OPTIMIZATION OF ELECTRICAL DISTRIBUTION SYSTEMS MAINTENANCE USING RELIABILITY CENTERED MAINTENANCE

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REZUMAT. Lucrarea dezvoltă un model matematic de stabilire a numărului optim de intervenţii, numite reînnoiri, pentru mentenanţa preventivă a sistemelor de distribuţie a energiei electrice. Modelul are la baza sa, funcţia de fiabilitate de tip Weibull, stabilită pentru sistemul în studiu, în baza datelor statistice privind incidenţele, intervenţiile şi costurile acestora. Modelul optimizării fiabilităţii bazate pe mentenanţă, este aplicat pe o linie electrică aeriană LEA 20 kV şi a fost soluţionată în baza mediului de programare MATLab 7.0.

Cuvinte cheie: fiabilitate, mentenanţă, reînnoire, optimizare, costuri, aplicaţii MATLab 7.0.

ABSTRACT. The paper develops a mathematical model for determining the optimal number of interventions, called renewals, for preventive maintenance of electrical power distribution. The model its based on its type Weibull reliability function which was established for the study system, based on statistical data on incidence, interventions and their cost. The optimization model of maintenance based on reliability has been applied to the situation to a 20 kV overhead transmission line and was resolved in the programming environment MATLab 7.0.

Keywords: reliability, maintenance, renewal, optimization, costs, MATLab 7.0 application.

1. INTRODUCTION

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 safty, 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.

T^{-} — System Reliability — T^{0} — System Maintenance — T^{+}

- t «____________________|____________________» +t

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.

2. RELIABILITY MODELING EDS

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):

$$R(t,\alpha,\beta)=e^{-\alpha\cdot t^{\beta}} \quad (1)$$

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 (1) 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.

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.

Table 1

Incidents database

Nr	1	2	3	4	5	6	7	8	9	10
t_i	62	68	80	200	210	212	254	290	407	418
t_{ri}	213	118	352	209	339	640	165	305	229	215

…	48	49	50	51	52	53	54
…	1483	1578	1596	1597	1608	1638	1712
…	150	343	270	200	403	178	841

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 α and β parameters with two parameters of Weibull law by the form of relationship (1), based on statistical data obtained from the analysis of operating arrangements of the OEL, as well as in the following assumptions:

a). there are significant records concerning the concerning to the number of defects and the operating times between them;

b). the average recovery times are negligible compared with the operating times.

For the OEL 20 KV in study, by replacing the parameters from Table 1 in the previous relations, the following values of parameters of the Weibull function distribution result:

$$\alpha = 1.2669 \cdot 10^{(-4)} \text{ and } \beta = 1.2939 \qquad (2)$$

Which allows modeling the reliability function *R(t)* of OEL the through the relationship:

$$R(t) = e^{-1.2669 \cdot 10^{(-4)} \cdot t^{1.2939}} \qquad (3)$$

and the graph presented in Figure 2.

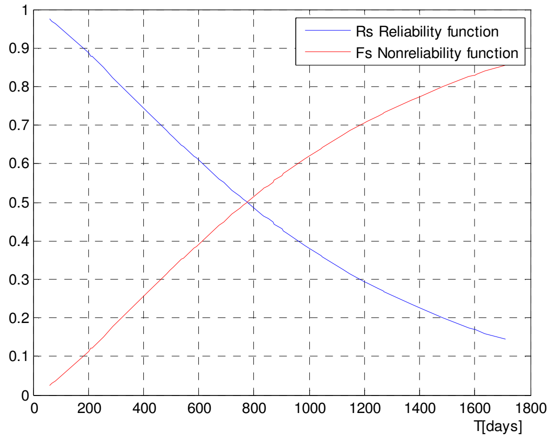

Fig. 2. Variation of reliability functions and failure probability

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 (3), with two parameters α, β, 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] = 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%.

