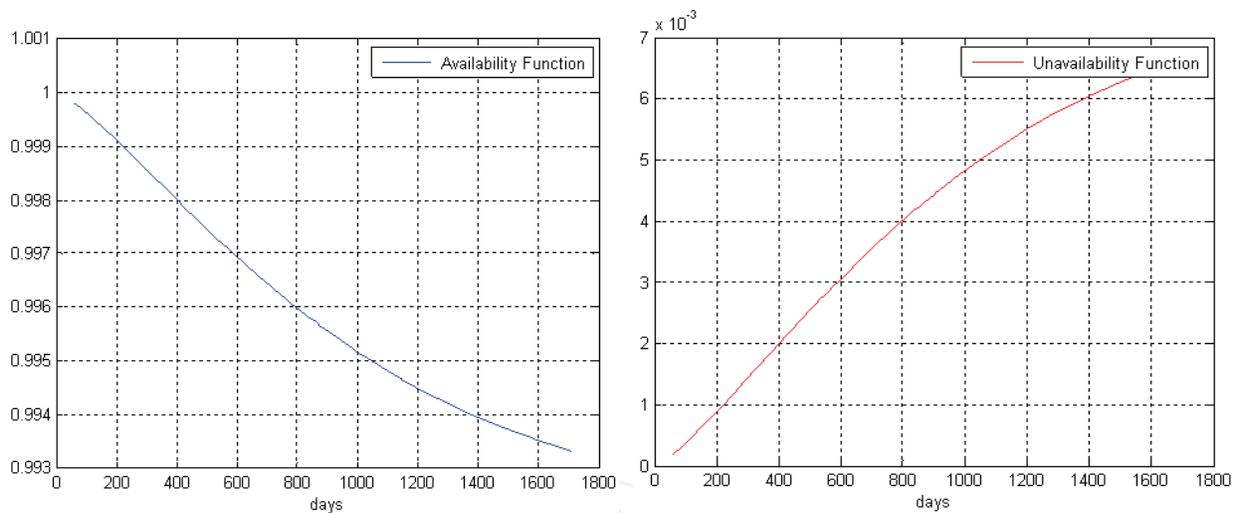


Fig. 4. Availability and unavailability functions for OEL 20 kV

The proposed algorithm allows to establishing the parameters and reliability indices for each component of OEL: pillar, conductor, insulator, assuming that we have a specific database for each component.

Considering these parameters and indices as the intrinsic dimensions of the OEL at a time, we can move on to preventive maintenance planning, namely the establishment of preventive maintenance strategies for a future period.

4. Modelling strategies by preventive maintenance with renewals

In accordance with the information presented in section 2 and section 3, it follows that the prophylactic strategy related to a system with RCM represents the combination of two

defining elements: *the type of wear and intervention operations, the renewal type and moment.*
In the cases in which at the time $t = T^0$ presented in Figure 1:

- The system is in operation, and has the probability function $P_0 (T^0)$, known by the relationship (21) ;
- the law of variation of system reliability is know, being expressed by the relationship (15);
- The system and its components will follow the same law of variation of reliability including during the periods of preventive maintenance (T^+), presented in Figure 1; we can shape the preventive renewal process for the following situations:

4.1 Modeling on a time interval

In the conditions of preventive maintenance actions for a period of $[0, \Delta T]$, with a number of renewals r performed during that period, we can express the system reliability function, on the relationship given by (Catuneanu & Popentiu, 1998), (Georgescu et al., 2010). and the nonreliability function $F(t)$, through the relationship:

$$R(r, \Delta T) = \exp\left(-\alpha(r+1)^{(1-\beta)} \cdot \Delta T^\beta\right) \quad (28)$$

where: α ; β - Weibull parameters, the relationship (14);

r - the number of preventive renewals during the study ΔT .

Figure 5 illustrates the graph in the case of the OEL in study, with the parameters given in the relations (15) and (21) with the purpose of exemplifying the variation of the reliability function $R(r, \Delta T)$, under the influence of PMA, carried out by varying the number of renewals r for $[0, 10, 50, 100]$, assuming a reliability of the OEL, at the beginning of the study period by $P_0(t) = 0.9922$.

$$R(r, \Delta T) = P_0(t) \cdot \exp\left(-\alpha(r+1)^{(1-\beta)} \cdot \Delta T^\beta\right) \quad (29)$$

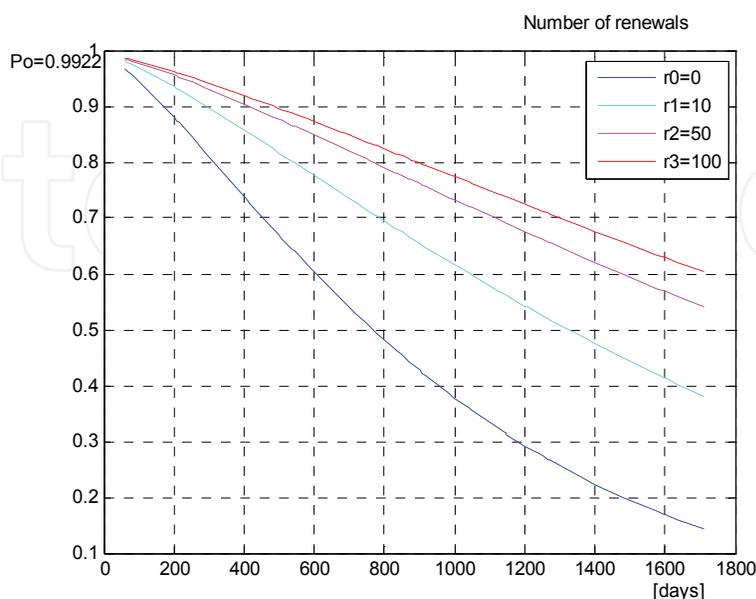


Fig. 5. The influence of the renewals r on the reliability of the OEL 20 kV

From the graphic of Figure 5, we note an increase reliability of the OEL at the end of the period ΔT , under the influence of renewals r_0, r_1, r_2, r_3 .

4.2 Modeling over n time intervals

Let us study the variation probability for a system operating with PM, over a period of time T_n , composed of n time intervals ΔT_i . A number r_i of renewals is performed over each interval ΔT_i for $i=1,n$, while the reliability of system at the beginning of the interval ΔT_1 is known $P_0 |_{t=0}$.

$$R(T_n) = P_0(t) \prod_{i=1}^n R_i(r_i, \Delta T_i) \quad (30)$$

where:
$$R_i(r_i, \Delta T_i) = \exp\left[-\alpha(r_i + 1)^{(1-\beta)} \cdot \Delta T_i^\beta\right] \quad | i = 1, n \quad (31)$$

or:
$$R(T_n) = P_0(t) \prod_{i=1}^n \exp\left[-\alpha(r_i + 1)^{(1-\beta)} \cdot \Delta T_i^\beta\right] \quad (32)$$

In the case of OEL in study, the variation of reliability was studied for:

- $T = \sum \Delta T_i$, with equal periods of time of $\Delta T_i = 600$ days $| i=1,2,3$;
- for each period i having a number $r_{ij} | j = 1, 2, 3$ renewals, or:
- $\Delta T_1 | r_1 = 0,5,20,50$; $\Delta T_2 | r_2 = 0,3,15,30$; $\Delta T_3 | r_3 = 0,1,10,20$;

With the parameters given in relations (15) and (21), we obtain the graph of variation presented in Figure 6:

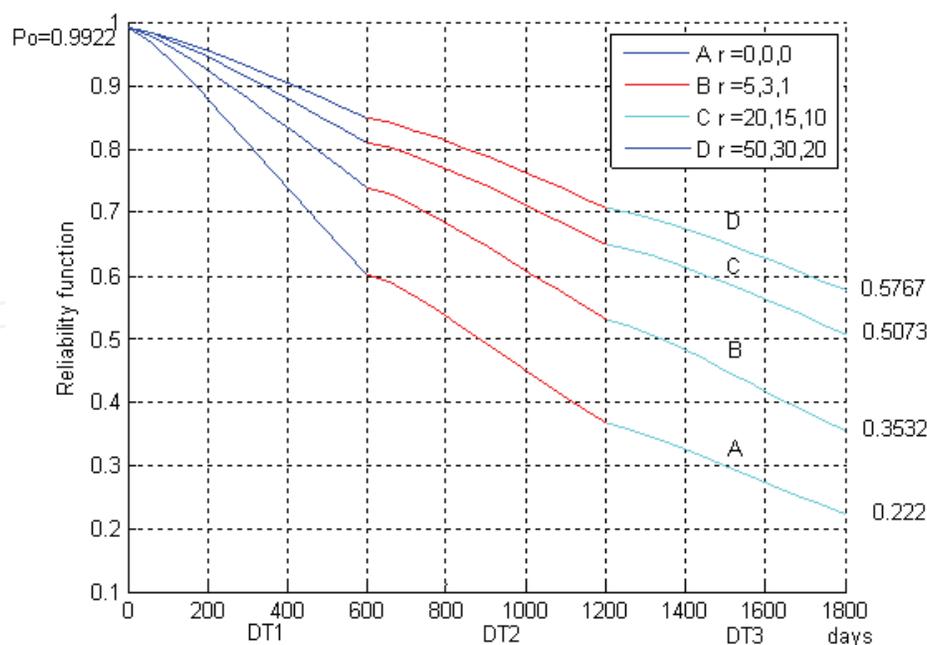


Fig. 6. Variation of reliability over time periods $\Delta T | i = 1,2,3$

From the graph of Figure 6, we note an increased reliability of OEL at the end of the three periods $\Delta T_i | i = 1, 2, 3$, under the influence of renewals.

4.3 Modeling on the components of the OEL

For the purpose of studying the PM of the system components, we consider the OEL with basic components: pillars, conductors, insulators, with the following assumptions:

- the exploitation data is known, due to corrective/preventive maintenance actions, for each component, for a certain period of operation;
- each component follows the same law of distribution reliability as the entire OEL, of form (6);
- using the model presented in section 3, it is possible to calculate the parameters and the reliability indicators for each component;

Through the OEL components, the structural model of the OEL reliability is the *series model*, such as the one presented in Figure 7. The reliability parameters and indicators of each component are known.

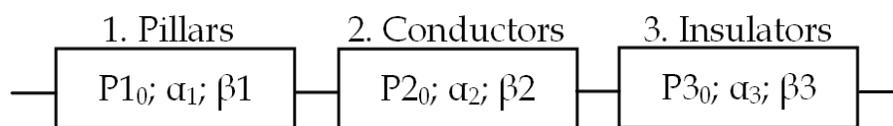


Fig. 7. Equivalent scheme of reliability on components of the OEL

In the line of these assumptions we can model the probability of operating with renewals, on each component over an interval ΔT , knowing the operating probability for each component in the early of period P_{i_0} , under the form:

$$R_i(r, \Delta T) = P_{i_0} \cdot \exp\left(-\alpha_i (r_i + 1)^{(1-\beta_i)} \cdot \Delta T^{\beta_i}\right) \quad | i = 1, 2, 3 \quad (33)$$

where: r_i - the number of renewals on the component $i = 1, 2, 3$.

In this case, the model of reliability of the OEL with renewals on components will take the form:

$$R(r, \Delta T) = \prod_{i=1}^3 R_i(\Delta T) = \prod_{i=1}^3 P_{i_0} \cdot \exp\left[-\alpha_i (r_i + 1)^{(1-\beta_i)} \cdot \Delta T^{\beta_i}\right] \quad (34)$$

Let us study the variation of the OEL reliability parameters and of its components for a period of time $\Delta T = 350$ days, assuming that the reliability parameters of the components and the number of preventive maintenance actions on each component are known, according to Table 2.

If we have the number of renewals $r_i | i=1,2,3$, each in four variants, the results are presented in Table 3. and their variation is presented in Figure 8.

i	Element	R_{0i}	$\alpha_i * 10^{-4}$	β_i	$r_i[\text{buc}]$
1	Pillars	0.99888	2.66883	1.29	0/5/10/20
2	Conductor	0.99750	9.56379	1.21	0/10/20/25
3	Insulators	0.99610	15.45002	1.33	0/10/15/30

Table 2. Reliability parameters of OEL components

** The data are estimates, because there is no information on the component maintenance

	R_{i0}	$r_i = 0 / 0 / 0$ $i = 1,2,3$	$r_i = 5/10/10$ $i = 1,2,3$	$r_i = 10/20/15$ $i = 1,2,3$	$r_i = 20/25/30$ $i = 1,2,3$
R1	0.9988	0.8762	0.9230	0.9344	0.9447
R2	0.9975	0.7300	0.8264	0.8465	0.8527
R3	0.9961	0.4055	0.6632	0.6954	0.7464
R_{OEL}	0.9922	0.2593	0.5058	0.5501	0.6012

Table 3. Renewal influence on OEL components reliability

From the study and comparison of the values presented in Table 3, we note an increase of reliability for each component and for the whole OEL, when the number of renewals is increased. Figure 8., graphically presents the influence of renewals on the components and on the OEL.