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 essembly which composes the OEL. The OEL 20 KV is studied as a reparable 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 tfi operating times with tri and repair times, for which, the following indices of reliability can be defined and calculated:

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

$$MTBF = \frac{\sum_{i=1}^{n} t_{fi}}{n} \,[day] \quad \text{with } t_{fi} = t_i - t_{i-1};\ MTBF = 31.7037\,[day] \qquad (4)$$

- λ, failure rate,

$$\lambda = \frac{1}{MTBF}\,[day^{-1}];\ \lambda = 0.031542\,[day^{-1}] \qquad (5)$$

- MTTR, Mean Time Repair,

$$MTTR = \frac{\sum_{i=1}^{n} tr_i}{n-1}\,[day];\ MTTR = 0.2506\,[day] \qquad (6)$$

- μ, repair rate,

$$\mu = \frac{1}{MTTR}\,[day^{-1}];\ \mu = 3.9897\,[day^{-1}] \qquad (7)$$

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 (β=1.2939), β=1, we used the relationships of availability associated with the exponential distribution with operating times and repair times.

- P, success probability,

$$P = \frac{\mu}{\lambda + \mu};\ P = 0.9922 \qquad (8)$$

- Q, failure probability,

$$Q = \frac{\lambda}{\lambda + \mu} \quad \text{or} \quad Q = 1 - P \qquad (9)$$

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

$$M(\alpha(t)) = P \cdot T \qquad (10)$$

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

$$M(\beta(t)) = Q \cdot T = (1 - P) \cdot T \qquad (11)$$

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

$$M(\gamma(t)) = \lambda \cdot P \cdot T = \mu \cdot Q \cdot T \qquad (12)$$

3. RENEWALS MODELING

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: $x_1, x_2, \dots, x_n \dots$ presented in the Figure 2.

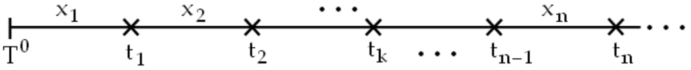

Fig. 3. The evolution of an equipment with renewal

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.

In accordance with the information presented in section 2, 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:

a) The system is in operation, and has the probability function P0 (T^0), known by the relationship (8);

b) The law of variation of system reliability is know, being expressd by he relationship (3);

c) 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:

Modeling on a time interval

In the conditions of preventive maintenance actions for a period of [0, ΔT], 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:

$$R(r, \Delta T) = \exp\left(-\alpha (r+1)^{(1-\beta)} \cdot \Delta T^{\beta}\right) \quad (13)$$

Where: α; β - Weibull parameters, the relationship (2);
r – the number of preventive renewals during the study ΔT. Figure 4 illustrates the graph in the case of the OEL in study, with the parameters given in the relations (3) and (8) with he purpose of exemplifying the variation of the reliability function R(r,ΔT), 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 P0 (t) = 0.9922.

$$R(r, \Delta T) = P_0(t) \cdot \exp\left(-\alpha (r+1)^{(1-\beta)} \cdot \Delta T^{\beta}\right) \quad (14)$$