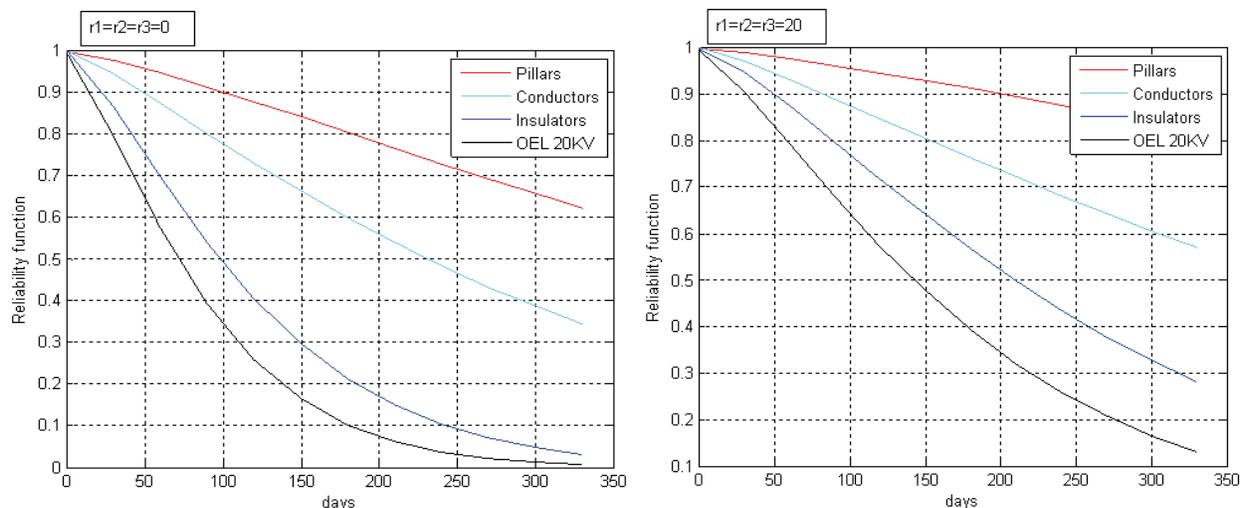


Fig. 8. The influence of renewals on the components and on the OEL

5. The economic modeling of preventive maintenance with renewals

The second component of the actions of the PM, after *strategy modeling*, is the *cost management* involved in the prophylactic strategy associated to the OEL systems with maintenance. In turn, the action of management and control of the maintenance plan of the electricity provider and in particular the implications of these actions on the financial relationship between the *electricity supplier* and *electricity consumers*, impose realizing an *economic model of PM*. Such a model should summarize all the costs and effects generated by the actions of the preventive and corrective maintenance, in all their aspects: planning, execution, management, etc., including the effect of inflation through the update method (Sarchiz et al., 2009), (IEC 60300-3-11, 2009).

To optimize the effect of RCM through the action and through the effect of the renewal processes for a period ΔT , belonging to the interval (T^+) , presented in Figure 1, we propose an economic model, based on the state parameters of the OEL and the number of r renewals.

5.1 Total costs

The economic model of the PMA, from the perspective of the total cost (TC), has three basic components, (Anders et al., 2007):

- C_F - the costs due to corrective maintenance actions;
- C_{PM} - the costs due to preventive maintenance actions;
- C_{INT} - the costs due to unplanned interruptions.

Or:

$$TC(r) = C_F(r) + C_{PM}(r) + C_{INT}(r) \quad [\text{cost / year}] \quad (35)$$

We express these costs depending on the parameters of reliability and on the number of planned interventions r during the period ΔT of by PMA for an OEL belonging to the EDS, through the following components.

5.2 Costs with unplanned interruptions

The costs due to unplanned interruptions, due to system failure, can be expressed as follows:

$$C_F(r) = N_F \cdot c_F \quad (36)$$

where: N_F , average number of failures for the reference interval ΔT from the relation (25),

or:

$$N_F = R_S \cdot \lambda_S \cdot \Delta T \quad (37)$$

where:

$$R_S = P_0 \cdot \exp\left(-\alpha(r+1)^{(1-\beta)} \cdot \Delta T^\beta\right) \quad \text{from the relationship (28)} \quad (38)$$

$a; \beta$ - Weibull parameters, the relationship (14);

λ_S - the failure rate of a EDS, considered constant during the study ΔT , OEL being half way through its life cycle, the relationship (18);

c_F - the average cost to fix a failure.

or:

$$C_F(r) = P_0 \cdot \exp\left(-\alpha(r+1)^{(1-\beta)} \cdot \Delta T^\beta\right) \cdot \lambda_S \cdot \Delta T \cdot c_F \quad (39)$$

5.3 Renewal costs

The cost of preventive maintenance activities performed on a system or system element is determined on the basis of existing statistical information available at each EDS operating unit. This cost can be appreciated as a function directly proportional to the number of interventions, i.e. renewals r on the system or on the system element, of the form:

$$C_{PM}(r) = r \cdot c_{PM} \quad (40)$$

with: c_{PM} - average cost of a preventive renewal.

5.4 Penalty costs

The penalties supported by the *electricity supplier*, due unplanned interruptions, for duration ΔT , can be by two types:

- PEN_S - proportional with the time of interruption T_F , for undelivered electricity at the average power on OEL by P_{OEL} , and
- PEN_U - for unrealized production during interruption by the electricity consumer connected to the OEL.

$$C_{\text{INT}}(r) = \text{PEN}_S + \text{PEN}_U \quad (41)$$

with:
$$\text{PEN}_S = P_{\text{OEL}} \cdot c_w \cdot T_F \quad (42)$$

$$\text{PEN}_U = \sum_{k=1}^K P_k \cdot c_k \cdot T_F \quad (43)$$

where:

P_{OEL} - average power on OEL; P_k - average power at the k consumer; c_w - electricity cost; c_k - production cost unrealized for a kilowatt hour of electricity undelivered, at the k consumer; T_F - total average duration of OEL nonoperation during the reference period ΔT , relation (24); K - number of consumers connected to the OEL in the study.

with:
$$T_F = (1 - R_S) \cdot \Delta T \quad (44)$$

By replacing the relations established in (41), it follows:

$$C_{\text{INT}}(r) = \left(P_{\text{OEL}} \cdot c_w + \sum_{k=1, K} P_k \cdot c_k \right) \cdot \left(1 - P_0 \cdot \exp\left(-\alpha(r+1)^{(1-\beta)} \cdot \Delta T^\beta\right) \right) \cdot \Delta T \quad (45)$$

By replacing the relations (39), (40) and (45) in relation (35), we obtain the expression of the total costs over a period of time ΔT , depending on the safety operating parameters of OEL and depending on the renewal actions of the PM.

$$\begin{aligned} \text{TC}_{(r)} = & P_0 \cdot \exp\left(-\alpha(r+1)^{(1-\beta)} \cdot \Delta T^\beta\right) \cdot \lambda_s \cdot \Delta T \cdot c_F + r \cdot c_{\text{PM}} + \\ & + \left(P_{\text{OEL}} \cdot c_w + \sum_{k=1, K} P_k \cdot c_k \right) \cdot \left(1 - P_0 \cdot \exp\left(-\alpha(r+1)^{(1-\beta)} \cdot \Delta T^\beta\right) \right) \cdot \Delta T \end{aligned} \quad (46)$$

With the following specifications on the relationship (46)

1. The term (43) is included into the optimization calculations for situations where an OEL provides electricity for consumer, which can calculate the costs of production according to the electric energy supplied, which allows the calculation of the coefficient c_k ;
2. To certain categories of electricity consumers, the higher production losses occur depending on the number of interruptions N_F during ΔT and less influence on time of interruption T_F ;
3. In a system with multiple components, each having a specific number of renewals r_i , the total costs are the sum of costs on each system element.

6. The optimization of RCM strategies

The literature in this field approaches a wide range of classifications, according to different criteria and parameters, used in the design and optimization of RCM strategies (Hilbert, 2008), (Anders et al., 2007). Further on, we will give examples of RCM strategies for an OEL belonging to EDS, for the following cases and mathematical models.

6.1 Study assumptions

The strategies of optimizing PM of OEL, depending on the optimal number of preventive renewals r over a given period $(0, T)$, can be approached from the perspective of the consequences it has on the relationship between electricity supplier and electricity consumer, based on two different criteria, which from the standpoint of the electricity supplier are (Sarchiz, 1993, 2005), (Georgescu, 2009):

- a. *The economic criterion*: through the total cost involved in providing a safe supply of electricity to consumers. This optimization model is:

$$\min\{TC(T,r)\} \quad (47)$$

in presence of technical constraints imposed on safety criteria:

$$R_s(t,r) \geq R_s^{\min} \quad \text{or} \quad N_F(t,r) \leq N_F^{\max} \quad (48)$$

where: - R_s^{\min} , the minimum reliability imposed on the study interval, and

- N_F^{\max} , the maximum number of failures permitted on the study interval.

- b. *The technical criterion*, aims to maximize safety in operation, respectively of system reliability on interval $(0, T)$.

$$\max\{R_s(T,r)\} \quad \text{or} \quad \min\{1 - R_s(T,r)\} \quad (49)$$

in presence of economic constraints due to maintenance actions:

$$TC(T,r) \leq TC^{\max} \quad (50)$$

where, TC^{\max} , the maximum cost allocated to the exploitation of the OEL on the studied interval.

The study of the strategies used to optimize the RCM based on models (47) and (49), can be performed depending on the degree of safety imposed to ensure electricity and/or depending on the degree of assurance of financial resources during the PM during $(0, T)$.

We will exemplify the application of the two models to the OEL 20KV in study, for the duration, T , a year, on these assumptions:

- we consider as action of renewal r , one or more specific PMA, or BRP type defined in section 2, for an OEL component and it can take one of the following forms (Mahdavi & Mahdavi 2009), (Teresa Lam & Yeh 1993):

Simple/minimal preventive maintenance and/or;

Maximal preventive replacement;

Sequential and/or continuous inspection strategies.

- we admit a periodic distribution of preventive renewals on the interval $(0, T)$, with a constant time between two renewals for:

$$OEL \quad \Delta t = T / r \quad \text{or}$$

$$OEL \text{ component } \Delta t_i = T / r_i \quad | \quad i = 1, 2, 3$$

- the technical parameters of OEL are given in the relations: (15); (18); (21)
- we admit an average power on OEL per year: $P_{OEL} = 5.16$ MW;
- the values of the economic parameters are only calculation values given in monetary units [m.u.];

$$c_F = 1000 \text{ m.u.}; \quad c_{PM} = 17500 \text{ m.u.}; \quad c_W = 530 \text{ m.u./MWh.}$$

Note: The values of costs used in the program are not real, that is why the obtained results are only *demonstrative theoretical results*.

- we ignore the PEN_U component from the relation (43), because we do not have data regarding the technical and economic parameters of the consumers connected to the electric line.

The solution of the mathematical optimization models (47) or (49) in relation with *r variable optimization*, impose the use of nonlinear optimization techniques in relation with *criterion functions* and the *restrictions of the models*. In order to solve the RCM strategy models presented below, we used the software package MATLAB 7.0\Optimization Toolbox\procedure *fmincon*.

The design of preventive strategies for renewal by type (47) or (49) can be done based on different criteria, which will be listed below within each RCM model optimization strategies.

6.2 The model: The minimum costs and imposed reliability

We will determine the optimum number of renewals, in the situation of minimum total costs, in such way that OEL reliability does not drop below the imposed value R_S^{\min} .

The *fmincon* procedure imposes the following structure of mathematical models to be optimized:

1. Vector of decision variable: $x \equiv r$ the number of renewals
2. Objective function: $\min\{TC(x)\}$

$$\begin{aligned} \text{where: } TC(x) = & P_0 \cdot \exp\left(-\alpha(x+1)^{(1-\beta)} T^\beta\right) \cdot \lambda_S \cdot T \cdot c_F + x \cdot c_{PM} + \\ & + P_{OEL} \cdot c_W \cdot \left(1 - P_0 \cdot \exp\left(-\alpha \cdot (x+1)^{(1-\beta)} T^\beta\right)\right) \cdot T \end{aligned} \quad (51)$$

3. Constraints of the model:

$$R_S(x) \geq R_S^{\min}; \quad 0 \leq x \leq x^{\max} \quad (52)$$

$$\text{or: } P_0 \cdot \exp\left(-\alpha(x+1)^{(1-\beta)} T^\beta\right) \geq R_S^{\min}; \quad -x \leq 0; \quad x \leq x^{\max} \quad (53)$$

with x^{\max} – the maximum imposed number of renewals.

By running the application program for different values imposed to the minimum reliability R_S^{\min} , we obtain the optimum number of renewals r^{opt} , for PM of OEL during a year, in conditions of the minimum total cost $TC(T, r)$, presented in Figure 9, i.e. the graph $r^{opt} = f(R_S^{\min})$. From the graph of variation we remark that in order to ensure reliability of 0.95, it is required to perform a number of 16 preventive renewals per year and for a reliability of 0.96, it is impose a number of 41 renewals. Also, we can extract the variation

costs with reliability R_S^{\min} imposed to the OEL or with the optimum number of renewals, i.e.: $TC = f(R_S^{\min})$ or $TC = f(r^{\text{opt}})$.

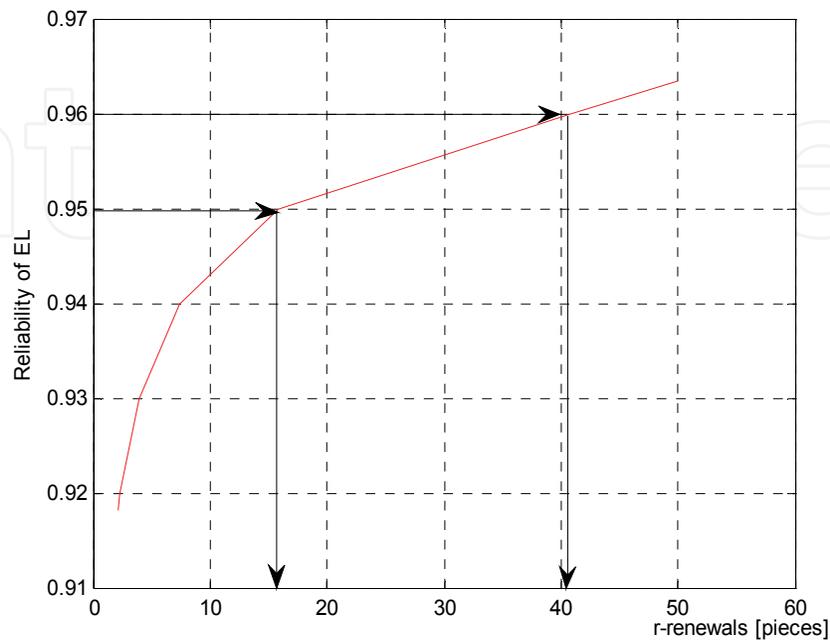


Fig. 9. Variation of the optimum number of renewals with reliability imposed to the OEL