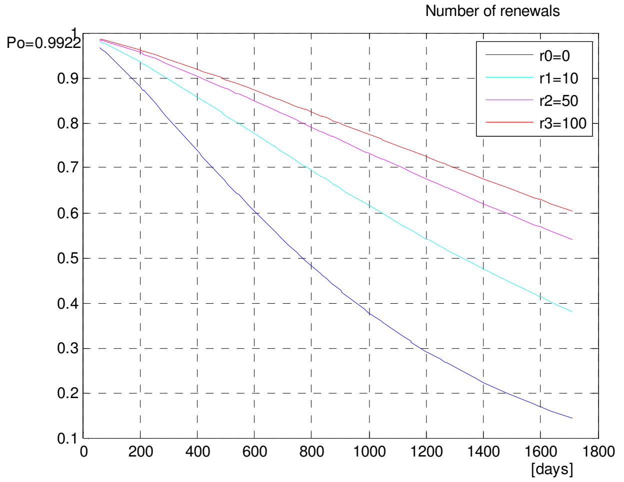

Fig. 4. The influence of the renewals r on the reliability of the OEL 20 kV

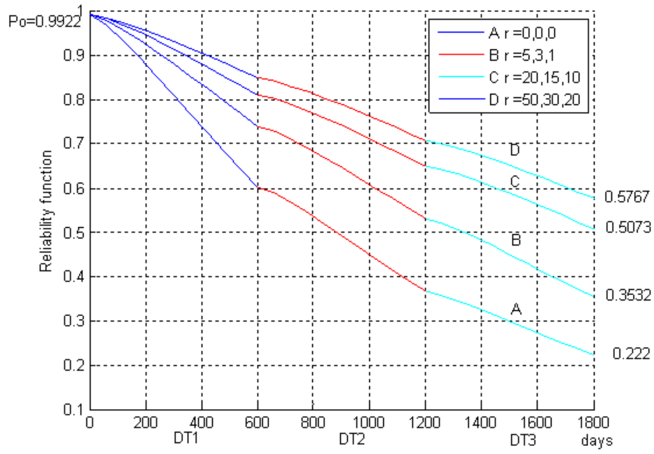

Fig. 5. Variation of reliability over time periods $\Delta T \;|i=1,2,3$

From the graphic of Figure 4, we note an increase reliability of the OEL at the end of the period ΔT, under the influence of renewals r0, r1, r2, r3.

Modeling over n time intervals

Let us study the variation probability for a system operating with PM, over a period of time Tn, composed of n time intervals ΔTi. A number ri of renewals is performed over each interval ΔTi for i=1,n, while the reliability of system at the beginning of the interval ΔT1 is known Po|t=0.

$$R(T_n) = P_o(t)\prod_{i=1}^{n} R_i(r_i, \Delta T_i) \qquad (15)$$

Where:

$$R_i(r_i, \Delta T_i) = \exp\left[-\alpha(r_i+1)^{(1-\beta)} \cdot \Delta T_i^{\beta}\right] \quad |i = 1,n \qquad (16)$$

Or:

$$R(T_n) = P_0(t)\prod_{i=1}^{n} \exp\left[-\alpha(r_i+1)^{(1-\beta)} \cdot \Delta T_i^{\beta}\right] \qquad (17)$$

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 ΔTi = 600 days |i=1,2,3;
- For each period i having a number rij | j = 1, 2, 3 renewals, or:
- ΔT1 | r1 = 0,5,20,50; ΔT2 | r2 = 0,3,15,30; ΔT3 | r3 = 0,1,10,20;

With the parameters given in relations (3) and (8), we obtain the graph of variation presented in Figure 5:

From the graph of Figure 5, we note an increased reliability of OEL at the end of the three periods ΔTi | i = 1, 2, 3, under the influence of 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.

Total costs

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

- CF - the costs due to corrective maintenance actions;
- CPM – the costs due to preventive maintenance actions;
- CINT – the costs due to unplaned intrreruptions.

Or:

$$TC(r) = C_F(r) + C_{PM}(r) + C_{INT}(r) \quad [cost/year] \qquad (18)$$

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.

Costs with unplanned interruptions

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

$$C_F(r) = N_F \cdot c_F \qquad (19)$$

where: NF, average number of failures for the reference interval ΔT from the relation (12),

Or:

$$N_F = R_S \cdot \lambda_S \cdot \Delta T \qquad (20)$$

Where:

$$R_S = P_0 \cdot \exp\left(-\alpha(r+1)^{(1-\beta)} \cdot \Delta T^{\beta}\right) \qquad (21)$$

from the relationship (13).

α ; β - Weibull parameters, the relationship (2);

λS - the failure rate of a EDS, considered constant during the study ΔT, OEL being half way through its life cycle, the relationship (5);

cF - the average cost to fix a failure.