6.3 The model: Minimum costs and number of interruptions imposed

We determine the optimum number of renewals with minimum total cost, in conditions in which the number of failures (unplanned interruptions) N_F does not exceed a maximum number imposed per year, N_F^{\max} . In this hypothesis, the structure of the mathematical model to be optimized is:

1. Vector of decision variable: $x \equiv r$ the number of renewals
2. Objective function: $\min\{TC(x)\}$

where :

$$TC(x) = P_0 \cdot \exp(-\alpha(x+1)^{(1-\beta)} T^\beta) \cdot \lambda_s \cdot T \cdot c_F + x \cdot c_{PM} + P_{OEL} \cdot c_w \cdot (1 - P_0 \cdot \exp(-\alpha(x+1)^{(1-\beta)} T^\beta)) \cdot T \tag{54}$$

3. Constraints of the model:

$$N_F(x) \leq N_f^{\max}; \quad 0 \leq x \leq x^{\max} \tag{55}$$

or:

$$P_0 \cdot \exp(-\alpha(x+1)^{(1-\beta)} T^\beta) \cdot \lambda_s \cdot T \leq N_F^{\max}; \quad -x \leq 0; \quad x \leq x^{\max} \tag{56}$$

with x^{\max} – the maximum imposed number of renewals.

By running the application program, for different maximum values imposed to the numbers of unplanned interruptions on the OEL, we obtain the optimum number of renewals that are

required to apply to the OEL during a year, in conditions of minimum total cost $TC(T,r)$, presented in Figure 10, i.e. $r^{opt} = f(N_F)$.

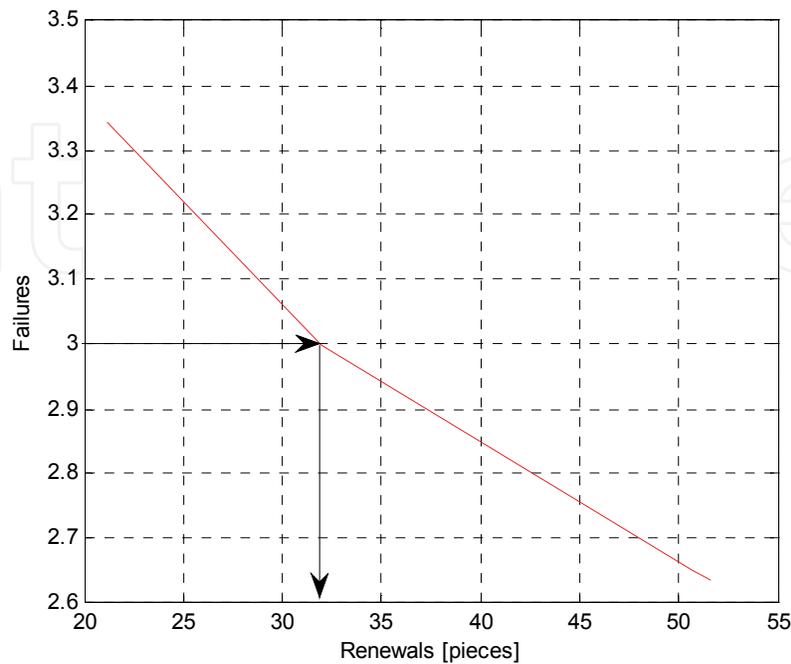


Fig. 10. Variation of the optimum number of renewals with the number of unplanned interruption

6.4 The model: Maximum safety and imposed costs

We determine the optimum number of renewals, to maximize the reliability of the OEL in conditions of total costs $TC(T,r)$ does not exceed a maximum value imposed TC^{max} .

In this hypothesis, the structure of mathematical model to be optimized is:

1. Vector of decision variable: $x \equiv r$ the number of renewals
2. Objective function: $\min\{F(x) = 1 - R_s(x)\}$

where:
$$F(x) = 1 - P_0 \cdot \exp\left(-\alpha(x+1)^{(1-\beta)} T^\beta\right) \quad (57)$$

3. Constraints of the model:

$$TC(x) \leq TC^{max}; \quad 0 \leq x \leq x^{max} \quad (58)$$

$$\begin{aligned} \text{or: } & P_0 \cdot \exp\left(-\alpha(x+1)^{(1-\beta)} T^\beta\right) \cdot \lambda_s \cdot T \cdot c_F + x \cdot c_{PM} + \\ & + P_{OEL} \cdot c_w \cdot \left(1 - P_0 \cdot \exp\left(-\alpha(x+1)^{(1-\beta)} T^\beta\right)\right) \cdot T \leq TC^{max}; \quad -x \leq 0; \quad x \leq x^{max}; \end{aligned} \quad (59)$$

with, x^{max} - the maximum imposed number of renewals.

By running the application program, for different values imposed for TC^{max} , we obtain the maximum reliability of the OEL, presented in Figure 11 and the optimum number of renewals required to achieve that reliability, presented in Figure 12.

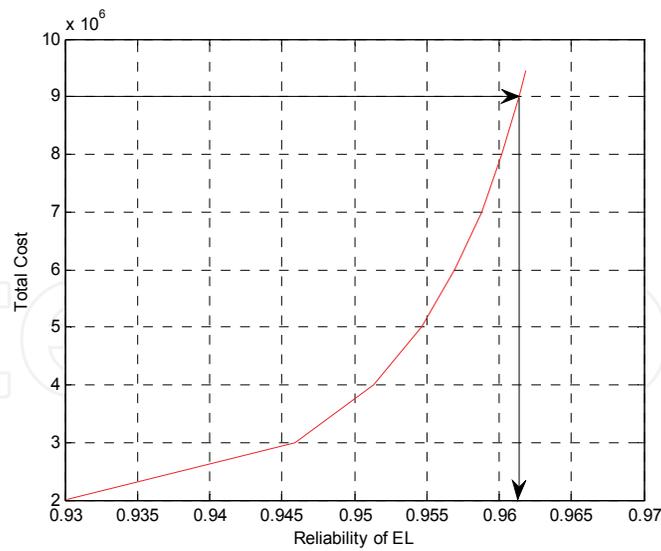


Fig. 11. Variation of the reliability of the OEL with TC^{max} imposed

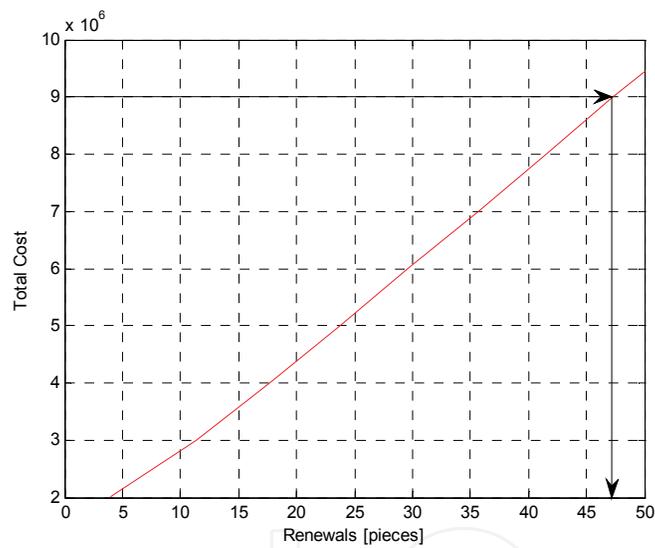


Fig. 12. Variation of the number of renewals with TC^{max} imposed

6.5 The model on components: The minimum costs and reliability imposed

We determine the optimum number of renewals on the three components of the OEL (pillars, conductors, and insulators), in the assumption of minimum total costs and on condition that the reliability of the OEL does not fall below an imposed value R_S^{\min} .