Or:

$$C_F(r) = P_0 \cdot \exp\left(-\alpha(r+1)^{(1-\beta)} \cdot \Delta T^{\beta}\right) \cdot \lambda_S \cdot \Delta T \cdot c_F \qquad (22)$$

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:

$$C_{PM}(r) = r \cdot c_{PM} \qquad (23)$$

with: cPM - average cost of a preventive renewal.

Penalty costs

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

- PENS - proportional with the time of interruption TF, for undelivered electricity at the average power on OEL by POEL, and
- PENU - for unrealized production during interruption by the electricity consumer connected to the OEL.

$$C_{INT}(r) = PEN_S + PEN_U \qquad (24)$$

With:

$$PEN_S = P_{OEL} \cdot c_w \cdot T_F \qquad (25)$$

$$PEN_U = \sum_{k=1}^{K} P_k \cdot c_k \cdot T_F \qquad (26)$$

Where:

POEL - average power on OEL; Pk - average power at the k consumer; cW - electricity cost;

ck - production cost unrealized for a kilowatt hour of electricity undelivered, at the k consumer; TF - total average duration of OEL nonoperation during the reference period ΔT, relation (11); K - number of consumers connected to the OEL in the study.

With:

$$T_F = (1 - R_S) \cdot \Delta T \qquad (27)$$

By replacing the relations established in (24), it follows:

$$C_{INT}(r) = \left(P_{OEL} \cdot c_w + \sum_{k=1,K} P_k \cdot c_k\right) \cdot \left(1 - P_0 \cdot \exp\left(-\alpha(r+1)^{(1-\beta)} \cdot \Delta T^{\beta}\right)\right) \cdot \Delta T \qquad (28)$$

By replacing the relations (22), (23) and (28) in relation (18), 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.

$$\begin{aligned} TC_{(r)} &= P_0 \cdot \exp\left(-\alpha(r+1)^{(1-\beta)} \cdot \Delta T^{\beta}\right) \cdot \lambda_S \cdot \Delta T \cdot c_F + r \cdot c_{PM} + \\ &+ \left(P_{OEL} \cdot c_w + \sum_{k=1,K} P_k \cdot c_k\right) \cdot \left(1 - P_0 \cdot \exp\left(-\alpha(r+1)^{(1-\beta)} \cdot \Delta T^{\beta}\right)\right) \cdot \Delta T \end{aligned} \qquad (29)$$

With the following specifications on the relashionsip (29).

1. The term (26) 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 ck;
2. To certain categories of electricity consumers, the higher production losses occur depending on the number of interruptions NF during ΔT and less influence on time of interruption TF;
3. In a system with multiple components, each having a specific number of renewals ri, the total costs are the sum of costs on each system element.

4. 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, (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.

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, 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:

$$\min\{TC(T,r)\} \qquad (30)$$

in presence of technical constraints imposed on safety criteria:

$$R_S(t,r) \ge R_S^{min} \quad \text{or} \quad N_F(t,r) \le N_F^{max} \qquad (31)$$

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 tehnical criterion, aims to maximize safety in operation, respectively of system reliability on interval (0, T).

$$\max\{R_S(T,r)\} \quad \text{or} \quad \min\{1-R_S(T,r)\} \qquad (32)$$

in presence of economic constraints due to maintenance actions:

$$TC(T,r) \le TC^{max} \qquad (33)$$

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 (30) and (32), 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, for an OEL component and it can take one of the following forms:

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 $\Delta t = T / r$ or

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

- The technical parameters of OEL are given in the relations: (3); (5); (7);

- We admit an average power on OEL per year: POEL = 5.16 MW;

- the values of the economic parameters are only calculation values given in monetary units [m.u.];

cF = 1000 m.u. ; cPM = 17500 m.u.; cW = 530 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 PENU component from the relation (26), 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 (30) or (32) 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 Toobox\procedure fmincon.

The design of preventive strategies for renewal by type (30) or (32) can be done based on different criteria, which will be listed below within each RCM model optimization strategies.