In this case, the structure of the mathematical model to be optimized will include the total costs $TC(T, r_i)$ corresponding to those three components.

1. In this case, the vector of variables to be optimized will have three components, corresponding to the number of renewals on the three components of the electric line: 1-pillars; 2-conductors; 3-insulators.

$$X = [x_1 x_2 x_3]^T \quad \text{with} \quad x_i \equiv r_i \quad | \quad i = 1, 2, 3$$

2. Objective function: $\min\{TC(X)\}$

where:

$$TC(X) = \sum_{i=1}^3 TC_i(X) \text{ where:}$$

$$TC_i(X) = P_{0i} \exp\left(-\alpha_i (x_i + 1)^{(1-\beta_i)} T^{\beta_i}\right) \cdot \lambda_i \cdot T \cdot c_{Fi} + x_i \cdot c_{PMi} +$$

$$+ P_{OEL} \cdot c_w \cdot \left(1 - P_{0i} \exp\left(-\alpha_i (x_i + 1)^{(1-\beta_i)} T^{\beta_i}\right)\right) \cdot T \quad (60)$$

3. Constraints of the model:

$$R_S(x) \geq R_S^{\min}; \quad 0 \leq x_i \leq x_i^{\max} \quad (61)$$

$$\text{or: } \prod_{i=1,2,3} P_{0i} \exp\left[-\alpha_i (x_i + 1)^{(1-\beta_i)} T^{\beta_i}\right] \geq R_S^{\min}; \quad -x_i \leq 0; \quad x_i \leq x_i^{\max}; \quad (62)$$

with: x_i^{\max} - the maximum imposed number of renewals on the i component for $|i=1, 2, 3$;

$\alpha_i; \beta_i; \lambda_i$ - the reliability parameters of components;

$c_{Fi}; c_{PMi}$ - the cost with the corrective and preventive maintenance on components.

where:

The reliability parameters of the components have the estimated values presented in the Table 2.

The maintenance costs of the components can be assessed as a percentage of the costs related to the maintenance on the electric line, in the absence of a database with the costs on the components.

By running the application program, for different values imposed to the reliability of the OEL, we obtain the optimum number of renewals $r_i^{\text{optim}} | i=1,2,3$; on each component of the OEL, to ensure the minimum reliability imposed R_S^{\min} , in the conditions of the minimum total cost TC, presented in Figure 13.

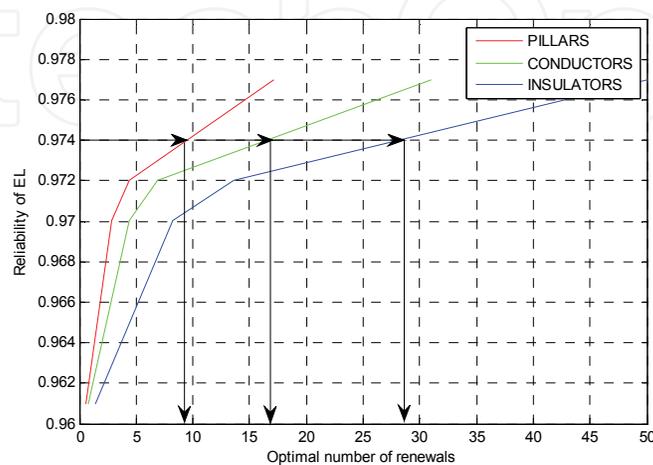


Fig. 13. Variation of the optimum number of renewals with the reliability imposed to the OEL

In conclusion, through the models of RCM optimization strategies that have been developed, we can obtain technical and economic information on the analysis, policy and planning maintenance actions for a period of time. This information pertains to:

- the optimum number of PMA on the components;
- the time interval between two actions;
- the optimum degree of safety in the electricity supply to consumers;
- the costs with preventive maintenance and/or corrective maintenance;
- the penalty costs due to improper maintenance.

7. RCM - maintenance management integrated software

Based on the algorithm for calculating and optimizing PM, presented in the previous sections, we propose an integrated model of software for the implementation and exploitation of the RCM. This model is specifically designed for OEL belonging to EDS.

To achieve the proposed information system we used the Matlab environment, because it offers the possibility to write and add programmes to the original files, allowing the development of the application characteristic to the EDS domain. The choice of Matlab was decisively influenced by the facilities offered by this environment in terms of achieving interactive user interfaces in the form of windows and menus, with the toolbox GUI (Graphical User Interface) and statistical processing with the Statistics Toolbox (Dulau et al., 2007), (Dulau et al., 2010).

For interactive control of various representations, we do the following steps:

- the application startup;
- choice and study of the OEL in operation according to the type of interruption;
- initialization and/or completing the database with the record of incidents;
- the reliability evaluation;
- the maintenance estimate by the preventive maintenance actions.

7.1 The application startup

The user interface that opens as a result of startup operations identifies two types of overhead electric lines, of 20 kV and 110 kV, and allows choosing the overhead electric line that will be examined by pressing the corresponding button, as in Figure 14 (Dulau et al., 2010).

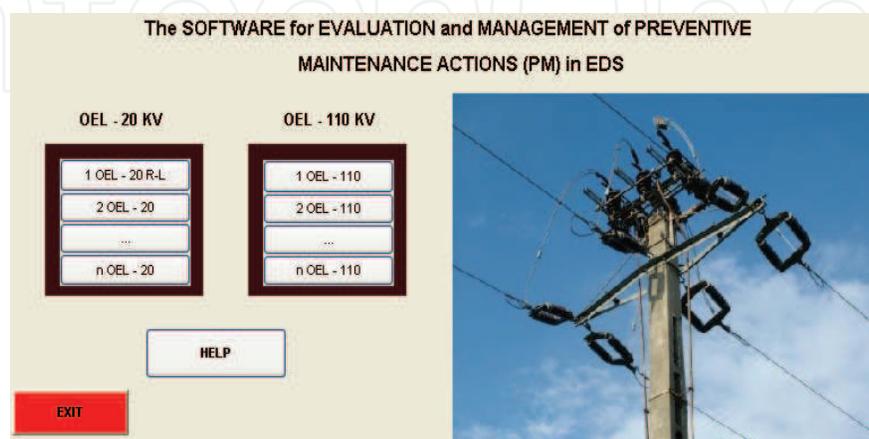


Fig. 14. User interface

7.2 Database of the events

Example: by selecting an OEL 20 KV, from the user interface, we obtain the technical and economical parameters of the OEL in a window. Further on, one is required to select the type of interruption to complete the database, corresponding to corrective maintenance or preventive maintenance, presented in the Figure 15.