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 away that OEL relaibility 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 ≡ r the number of renewals

2. Objective function:

$$\min\{TC(x)\}$$

$$\text{where: } TC(x) = P_0 \cdot \exp\left(-\alpha (x+1)^{(1-\beta)} T^{\beta}\right) \cdot \lambda_S \cdot T \cdot c_F + x \cdot c_{PM} + P_{OEL} \cdot c_W \cdot \left(1 - P_0 \cdot \exp\left(-\alpha \cdot (x+1)^{(1-\beta)} T^{\beta}\right)\right) \cdot T \qquad (34)$$

3. Constraints of the model:

$$R_S(x) \ge R_S^{min}; \quad 0 \le x \le x^{max} \qquad (35)$$

or: $$P_0 \cdot \exp\left(-\alpha(x+1)^{(1-\beta)}T^{\beta}\right) \geq R_S^{min}; \; -x \leq 0; \; x \leq x^{max} \quad (36)$$

with xmax – 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 ropt, for PM of OEL during a year, in conditions of the minimum total cost TC (T,r), presented in Figure 6, i.e. the graph $r^{opt} = f\left(R_S^{min}\right)$. 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.: $TC = f\left(R_S^{min}\right)$ or $TC = f\left(r^{opt}\right)$.

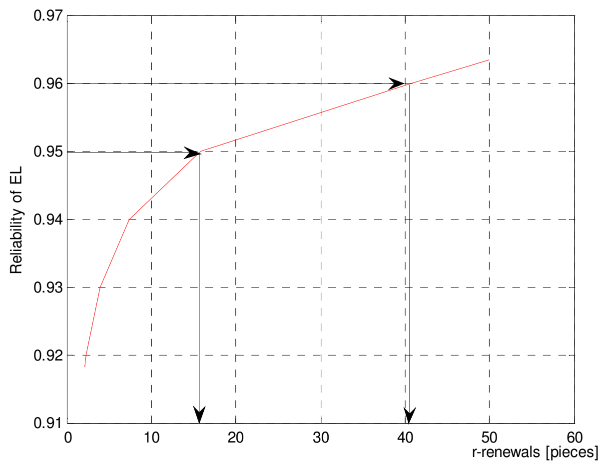

Fig. 6. Variation of the optimum number of renewals with reliability imposed to the OEL

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) NF 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 ≡ r the number of renewals

2. Objective function:

$$\min\{TC(x)\}$$

where: $$TC(x) = P_0 \cdot \exp\left(-\alpha(x+1)^{(1-\beta)}T^{\beta}\right) \cdot \lambda_S \cdot T \cdot c_F + x \cdot c_{PM} + P_{OEL} \cdot c_w \cdot \left(1 - P_0 \cdot \exp\left(-\alpha(x+1)^{(1-\beta)}T^{\beta}\right)\right) \cdot T \quad (37)$$

3. Constraints of the model:

$$N_F(x) \leq N_f^{max}; \quad 0 \leq x \leq x^{max} \quad (38)$$

Or:

$$P_0 \cdot \exp\left(-\alpha(x+1)^{(1-\beta)}T^{\beta}\right) \cdot \lambda_s \cdot T \leq N_F^{max}; \; -x \leq 0; \; x \leq x^{max} \quad (39)$$

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 7, i.e. ropt = f(NF).

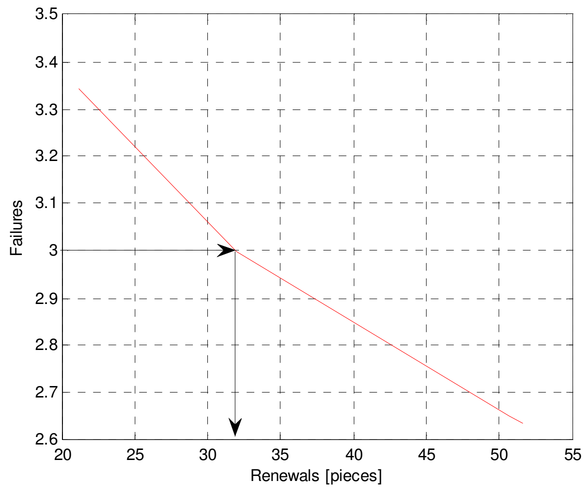

Fig. 7. Variation of the optimum number of renewals with the number of unplanned interruption