The interface displays the title "PARAMETERS" and a dropdown menu set to "1 OEL - 20 KV R - L". On the left, there are three buttons: "UNPLANNED INTERRUPTIONS", "PLANNED INTERRUPTIONS", and a red "EXIT" button. On the right, a list of technical parameters is shown:

- Transmission length: 90,589 km
- Capacity: 8,6 MVA
- Simple concrete pillars: 840 pieces
- Special concrete pillars: 257 pieces
- Special metal pillars: 9 pieces
- Porcelain insulation: 1097 pieces
- Glass insulation: 10 pieces
- Conductor type: ACSR 50
- Ground sockets: 720 pieces

Fig. 15. User interface for line 1 OEL 20 kV

For each of the two possible directions, one must access the database for OEL and/or OEL component and fill in with technical and economic data corresponding to the type of interruption, presented in the Figure 16.

The interface is titled "INTERRUPTION PARAMETERS" and shows a dropdown menu for "1 OEL - 20 KV R - L". It contains several input fields and radio buttons:

- Day:** dropdown menu with "xx" selected.
- Month:** dropdown menu with "xx" selected.
- Year:** dropdown menu with "xxxx" selected.
- Duration:** input field with "xxxx" and "min." label.
- Costs:** input field with "xxxx" and "euro" label.
- Undelivered energy:** input field with "xxxx" and "kWh" label.
- Radio buttons:** "1. Pillar" (checked), "2. Conductor", and "3. Insulator".

At the bottom, there are two blue buttons: "EXPLANATIONS regarding to the INTERRUPTION" and "HISTORY of INTERRUPTIONS". A yellow "RESET" button is on the right, and a red "EXIT" button is at the bottom left.

Fig. 16. Interface for the database with the history of incidents and their update

7.3 Reliability evaluation

The database thus created allows moving on to the operations of estimation and graphical representation of the reliability of the system or of the studied component, based on data from historical events until that date presented in Figures 17, 18, 19, 20 (Dulau et al., 2007), (Dulau et al., 2010).

The numerical values associated data are saved in specific files of Matlab environment, respectively matrix or vectors.

All vectors are initialized and any subsequent call will add new data to existing ones and will save the new content.

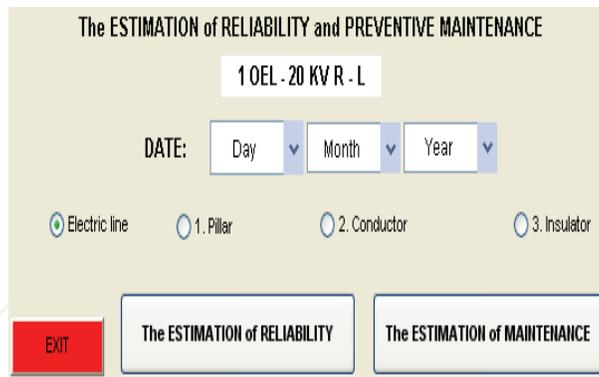


Fig. 17. RCM interface

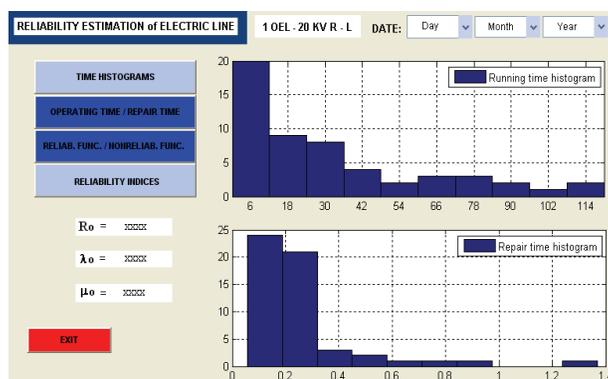


Fig. 18. Interface of the time histograms

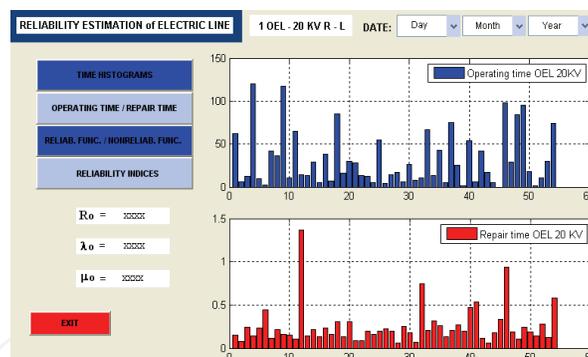


Fig. 19. Interface distribution of the operation times and repair times

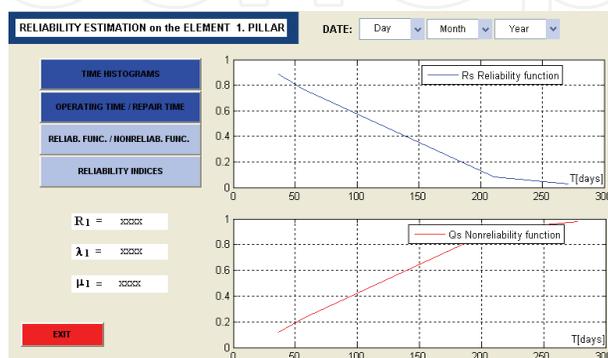


Fig. 20. Interface for the reliability and nonreliability functions

7.4 Preventive maintenance planning

The button MAINTENANCE ESTIMATION comand, presented in Figure 17, opens the interface for planning preventive maintenance for OEL or for its components, for a determined period and in the required technical and economic conditions, presented in Figure 21.

Fig. 21. Interface for planning PM on the OEL or its components

The influence of the number of renewals r [pieces], calculated on the OEL or on its components, allows a study of renewals influence on the reliability at the end of the period of study, presented in Figure 22.

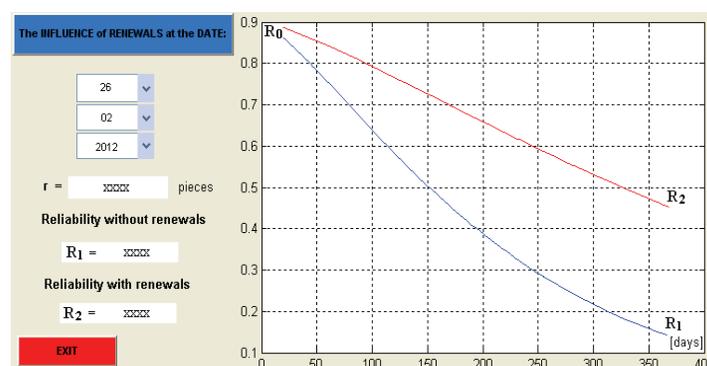


Fig. 22. Influence of the number of renewals

Do to its complexity, the developed program, which was conducted on the basis of theoretical considerations presented in previous sections, allows a much easier assessment of the reliability of the studied system and allows an optimization in planning PM, in different technical and/or economic situations.