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 ≡ r the number of renewals

2. Objective function:

$$\min\{F(x) = 1 - R_S(x)\}$$

Where:

$$F(x) = 1 - P_0 \cdot \exp\left(-\alpha(x+1)^{(1-\beta)}T^{\beta}\right) \quad (40)$$

3. Constraints of the model:

$$TC(x) \leq TC^{max}; \quad 0 \leq x \leq x^{max} \quad (41)$$

Or:

or: $$P_0 \cdot \exp\left(-\alpha(x+1)^{(1-\beta)}T^{\beta}\right) \cdot \lambda_s \cdot T \cdot c_F + x \cdot c_{PM} + P_{OEL} \cdot c_w \cdot \left(1 - P_0 \cdot \exp\left(-\alpha(x+1)^{(1-\beta)}T^{\beta}\right)\right) \cdot T \leq TC^{max}; \; -x \leq 0; \; x \leq x^{max}; \quad (42)$$

with, xmax – 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 8 and the optimum number of renewals required to achieve that reliability, presented in Figure 9.

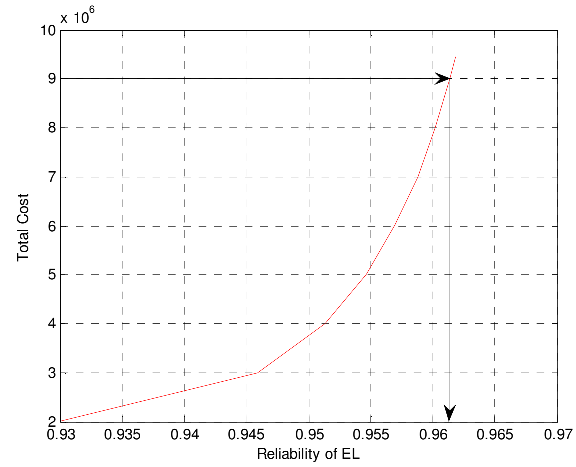

Fig. 8. Variation of the reliability of OEL with TC^{max} imposed

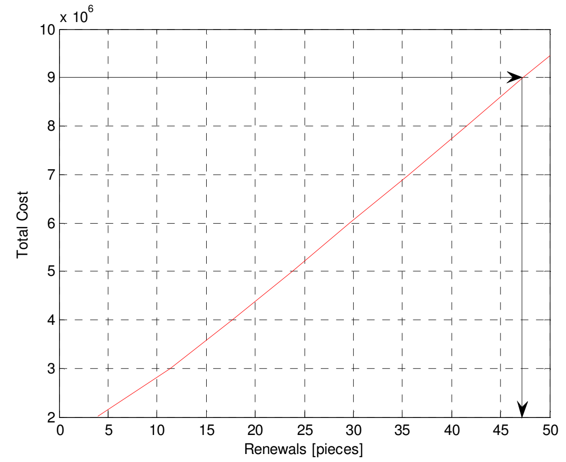

Fig. 9. Variation of the number of renewals with TC^{max} imposed

The model on components: The minimun 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,ri) 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.

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

2. Objective function:

$$\min\{TC(x)\}$$

Where:

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

$$TC_i(X) = P_{0i}\exp\left(-\alpha_i(x_i+1)^{(1-\beta i)}T^{\beta i}\right)\cdot\lambda_i\cdot T\cdot c_{Fi} + x_i\cdot c_{PMi} + P_{OEL}\cdot c_W\cdot\left(1-P_{0i}\exp\left(-\alpha_i(x_i+1)^{(1-\beta i)}T^{\beta i}\right)\right)\cdot T \quad (43)$$

3. Constraints of the model:

$$R_S(x) \geq R_S^{min}; \quad 0 \leq x_i \leq x_i^{max} \quad (44)$$

$$\text{or: } \prod_{i=1,2,3}\left[P_{0i}\exp\left[-\alpha_i(x_i+1)^{(1-\beta i)}T^{\beta i}\right]\geq R_S^{min}; \; -x_i \leq 0; \; x_i \leq x_i^{max}; \quad (45)$$

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 parametres 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.

Table 2

Reliability parameters of OEL components

i	Element	R_{0i}	$\alpha_i * 10^{-4}$	β_i	r_i[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

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

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 rioptim | 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 10.

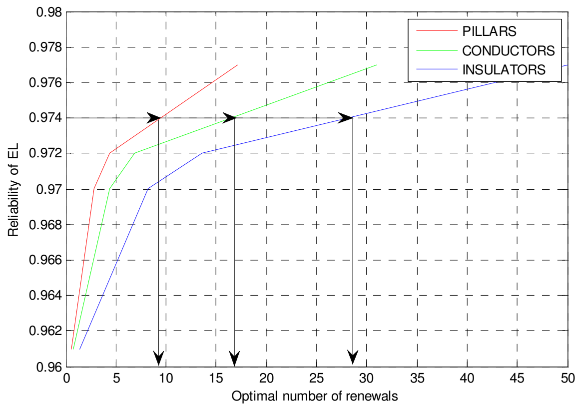

Fig. 10. Variation of the optimum number of renewals with the reliability imposed to the OEL

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.

6. 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 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.

BIBLIOGRAPHY

[1] **Anders, G., Bertling, L., & Li, W.** 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, (2007).

[2] **Baron, T., Isaia-Maniu, A., Tővissi, L.** *Quality and Reliability*, Vol. 1, Technical Publisher, Bucharest, Romania, (1988).

[3] **Catuneanu, V.M., & Popentiu, F.** *Optimization of Systems Reliability*, Romanian Academy Publisher House, ISBN 973-27-0057-2, Bucharest, Romania, (1998).

[4] **Catuneanu, V.M., & Mihalache, A.** *Theoretical Fundamentals of Reliability*, Romanian Academy Publisher House, Bucharest, Romania, (1983).

[5] **Dickey, J.M.** *The renewal function for an alternating renewal process, wich has a Weibull failure distribution and a constant repair time*, In: Reliability Engineering & System Safety. Vol. 31, Issue 3, 1991, pp.321-343.

[6] **Dulau, M., Sarchiz, D., Bucur, D.** 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 Techinal Sciences of Romania, Technical University of Cluj-Napoca, Vol. 51, No. 5, 2010, Mediamira Science Publisher, pp.134-137, ISSN 1841-3323.

[7] **IEC 61649**, International Standard, Edition 2.0, 2008-08, *Weibull analysis*, ISBN 2-8318-9954-0.

[8] **IEC 60300-3-11**, International Standard, Edition 2.0, 2009-06, Application Guide-*Reliability centred maintenance*, ISBN 2-8318-1045-3.

[9] **Georgescu, O.** *Contributions to maintenance of electric power distribution*. PhD Thesis, "Transilvania" University, Brasov, Romania, (2009). Available from http://www.unitbv.ro/biblio.

[10] **Sarchiz, D.** *Optimization of the Electric System Reliability*, Matrixrom Publisher, ISBN 973-685-990-8, Bucharest, Romania, (2005).

[11] **Sarchiz, D., Dulau, M., Bucur, D., Georgescu, O.** Book Chapter *Reliability Centered Maintenance Optimization of Electric Distribution Systems* in the book "Electrical Generation and Distribution Systems and Power Quality Disturbances" edited by Gregorio Romero Rey and Luisa Martinez Muneta, ISBN 978-953-307-329-3, InTech, November 11, 2011.

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