8. Conclusions

The paper is the result of basic research in the field of operational research and maintenance management, with contributions and applications in optimization strategies of RCM for EDS. The contributions refer to the formulation the mathematical models of preventive maintenance strategies belonging to RCM, solving technical and economic objectives of the exploitation distribution systems and systems use electrical energy.

The optimal solutions to these models, with applications on a OEL 20KV as an EDS subsystem, allow a fundamental planning of RCM, through: setting the optimal number of future actions for the preventive maintenance PM, on overhead electric line or its

components; the optimal interval between actions; the optimum degree of safety in electricity supply; the optimal management of financial resources for RCM.

The results are summarized by an integrated software for the maintenance management, to manage the database regarding the history of events, as well as the RCM design and analysis. We consider the models presented can be developed in the following research directions: failure rate λ was considered constant throughout the PMA, although in reality it changes value after every action; the time between two successive renewals was considered constant, although it may be placed in the model, as a new variable to be optimized; in evaluation of costs did not take into account the influence of inflation, which could influence the results; last but not least, the lack of real databases, on technical and maintenance events, and their costs in relation to the components of the OEL.

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Dorin Sarchiz

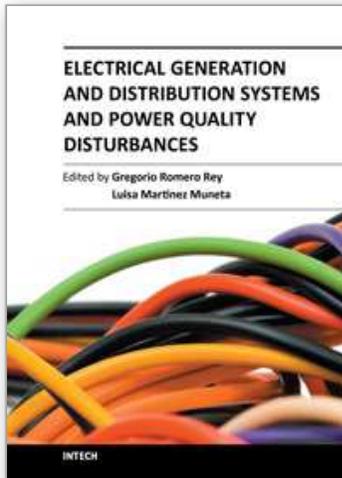
“Petru Maior” University of Targu Mures, Romania

10. References

- Anders, G., Bertling, L., & Li, W. (2007). *Tutorial book on Asset Management – Maintenance and Replacement Strategies at the IEEE PES GM 2007*, KTH Electrical Engineering, Stockholm, Sweden, Available from http://eeweb01.ee.kth.se/upload/publications/reports/2007/IRE-EE-ETK_2007_004.pdf
- Baron, T., Isaia-Maniu, A., & Tóvissi, L. (1988). *Quality and Reliability*, Vol. 1, Technical Publisher, Bucharest, Romania
- Bлага, P. (2002). *Statistics with Matlab*. “Babes-Bolyai” University, Cluj University Press, ISBN 973-610-096-0, Cluj-Napoca, Romania
- Catuneanu, V.M., & Popentiu, F. (1998). *Optimization of Systems Reliability*, Romanian Academy Publisher House, ISBN 973-27-0057-2, Bucharest, Romania
- Catuneanu, V.M., & Mihalache, A. (1983). *Theoretical Fundamentals of Reliability*, Romanian Academy Publisher House, Bucharest, Romania
- Dickey, J.M. (1991). The renewal function for an alternating renewal process, which has a Weibull failure distribution and a constant repair time, In: *Reliability Engineering & System Safety*. Vol. 31, Issue 3, 1991, pp.321-343
- Dub, V. (2008). *System Reliability*, Didactic and Pedagogic Publisher, ISBN 978-973-30-2371-5, Bucharest, Romania
- Dulau, M., Dub, V., Sarchiz, D., & Georgescu, O. (2007). Informatic system for preventive maintenance actions in electric systems, In: *Proceedings of the 3rd International symposium on modeling, simulation and system's identification SIMSIS 13*, September 21-22, 2007, “Dunarea de Jos” University of Galati, ISBN 978-973-88413-0-7, pp.203-208, Galati University Press, ISSN 1843-5130
- Dulau, M., Sarchiz, D., & Bucur, D. (2010). Expert system for Maintenance Actions in Transmission and Distribution Networks, In: *Proceedings of the 3rd International*

- Conference on Power Systems MPS 2010.*, Acta Electrotehnica Journal, Academy of Technical Sciences of Romania, Technical University of Cluj-Napoca, Vol. 51, No. 5, 2010, Mediamira Science Publisher, pp.134-137, ISSN 1841-3323
- Georgescu, O. (2009). *Contributions to maintenance of electric power distribution*. PhD Thesis, "Transilvania" University, Brasov, Romania, Available from <http://www.unitbv.ro/biblio>
- Georgescu, O., Sarchiz, D., & Bucur, D. (2010). Optimization of reliability centered maintenance (RCM) for power transmission and distribution networks, In: *CIREC Workshop - Lyon, 7-8 June 2010, Sustainable Distribution Asset Management & Financing.*, ISSN 2032-9628, Available from <http://www.cired2010-workshop.org/pages/012/title/Home.en.php>
- Hilber, P. (2008). *Maintenance Optimization for Power Distribution Systems*. PhD Thesis, defended 18th of April 2008, KTH, Stockholm, Sweden, ISBN 978-91-628-7464-3
- IEC 61649, International Standard, Edition 2.0, 2008-08, *Weibull analysis*, ISBN 2-8318-9954-0
- IEC 60300-3-11, International Standard, Edition 2.0, 2009-06, *Application Guide-Reliability centred maintenance*, ISBN 2-8318-1045-3
- Mahdavi, M., Mahdavi, M. (2009). Optimization of age replacement policy using reliability based heuristic model, In: *Journal of Scientific & Industrial Research*, Vol.68, August 2009, pp. 668-673
- Sarchiz, D. (1993). *Optimization of the Electric Power Systems*, Multimedia System Publisher, ISBN 973-96197-9-7, Targu-Mures, Romania
- Sarchiz, D. (2005). *Optimization of the Electric System Reliability*, Matrixrom Publisher, ISBN 973-685-990-8, Bucharest, Romania
- Sarchiz, D., Bica, D., & Georgescu, O. (2009). Mathematical model of reliability centred maintenance (RCM)-Power transmission and distribution networks application, In: *2009 IEEE Bucharest Power Tech Conference.*, ISSN 978-1-4244-2235-7, Available from <http://ieeexplore.org/search/freeresearchresult.jsp?newsearch=true&queryText=sarchiz&x=39&y=4>
- Teresa Lam, C., Yeh, R.H. (1993). Comparison of Sequential and Continuous Inspection Strategies for Deteriorating Systems, In: *Department of Industrial and Operations Engineering*, The University of Michigan. Technical Report No: 92-22, Available from <http://www.jstor.org/pss/1427444>

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The utilization of renewable energy sources such as wind energy, or solar energy, among others, is currently of greater interest. Nevertheless, since their availability is arbitrary and unstable this can lead to frequency variation, to grid instability and to a total or partial loss of load power supply, being not appropriate sources to be directly connected to the main utility grid. Additionally, the presence of a static converter as output interface of the generating plants introduces voltage and current harmonics into the electrical system that negatively affect system power quality. By integrating distributed power generation systems closed to the loads in the electric grid, we can eliminate the need to transfer energy over long distances through the electric grid. In this book the reader will be introduced to different power generation and distribution systems with an analysis of some types of existing disturbances and a study of different industrial applications such as battery charges.

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